SECOND EDITION

PNEUMATIC CONVEYING DESIGN GUIDE

DAVID MILLS

Pneumatic Conveying Design Guide

This page intentionally left blank

Pneumatic Conveying Design Guide

Second Edition

David Mills

ELSEVIER
BUTTERWORTH
HEINEMANN

AMSTERDAM BOSTON HEIDELBERG LONDON NEW YORK OXFORD PARIS
SAN DIEGO SAN FRANCISCO SINGAPORE SYDNEY TOKYO

Elsevier Butterworth-Heinemann
Linacre House, Jordan Hill, Oxford OX2 8DP
200 Wheeler Road, Burlington, MA 01803

First published 1990
Second edition 2004

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging in Publication Data
A catalog record for this book is available from the Library of Congress

ISBN 0 7506 5471 6

Typeset by Charon Tec Pvt Ltd, Chennai, India
Printed and bound in Great Britain

Contents

This page intentionally left blank

Preface

For this second edition of the *Pneumatic Conveying Design Guide* I have followed a similar format to the first edition, in that it is in three parts plus appendices. There the similarity ends, however, for the material within these parts has been completely updated, substantially extended and re-developed to make it more accessible. The figures and illustrations are incorporated into the text for easy reference and the work is presented in a single volume.

The first part of the *Design Guide* is devoted to Systems and Components and general information on pneumatic conveying. This provides an understanding of dilute and dense phase conveying modes, solids loading ratio and the influence of pressure and conveying distance, and hence pressure gradient, on flow mechanisms and capabilities. It also provides a review of major system types, feeding devices, air movers and filtration devices. A multitude of decisions have to be made with regard to the selection of a conveying system for a given duty and these chapters will be invaluable in this process. The new book brings all this information right up to date. Feeding devices are covered in two chapters and are divided between high and low pressure (including vacuum) systems, following developments in this area with regard to blow tanks, rotary valves and the application of lock hoppers. A completely new chapter has been included on pipelines and valves, which is probably unique, and reinforces the very practical approach of the book.

The second part of the *Design Guide* is devoted entirely to System Design and is an entirely new and updated presentation. In this second edition I have incorporated the main features of the Abbreviated Design Guide in two case studies. These help to reinforce the application of the scaling parameters and design procedures that are presented. Particular emphasis is placed on material types and conveying capability, since this is where there have been major advancements in the understanding of the technology. Different grades of exactly the same material can give totally different conveying results and so this aspect of conveying performance is highlighted. Entire chapters are devoted to topics such as First Approximation Design Methods and Multiple Use Systems. For feasibility studies, a quick solution is often required so that system economics can be assessed and particularly operating costs. There is often a need for a single system to convey a number of different materials, and possibly to a number of different locations, and these design issues are addressed.

The third part of the *Design Guide* is devoted to System Operation and covers a multitude of very practical operational issues, such as damage to the plant when conveying abrasive materials, and damage to the conveyed material by the conveying plant when handling friable materials. I have re-written the first edition chapters and have included additional chapters on Moisture and Condensation, and Health and Safety. This part of the book will be invaluable to any engineer who has to commission a pneumatic conveying system or is responsible for the maintenance and operation of such systems. Pneumatic conveying systems have a reputation for their operational difficulties and so problems of pipeline blockages and systems not capable of meeting the required duty are considered in detail. The twin problems of erosive wear and particle degradation are also considered in depth, with numerous means presented on how these problems can be minimized, if not eliminated.

I have included two Appendices: one is concerned with the determination of material properties; and the other contains additional data not incorporated in the text. A particular feature of the *Design Guide* is that it provides an understanding of the relationship between the conveying capability of a given bulk particulate material and measurable properties of the material. A correlation is included that will give a reasonably reliable indication of whether a material is capable of being conveyed in dense phase and hence at low velocity. A vast amount of practical data, in the form of conveying characteristics, is included and throughout the book this data has been used to illustrate the derivation of scaling parameters and performance capabilities. This data, and that included in the second appendix, can be used for design purposes.

The main design and operating parameter required by engineers working with pneumatic conveying systems is the value of the minimum conveying air velocity for a material. I have provide this information for all materials included in the *Design Guide* and have given guidelines for its assessment for any that are not. Pipeline bends, stepped pipelines, conveying through flexible hoses, and conveying both vertically up and down are all issues that tend to cause problems. These pipeline features influence all aspects of pneumatic conveying and are addressed at appropriate points throughout the *Design Guide*.

I have been working in the field of pneumatic conveying for thirty years. In this time I have written over 170 technical papers for journals and conferences, I have supervised numerous PhD programmes and have presented many short courses to industry. My own PhD was on the erosive wear of bends in pneumatic conveying system pipelines. I was then commissioned by the Department of Trade and Industry to write the original Pneumatic Conveying *Design Guide*. In 1988 I was appointed Professor of Bulk Solids Handling at Glasgow Caledonian University and since 1996 I have worked as an independent consultant in pneumatic conveying.

Dr David Mills
Canterbury
July 2003

Part A

Systems and Components

This page intentionally left blank

Chapter 1

Introduction to pneumatic conveying and the guide

1.1 Introduction

The Pneumatic Conveying Design Guide is intended to be of use to both designers and users of pneumatic conveying systems. It has been written on the basis that the reader knows little or nothing about pneumatic conveying or pneumatic conveyors, hence each aspect of the subject is discussed from basic principles and many of the chapters are of an introductory nature. The Guide, however, also includes detailed data and information on the conveying characteristics of a number of materials embracing a wide range of properties.

The data can be used to design pneumatic conveying systems for the particular materials, using logic diagrams for design procedures, and scaling parameters for the conveying line configuration. Where pneumatic conveyors already exist, the improvement of their performance is considered, based on strategies for optimizing and up-rating, and the extending of systems or adapting them for a change of material is also considered.

In this introductory chapter a brief introduction to pneumatic conveying is given to introduce the common terms and concepts. First among these are dilute and dense phase conveying and the specific problem of compressibility of air and other gases that might be used. The capability of pneumatic conveying systems in terms of distance, tonnage and orientation are addressed, together with a brief history of developments. A very brief review of the chapters is given, along with some of the basic definitions, and the nomenclature adopted in the book is presented here for reference.

1.2 Pneumatic conveying

Pneumatic conveying systems are basically quite simple and are eminently suitable for the transport of powdered and granular materials in factory, site and plant situations. The system requirements are a source of compressed gas, usually air, a feed device, a conveying pipeline and a receiver to disengage the conveyed material and carrier gas.

The system is totally enclosed, and if it is required, the system can operate entirely without moving parts coming into contact with the conveyed material. High, low or negative pressures can be used to convey materials. For hygroscopic materials dry air can be used, and for potentially explosive materials an inert gas such as nitrogen can be employed. A particular advantage is that materials can be fed into reception vessels maintained at a high pressure if required.

1.2.1 System flexibility

With a suitable choice and arrangement of equipment, materials can be conveyed from a hopper or silo in one location to another location some distance away. Considerable flexibility in both plant layout and operation are possible, such that multiple point feeding can be made into a common line, and a single line can be discharged into a number of receiving hoppers. With vacuum systems, materials can be picked up from open storage or stockpiles, and they are ideal for clearing dust accumulations and spillages.

Pipelines can run horizontally, as well as vertically up and down, and with bends in the pipeline any combination of orientations can be accommodated in a single pipeline run. Conveying materials vertically up or vertically down presents no more of a problem than conveying horizontally. Material flow rates can be controlled easily and monitored to continuously check input and output, and most systems can be arranged for completely automatic operation.

Pneumatic conveying systems are particularly versatile. A very wide range of materials can be handled and they are totally enclosed by the system and pipeline. This means that potentially hazardous materials can be conveyed quite safely. There is minimal risk of dust generation and so these systems generally meet the requirements of any local Health and Safety Legislation with little or no difficulty.

Pneumatic conveying plants take up little floor space and the pipeline can be easily routed up walls, across roofs or even underground to avoid existing equipment or structures. Pipe bends in the conveying line provide this flexibility, but they will add to the overall resistance of the pipeline. Bends can also add to problems of particle degradation if the conveyed material is friable, and suffer from erosive wear if the material is abrasive.

1.2.2 Industries and materials

A wide variety of materials are handled in powdered and granular form, and a large number of different industries have processes which involve their transfer and storage. Some of the industries in which bulk materials are conveyed include agriculture, mining, chemical, pharmaceuticals, paint manufacture, and metal refining and processing.

In agriculture very large tonnages of harvested materials such as grain and rice are handled, as well as processed materials such as animal feed pellets. Fertilizers represent a large allied industry with a wide variety of materials. A vast range of food products from flour to sugar and tea to coffee are conveyed pneumatically in numerous manufacturing processes. Confectionery is a particular industry in which many of these materials are handled.

In the oil industry fine powders such as barytes, cement and bentonite are used for drilling purposes. In mining and quarrying, lump coal and crushed ores, and minerals are conveyed. Pulverized coal and ash are both handled in very large quantities in thermal power plants. In the chemical industries materials include soda ash, polyethylene, PVC and polypropylene in a wide variety of forms from fine powders to pellets. Sand is used in foundries and glass manufacture, and cement and alumina are other materials that are conveyed pneumatically in large tonnages in a number of different industries.

1.2.3 Mode of conveying

Much confusion exists over how materials are conveyed through a pipeline and to the terminology given to the mode of flow. First it must be recognized that materials can either be conveyed in batches through a pipeline, or they can be conveyed on a continuous basis, 24 h a day if necessary. In batch conveying the material may be conveyed as a single plug if the batch size is relatively small.

For continuous conveying, and batch conveying if the batch size is large, two modes of conveying are recognized. If the material is conveyed in suspension in the air through the pipeline it is referred to as dilute phase conveying. If the material is conveyed at low velocity in a non-suspension mode, through all or part of the pipeline, it is referred to as dense phase conveying.

1.2.3.1 Dilute phase

Almost any material can be conveyed in dilute phase, suspension flow through a pipeline, regardless of the particle size, shape or density. It is often referred to as suspension flow because the particles are held in suspension in the air as they are blown or sucked through the pipeline. A relatively high velocity is required and so power requirements can also be high but there is virtually no limit to the range of materials that can be conveyed.

There will be contact between the conveyed material and the pipeline, and particularly the bends, and so due consideration must be given to the conveying of both friable and abrasive materials. With very small particles there will be few impacts but with large particles gravitational force plays a part and they will tend to 'skip' along horizontal pipelines.

Many materials are naturally capable of being conveyed in dense phase flow at low velocity. These materials can also be conveyed in dilute phase if required. If a high velocity is used to convey any material such that it is conveyed in suspension in the air, then it is conveyed in dilute phase.

1.2.3.2 Dense phase

In dense phase conveying two modes of flow are recognized. One is moving bed flow, in which the material is conveyed in dunes on the bottom of the pipeline, or as a pulsatile moving bed, when viewed through a sight glass in a horizontal pipeline. The other mode is slug or plug type flow, in which the material is conveyed as the full bore plugs separated by air gaps. Dense phase conveying is often referred to as non-suspension flow.

Moving bed flow is only possible in a conventional conveying system if the material to be conveyed has good air retention characteristics. This type of flow is typically limited to very fine powdered materials having a mean particle size in the range of approximately 40–70 μm, depending upon particle size distribution and particle shape.

Plug type flow is only possible in a conventional conveying system if the material has good permeability. This type of flow is typically limited to materials that are essentially mono-sized, since these allow the air to pass readily through the interstices between the particles. Pelletized materials and seeds are ideal materials for this type of flow.

1.2.3.3 Conveying air velocity

For dilute phase conveying a relatively high conveying air velocity must be maintained. This is typically in the region of 12 m/s for a fine powder, to 16 m/s for a fine granular material, and beyond for larger particles and higher density materials. For dense phase conveying, air velocities can be down to 3 m/s, and lower in certain circumstances. This applies to both moving bed and plug type dense phase flows.

These values of air velocity are all conveying line inlet air velocity values. Air is compressible and so as the material is conveyed along the length of a pipeline the pressure will decrease and the volumetric flow rate will increase.

For air the situation can be modelled by the basic thermodynamic equation:

$$\frac{p_1\dot{V}_1}{T_1} = \frac{p_2\dot{V}_2}{T_2} \tag{1.1}$$

where p is the air pressure (kN/m^2·abs), $\dot{V}$, the air flow rate (m^3/s), T, the air temperature (K) and subscripts 1 and 2 relate to different points along the pipeline.

If the temperature can be considered to be constant along the length of the pipeline this reduces to:

$$p_1\dot{V}_1 = p_2\dot{V}_2 \tag{1.2}$$

Thus if the pressure is one bar gauge at the material feed point in a positive pressure conveying system, with discharge to atmospheric pressure, there will be a doubling of the air flow rate, and hence velocity in a single bore pipeline. If the conveying line inlet air velocity was 20 m/s at the start of the pipeline it would be approximately 40 m/s at the outlet. The velocity, therefore, in any single bore pipeline will always be a minimum at the material feed point.

It should be emphasized that absolute values of both pressure and temperature must always be used in these equations. These velocity values are also superficial values, in that the presence of the particles is not taken into account in evaluating the velocity, even for dense phase conveying. This is universally accepted. Most data for these values, such as that for minimum conveying air velocity are generally determined experimentally or from operating experience. It is just too inconvenient to take the presence of the particles into account.

1.2.3.4 Particle velocity

In dilute phase conveying, with particles in suspension in the air, the mechanism of conveying is one of drag force. The velocity of the particles, therefore, will be lower than that of the conveying air. It is a difficult and complex process to measure particle velocity, and apart from research purposes, particle velocity is rarely measured. Once again it is generally only the velocity of the air that is ever referred to in pneumatic conveying.

In a horizontal pipeline the velocity of the particles will typically be about 80% of that of the air. This is usually expressed in terms of a slip ratio, defined in terms of the velocity of the particles divided by the velocity of the air transporting the particles, and in this case it would be 0.8. The value depends upon the particle size, shape and density, and so the value can vary over an extremely wide range. In vertically upward flow in a pipeline a typical value of the slip ratio will be about 0.7.

These values relate to steady flow conditions in pipelines remote from the point at which the material is fed into the pipeline, bends in the pipeline and other possible flow disturbances. At the point at which the material is fed into the pipeline, the material will essentially have zero velocity. The material will then be accelerated by the conveying air to its slip velocity value. This process will require a pipeline length of several metres and this distance is referred to as the acceleration length. The actual distance will depend once again on particle size, shape and density.

There is a pressure drop associated with acceleration of the particles in the air stream and it has to be taken into account by some means. It is not only at the material feed point that there is an acceleration pressure drop. It is likely to occur at all bends in the pipeline. In traversing a bend the particles will generally make impact with the bend wall and so be retarded. The slip velocity at exit from a bend will be lower than that at inlet and so the particles will have to be re-accelerated back to their steady-state value. This additional element of the pressure drop is usually incorporated in the overall loss associated with a bend.

1.2.3.5 Solids loading ratio

Solids loading ratio, or phase density, is a useful parameter in helping to visualize the flow. It is the ratio of the mass flow rate of the material conveyed divided by the mass flow rate of the air used to convey the material. It is expressed in a dimensionless form:

$$\phi = \frac{\dot{m}_{\mathrm{p}}}{3.6\,\dot{m}_{\mathrm{a}}} \tag{1.3}$$

where ϕ is the solids loading ratio (dimensionless), $\dot{m}_{\mathrm{p}}$, the mass flow rate of material (tonne/h) and $\dot{m}_{\mathrm{a}}$, the mass flow rate of air (kg/s).

Since the mass flow rate of the conveyed material, or particles, is usually expressed in tonne/h and the mass flow rate of the air is generally derived by calculation in kg/s, the constant of 3.6 in Equation (1.3) is required to make the term dimensionless. A particularly useful feature of this parameter is that its value remains essentially constant along the length of a pipeline, unlike conveying air velocity and volumetric flow rate, which are constantly changing.

For dilute phase conveying, maximum values of solids loading ratio that can be achieved are typically of the order of about 15. This value can be a little higher if the conveying distance is short, if the conveying line pressure drop is high, or if a low value of conveying air velocity can be employed. If the air pressure is low or if the pipeline is very long, then the value of solids loading ratio will be very much lower.

For moving bed flows, solids loading ratios need to be a minimum of about 20 before conveying at a velocity lower than that required for dilute phase can be achieved. Solids loading ratios, however, of well over 100 are quite common. For much of the data presented in this Design Guide on materials such as cement and fine fly ash, solids loading ratios in excess of 100 are reported, whether for horizontal or vertical flow.

In conveying barytes vertically up the author has achieved a solids loading ratio of about 800 with a short pipeline. Conveying at very low velocity is necessary in order to achieve very high values of solids loading ratio in moving bed flow. This is because air flow rate is directly proportional to air velocity and air flow rate is on the bottom line of Equation (1.3).

For plug type flow the use of solids loading ratio is not as appropriate, for the numbers do not have the same significance. Since the materials have to be very permeable, air permeates readily through the plugs. Maximum values of solids loading ratio, therefore, are only of the order of about 30, even with high values of conveying line pressure drop. If a material is conveyed at a solids loading ratio of 10, for example, it could be conveyed in dilute phase or dense phase. It would only be with the value of the conveying line inlet air velocity that the mode of flow could be determined.

1.2.4 Recent developments

Although pneumatic conveying systems have numerous advantages over alternative mechanical conveying systems for the transport of materials, they do have drawbacks, particularly for materials that can only be conveyed in dilute phase. Particle degradation and erosive wear of pipeline bends are particular examples. Due to the high conveying air velocity required, energy requirements are also high.

In recent years there have been many developments of pneumatic conveying systems aimed at increasing their capability for conveying a wider range of materials in dense phase, and hence at low velocity. This has generally been achieved by conditioning the material at the feed point into the pipeline, or by providing a parallel line along the length of the pipeline to artificially create either permeability or air retention in the material.

1.2.4.1 System types

Pneumatic conveying system types can be divided into conventional and innovatory types. In conventional systems the material to be conveyed is simply fed into the pipeline and it is blown or sucked to the discharge point. It must be realized that low velocity, dense phase, conveying in conventional pneumatic conveying systems is strictly limited to materials that have the necessary bulk properties of good air retention or good permeability. The use of high pressure air is not synonymous with dense phase conveying. It is dictated entirely by the properties of the material to be conveyed in a conventional conveying system.

Probably the majority of materials that are conveyed have neither of these properties. There has, therefore, been much research undertaken into pneumatic conveying with a view to developing systems that are capable of conveying a much wider range of materials in dense phase and hence at low velocity. Making these systems more suitable for abrasive and friable materials has provided a particular driving force.

1.2.5 Conveying capability

It has already been mentioned that pneumatic conveying systems are capable of conveying almost any material. Distance, however, does impose a practical limit. Although hydraulic conveying systems are capable of conveying material at a flow rate in excess of 100 tonne/h, over a distance of 100 km, or more in a single stage, the limit for pneumatic conveying is typically about 1½ km for most applications.

With water having a density that is about 800 times greater than that of air, at free air conditions, the difference in density between the conveyed material and that of the conveying fluid is widely different. As a consequence conveying air velocities are a factor of about ten times greater than those required for water in order to convey material in suspension.

1.2.5.1 High pressure conveying

The biggest problem with high pressure for pneumatic conveying derives from Equation (1.2). Water can be modelled, as being essentially incompressible and so there is little change in velocity along the length of the pipeline. Water pressures up to about 150 bar are therefore used. With air being compressible very few systems, anywhere in the world, operate at a pressure much above 5 bar gauge when delivering material to a reception point at atmospheric pressure.

In terms of pneumatic conveying, high pressure virtually means anything above 1 bar gauge. This is a typical operating limit with possibly the majority of pneumatic conveying systems in industry. This corresponds with a doubling in conveying air velocity, as mentioned above. With any higher air supply pressure it would always be recommended that the pipeline should be stepped to a larger bore part way along its length in order to prevent high values of velocity from occurring.

Apart from magnifying problems of erosive wear and particle degradation, velocity has an adverse effect on pressure drop. The appropriate relationship here is:

$$\Delta p \propto \frac{L \rho C^2}{d} \qquad (1.4)$$

where Δp is the pressure drop, L, the length of straight pipeline, ρ, the air density, C, the conveying air velocity and d, the pipeline bore.

It will be seen from this that velocity is on the top line of the equation and its value has to be squared. This, therefore, is an extremely important term and anything that can be done to keep conveying air velocities to as low a value as possible is generally to be advised. In this respect the stepping of a pipeline is generally an advantage, not just in minimizing wear and degradation, but generally in terms of achieving an improvement in conveying performance.

A particular advantage of pneumatic conveying systems is that they can be operated at high pressure if required. There are many instances in industry where it is necessary to deliver bulk particulate materials into vessels that operate at high pressure. Again, by reference to Equation (1.2), it will be seen that this situation does not present a significant expansion problem. Thus coal, limestone and bed material, for example, can be delivered to high pressure fluidized bed combustors that operate continuously at pressures of about 20 bar gauge and above.

1.2.5.2 Long distance conveying

Thermal power stations often employ long distance pneumatic conveying in order to transfer the pulverized fuel ash to a point on the site boundary for subsequent disposal. At a power station in Ropar, India, the Punjab State Electricity Board operates a plant consisting of six 210 MW generating units. Dry ash is conveyed from the electrostatic precipitators to a group of five storage silos, a distance of about 2 km, where it is available to cement manufacturers. The transfer is in two stages: The first conveys the ash from the electrostatic precipitators to two intermediate storage silos over a distance of 400 m. Denseveyor ash vessels are used, the lines are 200 mm bore and 30 tonne/h per line is achieved.

In the second stage the ash is conveyed over a distance of 1550 m at a rate of 40 tonne/h per line. Twin blow tanks are used (three to each intermediate silo) and the pipelines are stepped from 200 to 250–300 mm bore. Four compressors are available to each silo, with two working and two on standby, each delivering 72 m^3/min at 4.2 bar gauge. This plant was commissioned in 1995. Several similar long distance pipelines have been built at power stations in India, some with much higher conveying capacities.

1.2.5.3 Vertical conveying

Most pneumatic conveying systems have an element of vertical conveying in the pipeline run. In the majority of pipelines it is usually conveying vertically up, and at the end of the pipeline, in order to discharge the material into a hopper or silo. The routing of the pipeline may include vertically up and vertically down sections to cross roads or railways, or to avoid obstructions or accommodate existing pipe racking.

Flow vertically up and down presents no undue problems, and is potentially easier, since the minimum conveying air velocity for flow vertically up is generally lower than that for horizontal flow. It is not often that advantage can be taken of this since most pipelines incorporate combinations of both horizontal and vertical pipeline. Since horizontal pipeline usually predominates, conveying air velocities are generally specified in terms of those required for horizontal conveying. It is probably in mining applications that significant lengths of vertical pipeline are found.

1.2.5.3.1 Conveying vertically up

In many old collieries, mechanization of coal cutting meant that the existing shaft winding gear could not cope with the increased output. This was the situation in the UK in the early 1970s, and so an economical means of increasing capacity had to be found. Of all the possible hoisting systems examined, the positioning of pipelines in the corner of existing shafts appeared to offer the best solution. Although the operating cost for pneumatic conveying systems was recognized as being high, the time and capital cost elements were very much in their favour.

Onley and Firstbrook [1] reported on tests undertaken at a coal mine having a 200 mm bore pipeline with a 420 m vertical lift; 18.6 tonne/h of −50 mm dolomite was conveyed with a pressure drop of 1.37 bar. With coal, 42 tonne/h was achieved with a conveying line pressure drop of 1.72 bar, although with wet −25 mm shale only 23 tonne/h could be achieved with the same air supply pressure.

At another UK colliery the pipeline bore was 300 mm and the vertical lift was 326 m [1]. In this case there were horizontal runs of 100 m from the feed point and 54 m to the reception point. 66 tonne/h of −25 mm coal was conveyed with an air supply pressure of 0.75 bar. The blower had a capacity of 1.0 bar, was provided with a 522 kW motor drive, and could deliver 3.7 m^3/s of air. It was subsequently reported that 80 tonne/h was achieved at this installation [2].

1.2.5.3.2 Conveying vertically down

Pulverized fuel ash, or fly ash, is often available at coal mines, particularly if a power station is built close to the mine. Disposal of this ash underground for back-filling is generally considered to be environmentally better than many surface alternatives. Cement is another material that is commonly used in back-filling operations. Curten [3] reports that typical applications involve the transport vertically down 700–1000 m and then directed up to 2000 m into the underground roadways. He reports that the distances are dependent upon the type of material conveyed and that considerably longer distances (up to 7000 m) can be achieved if pulverized material is transported compared with granular support material.

Associated with deep level mining is the problem of providing a tolerable working environment. For this purpose underground refrigeration plants, evaporative cooling and the pumping of chilled water from surface refrigeration plants to underground heat exchangers are some of the methods employed. Sheer et al. [4] reported on the use of ice in South African gold mines for this purpose. By virtue of latent heat considerations, four times less water needs to be pumped when using ice in preference to chilled water. Ice making plant is located at the surface level and the ice produced is pneumatically conveyed over distances up to about 5 km, with vertically down distances up to about 2400 m.

1.2.5.4 Flow rate capability

The capability of a pneumatic conveying system, in terms of achieving a given material flow rate, depends essentially on the conveying line pressure drop available and the diameter of the pipeline. As mentioned above, the use of pressure is generally limited in the majority of applications to about 5 bar and so pipeline bore is increased to achieve an increase in material flow rate if this is required.

In many cases pressure capability is set by the desire to use a particular type of compressor or blower. In most cases the duty of conveying a given flow rate of material can be met by a wide range of combinations of pressure drop and pipeline bore. There is rarely a single solution to the design of any pneumatic conveying system. Where there is a choice it is well worthwhile comparing the systems in terms of operating cost as well as capital cost. Only if a very high material flow rate is required will the options be limited.

Lithgart [5] reports on a pneumatic system for off-loading cement from bulk carriers at 800 tonne/h, and its onward conveying to silos 500 m distant through twin pipelines. Castle Cement had a need to import up to one million tonne/year of cement at a terminal 20 km east of London on the River Thames. As the river is tidal (7 m) it was necessary to build a jetty in the river against which the ships could berth, and hence the long conveying distance.

A single vacuum nozzle was employed to off-load at 800 tonne/h, but it was decided to use two pipelines at 400 tonne/h each for the transfer to the silos, as it was considered that a single bore pipeline would be more expensive to build. It was estimated that the power required for conveying the cement at 800 tonne/h to the silos was 2400 kW.

1.2.5.4.1 Pressure gradient influence

Conveying distance has a very significant influence on pneumatic conveying system performance. Assume, for example, that a system is capable of conveying 100 tonne/h over a distance of 100 m, with a pressure drop of 2 bar. If the distance is doubled, and there is no change in pressure, the material flow rate will be reduced by at least half, to a maximum of 50 tonne/h, if there is no change in pipeline bore, and hence air flow rate, and also power. With a halving of material flow rate and no change in air flow rate, the solids loading ratio will also be halved.

A high value of solids loading ratio must be maintained in order to convey a material in dense phase. With increase in conveying distance, this capability will be reduced because there is a limit with regard to air supply pressure to help in this respect. To illustrate this effect a graph of conveying line pressure gradient is plotted against solids loading ratio in Figure 1.1. This is a very approximate relationship and only for illustration purposes, since there is no reference to either material type or conveying air velocity.

Pressure gradient is given in units of mbar/m. The distance in metres in this case is the equivalent length of the pipeline. In addition to the length of horizontal pipeline, therefore, an allowance is also included for the length of pipeline routed vertically up

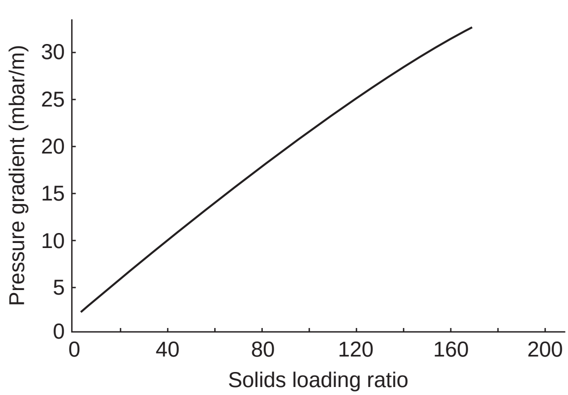


Figure 1.1 Influence of solids loading ratio on conveying line pressure gradient.

and the number of bends in the pipeline. It will be seen that to convey at a solids loading ratio of about 100 requires a pressure gradient of about 20 mbar/m.

If only 2 bar is available for conveying, the maximum value of equivalent length possible will only be 100 m. If the equivalent length of a pipeline is 1000 m and 2 bar is available for conveying, the pressure gradient will only be about 2 mbar/m and so the maximum value of solids loading ratio at which the material can be conveyed will be about 10, which only relates to dilute phase conveying. A much higher pressure would be needed to maintain a dense phase conveying capability over this distance.

1.2.5.4.2 Material influences

It has already been mentioned that different materials have different conveying capabilities in terms of the minimum value of conveying air velocity required, and hence air flow rate. Different materials can also achieve very different mass flow rates when conveyed through the same pipeline under identical conveying conditions. And it is not just different materials! Different grades of exactly the same material can exhibit totally different performances. Thus a conveying system designed for one material may be totally unsuitable for another.

1.3 Information provided

It is for this reason that a considerable amount of conveying data for different materials is included in this Design Guide and that a lot of consideration is given to this topic throughout the book.

1.3.1 Availability of design data

Pneumatic conveying system design may be based upon previous experience or upon test results. Unfortunately commercial interests dictate that manufacturers of pneumatic conveyors rarely publish information that could be of value in system design. A single value of material flow rate, conveying distance, and possibly pipeline bore and air supply pressure, is normally the extent of the information given. Even user companies, many of whom have had to 'tune' their own systems are generally reluctant to divulge detailed information on the performance of their conveying systems, for commercial reasons.

Different materials are quite likely to have totally different conveying properties and if a system has to be designed for a material for which no previous experience is available, it will be necessary to carry out pneumatic conveying trials. These will generate the data upon which the design can be based.

In this Guide, conveying characteristics for a number of materials are presented which detail the relationship between the main conveying parameters for a material, over a wide range of conveying conditions, and the limits of conveying are clearly identified. With data presented in this form system design is relatively straightforward.

This type of data also allows analysis of existing systems to be carried out. Checks can be made to determine whether a system is operating under optimum conditions and, if not, how this can best be achieved. Similar checks will enable an assessment to be made of the potential for up-rating a system.

1.3.2 Scope of the work

The Guide is intended to be used by both designers and users of pneumatic conveying systems. For those not familiar with pneumatic conveying it provides information on the types of system available and the capabilities of pneumatic conveying systems in terms of material flow rates, conveying distances and power requirements. This should enable a project engineer both to assess alternative tenders received for a pneumatic conveying system and to make comparisons with mechanical systems.

For the designer, data on a number of materials is presented which could be used for the design of systems to handle these materials. Where system design is based on results obtained from a test facility the actual plant pipeline will have a totally different configuration. To overcome this problem scaling parameters are presented for conveying distance, pipeline bore, vertical sections and pipeline bends to enable the test data to be used reliably. For any given conveying duty a range of air supply pressures and pipeline bores will be capable of meeting the required duty. The design procedures outlined will allow selection of the combination that will give the lowest power requirement.

For users of systems the Guide will explain how to check whether an existing system is operating under optimum conditions. The possibilities of up-rating systems, extending systems, and changing to a different material are also considered. Operational problems are featured with separate chapters devoted to an analysis of problems such as erosive wear, particle degradation, explosions, and moisture and condensation. The commissioning of systems and troubleshooting are also considered so that the cause of plant operating problems, such as pipeline blockage, can be determined and corrected.

1.4 Review of chapters

The layout of this second edition follows the style of the original guide. The work is divided into three main parts:

- Systems and components
- System design
- System operation

A number of chapters are presented in each part and these are numbered continuously, as referenced below. Two appendixes are included. One is used to present information on material characterization, specifically for pneumatic conveying, and additional conveying data is presented in the second.

1.4.1 Systems and components

This section of the book presents an introduction to all the systems and components that comprise a pneumatic conveying system. This provides both an introduction to the subject of pneumatic conveying and background to the selection of systems and components for a given duty.

1.4.1.2 Review of pneumatic conveying systems

A review is given of all the various types of pneumatic conveying system that are currently employed and available. This includes:

- Open and closed systems
- Positive pressure and vacuum conveying systems
- Fixed and mobile systems
- Conventional and innovatory systems
- Batch and continuously operating systems
- Pipeline and channel flow systems

Comparisons between the different types of system are given in order to help in the selection process. The influence of the properties of conveyed materials is incorporated into this review. Such properties include abrasive, friable, hygroscopic, toxic, explosive and cohesive. The suitability for multiple product conveying and multiple distance conveying is also examined.

1.4.1.3 & 4 Pipeline feeding devices

A review is given of all the commercially available devices that are used for feeding materials into pneumatic conveying system pipelines, and that meet the requirements of all the different types of conveying system considered in the previous chapter. This includes:

- Rotary valves and the many derivatives
- Screw feeders and the various types available
- Venturi feeders
- Gate lock valve feeders
- Blow tank devices and the multitude of arrangements and configurations
- Vacuum and suction nozzles
- Trickle valves

Chapter 3 concentrates on feeding devices for low pressure and vacuum conveying systems and Chapter 4 considers high pressure systems. Issues such as feed rate capability, control, problems of air leakage, and suitability for different types of conveyed materials are discussed.

1.4.1.5 Pipelines and valves

Both pipeline bends and valves represent major problems in pneumatic conveying and are probably responsible for the majority of operating problems with regard to pneumatic conveying systems, particularly when abrasive materials have to be handled. As a consequence there have been many developments with regard to both bends and valves that have resulted specifically from pneumatic conveying.

1.4.1.6 Air movers

The blower, compressor or exhauster is at the heart of the pneumatic conveying system. It is essential that the correct type of machine is selected and that it is correctly specified, particularly in terms of free air delivered. A wide variety of machines are considered, from fans and blowers to compressors, together with their operating characteristics. Most of the power required for a pneumatic conveying system is that for the compressor and much of this goes into increasing the temperature of the air. Both of these features are considered in detail. The possible benefits of cooling air and the provision of oil free air are also considered.

1.4.1.7 Gas–solids separation devices

This is a particular area of the system in which health and safety issues impact. Disengagement of coarse particles can be achieved by using a gravity-settling chamber. With finer materials a cyclone may be suitable. For dust and very fine materials a fabric filter is probably most appropriate. The methods and associated equipment are reviewed and their applications, limitations and control discussed.

1.4.1.8 System selection considerations

The selection of a pneumatic conveying system for a particular application involves consideration of numerous parameters associated with the conveyed material, the conveying conditions and the conveying system. The primary aim is usually for a material to be conveyed at a specified flow rate over a given distance. For illustration purposes extremes of material type are considered. The conveying requirements can usually be met by a wide combination of pipeline bores and conveying line pressure drops. Power consumption, and hence system-operating costs, are factors that can be used in the decision-making process but problems of material and system compatibility have to be taken into account. The inter-relating effects of all these parameters are considered.

1.4.2 System design

This group of chapters is concerned with the design of pneumatic conveying systems. The first two chapters are devoted to the considerations of air alone, but it is here that the basic modelling for pneumatic conveying begins. Materials are then added to the pipeline and the influence of the materials is considered and compared. Scaling parameters and design procedures are then introduced and these are reinforced with two case studies. Some first approximation design methods are presented to allow feasibility studies and system checks to be undertaken quickly, and the possibilities of multiple-material and multiple distance conveying are considered.

1.4.2.1 Air flow rate evaluation

Air is compressible with respect to both pressure and temperature, and air movers are generally specified in terms of 'free air conditions'. The correct specification of an air mover in terms of volumetric flow rate is essential in terms of achieving the correct conveying air velocity. The derivation of all the models necessary is given and the results are displayed graphically. The equations are presented in terms of both volumetric flow rate and conveying air velocity, so that they can be used for the design of future systems, as well as the checking of existing systems. In addition to the influence of pressure and temperature, stepped pipelines, pipeline purging and plant elevation are also considered.

1.4.2.2 Air only relationships

The reference point for any pneumatic conveying system is the performance of the empty pipeline, and so equations are developed that will allow the air only pressure drop to be evaluated for any pipeline system. Bends and other pipeline features are considered for both positive pressure and vacuum conveying systems. Models and methods for air flow rate control are also included.

1.4.2.3 Conveying characteristics

Conveying characteristics for a material provide a valuable aid to system design. They provide the design data in terms of air flow rate and air supply pressure for a given material flow rate and quantify the effect of pipeline bore and conveying distance. In addition the conveying characteristics identify the minimum conveying conditions and provide the means to determine power requirements, thus enabling comparisons to be made for different conveying systems. Conveying characteristics are presented for representative materials and, in addition to total pipelines, data is also presented for individual sections of pipeline, as well as bends.

1.4.2.4 Conveying capability

In this chapter the conveying characteristics of a much wider range of materials are presented to illustrate the full influence that different materials can have on conveying capability and performance. High and low pressure and dilute and dense phase conveying are considered for a broad range of materials.

1.4.2.5 Material property influences

A goal in pneumatic conveying is to make it possible to design a pneumatic conveying system without the need for carrying out full-scale conveying tests with a material. The results of a study into correlations between material properties obtained from bench scale tests and material conveying characteristics obtained from full-scale pneumatic conveying trials are given. Correlations were sought as to whether a material will convey in dense phase and what type of pressure drop/material flow rate characteristic is to be expected. The work is extended by investigating the influence that conveying itself might have on the subsequent conveying performance of a material.

1.4.2.6 Pipeline scaling parameters

It is generally not practical to replicate a plant pipeline for the purposes of undertaking tests in order to design a conveying system. Over the years, however, with the accumulation of practical experience and specific research programmes, scaling parameters have been developed for the purpose. These will take account of the differences between a test facility pipeline and a plant pipeline with respect to lengths of horizontal and vertical pipeline, number and geometry of bends, and pipeline bore. In addition to these parameters, pipeline material and pipeline steps are also considered.

1.4.2.7 Design procedures

Logic diagrams are presented for pneumatic conveying system design based on both mathematical models and test data. They are presented for the purpose of checking the capability of an existing system, as well as for the design of a new system. Some of the available equations and bench scale test correlations are evaluated and the more useful relationships are included to show how they can be used in conjunction with the logic diagrams.

1.4.2.8 Case studies

Two case studies are presented. One is for a fine material that is capable of dense phase conveying, in sliding bed flow, in Chapter 16. The other is for a coarse material that is only capable of dilute phase conveying, in Chapter 17. The scaling process is illustrated, by way of example in each case, and for the fine material an investigation into the unstable region in sliding bed flow is also presented.

1.4.2.9 First approximation design methods

Very often a first approximation solution is all that is required. This may be for system design purposes, particularly if a feasibility study is being carried out, or to provide a quick check on the performance of an existing system. An approximate value of power required is often required so that the operating cost of such a system can be estimated in terms of pence per tonne. Two such methods are included, one of which can be used for dense phase conveying systems in addition to dilute phase.

1.4.2.10 Multiple use systems

In many industries more than one material is required to be conveyed by the same system. Different materials, however, can have very different conveying characteristics. Some have very different air requirements as well as different flow rate capabilities. There are also many systems that require material to be conveyed over a range of distances. Conveying distance, however, has a marked effect on material flow rate and can influence air flow rate in certain situations. These various conveying situations are considered and a variety of solutions are presented.

1.4.3 System operation

This group of chapters is concerned with the operation of pneumatic conveying systems. Pipeline blockages, do unfortunately occur, but mainly due to poor design and maintenance and so this topic is given particular consideration. Means of improving the performance of an existing system are considered, which may be to reduce power requirements or to increase material flow rate. Many problems relate to the properties of the conveyed material, and not least of these are abrasive and friable materials and so one chapter is devoted to erosive wear and another to particle degradation. Moisture and condensation is similarly considered, as well as the issues relating to health and safety.

1.4.3.20 Troubleshooting and material flow problems

Due to the complexities of system design, a lack of reliable design data, and a poor understanding of compressible flow, many pneumatic conveying systems pose numerous problems on commissioning. Pipeline blockage and conveying systems not capable of achieving the desired material flow rate are common problems. A detailed analysis of all possible causes is given and a checklist is provided for quick reference.

1.4.3.21 Optimizing and up-rating of existing systems

In some cases, if a system is over designed, it may be possible to optimize the conveying parameters and either reduce the power requirement for the system or increase the conveying capability. Very often an increase in conveying performance is required for an existing system and so the procedures for reviewing the possibility are explained in detail. The procedures are given for both positive pressure and vacuum conveying systems.

1.4.3.22 Operating problems

Potential users are often reluctant to install a pneumatic conveying system because they anticipate operating problems. Pneumatic conveyors can experience problems but the situation has been improved by the introduction of new types of conveyor and by the modification of existing systems, based on a better understanding of the mechanisms of conveying. This often results in a choice of solutions to a particular problem. The most common problems affecting pneumatic conveyors are examined, such as static electricity and material deposition. Some practical solutions to these problems are presented.

1.4.3.23 Erosive wear

Many materials that have to be conveyed are very abrasive, such as silica sand, alumina, cement and fly ash. As a consequence the conveying pipeline, bends and various components that are exposed to impact by the gas–solids flows have to be specified such that the problem is minimized to an acceptable level. It is not uncommon for steel bends installed in a pipeline conveying an abrasive material to fail in a matter of hours. The mechanics of the erosive wear process is explained, and a review of possible preventative measures that can be taken, and alternative components or materials that can be used, is given.

1.4.3.24 Particle degradation

Many materials that have to be conveyed are friable and so particles are liable to be broken when they impact against retaining surfaces, such as bends in the pipeline. It is for this reason that pneumatic conveying systems are not generally used for this type of material. There are numerous means by which the problem can be reduced, however, relating to conveying conditions, bend geometry and materials of construction and so a detailed review of these is given.

1.4.3.25 Moisture and condensation

As the temperature of air reduces the capacity for air to support moisture reduces and condensation is likely to occur. The same situation occurs with an increase in pressure. Air is the prime mover in pneumatic conveying systems and changes in both temperature and pressure are very common. The modelling of air with respect to moisture is presented to illustrate the nature of the problem and to provide guidance on the potential magnitude of the problem, and for the sizing of air drying plant and equipment should this be required.

1.4.3.26 Health and safety

Most dusts pose a potential health problem, and many materials that have to be conveyed are potentially toxic. Pneumatic conveying is often chosen for hazardous materials because the system provides a theoretically totally enclosed environment for their transport. It is also considered that the majority of conveyed materials are potentially explosive, and this certainly applies to most food products, fuels, chemicals and metal powders. In this chapter a detailed review of precautions and modifications to plant and components is given. The nature of the problems is explained and information on appropriate measurable properties of dust clouds is provided.

1.5 Definitions

To provide a uniform approach to the work, basic definitions of conveying phases, velocities, operating pressures and conveying conditions are given here for reference. The most important point is that the dilute and dense are the only conveying phases that are recognized in this Guide and to which reference is made. This is primarily a function of material properties. The vast majority of materials are capable of being conveyed in dilute phase, or suspension flow, but only certain materials are capable of being conveyed in dense phase, or non-suspension flow, in a conventional pneumatic conveying system.

1.5.1 Solids loading ratio

Solids loading ratio, ϕ, is the ratio of the mass flow rate of the material conveyed to the mass flow rate of the air used for conveying, as presented in Equation (1.3). It is used by pneumatic conveying engineers to describe the nature of the gas–solid flow in a pipeline. Other terms used include phase density, mass ratio and mass flow ratio. It is a useful dimensionless quantity since its value does not vary with the conveying air pressure and so its value remains constant throughout the pipeline.

1.5.2 Dilute phase conveying

Dilute phase conveying occurs when a material is conveyed in suspension in the flowing air.

Note: The dilute phase mode of conveying is sometimes referred to as lean phase or suspension flow. To keep the material in suspension in the pipeline it is necessary to maintain a minimum value of conveying line inlet air velocity that, for most materials, is of the order of 13–15 m/s.

1.5.3 Dense phase conveying

Dense phase conveying occurs when materials are conveyed with air velocities lower than those required for dilute phase over all or part of the pipeline.

Note: The nature of dense phase flow is very varied, for it depends upon the properties of the material being conveyed, the solids loading ratio and the conveying air velocity. Typically it includes flow over a deposited layer, which may itself be moving slowly, and flow in discrete or separate plugs of material. In terms of solids loading ratio the appropriate range, for most materials, is normally above about 15, provided that the conveying line inlet air velocity is below that required for dilute phase conveying of the material.

1.5.4 Low pressure and negative pressure (vacuum) conveying

Low pressure conveying systems are those that operate with air pressures below about 1 bar gauge.

Note: These systems cover the normal operating range of positive displacement blowers and conventional low pressure rotary valve systems. Low pressure is not synonymous with dilute phase conveying. If a material is capable of being conveyed in dense phase, a low pressure, or vacuum system, could be used to convey the material in dense phase, since for these materials it is only a function of pressure gradient, as illustrated in Figure 1.1.

1.5.5 High pressure conveying

High pressure conveying systems are those that operate with air pressures above about 1 bar gauge.

Note: High pressure is not synonymous with dense phase conveying. It is only possible in conventional conveying systems with materials having appropriate properties, and then only if the pressure gradient is sufficiently high, since conveying distance can have an over-riding effect.

1.5.6 Free air conditions

Free air conditions are specified as those at which $p = 101.3\,\text{kN/m}^2$ absolute (standard atmospheric pressure) and $t = 15°\text{C}$ (standard atmospheric temperature).

Note: Free air conditions are generally used as the reference conditions for the specification of blowers and compressors.

1.5.7 Superficial air velocity

This is the velocity of the air disregarding the presence of the solid particles or porous media.

Note: In a pipeline it is the air velocity based upon the cross-sectional area and neglecting the space occupied by the conveyed material. For flow across a membrane or filter it is the open duct velocity normal to the surface. Air velocity, for a given mass flow rate, is dependent upon both pressure and temperature. When conveying air velocities are evaluated at any point in the system, the local values of pressure and temperature at that point must be used.

1.5.8 Free air velocity

This is the superficial velocity of the air when evaluated at free air conditions.

1.5.9 Minimum conveying air velocity

The minimum conveying air velocity is the lowest superficial air velocity that can be used to convey a material.

Note: In dilute phase flow this is the lowest air velocity that can be achieved without saltation or choking occurring. The value of the minimum conveying air velocity in dense phase flow is significantly influenced by the solids loading ratio of the conveyed material, in the case of materials having good air retention properties.

1.5.10 Conveying line inlet air velocity

This is the superficial air velocity at the point where the material is fed into the pipeline.

Note: In a single bore pipeline this will be the lowest air velocity in the conveying line and so it must be greater than the minimum conveying air velocity required to ensure successful conveying of a material. This is variously referred to as the pick-up or entrainment velocity. In a vacuum conveying system it is approximately equal to the free air velocity.

1.5.11 Conveying line exit air velocity

This is the superficial air velocity at the end of a conveying line where the material is discharged into the receiving vessel.

Note: In a single bore pipeline this will be the highest air velocity in the conveying line. In a positive pressure conveying system it is approximately equal to the free air velocity.

1.5.12 Saltation

Saltation is the process of deposition of solid particles along a horizontal pipeline.

Note: This phenomenon occurs in dilute phase flow when the air velocity falls below the minimum conveying value. The saltation velocity is the minimum velocity at which a dilute phase system will operate and is equivalent to the minimum conveying air velocity.

1.5.13 Choking

Choking occurs in vertically upward flow and is the process that commences when solid particles near the pipe wall begin to flow downwards. As the process continues the pipeline eventually becomes blocked or chokes.

Note: Choking in vertical transport is somewhat analogous to saltation in horizontal transport, for both phenomena represent the onset of saturation conditions in dilute phase flow.

1.5.14 Acceleration length

This is the length of pipeline required for particles to reach their terminal velocity.

Note: When material is fed into a pipeline the particles are essentially at zero velocity and so have to be accelerated to their terminal value. A similar situation occurs following bends since a degree of retardation is likely to occur in the flow around a bend.

1.5.15 Null point

The null point in a system is the position where the pressure is equal to the ambient pressure.

Note: This is generally used in relation to closed loop systems and identifies a natural point of access to the system for monitoring or conditioning.

1.5.16 Specific humidity

Specific humidity, ω, is the ratio of the mass of water vapour to the mass of air in a given volume of the mixture.

1.5.17 Relative humidity

Relative humidity, φ, is the ratio of the partial pressure of the air, at a given temperature, to the partial pressure of the air when saturated, at the same temperature.

Note: Whereas specific humidity gives an indication of the amount of water vapour that is actually contained in air, relative humidity gives an indication of how much more water vapour the air is capable of supporting before it becomes fully saturated. Its value is usually expressed as a percentage.

1.5.18 Stoichiometric value

The dust cloud concentration at which the quantity of air available exactly matches that necessary for combustion of a material.

1.5.19 Pulsating flow

Pulsating flow is continuous alternating high and low rates of flow.

Note: Pulsating solids flow in a pipeline can be caused by pulsating material flow from the feeding device, such as rotary valves, or by pulsating conveying air flow from an air mover, such as a positive displacement blower. Pulsating air flow is a result of continuous alternating high and low air compression by the air mover due to the manner in which the machine operates. Pulsating air flow in the conveying line can be reduced by the use of an air receiver.

1.5.20 Stepped pipeline

A continuous pipeline in which the diameter of the conveying pipe changes, generally to a larger bore, at points along its length. The purpose is to accommodate the change in volumetric flow rate of the conveying air as the pressure changes, without the velocity falling below the minimum value of conveying air velocity at any point. This is sometimes referred to as a telescoped pipeline.

1.5.21 Air retention

The ability of a bulk material to retain air in the interstitial spaces between particles for a period of time. Very fine materials such as cement can exhibit this property, and when first poured into a container the material can behave almost like a liquid.

1.5.22 Permeability

This is a measure of the ease with which air will pass through a bed of bulk particulate material when a pressure difference is applied. Pelletized materials generally have very good permeability for there is little resistance to the flow of air through the interstitial passages. Materials that have a very wide particle size distribution generally have very poor permeability. If a pipeline blockage occurs with such a material a small plug of the material is often capable of holding an upstream pressure of 5 bar for a period of several minutes.

1.5.23 Hardness

Hardness can be defined as the resistance of a material to an applied pressure or force.

1.5.24 Mohs' scale

The Mohs' scale of hardness is based on the ability of each material to scratch ones that come before it on the scale. Each material is allocated a number, 1 for the least hard material through to 10 for the hardest material. These are talc 1, gypsum 2, calcite 3, fluorite 4, apatite 5, feldspar 6, quartz 7, topaz 8, corundum 9 and diamond 10.

1.5.25 Brinell hardness

The Brinell hardness number is a number proportional to the load or test force of a hard steel ball to the calculated curved area of the indentation formed. The ball diameter is 1, 2.5, 5 or 10 mm.

1.5.26 Vickers hardness

Vickers hardness is a ratio of the load expressed as kilograms force, of a square base diamond pyramid shaped indenter, to the sloping area of the indentation formed. Very small indenters are used to measure the harness of small particles.

1.5.27 Transient

A temporary continuous changing rate of flow caused by non-steady state flow conditions, such as starting up and shutting down conveying systems, particularly where blow tanks are employed.

1.6 Nomenclature

The notation used throughout the book is given here for general reference as it presents the style adopted and the form of SI units used in one place. Where equations are developed in the book an abbreviated notation will also be given for reference at the point of use.

1.6.1 Symbols

Symbols	*Parameter*	*Units*
A	Section area $= \pi d^2/4$ for a circular pipe	m^2
C	Conveying air velocity	m/s
C_p	Specific heat at constant pressure	kJ/kg·K
C_v	Specific heat at constant volume	kJ/kg·K
d	Pipeline bore	m
D	Pipe bend diameter	m
f	Pipeline friction coefficient	–
g	Gravitational acceleration $= 9.81\,m/s^2$	m/s^2
h	Head loss or gain	m
k	Bend loss coefficient	–
L	Pipeline length	m
m	Mass	kg
$\dot{m}_a$	Air mass flow rate	kg/s
$\dot{m}_p$	Material flow rate	tonne/h
M	Molecular weight	mol
N	Number of bends	–
p	Air pressure – absolute	N/m^2, kN/m^2 and bar
P	Power required	kW
R	Characteristic gas constant $= 0.287$ kJ/kg·K for air	kJ/kg·K
R_0	Universal gas constant $= 8.3143$ kJ/kg-mol·K	kJ/kg-mol·K
s	Specific entropy	kJ/kg·K
t	Actual temperature	°C
T	Absolute temperature $= t$°C $+ 273$	K
v	Specific volume of air $= 1/\rho$	m^3/kg

V	Volume	m^3
$\dot{V}$	Volumetric flow rate of air	m^3/s
z	Plant elevation	m

1.6.1.1 Greek

ε	Pipe wall roughness	m
μ	Viscosity	kg/m·s
ρ	Air density $= p/RT$	kg/m^3
ϕ	Solids loading ratio or phase density $= \dot{m}_p/\dot{m}_a$ *Note:* divide this by 3.6 since $\dot{m}_a$ is in kg/s and $\dot{m}_p$ is in tonne/h	–
φ	Relative humidity	%
Ψ	Pipeline friction loss constant	–
ω	Specific humidity $= m_v/m_a$	–

1.6.2 Non-dimensional parameters

Re	Reynolds number $= \rho\, C\, d/\mu$
ϕ	Solids loading ratio $= \dot{m}_p/\dot{m}_a$
χ	Slip ratio $= C_p/C_a$

1.6.3 Superscripts

n	Adiabatic index
·	Per unit time or rate e.g. /s
γ	Ratio of specific heats $= C_p/C_v$

1.6.4 Subscripts

a	Conveying air
atm	Atmospheric value
b	Bends
c	Conveying
e	Equivalent value
ex	Exhauster inlet conditions
f	Saturated liquid
fg	Change of phase (evaporation) (=g − f)
g	Saturated vapour
h	Horizontal
i	Inlet conditions
min	Minimum value
p	Conveyed material or particles
pp	Plant pipeline
s	Suspension of air and particles
sat	Saturation value or conditions

t	Throat conditions
tf	Test facility
v	Water vapour
vd	Vertically down
vu	Vertically up
0	Free air conditions $p_0 = 1013\,\text{kN/m}^2$ $T_0 = 288\,\text{K}$
1	Pipeline inlet – material feed point
2	Pipeline outlet – material discharge point
3	Inlet to exhauster/compressor
4	Outlet from exhauster/compressor

These numerical reference points are illustrated in relation to a vacuum conveying system in Figure 1.2 and in relation to a positive pressure system in Figure 1.3.

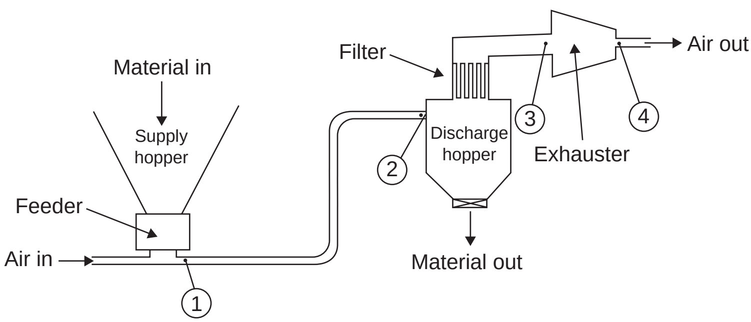


Figure 1.2 System reference points in relation to a negative pressure or vacuum conveying system.

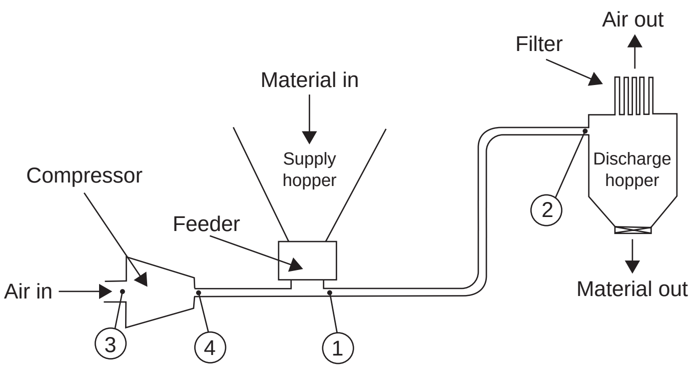


Figure 1.3 System reference points in relation to a positive pressure pneumatic conveying system.

Note

(a) In a negative pressure system, p_1 will be slightly below atmospheric pressure if an artificial resistance is added to the air supply pipeline inlet for the purpose of assisting the feed of material into the pipeline; p_2 and T_2 will generally be equal to p_3 and T_3; but the mass flow rate of air at 3 might be higher than that at 2 if there is a leakage of air across the material outlet valve on the discharge hopper.

(b) In a positive pressure system; p_1 will generally be equal to p_4 unless there is a pressure drop across the feeding device; p_2 and p_3 will generally be equal to the local atmospheric pressure; and the mass flow rate of air at 1 will be lower than that at 4 if there is a leakage of air across the feeding device.

1.6.5 Prefixes

Δ Difference in value e.g. Δp = pressure drop

Σ Sum total

References

1. J K Onley and J Firstbrook. The practical application of pneumatic transport techniques to the raising of mineral from deep shafts. Proc Pneumotransport 4. BHRA Conf, California. June 1978.
2. J Firstbrook. Operation and development of the pneumatic pipeline coal transportation system. Proc Pneumotransport 5. BHRA Conf, London. April 1980.
3. H J Curten. Concepts and results of pneumatic conveying of support materials in German underground mining. Proc Pneumatech 1. Stratford-upon-Avon. Powder Advisory Centre Conf. May 1982.
4. T J Sheer, R Ramsden and M Butterworth. The design of pipeline systems for transporting ice into deep mines. Proc 3rd Israeli Conf for Conveying and Handling of Particulate Solids. pp 10.75–10.80. Dead Sea. May/June 2000.
5. A Lithgart. World's largest cement unloader. Bulk Solids Handling. Vol 11, No 3. pp 671–676. August 1991.

Chapter 2

Review of pneumatic conveying systems

2.1 Introduction

A wide range of different pneumatic conveying systems are available to cater for an equally wide range of different applications. The majority of systems are generally conventional, continuously operating, open systems in a fixed location. To suit the material being conveyed, the application, or the process, however, innovatory, batch operating and closed systems are commonly used, as well as mobile systems.

To add to the complexity of selection, systems can be either positive or negative pressure in operation, or a combination of the two. The combined system is effectively achieved by means of staging, but this is a further possibility in its own right. In this brief review some of the more common systems are presented, and an explanation is provided of the different types to help in the selection process.

Numerous requirements of the conveying system, and conditions imposed by the material to be conveyed, also have to be taken into account as they present a number of important points to consider in the selection process. A checklist is provided, therefore, of possible system requirements, and specific features of bulk particulate materials, as these may ultimately dictate choice.

2.2 System types

The problem of system selection is illustrated in Figure 2.1. This shows the range of combinations that are possible just for conventional pneumatic conveying systems

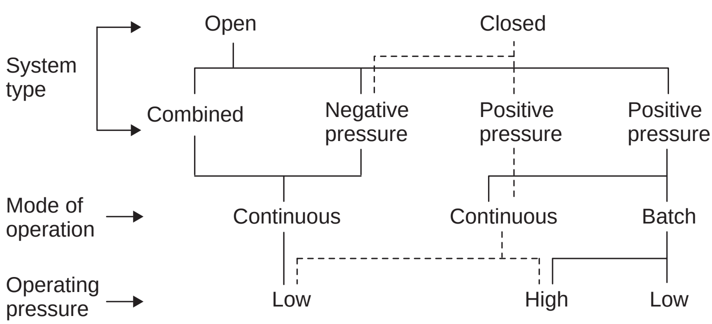


Figure 2.1 Diagram to illustrate the wide range of conveying systems available for conventional systems operating with a single air source.

with a single air source. Only system types are presented in detail, with positive pressure, vacuum, and combined positive and negative pressure systems considered, in relation to both open and closed systems.

Material fed into the conveying pipeline is only expressed in terms of mode of operation at this point, as feeding devices are considered in detail in Chapters 3 (low pressure) and 4 (high pressure). With a natural limit on operating pressure with vacuum systems, air requirements are included here in terms of a high or low operating pressure. Air movers are also considered separately in Chapter 6.

2.2.1 Open systems

Where strict environmental control is not necessary, an open system is generally used. Most pneumatic conveying pipeline systems can ensure totally enclosed material conveying, and so with suitable gas–solid separation and venting, the vast majority of materials can be handled quite safely in open systems. Many potentially combustible materials are conveyed in open systems by incorporating necessary safety features. Air is used for the conveying of most materials. Nitrogen and other gases can be used for particular materials and applications, but because of the added cost of operation closed loop systems are more commonly used in these cases.

2.2.1.1 Positive pressure systems

Although positive pressure conveying systems discharging to a reception point at atmospheric pressure are probably the most common of all pneumatic conveying systems, the feeding of a material into a pipeline in which there is air at pressure does present a number of problems. A wide range of material feeding devices, however, are available that can be used with this type of system, from verturis and rotary valves to screws and blow tanks, and these are considered in detail in Chapters 3 and 4. A sketch of a typical positive pressure system is given in Figure 2.2.

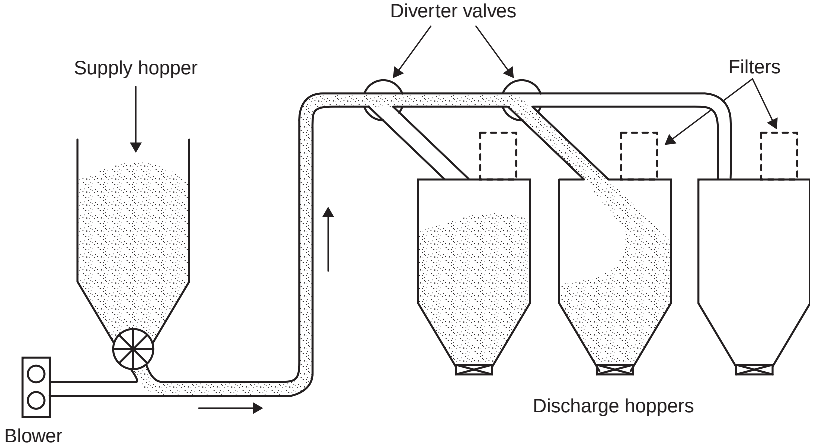


Figure 2.2 Typical positive pressure conveying system.

With the use of diverter valves, multiple delivery to a number of reception points can be arranged very easily with positive pressure systems, as illustrated in Figure 2.2. Although multiple point feeding into a common line can also be arranged, care must be taken, particularly in the case of rotary valve feeding of the pipeline, since air leakage through a number of such valves can be quite significant in relation to the total air requirements for conveying.

2.2.1.2 Negative pressure (vacuum) systems

Negative pressure systems are commonly used for drawing materials from multiple sources to a single point. There is little or no pressure difference across the feeding device and so multiple point feeding into a common line presents few problems. As a consequence, the feeding device can be a very much cheaper and simpler item in a negative pressure system than in a positive pressure system. A sketch of a typical system is given in Figure 2.3.

It will be seen from Figure 2.3 that the receiving hopper and filtration unit both have to operate under vacuum in this system. As a consequence of this there are three further basic differences between the negative and positive pressure conveying systems to be considered:

1. The receiving vessel has to be designed to withstand the appropriate vacuum.
2. The filtration plant has to be larger, as a higher volume of air has to be filtered under vacuum conditions.
3. In continuously operating systems material will need to be withdrawn from the reception vessel, but with it operating under vacuum air may leak across the discharge valve. This is effectively a 'mirror image' of the problem of feeding material against an adverse pressure gradient reported above for the positive pressure system in Figure 2.2.

Negative pressure systems are also widely used for drawing materials from open storage and stockpiles, where the top surface of the material is accessible. This is

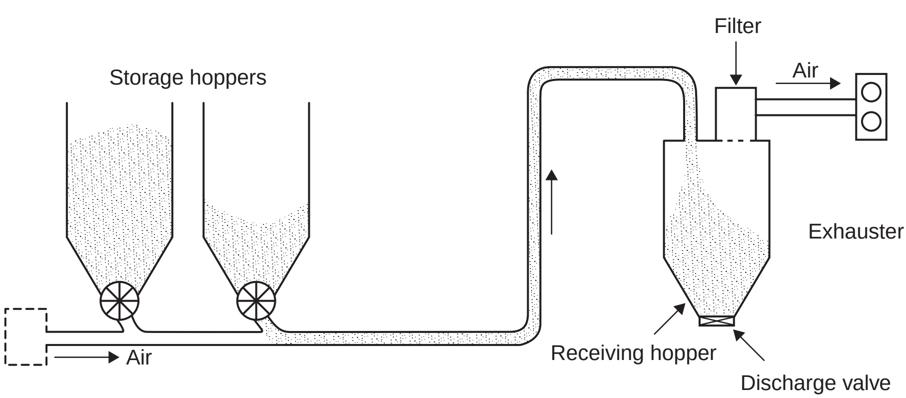


Figure 2.3 Typical negative pressure conveying system.

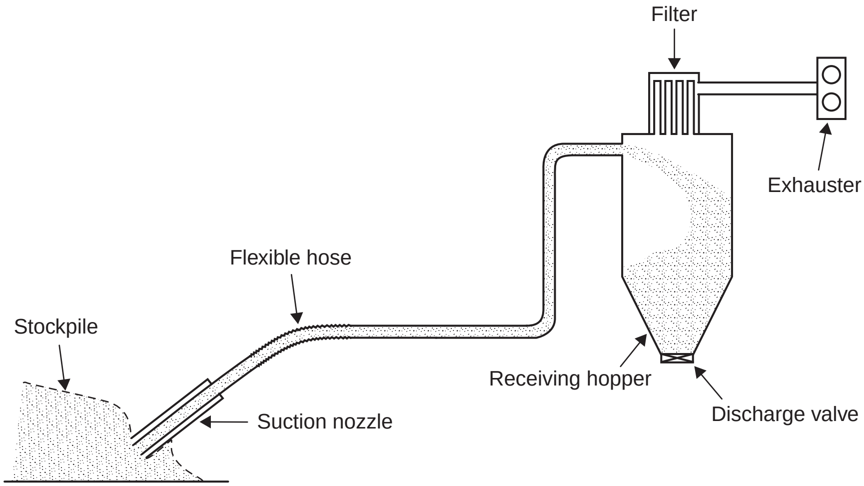


Figure 2.4 Vacuum conveying from open storage.

achieved by means of suction nozzles. Vacuum systems, therefore, can be used most effectively for off-loading ships. They are also particularly useful for cleaning processes, such as the removal of material spillages and dust accumulations. A sketch of a typical system is given in Figure 2.4.

Vacuum systems have the particular advantage that all gas leakage is inward, so that injection of dust into the atmosphere is virtually eliminated. This is particularly important for the handling of toxic and explosive materials. It is not always necessary to employ a closed system with these materials, therefore, provided that adequate safety measures are taken, particularly with regard to exhaust venting.

As a result of the conveying air being drawn through the air mover, it is essential that the exhauster should be protected from the possibility of the failure of one or more of the filter elements in the gas–solids separation system. This can be achieved by incorporating a back-up filter. Stand-by filters are rarely employed and so the purpose of the back-up filter is simply to allow sufficient time for the plant to be shut down safely and conveniently so that repairs can be carried out. The back-up filter, therefore, can be a simple device, but the upstream pipeline must be provided with monitoring equipment for detection purposes.

2.2.2 Staged systems

The systems illustrated above have all been single stage systems. In hydraulic conveying, for very long distance conveying, it is usual to stage systems. At the end of one stage the material is pumped back to pressure and fed into the pipeline of the next stage. Although this is perfectly possible for pneumatic conveying, it is very rare that it is ever done. Distance capability is limited with pneumatic conveying and the cost implications are probably against it. Combined systems, however, are quite common in which vacuum systems feed into positive pressure systems.

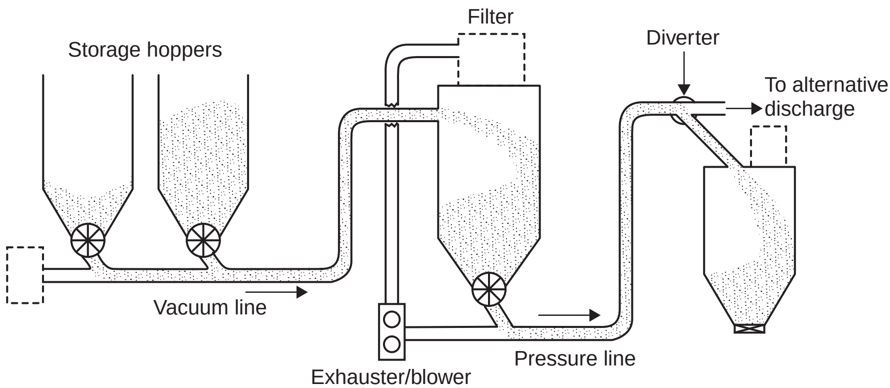


Figure 2.5 Sketch of shared negative and positive pressure system.

2.2.2.1 Shared negative and positive pressure systems

Combined negative and positive pressure systems that share a common air mover represent a very versatile type of pneumatic conveying, combining many of the advantageous features of both the negative pressure and positive pressure systems. They are often referred to as suck–blow or push–pull systems. They can be used to transfer material from multiple sources to multiple discharge locations and can thereby extend vacuum systems over much longer distances.

Protection has to be provided for the exhauster/blower from the possible ingress of material, as with negative pressure systems. It should be noted that the available power for the system has to be shared between the two sections, and that the pipelines for the two parts have to be carefully sized to take account of different operating pressures. Account must also be taken of the possible loss or ingress of air through material feeding and transfer devices.

Some air movers, such as positive displacement blowers, operate on a given pressure ratio, and this will mean that the machine will not be capable of operating over the same pressure range with the combined duty as compared with their individual operation. It should also be noted that although the air mover is shared between the two systems, each part of the system would require its own filtration unit. A sketch of a typical system is given in Figure 2.5.

2.2.2.2 Dual vacuum and positive pressure systems

If the conveying potential of a system requiring the vacuum pick-up of a material needs to be improved beyond that capable with a shared negative and positive pressure system, particularly in terms of conveying distance, then a dual system should be considered. In this combination the two conveying elements are separated and two air movers are provided. By this means the most suitable air mover can be dedicated to the vacuum system and the most appropriate positive pressure system can be used for the onward transfer of material.

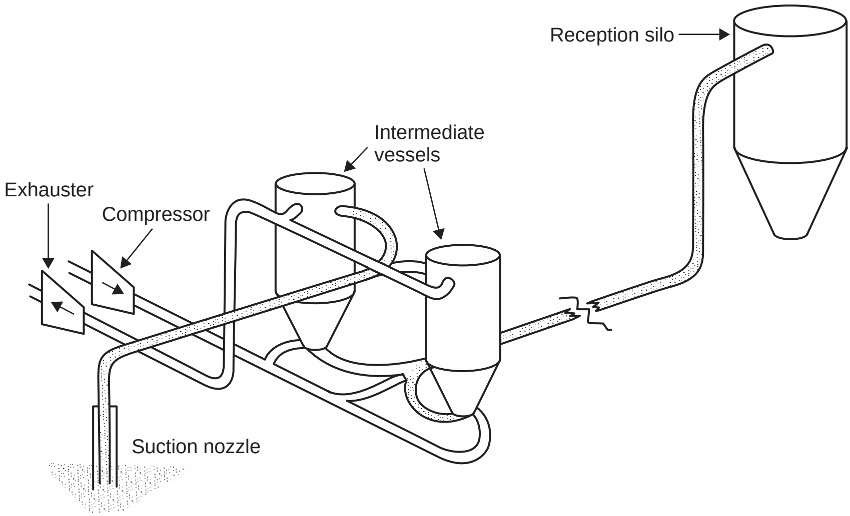


Figure 2.6 Sketch of typical dual vacuum and positive pressure system.

With the capability of using high pressure air for the onward conveying, dense phase conveying will be a possibility for appropriate materials. If the vacuum off-loading section is only a short distance, it is possible that the material could be conveyed in dense phase in this section also. Once again as there are two separate systems, two gas–solid separation devices also have to be provided. A sketch of a typical system is given in Figure 2.6. Filters and valves have been omitted for clarity. The various material feeding devices depicted will be considered in detail in Chapters 3 and 4.

2.2.3 Batch conveying systems

The systems illustrated above have all been capable of continuous operation, conveying 24 h a day if required. In many processes, however, it may be more convenient to convey one batch at a time. If such a choice is possible it does mean that there will be a wider range of available system types from which to select. An additional classification of conveying systems, as indicated on Figure 2.1, is based on mode of operation. Conveying can either be carried out on a continuous basis or in isolated batches. If a reasonably steady flow of material is required, or a high flow rate, a continuous sequence of batches can be conveyed.

Although a batch conveying system may be chosen for a specific process need, the mode of conveying is, to a large extent, dictated by the choice of pipeline feeding device. The majority of batch conveying systems are based on blow tanks, and blow tanks are selected either because of their high pressure conveying capability, or because of the nature of the material fed into the pipeline. Single blow tank systems are often used for this type of conveying. Blow tanks as feeding devices are considered in detail in Chapters 3 and 4.

There are two main types of batch type conveying system to be considered. In one, the batch size is relatively large, and the material is fed into the pipeline gradually over

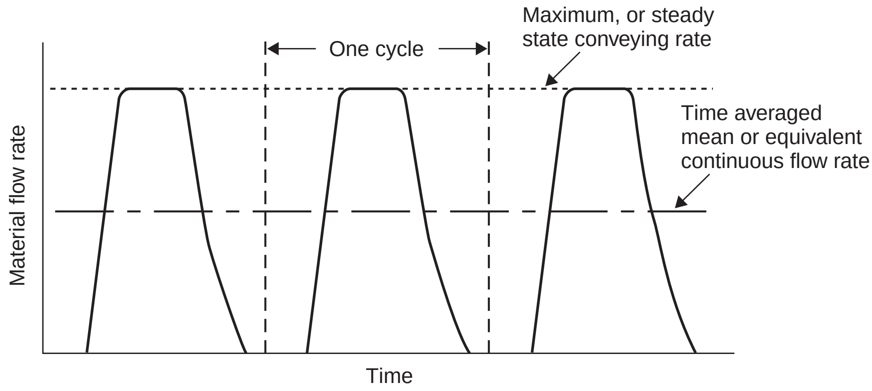


Figure 2.7 Sketch showing the transient nature of batch conveying.

a period of time, and so can be considered as a semi-continuous system. In the other, the entire batch of material is fed into the pipeline as a single plug.

2.2.3.1 Semi-continuous systems

It should be noted that when batches of material are fed into the pipeline gradually, there is essentially no difference in the nature of the gas–solids flow in the pipeline with respect to the mode of conveying, at any given value of solids loading ratio. The blow tanks used vary in size from a fraction of a cubic metre to 20 m^3 or more, generally depending upon the material flow rate required, and hence pipeline diameter, and a need to maintain a reasonable frequency of blow tank cycling. The material can be conveyed in dilute or dense phase, depending upon the capability of the material, the pressure available and the conveying distance, as with continuously operating systems.

With a single blow tank it is not possible to utilize the pipeline, while the blow tank is being filled with material or when the system is being pressurized. Since batch conveying is discontinuous, steady state values of material flow rate, achieved during conveying, have to be higher than those for continuously operating systems in order to achieve the same time averaged mean value of material flow rate. This means that air requirements and pipeline sizes have to be based on the maximum, or steady state, conveying rate. The intermittent nature of the conveying cycle is illustrated in Figure 2.7.

In comparison with a continuously operating system, therefore, the batch operating system would appear to be at a disadvantage. Blow tank systems, however, can operate at very much higher pressures to compensate, and they can be configured to operate continuously, as considered in Chapter 4 on high pressure pipeline feeding systems. With their very high pressure capability they can also be used in situations where material has to be fed into a process which is also at a high pressure. A typical batch conveying system based on a single blow tank is illustrated in Figure 2.8.

2.2.3.2 Single plug systems

In the single plug conveying system the material is effectively extruded into the pipeline as a single plug of material, typically about 10 m long. This plug of material is

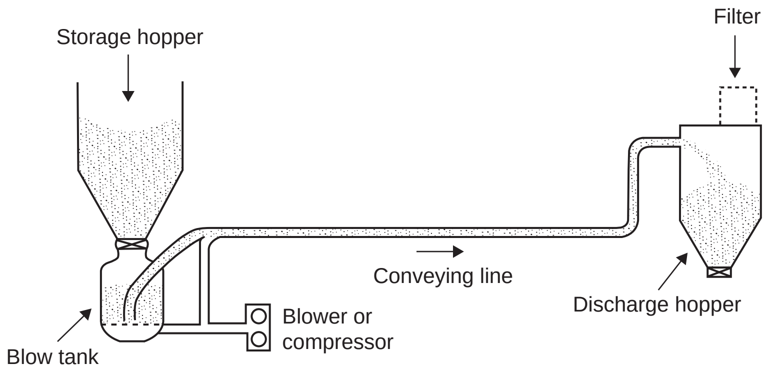


Figure 2.8 Batch conveying system using a single blow tank.

then blown through the pipeline as a single plug. A certain amount of material will tail off the end of the plug as it is conveyed, but the front of the plug will sweep up material deposited in the pipeline by the previous plug. It therefore takes a few conveying cycles to 'condition' the pipeline before regular or steady conveying is achieved.

The material will be conveyed at a low velocity, in what may be regarded as dense phase, but solids loading ratios do not have the same significance here, and steady state conveying, as depicted in Figure 2.7, does not apply either. Regardless of this, companies do quote solids loading ratios for these systems, but they can be used as a basis of comparison between systems with regard to air requirements.

The air pressure has to overcome the frictional resistance of the plug of material in the pipeline. As a result blow tank sizes are rarely larger than 3 or 4 m^3 unless very large diameter pipelines are employed. In terms of system design, a cycling frequency is selected to achieve the required material flow rate, which determines the batch size. The pipe diameter is then selected such that the frictional resistance of the plug results in a reasonable air supply pressure to propel the plug at the given velocity. A sketch of a typical single plug conveying system is given in Figure 2.9.

Single plug systems are capable of conveying a wide range of materials, and generally at much lower velocities than can be achieved in continuously operating systems. Many coarse, granular materials are either friable or abrasive and can only be conveyed in dilute phase with conventional conveying systems, and so single plug systems can represent a viable alternative. Material discharge often represents a problem with this type of system. Although the plugs of material are conveyed at a relatively low velocity, once they are discharged from the pipeline the high pressure air released behind the plug can cause severe erosion of the pipeline on venting.

2.2.4 Mobile systems

The systems illustrated above have all been fixed in a given location and the only mobility has been in terms of vacuum nozzles where, with flexible hose, limited movement is possible such as that required for ship off-loading and the clearing of materials

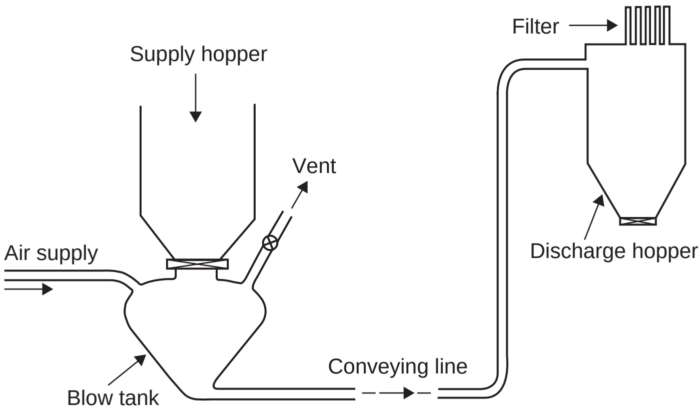


Figure 2.9 Single plug conveying system.

from stockpiles and spillages. Many bulk particulate materials are transported from one location to another by road, rail and sea.

Many materials, of course, are transported in a pre-packaged form, or in bulk containers, and can be transported by road, rail, sea or air, in a similar manner to any other commodity. Many transport systems, however, are specifically designed for bulk particulate materials and have a capability of self-loading, self-off-loading or both. These are generally mobile versions of the above static conveying systems, depending upon the application and duty.

Where materials are transported by road, rail and sea they will be subject to considerable vibration, and hence compaction and de-aeration, and so this must be taken into consideration when designing the off-loading facilities.

2.2.4.1 Road vehicles

Many road sweeping vehicles employ vacuum conveying for their operation. These are generally single stage in operation with an on-board exhauster providing the power for material pick-up. The reception hopper on-board the vehicle is generally hinged so that it can be off-loaded by gravity. Vehicles used for clearing materials from stockpiles are generally designed on the basis of Figure 2.5 so that they have the capability of delivering the collected material into a reception vessel.

Road vehicles are widely used for the transport of a multitude of bulk particulate materials, such as cement; sugar, flour and milk powder in the food industry; sand and soda ash in the glass industry; and nylon, PVC and polyethylene in the chemical industry. Road vehicles often have their own positive displacement blower mounted on-board and so can off-load their materials independently of delivery depot facilities. The material-containing vessel on-board doubles as a reception hopper for the collection of material and its ultimate discharge. This may be tipped to facilitate discharge, which can be via a rotary valve, or the vessel may be capable of being pressurized so that it discharges as a blow tank.

2.2.4.2 Rail vehicles

Railway wagons generally rely on delivery depot facilities for off-loading, because of their length tilting is not an option and multiple point off-loading is often employed. They may be off-loaded by rotary valve, or the wagon may be capable of being pressurized so that it can be off-loaded as a blow tank.

Whereas road vehicles are typically designed to operate with air at 1 bar gauge for this purpose, railway wagons are generally designed to 2 bar gauge and a full length wagon can usually be off-loaded in about 1 h. The base of the wagon is generally sloped at about 5 degrees in herringbone fashion around each discharge point and fluidized to facilitate removal of as much of the material as possible.

2.2.4.3 Ships

Large bulk carriers usually rely on port facilities for off-loading and these are generally similar to that depicted in Figure 2.6. Intermediate bulk carriers, however, often have on-board facilities for self-off-loading. Such vessels are often used for the transfer of materials, such as cement, to storage depots at ports for local supply, or to off-shore drilling rigs.

Materials are typically transferred from storage holds in the ship by a combination of air-assisted gravity conveyors and vacuum conveying systems, into twin blow tanks located in the centre of the vessel. High pressure air is supplied by on-board diesel driven compressors and materials are conveyed to dock-side storage facilities through flexible rubber hose, which solves the problems of both location and tidal movements.

2.2.5 Closed systems

The systems illustrated above have all been open systems in which air is usually the conveying gas and this is simply drawn from the atmosphere and returned back to it, after being filtered. For certain conveying duties, however, it is necessary to convey the material in a strictly controlled environment. If a dust cloud of the material is potentially explosive, nitrogen or some other gas can be used to convey the material. In an open system such environmental control can be very expensive, but in a closed system the gas can be re-circulated and so the operating costs, in terms of inert gas, are significantly reduced.

If the material to be handled is toxic or radioactive, it may be possible to use air for conveying, but very strict control would have to be maintained. A closed system would be essential in this case, and probably designed to operate entirely under vacuum. Continuous conveying systems are probably the easiest to arrange in the form of a closed loop. A sketch of a typical system is given in Figure 2.10.

A null point needs to be established in the system where the pressure is effectively atmospheric and provision for make-up of conveying gas can be established here. If this is positioned after the blower the conveying system can operate entirely under vacuum. If the null point is located before the blower it will operate as a positive pressure system.

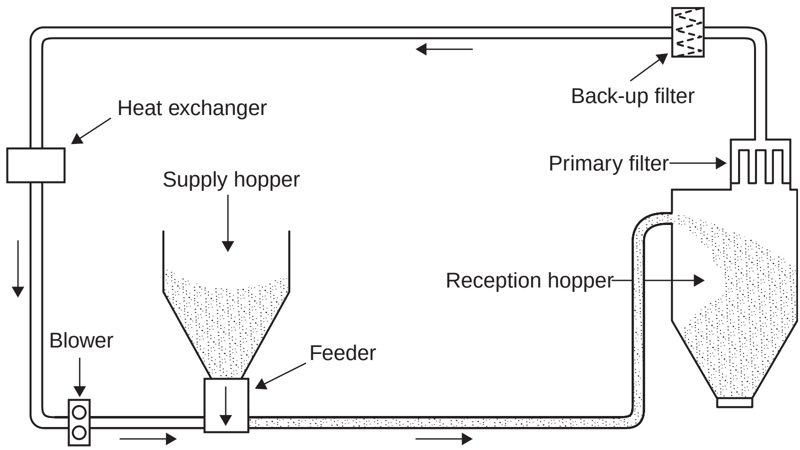


Figure 2.10 Closed loop pneumatic conveying system.

A back-up filter would always be recommended, because positive displacement blowers are very vulnerable to damage by dust. This is simply a precaution against an element in the filter unit failing. There will generally be an increase in temperature across a blower, and in a closed loop system it may be necessary to include a heat exchanger, otherwise there could be a gradual build-up in temperature. The heat exchanger can be placed either before or after the blower, depending upon the material being conveyed.

2.2.6 Innovatory systems

The systems illustrated above have all been conventional systems in which the material is simply fed into a pipeline and either blown or sucked to its destination. Unless the material to be conveyed has natural bulk characteristics such as good air retention or permeability, however, it is unlikely that it will be possible to convey the material at low velocity, and in dense phase, in a conventional conveying system such as those described above. Even if a high pressure system is employed it is unlikely that such a material will convey in dense phase, since dense phase conveying capability is dictated by the properties of the material.

For materials that are either friable or abrasive, alternatives to conventional systems may have to be considered, particularly if the materials are not capable of being conveyed in the dense phase mode, and hence at low velocities. For friable materials considerable particle degradation can occur in a high velocity suspension flow, and erosion of bends in the pipeline and other plant surfaces subject to particle impact will occur if an abrasive material is conveyed in dilute phase.

For a material that is only slightly hygroscopic, successful conveying may be achieved if the material is conveyed in dense phase, without the need for special air drying equipment, since air quantities required for conveying can be significantly lower than those for dilute phase. For food products, which may be subject to a loss in flavour in contact with air, dense phase conveying would automatically be recommended. If any such material is not capable of being conveyed in dense phase in conventional systems, however, alternative systems will also have to be considered.

With a need to convey many materials at low velocity, much development work has been undertaken since the late 1960s to find means of conveying materials, having no natural dense phase conveying capability, at low velocity. The innovatory systems produced as a result of these developments have centred around some form of conditioning of the conveyed material, either at the feed point into the pipeline or along the length of the pipeline. Since the modifications are essentially based on the pipeline, types of conveying system have not changed significantly.

2.2.6.1 Plug forming systems

The pulse phase system was developed in the late 1960s at the Warren Spring Laboratory in the UK. It was based on the use of a bottom discharge blow tank feeding material into a pipeline. Air is supplied to the top of the blow tank to pressurize the system, to aeration rings near the bottom of the blow tank and to the air knife at the start of the conveying line. A timer switches the air to the knife on and off at a pre-determined frequency. When the air supply to the knife is on, the air pulse splits the material in the pipe-line, stops the flow of additional material from the blow tank, and pushes the severed plug a short distance along the pipeline. When the air to the knife switches off, the material again flows from the blow tank, past the air knife, and the cycle repeats itself.

No further conditioning of the material occurs along the length of the pipeline. The pulse phase system was initially developed for the handling of fine materials of a cohesive nature that are difficult to convey in conventional systems, but subsequent developments have shown that a wider range of materials can be conveyed successfully. A typical pulse phase system is shown in Figure 2.11.

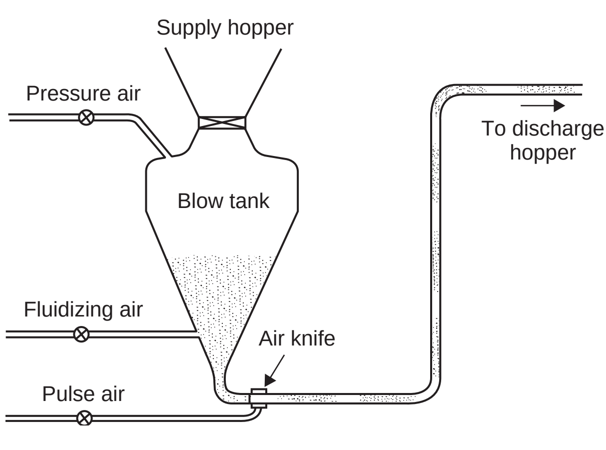


Figure 2.11 Pulse phase conveying system.

2.2.6.1.1 Pressure drop considerations

For materials that are impermeable and do not retain air, a short plug will completely block a pipeline, as reported in Chapter 1 (at 1.5.22). This situation corresponds to mechanically pushing a plug of material for which the pressure required varies exponentially with plug length, as illustrated in Figure 2.12. It is for this reason that bulk solids cannot be 'pumped' as a continuous plug over an appreciable distance in the same sense that a liquid can, since the pressures required are prohibitively high.

To transport bulk solids in this mode the wall friction properties must be drastically reduced and it is here that air as the motive force plays a vital role. Under such circumstances the effect of air expanding through the interstices aerates the material so as to reduce the friction between the particles and the pipeline wall. A comparison of the pressures required to maintain movement of mechanical and aerated plugs of material in a pipeline is also shown in Figure 2.12. The exact nature of the relationship of the pressure required is not known but research suggests that it is somewhere between a linear and a square law dependence on the length of the plug, the value depending upon the properties of the material:

$$p \propto L^n \tag{2.1}$$

where p is the air pressure and L, the length of plug for $1 < n < 2$.

For materials that have a high value of the exponent, n, long distance conveying in this mode requires prohibitively high pressures. If the material is conveyed as a number of short plugs, separated by air gaps, then the pressure requirements can be reduced substantially. On account of the non-linear relationship between pressure and plug length, the pressure required to convey a number of short plugs is significantly less than that required to convey a single plug of equivalent length, as illustrated in Figure 2.13. By increasing the length of the air cushions, and thereby decreasing the number of plugs in the pipeline, for a given system pressure, it is possible to convey over longer distances.

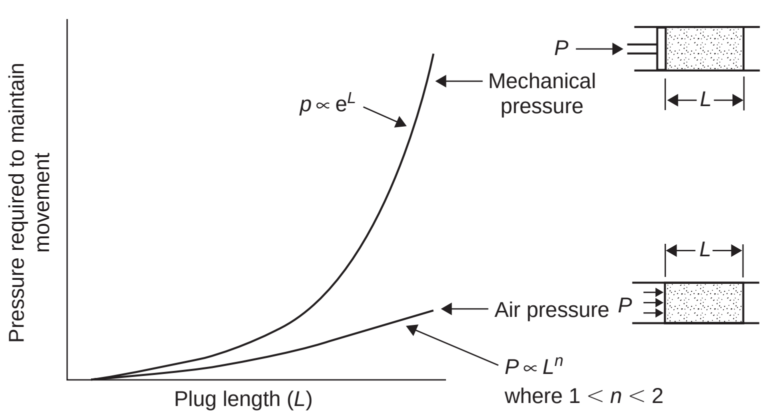


Figure 2.12 Pressure required to maintain movement of a plug of material in a pipeline.

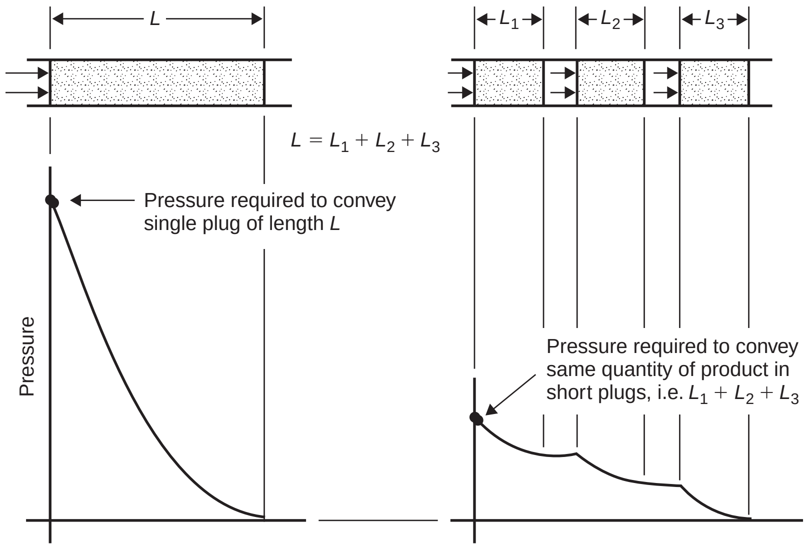


Figure 2.13 Relationship between pressure and plug length for continuous and pulse phase conveying.

2.2.6.2 By-pass systems

The most common by-pass systems employ a small pipe running inside the conveying line, having fixed ports, or flutes, at regular intervals along its length. An alternative arrangement is to have the by-pass external to the conveying pipeline and connected to it at intervals along the length. The bore of the by-pass pipe is typically 20–25 per cent of the bore of the conveying pipeline.

The spacing of the cross-connections to the external pipe, or the flutes along the length of the internal pipe, depends upon the permeability of the conveyed material. These parallel pipes are not supplied with an external supply of air, but air within the conveying line can enter freely through the regular openings provided.

The by-pass pipe may run continuously when external to the pipeline, and so include bends, but the internal fluted pipe is generally confined to straight lengths of pipeline only. A sketch of these by-pass systems is given in Figure 2.14.

Air by-pass systems are generally employed for materials that are impermeable to air and which tend to form solid plugs when conveyed at low velocity. If the material is impermeable the air will be forced to flow through the by-pass pipe if the pipeline blocks. The by-pass pipe allows air to be advanced to a point where it is capable of splitting up the plug at the forward end and so allow conveying to continue. As the by-pass pipe is much smaller in diameter than the conveying pipeline, the air will be forced back into the pipeline through subsequent flutes, and this will effect a break-up of the plug of material causing the blockage. A long plug of material is thus divided up into short slugs that are readily conveyed.

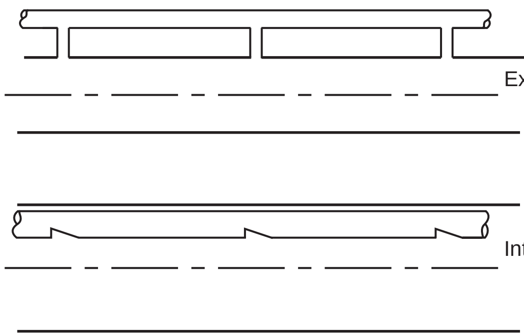


Figure 2.14 Sketch of various by-pass systems.

2.2.6.2.1 Pressure drop considerations

If the material is impermeable the air will be forced to flow through the by-pass pipe, if the pipeline blocks. Even if the material has a little permeability, most of the air is likely to enter the by-pass pipe. From the Darcy Equation the pressure drop, Δp_a, for air flowing through a pipeline is given by:

$$\Delta p_a \propto \frac{L\rho C^2}{d} \tag{2.2}$$

where L is the pipeline length (m), ρ, the air density (kg/m^3), C, the air velocity (m/s) and d, the pipeline bore (m).

Neglecting changes in air density and expressing in terms of pressure gradient gives:

$$\frac{\Delta p_a}{L} \propto \frac{C^2}{d} \tag{2.3}$$

The volumetric flow rate of the air, $\dot{V}$, is given by:

$$\dot{V} = C \times \frac{\pi d^2}{4} \tag{2.4}$$

This will be reasonably constant at any point and so this gives:

$$C = \frac{1}{d^2} \tag{2.5}$$

Substituting Equation (2.5) into Equation (2.3) gives:

$$\frac{\Delta p_a}{L} \propto \frac{1}{d^5} \tag{2.6}$$

If the bore of the by-pass pipe is one quarter of that of the conveying pipeline, for example, the pressure gradient in the by-pass pipe, with all the air flowing through it, will be 4^5, which is more than 1000 times greater than that in the pipeline. This means that it will not be possible for the air to by-pass the plug, but will be forced back into the pipeline through the next and subsequent flutes, and this air flow will effect a break-up of material causing the blockage [1].

2.2.6.3 Air injection systems

A number of systems have been developed that inject air into the pipeline at regular points along its length. While by-pass pipe systems artificially create permeability in the bulk material, air injection will help to maintain a degree of air retention within the material. As with the by-pass system, a parallel line runs alongside the conveying pipeline. With air injection systems, however, this parallel line is provided with an independent air supply.

The injection of additional air into the pipeline does mean, of course, that conveying air velocities towards the end of the pipeline will be increased, and such an increase in velocity will magnify problems of erosive wear and particle degradation, and could adversely affect conveying performance. Air addition, therefore, should be kept to a minimum consistent with achieving dense phase conveying in a material that would otherwise not be capable of low velocity, dense phase flow.

Air injection systems take a number of different forms. In some cases a small number of injection points are situated at strategic points along a conveying line, usually after each bend and pipeline fitting. In others they are positioned at regular intervals along the length of the pipeline, spaced from less than 1 m to more than 10 m apart, depending upon the air retention properties of the material to be conveyed. In more recent developments the air is injected only at points where and when it is considered to be necessary, rather than on a continuous basis. A sketch of various air addition systems is given in Figure 2.15.

2.2.6.3.1 The Gattys system

A patented method that can give a material artificial air retention properties is the Gattys 'Trace Air' system. This was one of the first innovatory conveying systems to be

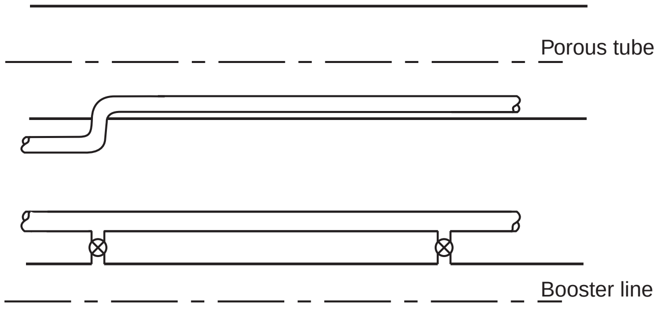


Figure 2.15 Sketch of various air addition systems.

commercially available. In this system air at relatively low pressure is supplied continuously to the material in the pipeline through an internal perforated pipe that runs the whole length of the conveying line. The motive force comes from a pressure drop along the conveying line created by pumping air in at the upstream end, as in conventional pneumatic conveying by pipeline, but the pressures are lower and the risk of blockage is smaller [2].

2.2.6.3.2 Booster systems

In booster systems a separate supply of air is provided to a parallel line. Air is injected into the conveying pipeline at regular intervals along its length, typically spaced from 3 to 15 m apart, depending upon the material. In some systems sensors are positioned between the parallel airline and the conveying pipeline so that air is only injected where required. If a change in pressure difference between the two lines is detected, which would indicate that a plug is forming in the conveying pipeline, air is injected at that point to break-up the plug and so facilitate its movement.

2.2.6.4 System selection considerations

Many of the innovatory systems are capable of being stopped and re-started during operation. With most conventional systems this is not possible, and would result in considerable inconvenience in clearing pipelines, if this were necessary. In any operation where this feature would be required, therefore, one of the innovatory systems would be well worthwhile considering.

An innovatory system may also be chosen for various other reasons. Since they are capable of conveying materials in dense phase, operating costs for power are likely to be lower than those for a conventional dilute phase system. Capital costs for the innovatory systems are almost certain to be higher, however, and so an economic assessment of the alternative systems would need to be carried out.

2.2.7 Fluidized motion conveying systems

The categorizing of fluidized motion conveying systems always represents a problem. They are not generally recognized as pneumatic conveying systems because they only use very low pressure air and the material does not flow through a pipeline. They are, however, clearly not in the mechanical conveying group of conveyors. Until recent years their application was relatively limited because the main driving force was gravity, and so they would only operate on a downward incline, although at a very low angle.

The material is conveyed along a channel which has a continuous porous base. Air enters the material through the porous base and fluidizes the material. In this condition the material will behave like a liquid and flow down an inclined channel. The channel is generally closed to keep the system dust tight. In early systems the channel ran with the material only partly filling the channel. The fluidizing air escaped into the space above the flowing material and was ducted to a filtration plant. In a recent development the channel runs full of material and horizontal conveying is possible.

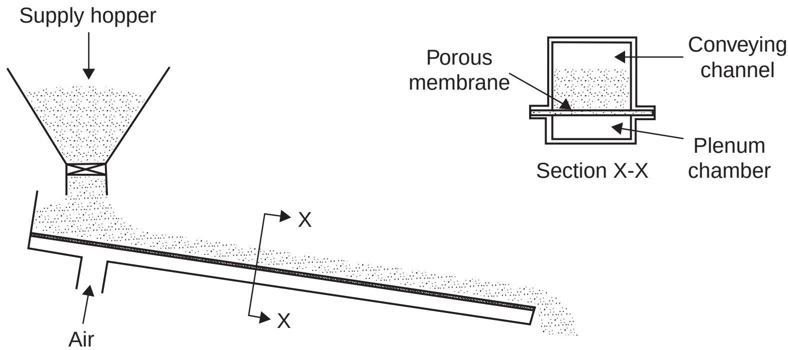


Figure 2.16 Air-assisted gravity conveyors.

2.2.7.1 Air-assisted gravity conveyors

In situations where the flow of a material can be downwards, the air-assisted gravity conveyor has a number of advantages over pneumatic conveying systems. Plant capital costs can be much lower, operating costs are significantly lower, and a wide range of materials can be conveyed at a very low velocity. Air-assisted gravity conveyors can be regarded as an extreme form of dense phase conveying.

The conveyor consists essentially of a channel, divided longitudinally by means of a suitable porous membrane on which the material is conveyed. A sketch of such a system is given in Figure 2.16. If a small quantity of low pressure air is fed through the membrane, the inter-particle and particle/wall contact forces will be reduced and the material will behave like a liquid. If a slight slope is imparted to the conveyor, the material will flow.

These conveyors are often referred to as 'air slides'. They have been in use for over 100 years and are still widely used today for materials such as alumina, cement and fly ash. Air-gravity conveyors, ranging in width from 100 to 600 mm, can convey materials over distances of up to 100 m, and are suitable for material flow rates of up to about 3000 tonne/h. In general, most materials in the mean particle size and density ranges from 40 to 500 μm and 1400 to 5000 kg/m^3, respectively, are the easiest to convey and will flow very well down shallow slopes.

2.2.7.1.1 The Geldart classification of fluidization behaviour

These materials correspond to Group B materials in Geldart's classification of fluidization behaviour [3] which is presented in Figure 2.17. When the supply of fluidizing air is shut-off with these materials they de-aerate rapidly, hence the bed collapses and flow stops almost instantaneously. This means that they are easy to control and will not flood feed. It is this group of materials, however, which cannot be conveyed in dense phase in conventional conveying systems, because they have little or no air retention capability. The Geldart classification can be used to a limited extent to identify which materials might be capable of dense phase conveying.

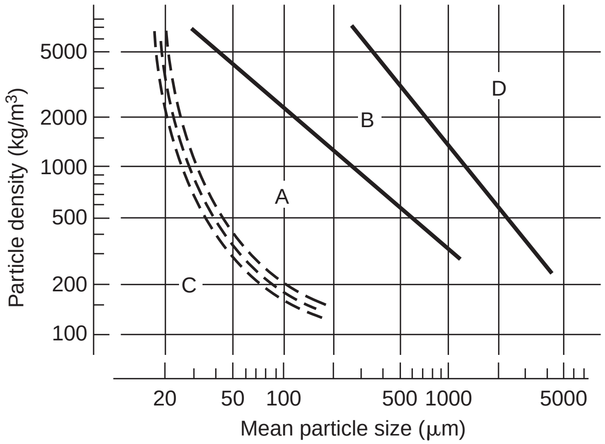


Figure 2.17 Geldart's classification of fluidization behaviour for fluidization with ambient air.

Materials of larger particle size and/or high density in Group D can usually be conveyed in a similar manner but the quantity of fluidizing air required tends to become rather high. This group of materials might be considered suitable for dense phase conveying in plug flow, but this is only the case if they are essentially mono-sized. Materials having a high value of mean particle size, with a wide size distribution, generally have very poor permeability and so are not capable.

Group A includes materials of small particle size and/or low density and these may have a tendency to continue flowing for a time after the air supply has been shut-off because of their air retention properties. It is generally this group of materials that are ideal candidates for dense phase pneumatic conveying in sliding bed flow.

Group C includes cohesive powders that are difficult to fluidize satisfactorily, because of high inter-particulate forces resulting from the very small particle size, and are unsuitable for conveying in this manner, although slightly cohesive materials can usually be conveyed provided that the slope of the channel is great enough. These materials will generally convey well in dense phase provided that they can be fed into the pipeline. Care must be taken with ultra-fine particles in pneumatic conveying systems, however, because they have a tendency to coat the pipeline wall. This issue is considered at various points in the Guide.

It is an essential requirement that the material is sufficiently aerated on the channel membrane for flow to take place. The porous base, therefore, must be of high enough resistance to ensure that when part of it is clear of material the remainder is not starved of air. Material segregation by size and density can occur during transport and can be significant in a long channel. In an extreme case a deposit of coarse particles may continuously build up on the bottom of the channel until the solids flow ceases altogether. The air-gravity conveyor, however, by virtue of its flow mechanism is particularly suitable for both abrasive and friable materials.

2.2.7.2 Full channel conveyors

Hanrot [4] describes a pressurized horizontal conveying system developed by Aluminium Pechiney to convey alumina. The alumina was conveyed from a single supply point to more than 100 outlets. Electrolysis pots on a modern aluminium smelter were required to be filled and the distance from the silo to the furthest outlet was about 180 m. Air at a pressure of 0.1 bar is used. A sketch of the system is given in Figure 2.18 and this illustrates the principle of operation.

A conveying channel is employed, as with the air-assisted gravity conveyor, but the channel runs full of material. Balancing columns are positioned on the conveying duct and are used for dedusting. This is not a continuously operating system in the application described. It is a batch type system and its object is to meet the demands of the intermittent filling of the pot hoppers. The system, however, is clearly capable of continuous operation and of significant further development.

2.3 System requirements

The uses, applications and requirements of pneumatic conveying systems are many and varied. A number of system requirements were highlighted at various points with regard to the systems. Some of the more common requirements of systems can be identified and are detailed here for easy access and reference, since these may feature prominently in the choice of a particular system.

2.3.1 Multiple pick-up

If multiple point feeding into a common line is required, a vacuum system would generally be recommended. Although positive pressure systems could be used, air leakage across feeding devices such as rotary valves represent a major problem. The air leakage from a number of feed points would also result in a significant energy loss. The air loss could be overcome by adding isolation valves to each feed point, but this would add to the cost and complexity of the system.

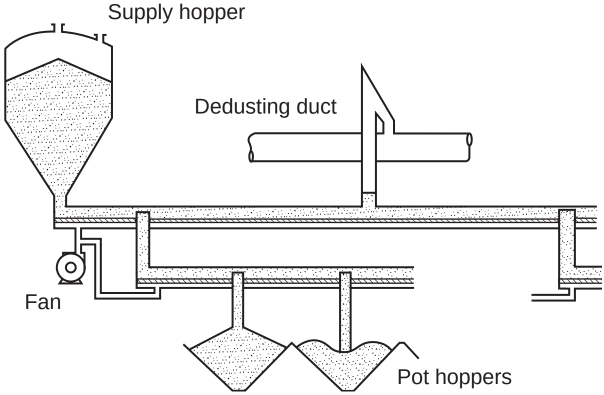


Figure 2.18 Principle of potential fluidization ducts.

2.3.2 Multiple delivery

Multiple delivery to a number of reception point can easily be arranged with positive pressure systems. Diverter valves can be used most conveniently for this purpose. The problem with vacuum systems performing this function is equivalent to the problem of using a positive pressure system for the multiple pick-up of materials.

2.3.3 Multiple pick-up and delivery

The suck–blow, or combined vacuum and positive pressure, system is ideal for situations where both multiple pick-up and delivery is required. The pressure available for conveying is rather limited with this type of system and so if it is necessary to convey over a long distance, a dual system would be more appropriate. In this the vacuum and positive pressure conveying functions are separated and a high pressure system can be used to achieve the distant conveying requirement.

2.3.4 Multiple material handling

If it is required to handle two or more materials with the one system, reference must be made to the conveying characteristics for each material to be conveyed. It is quite likely that the air requirements for the materials will differ to a large extent. In this case it will be necessary to base the air requirements, to be specified for the air mover, on the material requiring the highest conveying line inlet air velocity. Consideration will then have to be given to a means of controlling the air flow rate, to lower values, for the other materials, if this should be required. It is also likely that the flow rate of each material will be different. The feeding device, therefore, will have to meet the needs of every material, in terms of flow rate and control. These issues are dealt with at length in the Guide.

2.3.5 Multiple distance conveying

If it is required to convey a material over a range of distances, such as a road tanker supplying a number of different installations, or a pipeline supplying a number of widely spaced reception points, consideration will again have to be given to differing air requirements and material flow rates. For a given air supply, the material flow rate will decrease with increase in conveying distance, and so the material feeding device will need to be controlled to meet the variation in conveying capability. For materials capable of being conveyed in dense phase there is the added problem that the air flow rate will also need to be increased for longer distance conveying.

2.3.6 Conveying from stockpiles

If the material is to be conveyed from a stockpile, then a vacuum system using suction nozzles will be ideal. The type of system required will depend upon the application and conveying distance. For a short distance a vacuum system will probably meet the demand on its own. Where access is available to a free surface, as in ship off-loading, vacuum nozzles can transfer material under vacuum to a surge hopper. If this is not the final destination for the material it could be the intermediate hopper in a combined positive and negative pressure conveying system, or the supply hopper for the second part of a dual system, from where the material can be blown to a distant reception point.

For clearing dust accumulations and spillages, and surplus material deposited in stockpiles, mobile units are particularly useful. These are generally suck–blow systems with a vacuum nozzle. Although they can be small versions of a continuously operating suck–blow system, they are more usually batch conveying systems with the transfer hopper acting also as a blow tank. Material is first drawn into the hopper/blow tank under vacuum, and when it is full it is pressurized and conveyed on to the reception point.

2.3.7 Start-up with full pipeline

If there is likely to be a need to stop and start the conveying system while it is conveying material, a system capable of doing this will need to be selected. This is rarely possible in conventional systems, unless a large air receiver is installed specifically for the purpose, and so consideration will have to be given to innovatory systems. Many of these systems are capable of starting with a full pipeline, although their capabilities on vertical sections may need to be checked, particularly if the stoppage is for a long period. The possibility of power cuts, from whatever source, should also be taken into account here.

2.4 Material property influences

The properties of the materials to be conveyed feature prominently in the decisions that have to be made with regard to the selection of a pneumatic conveying system. As with 'System Requirements', considered above, some of the more common material properties can be identified and are detailed here for easy access and reference.

2.4.1 Cohesive

Problems may be experienced with cohesive materials in hopper discharge, pipeline feeding and conveying. If there is any difficulty in discharging a cohesive material from a rotary valve, a blow-through type should be used. If there is any difficulty in conveying a cohesive material in a conventional system, then an innovatory system should be considered. The pulse phase system, for example, was developed for the handling of such fine cohesive powders.

2.4.2 Combustible

There is a wide range of materials which, in a finely divided state, dispersed in air, will propagate a flame through the suspension if ignited. These materials include foodstuffs such as sugar, flour and cocoa, synthetic materials such as plastics, chemical and pharmaceutical materials, metal powders, and fuels such as wood and coal. If a closed system is used the oxygen level of the conveying air can be controlled to an acceptable level, or nitrogen can be used. If an open system is to be used, then adequate safety devices must be put in place. One possibility is to use a suppressant system. Another is to employ pressure relief vents and other safety features.

2.4.3 Damp or wet

Materials containing a high level of moisture can generally be conveyed in conventional systems if they can be fed into the pipeline, and do not contain too many fines. Most of the handling problems with wet materials occur in trying to discharge them from hoppers. Fine materials may not discharge satisfactorily from a conventional rotary valve and so a blow-through type should be used.

Fine materials which are wet will tend to coat the pipeline and bends, and gradually block the line. Lump coal having a large proportion of fines is a particular problem in this respect. Single plug blow tank systems and some of the innovatory systems are capable of handling this type of material. If a conventional system must be used, the problem can be relieved by heating the conveying air, if the material is not too wet.

2.4.4 Electrostatic

If the build-up of electrostatic charge is a problem when conveying a material, the air can be humidified. This process can be carried out on-line and does not usually require a closed system. In dense phase the quantity of air which needs to be conditioned is much less than in dilute phase systems, and so for materials capable of being conveyed in dense phase, the operating costs for air quality control will be lower. The entire system and pipework network should be earthed.

2.4.5 Erosive

If the hardness of the particles to be conveyed is higher than that of the system components, such as feeders and pipeline bends, then erosive wear will occur at all surfaces against which the particles impact. Velocity is one of the major parameters and so the problem will be significantly reduced in a low velocity system. If a dilute phase system must be used, feeding devices with moving parts, such as rotary valves and screws, should be avoided, and all pipeline bends should be protected.

2.4.6 Friable

If degradation of the conveyed material is to be avoided, a system in which the material can be conveyed at low velocity should be used. The magnitude of particle impacts, particularly against bends in the pipeline, should be reduced as this is one of the major causes of the problem. Pipeline feeding devices that can cause particle breakage, such as screws, should also be avoided.

2.4.7 Granular

Granular materials can be conveyed with few problems in pneumatic conveying systems provided that they can be fed into the pipeline. Problems with feeding can occur with top discharge blow tanks and conventional rotary valves. Air will often permeate through granular materials in top discharge blow tanks and the materials will not convey, particularly if the blow tank does not have a discharge valve. Granular materials containing a large percentage of fines, and which are not capable of dense phase conveying, may block in a top discharge line. In rotary valves, shearing of granular materials should be avoided, and so a valve with an off-set inlet should be used.

2.4.8 Hygroscopic

If a material is hygroscopic the air used for conveying can be dried to reduce the moisture level to an acceptable level. This process can be carried out on-line and does not usually require a closed system. For a material which is only slightly hygroscopic, successful conveying may be achieved if the material is conveyed in dense phase, without the need for air drying equipment, since air quantities required for conveying can be significantly lower than those for dilute phase conveying.

2.4.9 Low melting point

The energy from the impact of particles against bends and pipe walls at high velocity in dilute phase conveying can result in high particle temperatures being generated. The effect is localized to the small area around the point of contact on the particle surface, but can result in that part of the particle melting. The problem is accentuated if the particles slide on the pipe wall. Plastic pellets such as nylon, polyethylene and polyesters are prone to melting when conveyed in suspension flow.

Velocity is a major variable and so the problem will be eliminated for most materials in a low velocity, dense phase system. If such materials have to be conveyed in dilute phase, a roughened pipeline surface will reduce the problem considerably as this will prevent the particles from sliding.

2.4.10 Radioactive

Radioactive materials must be conveyed under conditions of absolute safety, and so it would be essential to employ a closed system so that strict control of the conveying environment could be obtained. A vacuum system would also be necessary to ensure that no conveying air could escape from the system, or material in the event of a bend eroding.

2.4.11 Toxic

If toxic materials are to be handled, strict control of the working environment must be maintained. A vacuum system, therefore, would be essential to ensure that there could be no possibility of material leakage. If the conveying air, after filtration, could be vented safely to the atmosphere, an open system would be satisfactory. If not, a closed loop system would have to be used.

2.4.12 Very fine

A problem of pipeline coating can occur with very fine powders in the low-micron and sub-micron range, such as carbon black and titanium dioxide. These materials tend to adhere to the pipe wall when conveyed in conventional systems. The coating gradually builds up and can cause a marked reduction in the pipe section area, and hence a reduction in conveying capacity. Many of the innovatory systems are capable of handling this type of material successfully.

If a conventional system is to be used the material should be conveyed through a flexible pipeline so that the material build-up can be shaken free on a regular basis. It is quite likely that the natural pulsations that occur within the system would be sufficient to vibrate the material free to enable it to be re-entrained in the conveying line.

References

1. D Mills. Similarities and differences between conventional and innovatory systems for dense phase pneumatic conveying. Powder and Bulk Handling. Vol 3. pp 15–23. July–September 1999.
2. C R Woodcock and J S Mason. Bulk Solids Handling – An Introduction to the Practice and Technology. Leonard Hill: Blackie & Son. 1987.
3. D Geldart. Types of gas fluidization. Powder Technology. Vol 7. pp 185–292. 1973.
4. J-P Hanrot. Multi-point feeding of hoppers, mounted on aluminium smelter pots, by means of potential fluidization piping. Proc 115th An Mtg, The Metallurgical Soc of AIME. pp 103–109. New Orleans. March 1986.

Chapter 3

Pipeline feeding devices

Part 1: Low pressure and vacuum

3.1 Introduction

All pneumatic conveying systems, whether they are of the positive or negative pressure type, conveying continuously or in a batch-wise mode, can be considered to consist of the basic elements depicted in Figure 3.1.

In terms of pneumatic conveying system components, a considerable number of devices have been specifically developed to feed materials into pipelines. The material feeding device is particularly critical to the successful operation of the system and so with a large number of devices from which to select, two chapters are devoted to this topic. A number of devices have also been developed to disengage materials from the conveying air at the reception point and these are considered separately in Chapter 7.

Air movers are equally important components and these are considered in Chapter 6. With air movers, however, it is more a matter of selection from existing machines, but an early choice for pneumatic conveying systems was made with the positive displacement blower. These can be used as either compressors or exhausters, but they are limited in operation to a pressure ratio of about 2. This means that their maximum positive pressure capability is about 1 bar gauge, and for vacuum duties it is about 0.5 bar. The conventional rotary valve has been a very commonly used feeding device and this has a very similar upper pressure limitation, and hence the division between these two chapters with regard to feeding devices.

3.1.1 Air leakage

In vacuum systems the material feeding is invariably at atmospheric pressure and so the pipeline can either be fed directly from a supply hopper or by means of suction

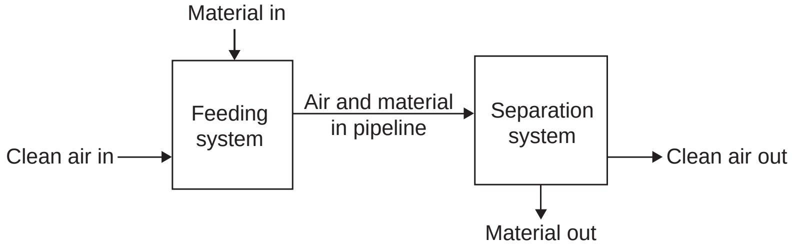


Figure 3.1 Basic elements of a pneumatic conveying system.

nozzles from a storage vessel or stockpile. The main point to bear in mind, however, is that there will be no adverse pressure gradient against which the material has to be fed. The feeder, therefore, does not have to be designed to additionally withstand a pressure difference. With no adverse pressure drop to feed across it also means that there will be no leakage of air across the device when feeding material into the pipeline. Separation systems in these cases, therefore, by necessity, do have to operate under vacuum conditions.

In positive pressure systems, separation devices invariably operate at atmospheric pressure. Pipeline feeding in positive pressure systems represents a particular problem, however, for if the material is contained in a storage hopper at atmospheric pressure, the material has to be fed against a pressure gradient. As a consequence of this there may be a loss of conveying air. The feeding device in this case has to be designed to withstand the pressure difference in addition.

In certain cases this air flow can hinder the downward gravity flow of material into the feeder and hence interfere with the feeding process. Also, if the loss is significant, the volumetric air flow rate will have to be increased to compensate, for the correct air flow rate to the pipeline must be maintained for conveying the material. This loss, therefore, represents a loss of energy from the system.

3.1.2 Pressure drop

Material flow rate through a pipeline is primarily dependent upon the pressure drop available across the pipeline. A basic requirement of any feeding device, therefore, is that the pressure loss across the device should be as low as possible in low pressure systems, and as small a proportion of the total as possible in high pressure systems.

If the feeder takes an unnecessarily high proportion of the total pressure drop from the air source, less pressure will be available for conveying the material through the pipeline, and so the material flow rate will have to be reduced to compensate. Alternatively, if a higher air supply pressure is employed to compensate, more energy will be required, and hence the operating cost will be greater.

3.1.3 Maintenance

Maintenance of these items is another important factor. If air leakage has to be accepted with a particular feeding system, the rate of loss must not increase unduly with time, otherwise insufficient air may ultimately be supplied to a pipeline and a blockage may occur after a period of time.

3.1.4 Material properties

Material properties are particularly important and have to be taken into account in the selection of feeding devices. In feeding systems that have moving parts, care has to be taken with both abrasive and friable materials. Material flow properties need to be taken into account with feeding devices, and particle size must be considered in all cases, particularly the two extremes of large lumps and very fine particles.

3.1.5 Devices available

Many diverse devices have been developed for feeding pipelines. Some are specifically appropriate to a single type of system, such as suction nozzles for vacuum systems. Others, such as rotary valves, screws and gate valves, can be used for both vacuum and positive pressure systems. The approximate operating pressure ranges for various pipeline feeding devices is shown in Figure 3.2.

It will be seen that there is no scale on the vacuum side of Figure 3.2. This is because the pressure of operation is only atmospheric and there will be essentially no pressure difference across the feeder, regardless of the type of feeder. In some situations a small resistance may be built into the system but this is generally only to help promote flow into the feeding device.

Developments have been carried out on most types of feeding device, both to increase the range of materials that can be successfully handled, and to increase the operating pressure range of the device. Each type of feeding device, therefore, can generally be used with a number of different types of conveying system, and there are usually many alternative arrangements of the feeding device itself.

3.1.5.1 Lock hoppers

It should be pointed out that Figure 3.2 is drawn for stand-alone feeding devices. The pressure capability of many of the positive pressure feeding devices listed can be improved significantly, with little further modification, if they are used in conjunction with lock hoppers. This puts the devices into the higher pressure rating and so this will be considered in the next chapter.

3.1.5.2 Blow tanks

For high pressure systems, and particularly where the material has to be fed into a system that is maintained at a high pressure, blow tanks are often employed. These are generally used for conveying batches, although they can quite easily be adapted for continuous conveying. This is the particular advantage of all the other feeding devices shown in Figure 3.2. Although blow tanks are generally associated with high pressure conveying, they are also used for low pressure conveying.

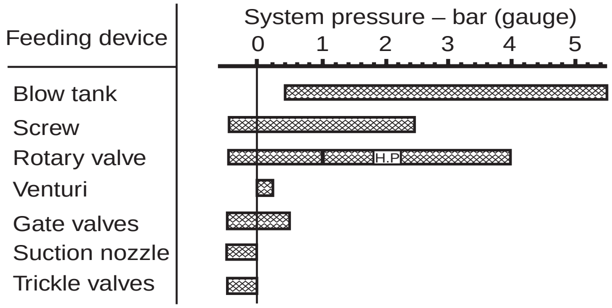


Figure 3.2 Approximate operating pressure ranges for various pipeline feeding devices.

Blow tanks are being more widely used in industry and so information on blow tanks is included in this chapter as well as in Chapter 4, apart from the fact that they cover a very wide range of operation. Blow tanks have no moving parts and so have particular advantages with regard to the feeding of abrasive and friable materials.

3.1.6 Feeding requirements

For a given conveying system the air mover can be positioned at either end, as will be seen with Figure 3.3. If the air is blown into the pipeline, therefore, the air at the feed point will be at a pressure close to that of the air supply. In this case the material has to be fed into the pipeline at pressure, and so consideration has to be given to the possibility of air leakage across the device. If the air mover is positioned downstream of the system, so that it acts as an exhauster to the separator/discharge hopper, the air at the material feed point will be close to atmospheric pressure. In this case the effect of a pressure gradient on the feeding device need not be taken into account.

A further requirement of the feeding device is that it should feed the material into the conveying line at as uniform a rate as possible. This is particularly so in the case of dilute phase systems, for the material is conveyed in suspension and quite high values of minimum conveying air velocity have to be maintained. With a mean conveying air velocity over the length of the pipeline of 20 m/s, for example, it will only take about 5 s for the air to pass through a 100 m long pipeline.

If there are any surges in material feed, the pipeline could be blocked very quickly. Alternatively, if the air mover has a pressure rating to make allowance for such surges, the output from the system could be increased if the flow rate, and hence the conveying line pressure drop, was kept constant at a higher value to match the rating more closely.

3.1.6.1 Flow metering

Positive displacement feeding devices, such as screws and rotary valves, can serve the dual purpose of metering the material into the pipeline, while effecting the airlock that is necessary for successful operation, in the case of positive pressure systems. Some feeders act only as airlocks and so require additional equipment to meter the material

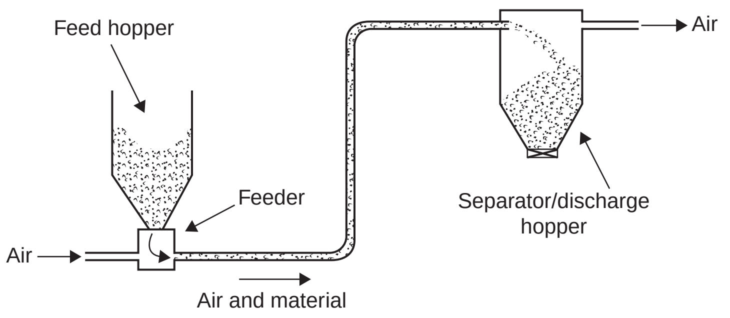


Figure 3.3 Typical low pressure conveying system capable of continuous operation.

into the conveying line. Some feeders have no moving parts, and so particular attention is given to them, as their means of material flow control may not be obvious.

3.2 Rotary valves

The rotary valve is probably the most commonly used device for feeding material into pipelines. This type of feeder consists of a bladed rotor working in a fixed housing. In many applications in which it is used its primary function is as an airlock, and so is often referred to as a rotary air lock. This basic type of valve is generally suitable for free flowing materials.

3.2.1 Drop-through valve

The type of valve described above is usually referred to as a 'drop-through' feeder and is depicted in Figure 3.4. This type of feeder is generally suitable for free flowing materials. Material from the supply hopper continuously fills the rotor pockets at the inlet port which is situated above the rotor. It is then transferred by the motor-driven rotor to the outlet where it is discharged and entrained into the conveying line.

3.2.1.1 Valve wear

By the nature of the feeding mechanism, rotary valves are more suited to relatively non-abrasive materials. This is particularly the case where they are used to feed materials into positive pressure conveying systems. By virtue of the pressure difference across the valve, and the need to maintain a rotor tip clearance, air will leak across the valve. Wear, therefore, will not only occur by conventional abrasive mechanisms, but by erosive wear also. The problem of erosive wear can be a particularly serious one in pneumatic conveying and so Chapter 23 is entirely devoted to the subject.

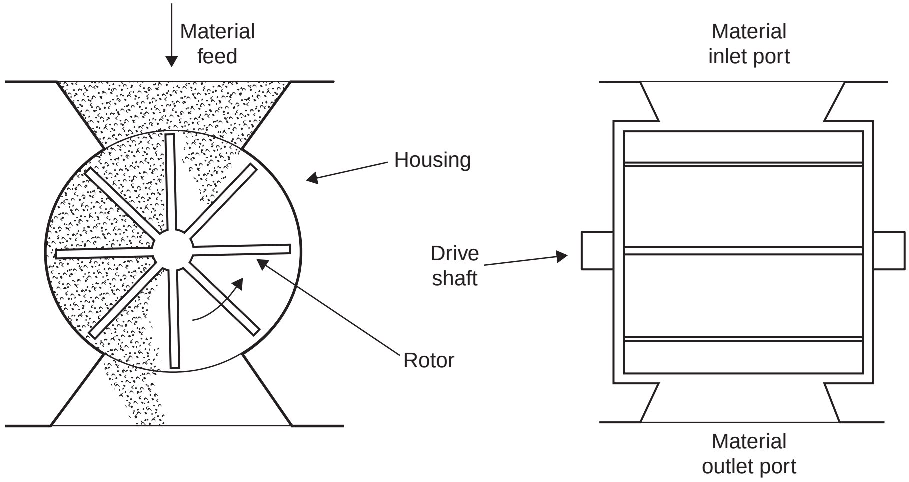


Figure 3.4 Drop-through rotary valve.

Air leakage through the blade tip clearances, as a consequence of the pressure difference, can generate high velocity flows. This high velocity air flow will entrain fine particles, and the resulting erosive wear can be far more serious than the abrasive wear. Wear resistant materials can be used in the construction of rotary valves, and removable lining plates can be incorporated to help with maintenance, but wear can only be minimized, it cannot be eliminated if an abrasive material is to be handled.

For vacuum conveying duties there is no pressure drop across the valve when feeding, and so with no air leakage there is no erosive wear, only abrasive wear. This is only the situation when a rotary valve is used to feed a pipeline for a vacuum conveying system. If a rotary valve is used to off-load material from a hopper in a vacuum conveying system the situation is effectively the same as described above for feeding a positive pressure system. In this case the leakage air will additionally by-pass the conveying system by being drawn directly into the exhauster, and so starve the conveying pipeline of air. This point is considered further below.

By the same reasoning there will be no air leakage, and hence no erosive wear, with a rotary valve when used for off-loading material from a reception hopper on a positive pressure conveying system.

3.2.2 Alternative designs

As the rotary valve is probably the most common feeding device in use, it is not surprising that much effort has gone into to developing it further. The improvement in materials and construction methods to make it more acceptable for handling abrasive materials is one such area. The reduction in air leakage and the development of a rotary valve capable of operating at much higher pressures, and across much higher pressure differentials, has been another. Its capability for handling a wider range of materials was an early development.

3.2.2.1 Off-set valve

Rotary valves that have an off-set inlet for material feed are often employed in applications where shearing of the material should be avoided. A sketch of such a valve is given in Figure 3.5. They employ a side inlet, generally with an adjustable flow control, so that the angle of flow of the material does not permit it to fill the rotor pocket. As the rotor rotates toward the housing, material flows into the trough of the rotor and so prevents shearing. This type of valve is widely used for feeding pelletized materials.

3.2.2.2 Blow-through valve

Another variation of the standard type of feeder is the 'blow-through' valve, which is also shown in Figure 3.5. Here the conveying air passes through and purges the discharging pockets such that the material entrainment into the conveying pipeline actually takes place in the valve itself. These valves are primarily intended for use with the more cohesive types of material, since these materials may not be discharged satisfactorily when presented to the outlet port of a 'drop-through' valve.

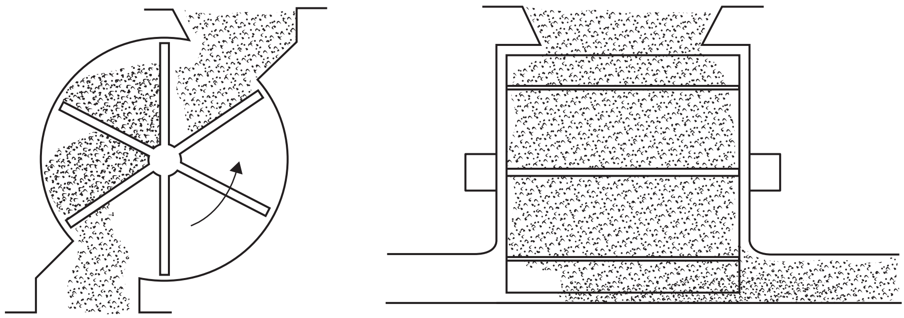


Figure 3.5 Alternative rotary valve configurations: (a) off-set valve and (b) blow-through valve.

3.2.3 Discharge period and pulsations

It should be borne in mind that for an eight-bladed rotor, such as that shown in Figure 3.4, rotating at a typical speed of 20 revolutions per minute (rev/min), a time span of only 0.375 s is available for the material to be discharged from each pocket. The time available for discharge, therefore, is very short, and although this is generally satisfactory for free flowing materials it is generally not for cohesive materials and hence the need for the alternative blow-through valve.

The reciprocal of this time period provides another important operating parameter. The importance of feeding material into a pipeline as smoothly as possible was mentioned above, and it was stated that in a dilute phase conveying system the air would traverse a 100 m long pipeline in about 5 s. For the rotary valve being considered above, about 13 pockets of material would be deposited into the pipeline in this period. Such a frequency of pulsations is generally acceptable for most conveying applications and the resulting fluctuation in the air supply pressure is usually acceptable also. Consideration of such pulsations in combustions systems, however, would be recommended.

3.2.4 Air leakage

It is an unavoidable physical characteristic of the rotary valve that, in a positive pressure pneumatic conveying system, there will be a leakage of air across the valve. This occurs in three areas:

- via the returning empty pockets;
- through the various rotor blade clearances between the blade tips and the rotor housing;
- through the gaps between the sides of the blades and the rotor housing.

3.2.4.1 Positive pressure systems

Typical air flows and leakage paths for a rotary valve operating in a positive pressure conveying system are shown in Figure 3.6. Appropriate pressures are also superimposed to help reinforce the various directions of flow that are also indicated.

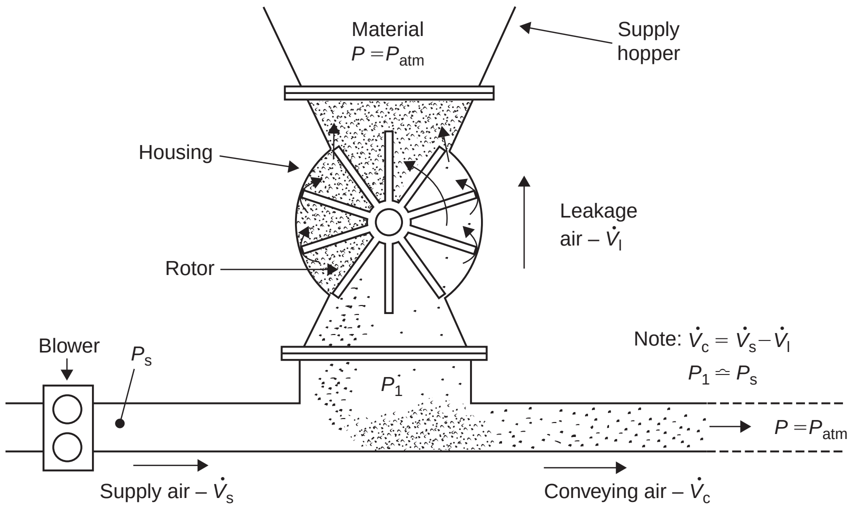


Figure 3.6 Air flows and leakage paths for a rotary valve feeding a positive pressure conveying system.

The air leaking across the rotary valve by-passes the conveying pipeline and so is not used for conveying, as can be seen from Figure 3.6. This problem is well recognized and most manufacturers of rotary valves supply information on the air leakage rate across their valves so that it can be taken into account. In specifying the air requirements for the blower or compressor, therefore, this leakage air must be taken into account as indicated on Figure 3.6.

3.2.4.2 Negative pressure systems

Although there will be no air leakage across a rotary valve that is feeding material into a negative pressure conveying system, the total conveying system must be taken into account in this case. With the system operating under vacuum there is plenty of scope for air to leak into the system from other sources. A typical system is shown in Figure 3.7.

With a rotary valve used to continuously off-load material from the discharge hopper there will be a leakage of air into the system. This has exactly the same influence on the correct specification of the air flow rate required from the exhauster as it does for the blower in a positive pressure system. With vacuum systems care must be taken with air leakage from any source into the system. The problem here is that it will not be seen, and against a background level of noise it may not be heard either.

If such air leakage occurs in a positive pressure system it is unlikely to present any problem at all to the operation of the system. This is because a loss of air along the length of the pipeline will compensate for the expansion of the conveying air, which could actually result in an improvement in performance, provided that the conveying air velocity did not fall below the minimum value for the material. In positive pressure systems,

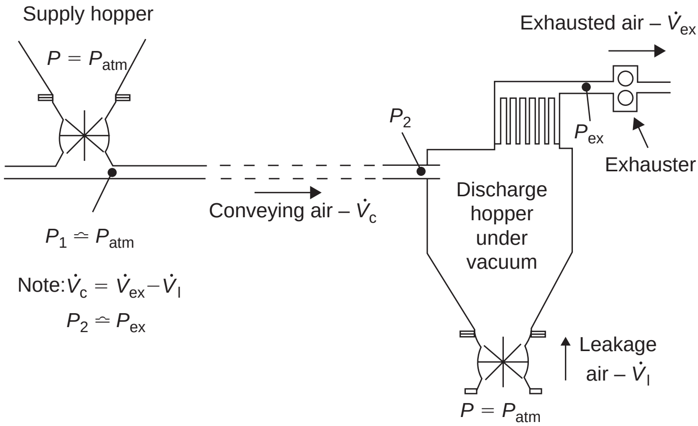


Figure 3.7 Air flows and leakage paths for rotary valves in a negative pressure conveying system.

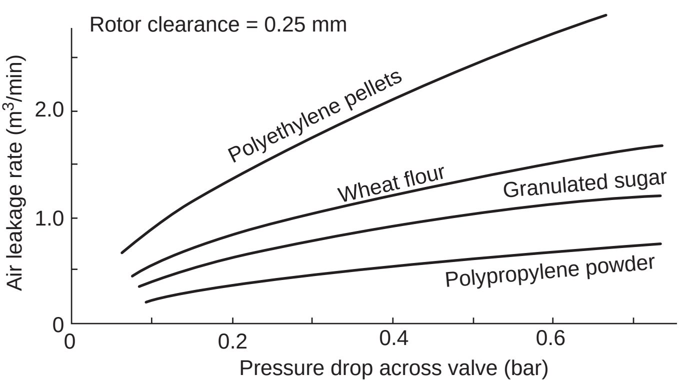


Figure 3.8 Typical influence of pressure drop and material on rotary valve leakage rate.

however, a loss of air from eroded bends and insecure couplings and flanges will be readily observed by everyone in the vicinity because of the dust cloud generated.

3.2.4.3 Influence of conveyed material

For a 100 mm bore pipeline the air leakage could be as much as 15% of the air supplied. For a material such as plastic pellets it will be even higher, and in smaller diameter pipelines the percentage will be proportionally greater. For a valve operating across a small pressure difference with a very fine material, however, air leakage will be significantly reduced. The magnitude of the loss will depend upon the pressure difference across the valve, the valve size and the rotor tip clearance, the nature of the material being handled, and the resistance to air flow by the head of material over the valve.

The potential influence of the material being conveyed on the leakage of air across a rotary valve is presented in Figure 3.8. This data is obtained from a nominal 200 mm

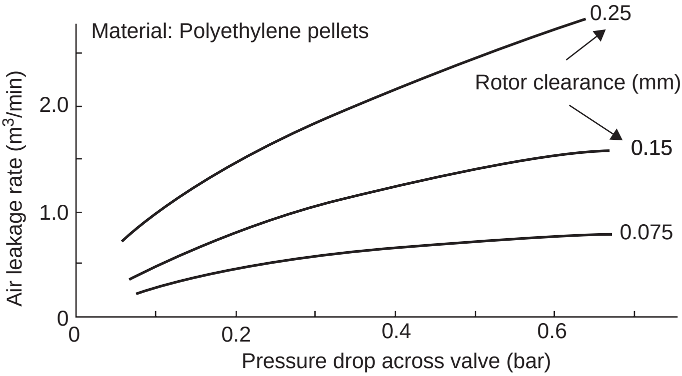


Figure 3.9 Typical influence of pressure drop and rotor clearance on rotary valve leakage rate.

diameter eight-bladed rotary valve [1]. Tests were carried out with four very different materials and with pressure drop values across the rotary valve of up to about 0.7 bar. In each case the blade tip clearances were set at 0.25 mm. It will be seen from this that fine materials such as polypropylene powder can have a significant sealing effect on the rate of leakage. Polyethylene pellets, being so very permeable, probably offer no resistance at all.

If air leakage across the valve is not taken into account, or if the anticipated leakage is incorrect for some reason, it can have a marked effect on the performance of the conveying line. If insufficient air is available for conveying the material in the pipeline, as a result of losses across a rotary valve, it is possible that the pipeline will block, for a loss of 10–20 per cent of the total air supply will significantly affect the velocity of the air in the conveying system. Also, if two or more rotary valves feed into a common line, and there is no additional valve over each rotary valve to minimize air losses from those not in use, the air, and hence energy loss, could be very considerable.

Rotor tip clearance is an important variable here. The gradual wear of a valve in use, such that the rotor clearances increase slightly over a period of time, will affect the balance of the air flows shown in Figure 3.8, and consequently affect the conveying line performance. This is one of the reasons why rotary valves are not generally recommended for the handling of abrasive materials. It is important, therefore, that rotary valves should be well maintained. The potential influence of blade tip clearance on the leakage of air across a rotary valve is shown in Figure 3.9.

This data was obtained with the same valve reported above with Figure 3.8 [1] and shows a significant effect of blade tip clearance. It is not only with gradual wear of a valve through handling abrasive materials that problems can arise. Consideration must also be given to expansion problems if the air from the blower is not cooled, or the material being conveyed is hot. In these cases particular attention should be given to start up and shut down transient influences on blade tip clearance, because this could become sub-zero and result in valve seizure under certain circumstances.

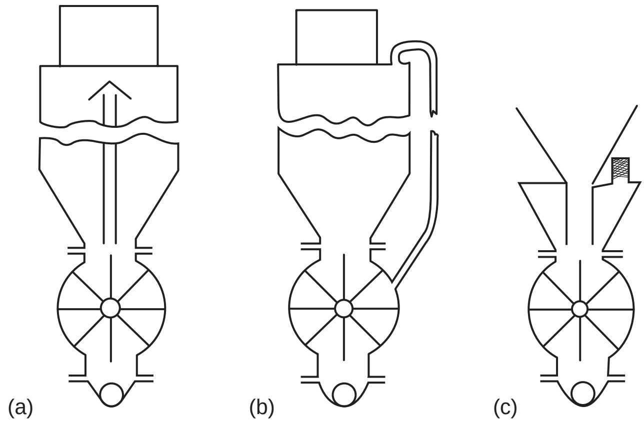


Figure 3.10 Methods of venting rotary valves: (a) internal vent, (b) external vent and (c) pellet vent.

3.2.5 Air venting

Unless the air leakage across the rotary valve is vented away, prior to the material entering the valve, material flow into the valve may be severely restricted. The magnitude of the problem depends very much upon the properties of the material being handled. For plastic pellets and granular materials, venting may not be necessary, but for fine cohesive materials and light fluffy materials the volumetric efficiency of the valve, in terms of pocket filling, may be very low. In this case material feed at a controlled rate might be difficult to achieve. A number of different ways of venting rotary valves are presented in Figure 3.10.

With pockets of material falling under gravity into a high pressure air stream, and a significant percentage of this air passing through the rotary valve, the turbulence generated beneath the rotary valve is considerable. It is not surprising, therefore, that this leakage air should carry a certain proportion of material with it, which is predominately dust and fines.

Since the vented air will contain some fine material, this is normally directed back to the supply hopper, or to a separate filter unit. Because there will be a carry-over of material this filter must be a regularly cleaned unit, otherwise it will rapidly block and cease to be effective. Indeed, the pipe connecting the vent to the filter should be designed and sized as if it were a miniature pneumatic conveying system, in order to prevent it from getting blocked.

A particular problem here is that the performance of such a peripheral item is rarely monitored, and so if the vent line does block it is rarely known or recognized as the source of subsequent operating problems.

3.2.6 Entrainment devices

In order to reduce the turbulence level, and hence energy loss, beneath a rotary valve, as a result of the pulsating nature of the material flow and opposing air flow, entrainment

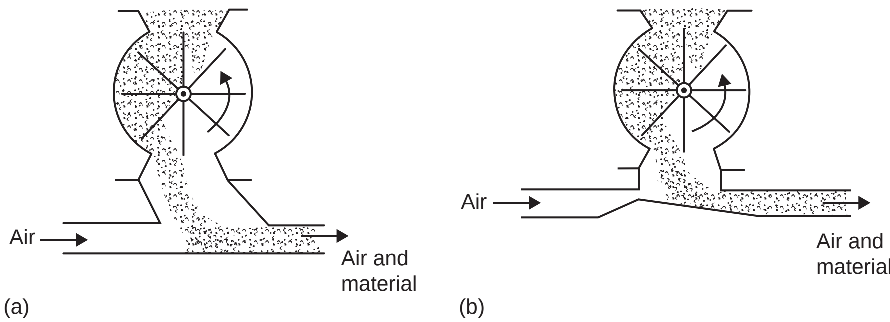


Figure 3.11 Entrainment sections for rotary valves: (a) drop-out box and (b) venturi.

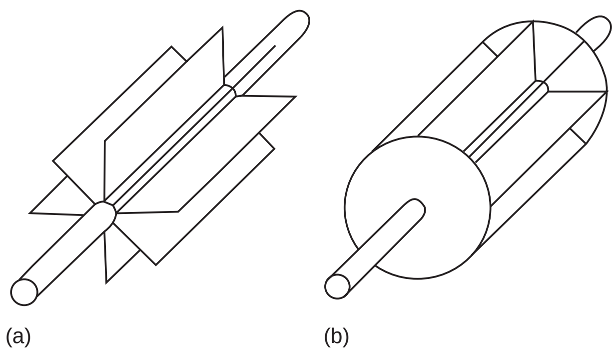


Figure 3.12 Rotor types: (a) open-end and (b) closed end.

devices are often used. A common device is a 'drop-out' box and this is illustrated in Figure 3.11.

Another configuration is the venturi entrainment section, and this is also shown in Figure 3.11. Here the cross section is reduced with a resultant increase in entrainment velocity and decrease in pressure in this region. A consequence of this decrease in static pressure is that there will be less leakage through the valve to interfere with material feeding, resulting in an improvement when handling the finer, free flowing types of material. As a consequence of the resulting high velocities this type of arrangement would not be recommended for either abrasive or friable materials.

3.2.7 Rotor types

Rotors are either of the 'open-end' type or 'closed-end' type. With 'open-end' types the blades are welded directly to the driving shaft, while with the 'closed-end' type discs or shrouds are welded to the shaft and blade ends to form enclosed pockets. These two types of rotor are illustrated in Figure 3.12.

Although open-end rotors are less expensive, they have several disadvantages. With the more abrasive materials wear of the rotor housing end plates is possible since the material is in constant contact with them. Also, they are not as rigid as the closed-end type as they only have one edge secured to the drive shaft. They cannot, of course, be used in the blow-through type of feeder shown in Figure 3.5b. The closed-end type of rotor provides a very much more rigid construction, and it is with this type of rotor that developments towards much higher pressure and lower leakage rate applications have been possible. These are considered further in Chapter 4.

3.2.7.1 Pocket types

There are three rotor pocket configurations in widespread use, and these are shown in Figure 3.13. The most common type has deep pockets and hence maximum volumetric displacement. This is more suited to the handling of free flowing materials. Type (b) has shallow, rounded pockets and so its volumetric capacity is reduced. This configuration is generally used with the more cohesive types of material that tend to stick in deep pockets. Blade tips are often employed, and a sketch of such a rotor is given in Figure 3.13c). Many of these blade tips are adjustable to maintain operating efficiency. They can be made of resilient, spark-proof, flexible or abrasion resistant materials.

The rotor clearance can have a significant effect on valve performance, and in an attempt to minimise the effect of the leakage on the feed rate, manufacturers make these clearances as small as possible. Clearances on new valves are typically of the order of 0.075–0.15 mm. Clearances smaller than this would add considerably to the cost of manufacture and may even lead to binding in the housing due to deflection of the rotor, or movement within the bearings, when subject to the applied pressure gradient in positive pressure applications.

The fitting of flexible elastomer/polymer wipers to the rotor blades, such that they are in sliding contact with the housing, is quite common. This approach, however, is generally limited to low pressure applications, typically up to about 0.25 bar gauge, since the leakage at pressure gradients greater than this can deflect the wipers and so lose their advantage.

The number of blades on the rotor will determine the number of blade labyrinth seals that the air must pass before escaping from the system. From an air loss point of view, therefore, a ten-bladed rotor would be specified for applications with pressure

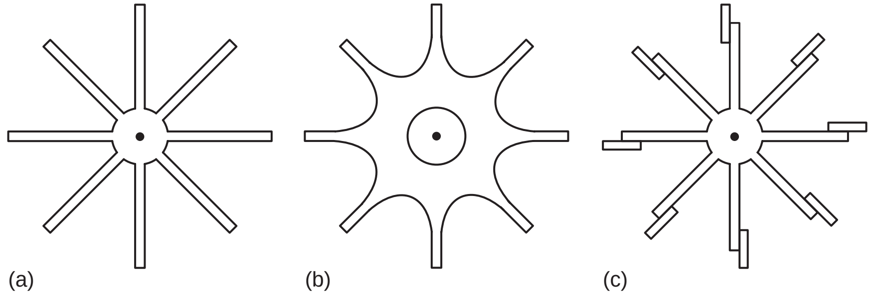


Figure 3.13 Rotor pocket configurations: (a) deep pocket rotor, (b) shallow pocket rotor and (c) rotor with blade tips.

differentials from 0.5 to 1.0 bar. Eight-bladed rotors are commonly used in applications with pressure differentials up to 0.5 bar, and six-bladed rotors where the pressure differential is below 0.2 bar.

There is obviously a practical limitation to the number of blades that can be used in a rotor when handling a given material. The number is largely dependent upon the material itself, since increasing the number of blades decreases the angle between them. A decrease in this angle is sufficient with some materials to prevent if from being discharged when presented to the outlet port and is certainly inappropriate for cohesive materials.

3.2.8 Material feed rate

The feed rate of a rotary valve is directly proportional to the displacement volume of the rotor and its rotational speed. The displacement volume is simply the pocket size or volume multiplied by the number of rotor pockets. If a mass flow rate of material is required this must then be multiplied by the bulk density of the material. The constant of proportionality here is the volumetric or filling efficiency of the rotary valve:

$$\dot{m}_{\mathrm{p}} = V n N \rho_{\mathrm{b}} \eta \times \frac{60}{1000} \text{ tonne/h} \tag{3.1}$$

where $\dot{m}_{\mathrm{p}}$ is the mass flow rate of material (tonne/h); V, the volume of pocket (m^3); n, the number of rotor pockets (1/rev); N, the rotational speed (rev/min); ρ_{b}, the bulk density of material (kg/m^3) and η the filling efficiency (–).

3.2.8.1 Pocket filling efficiency

If air leakage impedes material flow, the pockets will not fill completely and so the volumetric efficiency will be reduced. Air leakage may also have the effect of reducing the bulk density of the material, for with some materials the fluidized bulk density can be very much lower than the 'as poured' bulk density. It should be noted that, because of air leakage, the volumetric efficiency of a rotary valve when feeding a negative pressure system will generally be much greater than when feeding a positive pressure system.

3.2.8.2 Feed rate control

As the rotary valve is a positive displacement device, feed rate control can be achieved quite simply by varying the speed of the rotor. Although the above approach might suggest that feed rate increases continually with rotor speed, there are in practice a number of factors that tend to reduce the feed rate below this maximum.

The pocket filling efficiency of a rotary valve, for example, is a function of rotor speed, for at increased speed the time available for pocket filling reduces. Up to a speed of about 20 rev/min the filling efficiency is reasonably constant, but above this speed it starts to decrease at an increasing rate. The situation is illustrated in Figure 3.14. There is also a lower limit on speed because of the problems associated with the low frequency

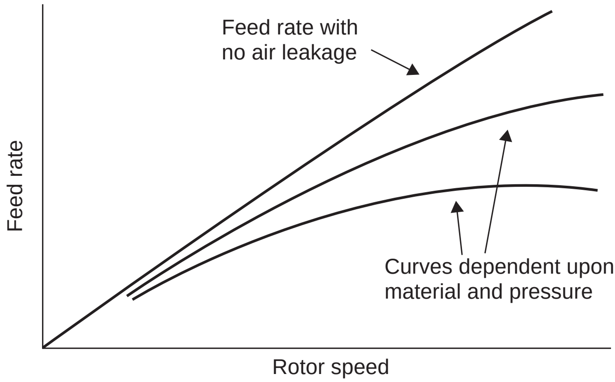


Figure 3.14 Typical feed rate characteristics for a rotary valve.

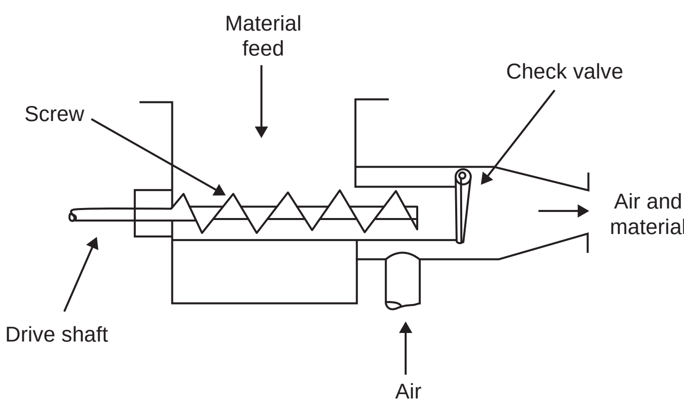


Figure 3.15 Simple screw feeder.

pulsations caused by pocket emptying. Thus there is a limit on feed rate with any given rotary valve, but they do come in a very wide range of sizes to meet almost any duty.

3.3 Screw feeders

Much of what has been said about rotary valves applies equally to screw feeders. They are positive displacement devices, feed rate control can be achieved by varying the speed, they can be used for either positive pressure or vacuum pipeline feeding duties, air leakage is a problem when feeding into positive pressure systems, and they are prone to wear by abrasive materials.

3.3.1 The simple screw feeder

A simple type of screw feeder is shown in Figure 3.15. Rotation of the screw moves a continuous plug of material into the pipeline, where it is dispersed and entrained with

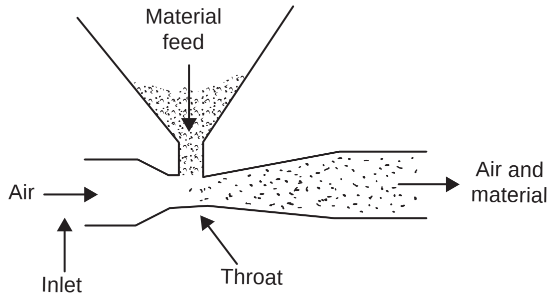


Figure 3.16 Basic type of venturi feeder.

the conveying air. A particular advantage of screw type feeders is that there is an approximate linear relationship between screw speed and material feed rate, and so the discharge rate can be controlled to within fairly close limits.

This type of screw feeder, however, is rarely used for feeding positive pressure conveying systems. This is because there is little in their design to satisfy the basic requirement of feeding across an adverse pressure gradient. Air leakage represents a major problem with many materials, and so they are generally limited to vacuum systems where operating pressure differentials do not have to be considered.

The simple screw feeder, however, can be used in high pressure applications in combination with a lock hopper. The simple screw feeder has also been adapted for high pressure duty with the incorporation of a variable pitch screw. Both of these cases are considered in Chapter 4.

3.4 Venturi feeders

Since the basic problem with feeding positive pressure systems is that the air leakage arising from the adverse pressure gradient can interfere with the flow of the material into the pipeline, this situation can be improved, to a certain extent, by using venturi feeders. These work on the principle of reducing the pipeline cross-sectional area in the region where the material is fed from the supply hopper, as shown in Figure 3.16.

It will be seen that there are no moving parts with this type of feeding device, which has certain advantages with regard to wear problems. There are, however, no inherent means of flow control either, and so this has to be provided additionally.

A consequence of the reduction in flow area is an increase in the entraining air velocity and a corresponding decrease in pressure in this region. With a correctly designed venturi the static pressure at the throat should be the same as that in the supply hopper which, for the majority of applications, is atmospheric pressure. This then encourages the material to flow more readily under gravity into the pipeline, since under these conditions there is no leakage of air in opposition to the material feed.

In order to keep the throat at atmospheric pressure, and also of a practical size that will allow the passage of material, and for it to be readily conveyed, a relatively low limit has to be imposed on the air supply pressure. These feeders, therefore, are usually incorporated into systems that are required to convey free flowing materials at low flow rates over short distances. Since only low pressures can be used with the basic type of venturi feeder shown in Figure 3.16, a standard industrial type of fan is all that is needed to supply the air required.

3.4.1 Commercial venturi feeder

To fully understand the limitations of this type of feeder the thermodynamic relationships need to be followed and these are presented in Chapter 10. In this it is shown that in a 100 mm bore pipeline, with air supplied at 0.2 bar gauge, the throat diameter would have to be about 36 mm. Although venturis capable of feeding materials into conveying systems with operating pressure drops of 0.3 bar are commercially available, the pressure drop across the venturi can be of the same order. Such a venturi is shown in Figure 3.17.

Venturi feeders, however, are yet another type of feeder that can have its operating pressure range extended significantly, should this be required, by means of incorporating the device in a lock hopper system. This is also considered further in Chapter 4.

For an operating pressure drop of 0.3 bar and a 50% energy recover rate in the venturi this means that the air supply will have to be at about 0.6 bar gauge and consequently the air will have to be supplied by a positive displacement blower. Since there are no moving parts these feeders are potentially suitable for abrasive and friable materials. Care must be exercised in using venturis to feed such materials into the conveying line, however, for the high air velocity in the throat may lead to considerable erosion and particle degradation in this region. To counter the wear problems venturis can generally be obtained with wear resistant sections.

A particular advantage of the venture feeder, compared with many other feeding devices, is that it is small, occupies little space, and can be relatively cheap. It also requires very little headroom, which is often of benefit where pneumatic conveying systems may need to be fitted into existing plant with little room for modifications. They are often used in combustion applications, for the firing of coal dust and petroleum coke into boilers and furnaces, where individual burners may be fired directly from their own venturi feeder.

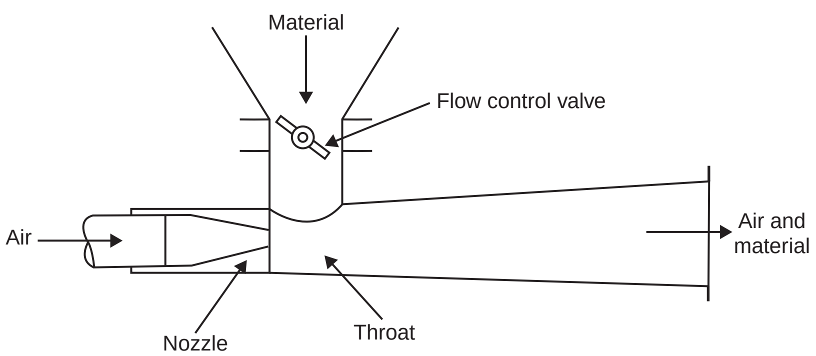


Figure 3.17 Commercial type of venturi feeder.

3.4.2 Flow control

Since experience has shown that these feeders are best suited to the handling of free flowing materials, care must be taken to continuously control the flow of materials, otherwise a blockage may occur. There is no inherent means of flow control, as mentioned earlier, and so this means that the venturi could either be fed from a belt, screw, rotary valve or vibratory feeder. Alternatively a supply hopper could be used if fitted with a trickle valve, calibrated orifice plate or gate/slide valve. A sketch of some mechanical feed control devices is given in Figure 3.18.

A sketch of some of the direct hopper fed control devices is given in Figure 3.19. A butterfly valve, for example, was illustrated with Figure 3.17. A problem with this class of control is that they are vulnerable to changes in material properties.

They are usually calibrated and set up on commissioning of the plant, but a slight change in particle size, shape or moisture content will affect the balance of the setting for the material and so change the flow rate. These are very simple and cheap devices but if strict control of the feed rate is required they do need to be provided with a separate controlling device, where possible, operating from a feedback signal based on conveying line pressure drop.

3.5 Gate lock valves

These are probably the least used of all devices for feeding pneumatic conveying system pipelines. They are variously known as double flap valves, double dump valves, and double door discharge gates. They basically consist of two doors or gates that

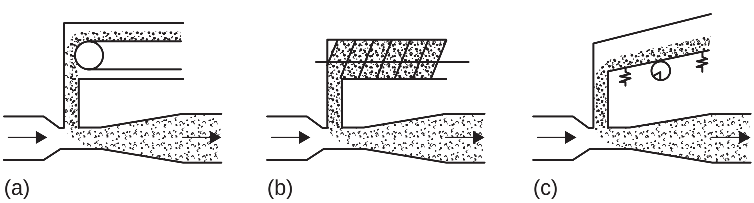


Figure 3.18 Sketch of some mechanical feed control devices for venturi feeders: (a) belt feeder, (b) screw feeder and (c) vibratory feeder.

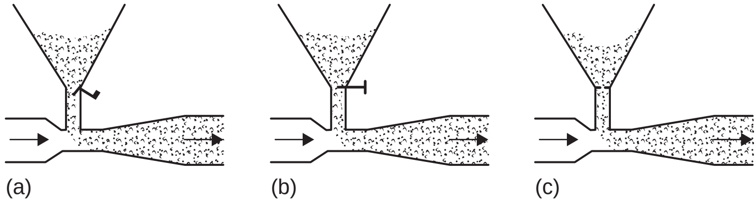


Figure 3.19 Sketch of some hopper fed control devices for venture feeders: (a) trickle valve, (b) gate/slide valve and (c) calibrated orifice plate.

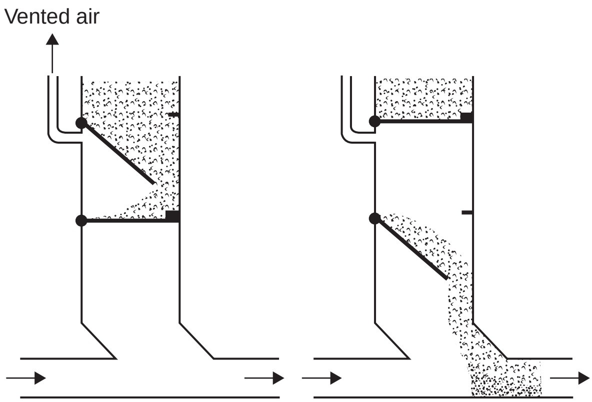


Figure 3.20 Operating sequence of gate lock valves.

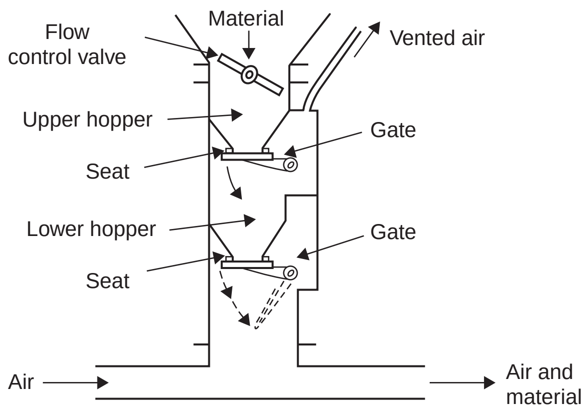


Figure 3.21 Commercial type of gate valve feeder.

alternately open and close to permit the passage of the material from the supply hopper into the conveying line, as illustrated in Figure 3.20.

These gates may be motor driven, cam or air cylinder operated, or may work under gravity. The air that passes the lower gate from the conveying pipeline is vented so that it does not interfere with the material about to flow through the upper gate, in positive pressure systems. As with rotary valves, the blower should be sized to allow for this leakage, although this is not as effective in this case, as there is an order of magnitude in difference in the operating frequency.

Like the venturi feeder, care must be taken to ensure that the material is metred into the gate lock since it will cease to function correctly under a head of material, as would be the case if it was situated directly beneath the outlet of the supply hopper. A typical commercial type of gate valve feeder is shown in Figure 3.21.

To a certain extent the gate lock might be termed an intermittent feeder, since it discharges material between 5 and 10 times a minute. In contrast, the rotary valve has approximately 150 to 200 discharges per minute from its pocketed rotor. This reduction in the number of discharges means that the air supply, in terms of flow rate, and particularly pressure, must be correctly evaluated to prevent the possibility of line blockage. With few moving parts this type of feeder can be used to feed friable materials, and with appropriate materials of construction it is also suited to the handling of abrasive materials.

Care has to be taken if this type of feeder is used with large and hard particles. If these get trapped in the lower gate when it closes a considerable amount of conveying air could be lost from the system, in a positive pressure conveying system, which could result in pipeline blockage. Once again this would not be a serious problem when feeding a negative pressure conveying system.

3.6 Suction nozzles

A specific application of vacuum conveying systems is the pneumatic conveying of bulk particulate materials from open storage and stockpiles, where the top surface of the material is accessible. Vacuum systems can be used most effectively for the off-loading of ships and for the transfer of materials from open piles to storage hoppers. They are particularly useful for cleaning processes such as the removal of material spillages and dust accumulations. In this role they are very similar to the domestic vacuum cleaner. For industrial applications with powdered and granular materials, however, the suction nozzles are rather more complex.

It is essential with suction nozzles to avoid filling the inlet tube solidly with material, and to maintain an adequate flow of air through the conveying line at all times. To avoid blocking the inlet pipe, sufficient air must be available at the material feed point, even if the suction nozzle is buried deep into the bulk solid material. Indeed, the vacuum off-loading system must be able to operate continuously with the nozzle buried in the material in order to maximise the material flow rate.

Sufficient air must also be available for conveying the material through the pipeline once it is drawn into the inlet pipe. In order to obtain maximum output through a vacuum line it is necessary to maintain as uniform a feed to the line as possible with the absolute minimum of pulsations. To satisfy these requirements two air inlets are generally required, one at the material pick-up point and another at a point downstream. A sketch of a typical suction nozzle for vacuum pick-up systems is shown in Figure 3.22.

3.6.1 Feed rate control

The conveying pipeline is provided with an outer sleeve at its end, and primary air for material feed is directed to the conveying line inlet in the annular space created. The length '*a*' of this sleeve has to be long enough to ensure that it is not buried by the movement of the material and so prevent the flow of primary air. There should not be a risk of an avalanche of material from covering the air inlet at the top of the sleeve either. This sleeve may be many metres long for a ship off-loading application.

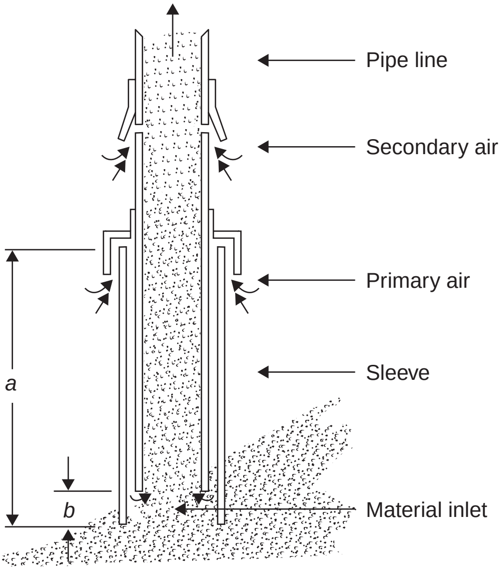


Figure 3.22 Suction nozzle for vacuum pick-up systems.

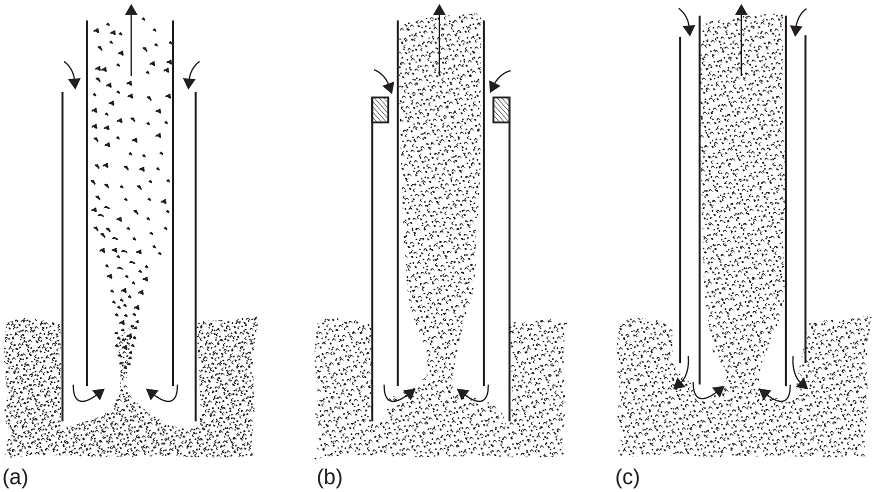


Figure 3.23 Suction nozzles showing typical modes of operation: (a) outer sleeve extended, (b) air inlet throttled and (c) outer sleeve retracted.

The position of the end of the sleeve relative to the end of the pipeline, '*b*', is partly material dependent, but also has a marked influence on material flow rate. In relation to the end of the conveying pipeline, the sleeve may be retracted or extended. To a large extent this dictates the efficiency with which the material is drawn into the conveying line. This influence is illustrated in Figure 3.23 [2].

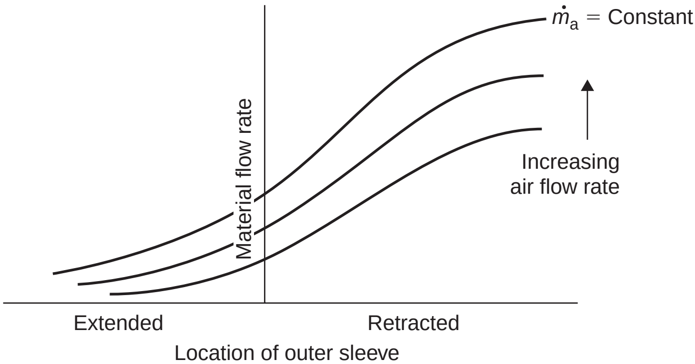


Figure 3.24 Influence of outer sleeve location on vacuum nozzle performance.

With the outer sleeve extended beyond the end of the pipeline it is more difficult for the material to be entrained in the air. If the sleeve is extended too far, the material flow rate will be zero. With the sleeve retracted behind the end of the pipeline the air readily flows into the pipeline and takes material with it. If the sleeve is retracted too far, however, it becomes less effective. There is, therefore, a very narrow band of potential movement over which the vast majority of control occurs. This influence of the location of the outer sleeve on vacuum nozzle performance is illustrated in Figure 3.24. For a 50 mm bore pipeline the relative position of the outer sleeve, '*a*', is approximately $\pm$25 mm [2]. These parameters are, of course, material dependent to a certain extent.

From Figure 3.23b it will be seen that an element of flow rate control can also be achieved by throttling the air flow into the sleeve. This is the primary air supply and so if the end of the pipeline is starved of air a partial vacuum will be created as a consequence and this will have a significant effect on promoting flow. Care must be exercised, however, because it is very easy to over-feed the nozzle and hence block the pipeline by this means.

The use of secondary air, as illustrated with Figure 3.22 provides yet another means of controlling material flow rate. Secondary air for conveying the material is generally introduced via a series of holes in the pipeline. Some form of regulation of both the primary and secondary air is necessary, and the proportion of the total air that is directed to the material inlet is particularly important. This is also material dependent, in a similar way to the proportion of the total air supply that is used in a blow tank for control of the discharge rate into the pipeline. In a way, the vacuum nozzle is very similar to a blow tank. Neither of them have any moving parts, but by proportioning the air between primary and secondary supplies, total control can be achieved over material feed rate. This is considered in more detail in Section 3.8.

3.6.2 Flow aids

The end of the pipeline at the material inlet point is often fabricated into a rectangular shape for manual applications in order to facilitate more effective surface cleaning.

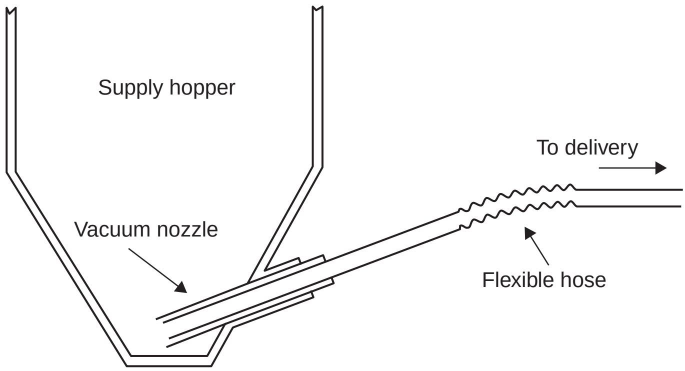


Figure 3.25 Application of vacuum nozzle to hopper off-loading.

Many variations in shape and design are possible, including the use of multiple 'tails' to a common suction line. In the case of large scale vacuum systems, such as ship off-loading, it is often necessary to attach mechanical dredging and paddle devices to the end of the nozzle. This is particularly so if materials with poor flow properties have to be unloaded, for it is essential to maintain a continuous supply of material to the nozzle to achieve the maximum potential of a vacuum line.

3.6.3 Hopper off-loading

Although suction nozzles are generally associated with mobile systems such as for spillage clearance and ship off-loading applications, they can equally be used in fixed systems for the emptying of hoppers and silos. In this application the nozzle is usually positioned close to the bottom of the hopper. A typical arrangement is illustrated in Figure 3.25.

The vacuum nozzle is generally fitted into the hopper via an external sleeve so that it can be easily removed when required. The controls over the primary and secondary air are also arranged to be external to the hopper. The location of the control for positioning the outer sleeve with respect to the conveying pipeline can also be external to the hopper. For these reasons a section of flexible hose is often incorporated into the conveying pipeline close to the hopper. The hopper cannot be 'drained' clear of material with this device, however.

3.7 Trickle valves

Trickle valves, as a device on their own, are only suitable for vacuum conveying systems, since there is no pressure drop against which to feed. The greatest problem with this class of feeder is that of flow rate control, as discussed in relation to the control of venturi feeders in Section 3.4.2. A sketch of a typical device is shown in Figure 3.26.

This type of device is widely used in industry, mainly because of the cost advantage over almost any alternative method of feeding vacuum conveying systems.

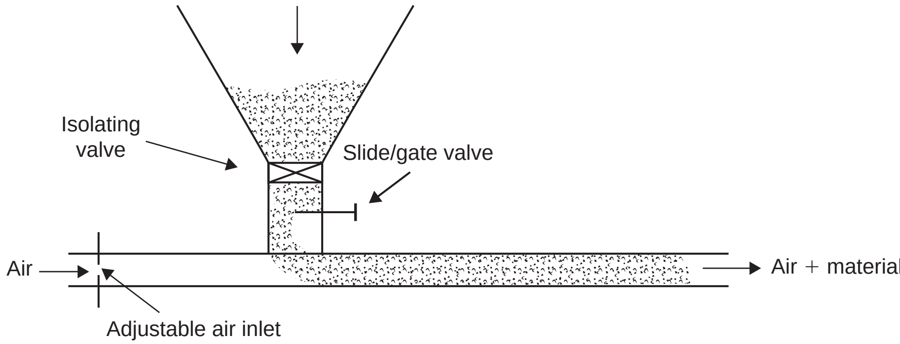


Figure 3.26 Sketch of typical trickle valve arrangement for feeding negative pressure pneumatic conveying systems.

In a typical 200 MW coal fired generating plant, for example, there will be thirty to forty ash hoppers. Vacuum conveying is widely used for this duty and every hopper requires a feeding device.

In this type of application the pipeline used to convey the material is generally extended a few metres ahead of the hopper. This is often done to make sure that the air inlet is in a safe place, as a health and safety requirement. It is usual to add a flow restriction in this section of pipeline, which is often a simple orifice plate. This resistance has the effect of slightly lowering the pressure in the pipeline at the material feed point and helping to promote flow.

3.8 Blow tanks

Blow tanks are generally associated with high pressure conveying. A particular feature of the blow tank, however, is that it has no moving parts and so is ideal for the feeding of abrasive and friable materials. In this respect it is like the vacuum nozzle, but that is only for vacuum conveying. It might, therefore, be likened to the venturi feeder, but the blow tank does not generate high velocities in the feeding process and so is even more suitable for these types of material.

Since the blow tank is not a positive displacement feeder, like the rotary valve and screw, it is ideally suited to the conveying of materials having extremes of density values. Thus the one blow tank, without any modifications, would be equally capable of conveying iron powder having a bulk density of 4000 kg/m^3 and exfoliated vermiculite having a bulk density of 80 kg/m^3. The main disadvantage of the blow tank is its size and hence headroom requirements.

Since there is a requirement to convey abrasive and friable materials at low pressure, the blow tank is an ideal feeder for this purpose. It means that a positive displacement blower can be used to provide the air supply, rather than a compressor, and as the operating pressure is limited to 1 bar gauge, the blow tank does not have to be a coded vessel, with all the attendant inspection and insurance requirements.

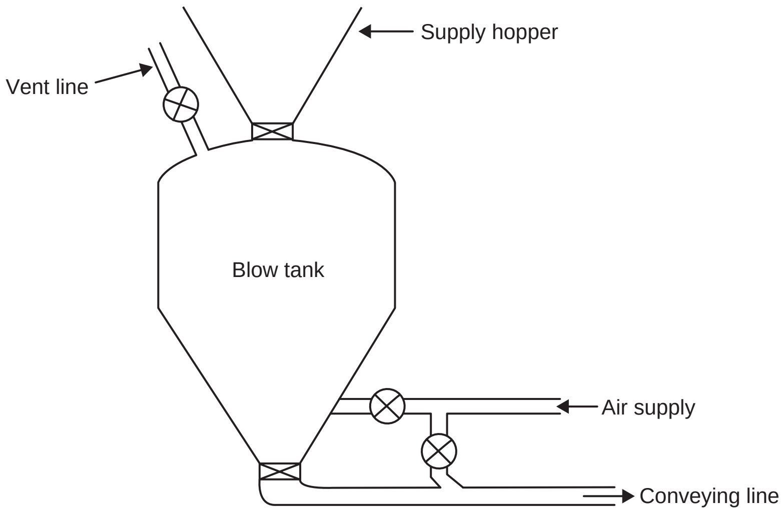


Figure 3.27 Sketch of low pressure bottom discharge blow tank.

3.8.1 Pressure drop

Although pressure drop was mentioned in Section 3.1.2 as an important point to consider with regard to feeders, it has not featured in any detail with any of the feeders considered so far as it has been marginal. With blow tanks, however, there will be a small pressure drop, the value depending upon the design, and this will be considered in more detail in the next chapter. A typical blow tank for low pressure applications is shown in Figure 3.27. This is a bottom discharge type, the term depending mostly on the direction of discharge from the vessel. As can be seen it is a batch type conveying system, but the batch size can be very large, for high tonnage duties.

3.8.2 Feed rate control

As with the vacuum nozzle, flow control for a feeder having no moving parts is by air proportioning. Part of the air is directed into the blow tank to pressurize the vessel and aerate the material. The rest of the air effectively by-passes the blow tank, but is used to dilute the very high concentration of the material discharged from the blow tank to a solids loading ratio appropriate for conveying. This air flow is often referred to as the supplementary air supply.

Where the two air streams meet is effectively the start of the conveying pipeline and the air supply needs to be sufficient to achieve the required velocity for conveying the given material. Although the supplementary air supply could be introduced behind the blow tank discharge valve, which would mean that there would be no additional pressure drop due to the blow tank, the arrangement shown in Figure 3.27 is preferred. The supplementary air is introduced about 0.5–1 m downstream and it is found that this provides better flow control for most materials. With this layout the additional

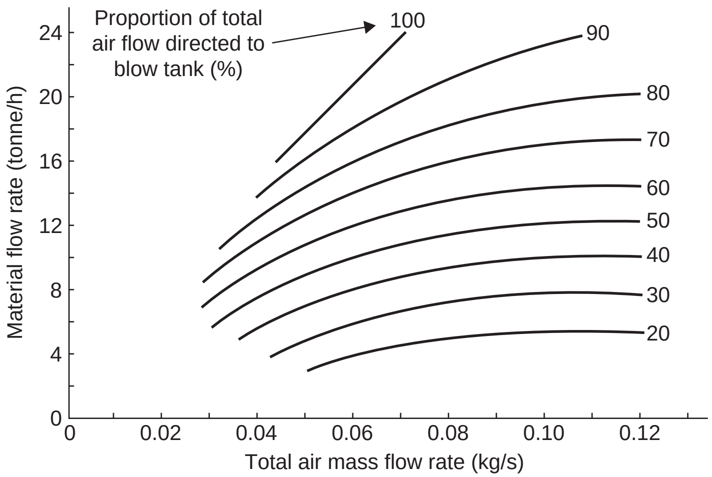


Figure 3.28 Typical blow tank discharge characteristics.

pressure drop is typically less than 0.1 bar. The nature of the flow control, by proportioning the air supply in the way described, is illustrated in Figure 3.28.

It will be seen from Figure 3.28 that the blow tank is capable of feeding material over a very wide range of flow rates. This is very much wider than could be obtained with a single rotary valve. Where blow tank systems are sold 'off the shelf' they come in a small number of sizes. The lines of constant air proportion do terminate as shown in Figure 3.28 as this represents the conveying limit for the material considered, which is cement in this case. This limit is dictated by the minimum conveying air velocity, and hence the air flow rate required to achieve this value of velocity.

The 100% line represents the maximum discharge capability of the blow tank. This will be considered in the next chapter, along with alternative designs and configurations of blow tanks.

References

1. A R Reed and D Mills. The effect of rotary valve air leakage on the performance of pneumatic conveying systems. Proc Pneumotransport 5. pp 197–207. BHRA Conf. London. April 1980.
2. A R Reed and J S Mason. The effect of suction nozzle design on the performance of vacuum pneumatic conveying systems. Journal of Powder and Bulk Solids Techniques. Vol 7, No 4. pp 9–14. 1983.

Chapter 4

Pipeline feeding devices

Part 2: High pressure

4.1 Introduction

The use of high pressure systems in pneumatic conveying has been a long and slow development. Part of this was probably due to a misunderstanding of the relationship between high pressure and dense phase conveying. There was very little published information on the subject and few universities, on a worldwide basis, were undertaking research in the area. This was one of the main reasons for the Department of Trade and Industry in the UK commissioning research work in the early 1980s for the preparation of the first edition of this Design Guide.

There was probably also a reluctance to venture into an unknown area, when the rotary valve and positive displacement blower were so dominant. The blow tank was being used, and at high pressure, but it was still very much a batch conveying system with limited demand. With an increasing need for high tonnage flows and long distance conveying, particularly in the cement and coal fired power generation industries, the screw conveyor was developed and became dominant in this market for many years.

Then in the mid-1980s with the start of globalization, and increasing competition in industry, manufacturing companies made advances with both rotary valves and blow tanks. Two manufacturers in Europe developed a rotary valve that would operate with air supply pressures greater than two bar gauge, and the use of lock hoppers was introduced with blow tanks so that they could operate continuously at high pressure.

Today, most companies manufacturing rotary valves offer high pressure rotary valves for a very wide range of materials, although they will be found most widely in use in the chemicals industry. The initial impetus for the continuously operating blow tank was to try to take over the market for high pressure screw feeders and this was successful to a large extent. Demand for the screw feeder has fallen significantly and that for the continuously operating blow tank has been well established.

4.1.1 Lock hoppers

Although the concept of lock hoppers has been known for a very long time, and has been utilized in many other areas of industry, it has been slow in being adopted in pneumatic conveying. It is not only blow tanks that can benefit from their use, however. As the lock hopper enables the feeder to operate without a pressure drop existing across it, conventional rotary valves and conventional screw feeders can also be used for the high pressure conveying of materials. These feeders, of course, have the advantage that they are positive displacement feeders so that feed rate control can be achieved simply by varying the speed of operation. Venturi feeders can also operate at significantly higher pressures.

4.2 Screw feeders

The simple screw feeder was introduced in Chapter 3 (Figure 3.15). Although ideal for feeding negative pressure conveying systems, it is just not appropriate for positive pressure conveying applications because of the air leakage problems. There is nothing in the design that will provide the necessary sealing to prevent air leakage with positive pressure operation.

The simple screw feeder, however, was developed by several companies into a device that can feed successfully into conveying lines at pressures of up to 2.5 bar gauge. One such device, which was manufactured by the Fuller Company of the USA, is known as a Fuller–Kinyon pump. In Germany, Claudius Peters developed a similar Peters pump at about the same time. A sketch of this type of screw feeder is given in Figure 4.1.

The main feature of these screw feeders is that the screw decreases in pitch along its length. By this means the material to be conveyed is compressed to form a tight seal in the barrel. These feeders used to be widely used in the cement industry, and for fly ash conveying in power stations. The material is fed from the supply hopper and is advanced through the barrel by the screw.

Since the screw pitch decreases towards the outlet, this compacts the material as it passes through the barrel. This is sufficient to propel the plug through the pivoted non-return valve at the end of the barrel and into a chamber into which air is continuously supplied through a series of nozzles. A pressure drop of about 0.5 bar must be allowed for the air across these nozzles, which adds significantly to the power requirement. A screw having a decreasing pitch does, however, require a very high power input for a given feed rate.

It is partly because of the high energy requirements, particularly for the screw, that the device has gone out of favour. It is probably equally due to the fact that as the materials that are mostly conveyed, such as cement and fly ash, are very abrasive, wear problems occur with the screw, adding to the maintenance problems. Being capable of

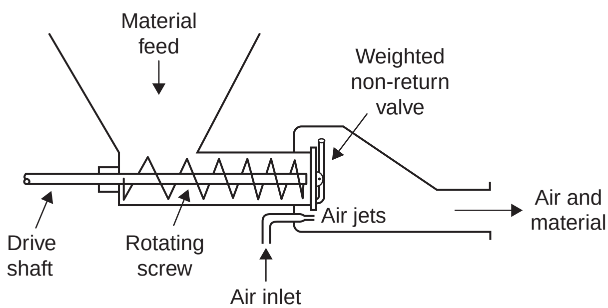


Figure 4.1 Commercial type of screw feeder.

continuous operation and having a high pressure capability means that it is often used in closed loop conveying systems, when a high operating pressure is required.

For high pressure operation the device is only suitable for materials that can be compressed, which generally restricts their use to materials that have very good air retention properties, such as cement and fly ash. These are Group A materials in Geldart's classification shown in Figure 2.17. Due to their very good air retention capability, their bulk density can be increased by up to 50 per cent simply by means of vibration. With Group B materials, however, the increase in bulk density achieved is typically about one-third of this, which is insufficient. The seal against the high pressure conveying air is effected in the reducing pitch screw. The required degree of compression cannot be obtained with granular materials (Group B) and so air will leak through the feeder at high operating pressure.

4.3 Rotary valves

The conventional rotary valve has been developed, as mentioned above, to have a capability of feeding material into positive pressure pneumatic conveying systems at pressures of up to 3–4 bar gauge. This is as a stand-alone feeder without the use of a lock hopper. With a lock hopper there is no pressure drop across the rotary valve and so a conventional rotary valve can operate at significantly higher pressures. This point should be understood because it does tend to cause a lot of confusion.

The closed end type of rotor, illustrated in Figure 3.12b, provides a significantly more rigid construction, and it is with this type of rotor that developments with much higher pressure and lower leakage rate applications have been possible. This new generation of rotary valves are often used in low pressure systems, instead of the conventional valve, simply because of the reduced air leakage.

With an end plate it is possible to provide a seal to significantly reduce the quantity of air that leaks across the valve by this route, and a more rigid construction allows rotor tip clearances to be reduced. Air leakage via the returning empty pockets remains a problem, but by these various improvements the operating pressure differential has been improved to about 3–4 bar gauge, compared with about 1 bar gauge for the conventional rotary valve, as indicated on Figure 3.2.

4.4 Blow tanks

Blow tanks are often employed in pneumatic conveying systems because of their capability of using high pressure air. A high pressure air supply is necessary if it is required to convey over long distances in dilute phase, or to convey at high mass flow rates over short distances through small bore pipelines. As an example of the latter, cement was conveyed at 25 tonne/h over a distance of 100 m through a 2 in. (53 mm actual) bore pipeline containing 17 bends, by the author, using a high pressure blow tank, to provide data for the first edition of this Pneumatic Conveying Design Guide.

Blow tanks are neither restricted to dense phase conveying nor to high pressure use. Low pressure blow tanks are often used as an alternative to screw feeders and rotary valves for feeding pipelines, particularly if abrasive materials have to be conveyed, as was considered in the previous chapter on 'low pressure feeding devices'. Materials not capable of being conveyed in dense phase can be conveyed equally well in dilute phase suspension flow from a blow tank. Depending upon their pressure rating, blow tanks have to be designed and manufactured to an appropriate pressure vessel code, and are subject to insurance and inspection. They can, therefore, be more expensive than alternative feeding systems.

The blow tank has no moving parts and so both wear of the feeder and degradation of the material are significantly reduced. Another advantage of these systems is that the blow tank also serves as the feeder, and so the problems associated with feeding against an adverse pressure gradient, such as air leakage, do not arise. There will, however, be a small pressure drop across the blow tank in order to achieve material feed, and so this must be taken into account when evaluating air requirements.

In most blow tank systems the air supply to the blow tank is split into two streams. One air stream pressurizes the blow tank and may also fluidize or aerate the material in the blow tank. This air stream serves to discharge the material from the blow tank. The other air stream is fed directly into the discharge line just downstream of the blow tank. This is generally referred to as supplementary air and it provides the necessary control over the material flow in the conveying line.

4.4.1 Basic blow tank types

There are numerous different types of blow tank, and for each type alternative configurations are possible. The basic features of different blow tanks are essentially similar, but different arrangements can result in very different conveying capabilities and control characteristics.

There are also a variety of blow tank configurations that are widely used. Apart from single blow tanks there are twin blow tank arrangements, with both parallel and series arrangements. Blow tanks operating in parallel basically consist of two identical blow tanks, generally placed alongside each other, and while one is being filled the other is being discharged, generally as a means of improving cycling efficiency.

Twin blow tanks that operate in series is another term for a single blow tank operating with a lock hopper and this is considered as a separate topic within this chapter. The top vessel is not a blow tank, but is the lock hopper, and this allows conveying on a continuous basis from the blow tank beneath. Due to headroom problems a further development here is to position the lock hopper alongside the blow tank.

4.4.1.1 Top and bottom discharge

The blow tank shown in Figure 4.2 is a top discharge type. It is shown with a discharge valve so that it can be isolated from the conveying line. It also has a vent line and valve so that it can be de-pressurized independently of the conveying line. Discharge is arranged through an off-take pipe which is positioned above the fluidizing membrane. The material is discharged vertically up and the discharge pipe exits the blow tank through the top of the vessel, and hence the term 'top discharge' in this case.

With this type of blow tank, however, it is not possible to completely discharge the contents, although with a conical membrane very little material will remain. Where a

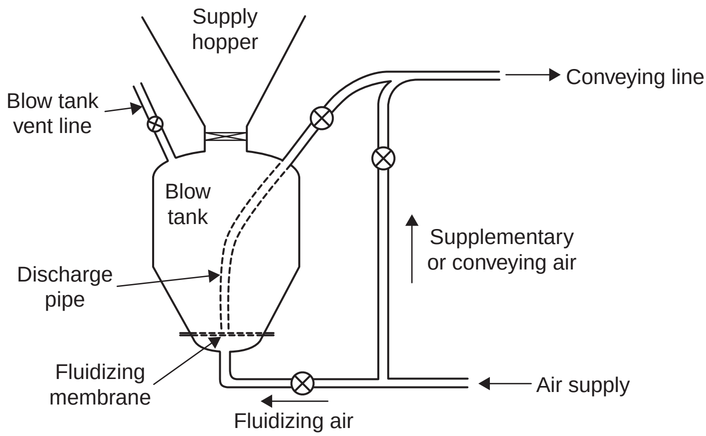


Figure 4.2 Top discharge blow tank with fluidizing membrane.

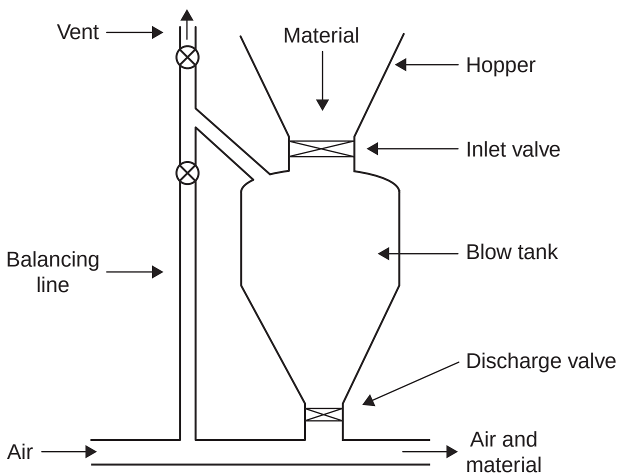


Figure 4.3 Bottom discharge blow tank.

conveying system is dedicated to a single material so that cross contamination does not have to be taken into account, and the material is not time limited, this does not generally represent a problem, although the possibility must be considered. The vessel is usually flanged as shown in Figure 4.2 for convenience of access to the fluidizing membrane.

In a bottom discharge blow tank there is no membrane. Material has an uninterrupted passage to be gravity fed into the pipeline and so the contents can be completely discharged. A sketch of such a blow tank is given in Figure 4.3.

The arrangement shown in Figure 4.3 is one that is commonly found in industry. A feature of blow tanks is that most designs will work, and for most materials to be conveyed. For those materials for which it will not work very well it would be suggested that it should be modified by adding an air supply to a point close to the discharge point

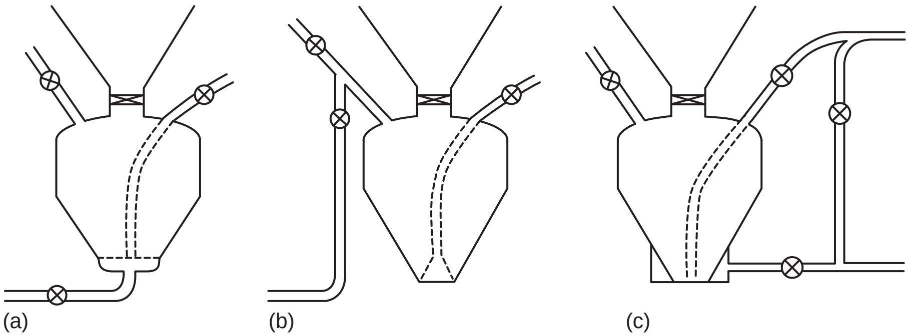


Figure 4.4 Alternative top discharge blow tank arrangements: (a) fluidizing membrane, (b) conical discharge and (c) fluidized base.

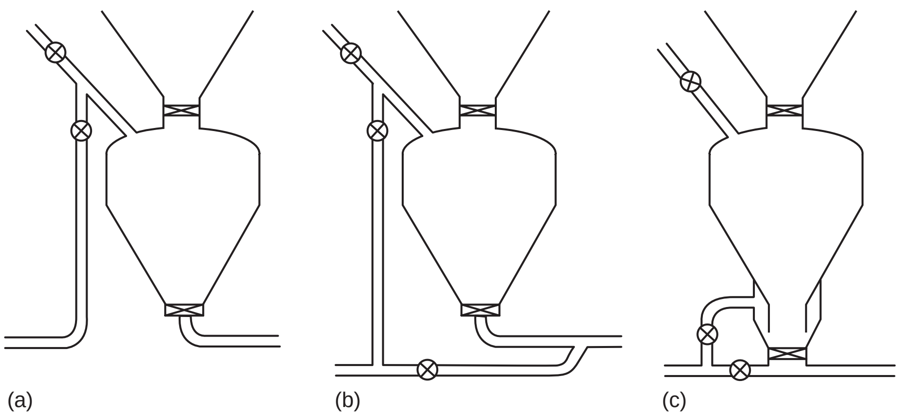


Figure 4.5 Alternative bottom discharge blow tank arrangements: (a) one air supply, (b) two air supplies and (c) fluidized base.

so that the material can be fluidized or aerated in this area, and that the supplementary air be introduced a short distance downstream, as shown with the blow tank illustrated in Figure 3.27.

Top and bottom discharge generally refers only to the direction in which the contents of the vessel are discharged. This simple classification, however, can become confused by the considerable number of different configurations that are used to admit air to the blow tank and conveying line. A number of alternative top discharge blow tank types are shown in Figure 4.4, and a number of alternative bottom discharge arrangements are shown in Figure 4.5.

In Figure 4.4a the discharge arrangement is ideal, with a fluidized base by means of a membrane, but this is the only air supply provided. With only one air supply the only means available of controlling the material flow rate is to vary the air flow rate, but as this additionally influences both the conveying line inlet air velocity and the conveying line pressure drop, it is not to be recommended.

The situation with regard to blow tank control is illustrated with Figure 3.28. The 100 per cent line represents the situation here and illustrates that there is little scope for control. If the conveying line to be fed is long, the pipeline is likely to block if the air supply pressure is not high enough, since the maximum material flow rate will be delivered. Only with supplementary air can the material flow rate be controlled to a lower value to match the pressure capability of the air supply.

Figure 4.4b presents a similar situation in that there is only one air supply. The situation here is potentially worse, for the air has to permeate through the material to get to the point of discharge. For materials that have a wide particle size distribution, and that de-aerate rapidly, the system is unlikely to work.

The blow tank illustrated in Figure 4.4c is ideal. Although it only has one air supply into the blow tank, that is used to fluidize the material, and a supplementary air supply is also available to dilute the material discharged to the required solids loading ratio for conveying through the pipeline. In this design the air enters a plenum chamber at the base of the blow tank and enters the blow tank in the area where the material is discharged. There is a gap of about 1 mm between the bottom of the conical wall of the blow tank and the flat base, and it is through here that the air passes to both aerate the material and pressurize the blow tank.

An air supply to the top of the blow tank is not essential, although it will increase the rate of pressurization. The use of the air through the base of the blow tank is particularly useful in transport applications and in situations where material is left for a period of time in a blow tank before being discharged. In both of these situations the material will tend to compact, de-aerate and consolidate and will be difficult to discharge. With fluidizing air entering at the base, also being used to pressurize the blow tank, it has the effect of stirring up the material and aerating the entire batch prior to being discharged.

It will be seen that this is a top discharge blow tank and has no membrane. A porous membrane is more effective at fluidizing material than an annular slot and so in some cases an additional air supply is taken directly to the entrance of the off-take pipe to provide further fluidization in this region. This is sometimes necessary for materials with very poor air retention, for they could block the discharge pipe if only a small percentage of the total air supply is directed to the blow tank for aerating the material and pressurizing the blow tank. At the end of the conveying cycle a small residue of material is likely to remain in the bottom of the blow tank.

The blow tank shown in Figure 4.5a has a similar deficiency to that of Figure 4.4b, with a single air supply into the top, although the bottom discharge blow tank has the advantage of gravity discharge. In this case it is quite likely to discharge material but with very little control, as discussed earlier. The application of these configurations of blow tank, therefore, is strictly limited unless air is introduced into the pipeline downstream of the blow tank via trace lines or boosters.

The blow tank shown in Figure 4.5b will also be limited in terms of the type of material that can be conveyed, and probably in terms of the discharge rate that can be achieved. There are two air supplies, which are necessary for full control, but for many materials air needs to be introduced near the discharge point to help promote flow.

The blow tank in Figure 4.5c has an aeration device similar to that shown in Figure 4.4c. The air enters into a plenum chamber and fluidizes or aerates the material in the blow tank close to the discharge point through a narrow (about 1 mm) annular slot. Under normal operation this type of aeration device will work very well. If there should be a situation in which the pressure in the blow tank is greater than that of the air supply, however, it is possible that fine materials will flow back into the plenum chamber. As a consequence of this it could become blocked and hence cease to operate effectively.

As a generalization, the top discharge type of blow tank, with fluidization of the material, is most suitable for powdered materials, and bottom discharge blow tanks are best suited to granular materials.

4.4.1.2 Fluidizing membranes

Fluidizing membranes may consist of a porous plastic, a porous ceramic, or a filter cloth sandwiched between perforated metal plates. The top perforated plate is required to support the filter cloth against the pressure of the air below, and the bottom plate is required to support the weight of the material in the blow tank. In top discharge blow tanks it is not usually necessary for the discharge pipe to have a conical end, as shown in Figure 4.4b, unless additional fluidization is required in this region. A sketch of such an arrangement is given in Figure 4.6.

If a porous membrane is used it is important that the fluidizing air is both clean and dry, for dust and moisture in the air will cause a gradual deterioration in performance. For powdered materials the off-take pipe needs to be spaced about 40 mm above the base or membrane. If it is further away the blow tank will simply discharge less material and hence reduce its effective capacity. If it is too close it may adversely affect the discharge rate.

4.4.1.3 Blow tank pressure drop

The pressure drop across the blow tank represents a potential source of energy loss to the conveying system and so should be kept as low as possible. In the case of top discharge blow tanks this is particularly important. The discharge pipe must be kept as short as possible because the pressure gradient in this line will be very high owing to

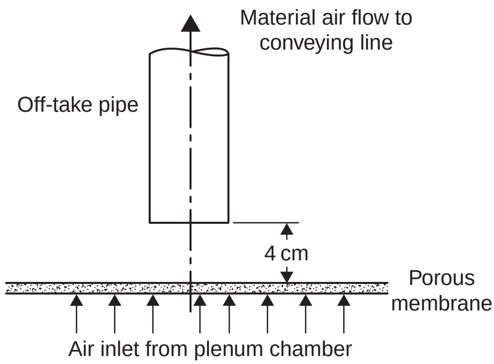


Figure 4.6 Sketch of straight end discharge pipe.

the very high material concentration, or solids loading ratio. Supplementary air should be introduced as close to the point of exit from the blow tank as possible.

In a test facility operated by the author it was necessary for the supplementary air to be introduced at a distance of about 2.6 m from the blow tank. This gave a total discharge line length of about 4 m and the resulting discharge line pressure drops were quite excessive. They are shown in Figure 4.7 together with the corresponding results obtained when the facility was rebuilt and the supplementary air was positioned just above the blow tank. In both cases the results correlated well with respect to the solids loading ratio of the material in the conveying pipeline.

With very large blow tanks the discharge pipe should be turned through 90° just above the membrane and be taken through the side of the vessel. Alternatively the supplementary air should be introduced within the blow tank, and be fed into the discharge pipe close to the membrane end. If the discharge pipe is kept to about 2 m the pressure drop across the blow tank will be about 0.2 bar, which includes the membrane resistance. In the case of bottom discharge blow tanks the discharge line is generally short can and so the pressure drop is generally no more than 0.1 bar.

4.4.1.4 Problems with moisture

With materials that are hygroscopic, air drying is normally recommended. For the majority of materials this is not generally necessary. With compressors, however, large quantities of moisture can be generated if the supply air is warm and humid, and this moisture can be carried over into the air supply lines. With materials such as fly ash and cement this moisture can cause blinding of the blow tank fluidizing membrane, which can result in a significant increase in pressure drop across the blow tank and hence a reduction in performance of the conveying system.

Owing to the intermittent nature of the conveying process it is also possible for water to collect in the air supply lines and this can be blown into the blow tank on start up. This has resulted in partial blockage of the blow tank discharge line on several occasions with both fly ash and cement in pneumatic conveying systems operated by the author. This particular topic of moisture and condensation is considered in detail in Chapter 25.

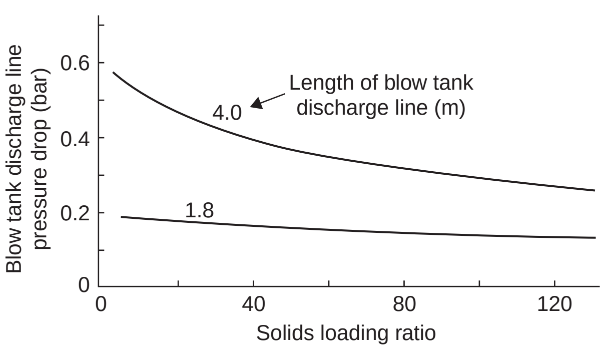


Figure 4.7 Influence of discharge line length and conveying line solids loading ratio on blow tank discharge line pressure drop.

4.4.1.5 Road and rail vehicles

Many road and rail vehicles used for the transport of bulk solids are essentially blow tanks. In the case of road tankers the vehicle usually has its own air supply for off-loading. These are generally rated at a pressure of 1 bar gauge and positive displacement blowers are used for the purpose. Rail vehicles generally rely on a site air supply for off-loading, with a much higher air pressure. A standard carriage length rail wagon transporting cement would typically carry about 70 tonne.

4.4.2 Single blow tank systems

A particular problem with single blow tank system is that conveying is not continuous, as it can be with rotary valve and screw feeding systems. In order to achieve an equivalent material mass flow rate, therefore, instantaneous values of the flow rate during conveying have to be somewhat higher. This point was illustrated earlier with Figure 2.7 in Chapter 2.

4.4.2.1 Blow tanks without a discharge valve

The simplest form of blow tank is one that has no discharge valve. Such an arrangement is shown in Figure 4.8. This is shown in a top discharge configuration with a fluidizing membrane, but any other type of top discharge blow tank could equally have been shown. Although there is no valve in the material discharge line, other valving is necessary. These valves, however, are not subject to the severe duty of a valve in the conveying line. With bottom discharge blow tanks a discharge valve is generally required simply to keep the material in the blow tank, for some materials will flood feed into the pipeline and block it.

A valve is required to isolate the blow tank from the material supply hopper, so that the blow tank can be pressurized, and a vent line valve is needed to allow the blow tank to be vented while it is being filled from the hopper above. If a vent on the blow tank is not used it will take considerably longer to fill the blow tank, for the air in the blow tank has to be displaced, and if it is not vented it will interfere with the flow of material from the hopper as this will be the only path of exit for the air. These valves are either fully open or closed. Valves, or possibly flow restrictions or orifices, are required in the

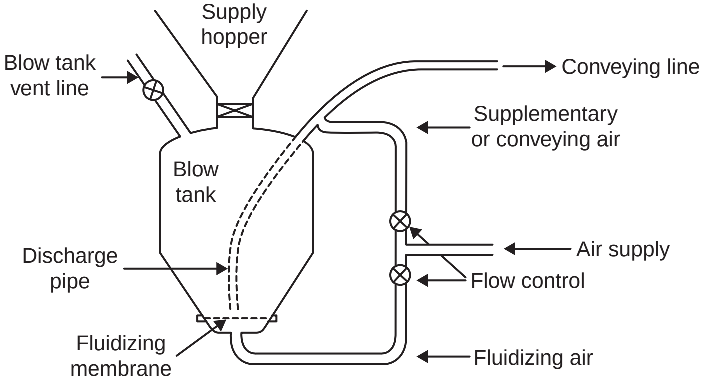


Figure 4.8 Single blow tank without discharge valve.

air supply lines in order to provide the necessary degree of control over the material discharge rate from the blow tank.

4.4.2.2 Conveying cycle analysis

With the arrangement shown in Figure 4.8 the blow tank starts to pressurize as soon as the vent line valve is closed. Both the blow tank and conveying line have to be pressurized to a certain extent before any material is delivered from the pipeline, and this process can take a significant proportion of the total cycle time. Even when the material is first discharged from the conveying line, the pressure, and hence conveying rate, will have to reach steady state values. The pressure builds up gradually as more material is conveyed, but it is a relatively slow process.

Towards the end of the conveying cycle, when the blow tank has almost been discharged, the blow tank has to be de-pressurized and the entire conveying line has to be cleared of material and vented. This process also takes a significant amount of time, particularly if the pipeline is long. The time required to fill the blow tank and set the valves has to be taken into account in addition. This type of blow tank system, however, is very easy to operate and maintenance costs are very low.

For material testing and research purposes this type of blow tank is very convenient since the steady state operating pressure will vary with conveying conditions. Without previous experience it is not possible to pre-set the blow tank to the required pressure in advance of a test being carried out to establish the pressure required to achieve a particular flow rate. This method, therefore, allows all testing to be carried out on the same basis. A typical cycle for conveying a 600 kg batch of cement over 100 m through a 53 mm bore pipeline with this particular blow tank is shown in Figure 4.9.

The mean flow rate of the blowing cycle shown in Figure 4.9 was approximately 8.5 tonne/h, and so this represents about 50 per cent of the steady state flow rate achieved. The time averaged mean, taking blow tank filling and valve setting operations into account was about 47 per cent. These percentages can be increased significantly if the batch size is increased, for if a larger batch is conveyed, the pressurizing and de-pressurizing stages of the blowing cycle will be changed very little. Thus the majority of any additional material will be conveyed at the maximum steady state flow rate.

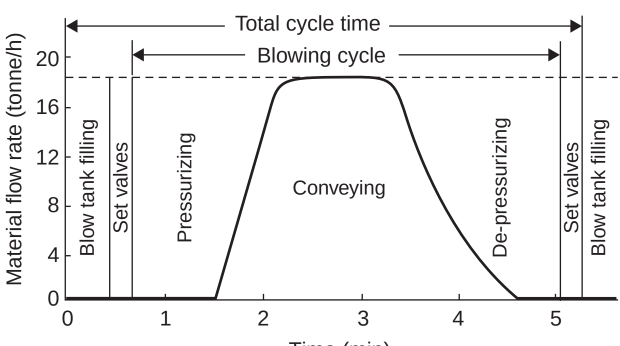


Figure 4.9 Typical cycle for a single blow tank operating without a discharge valve.

4.4.2.2.1 Blowing cycle

The time taken to fill the blow tank and set the valves will not be influenced by any of the variables associated with the material conveying. Within the total cycle time, therefore, the blowing cycle, in which the air supply is required, can be isolated and investigated separately. The difficulty in such an analysis is that there are so many variables to take into account. There are different stages in the blowing cycle and each of these is influenced by the air flow rate, conveying line pressure drop, and the mode of conveying the material in the pipeline. To illustrate the point two typical blowing cycles, in terms of material mass flow rate, are shown in Figure 4.10.

In programmes of conveying trials carried out with materials such as barytes, cement and fly ash, the ratio of the time averaged mean conveying rate to the maximum steady state value achieved during the cycle was evaluated in every test. In order to determine whether conveying air velocity, solids loading ratio, material flow rate and conveying line pressure drop, have any effect of the value of the ratio, these values were plotted on a graph of material flow rate against air flow rate. In each case there was remarkably little variation over the entire range of solids loading ratios and material flow rates. For both cycles on Figure 4.10, for example the value of the ratio was about 0.5.

4.4.2.2.2 Influence of batch size

Although only one batch size of 0.6 tonne was used in the programme of tests with the 53 mm bore pipelines, the influence of batch size can be evaluated quite easily, and with a reasonable degree of reliability. If a larger batch is conveyed it will have little effect on the time required to pressurize the blow tank and to condition the pipeline before conveying commences. The volume of the blow tank for the air to pressurize will be reduced if the batch size if increased in a given blow tank, but that of the pipeline will be the same. If a proportionally larger blow tank is used for a larger batch size there will be a proportional increase in volume. The material 'lead in' and 'tail out' times either side of the steady state section are unlikely to be influenced by batch size.

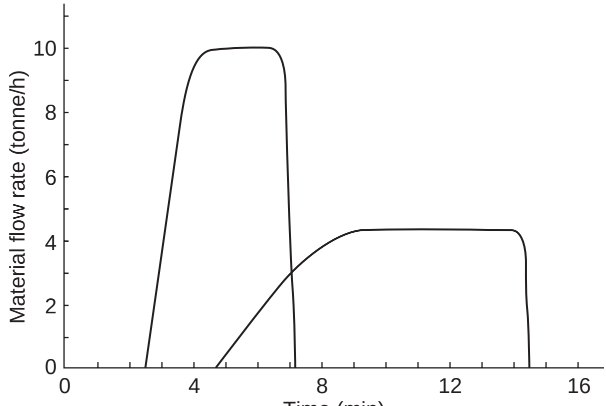


Figure 4.10 Typical blowing cycle transients.

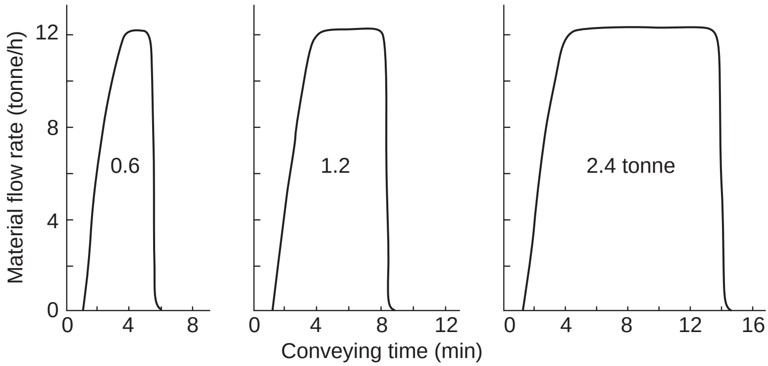


Figure 4.11 Influence of batch size on blowing cycle time.

When steady state conditions are reached these will prevail regardless of the batch size, and so if an additional quantity of material is to be conveyed it will only influence the duration of the steady state stage. If the batch size was doubled, for example, to 1.2 tonne the extra 0.6 tonne would all be conveyed at the steady state rate, and so in a case where this was 12.3 tonne/h, it would only take a further 2.93 min to convey the additional material.

In Figure 4.11 the influence of batch size on the blowing cycle time is shown for three batch sizes. This illustrates quite clearly the assumption made and the procedure for the analysis. With a 0.6 tonne batch of barytes conveyed over 100 m through a 53 mm bore pipeline the ratio was 0.5. If the batch size is doubled the ratio will increase to 0.67, and if it is doubled again to 2.4 tonne the ratio will increase to 0.80.

4.4.2.2.3 Blow tank filling

It should be noted that the time for the filling of the blow tank and valve setting has not been taken into account in the above analysis, for the time is quite clearly not influenced by any of the variables associated with the blowing cycle, except for batch size. The average time taken to fill the blow tank with 0.6 tonne of barytes from the hopper above was about 10 s. If a time allowance based on this is added to the blowing cycle time, together with an allowance of 3 s for each valve setting operation, an estimate of the overall conveying cycle time can be obtained.

4.4.2.2.4 Conveying distance

The result of an analysis of this type, for the complete cycle, is presented in Figure 4.12. From this it can be seen that batch size can have a significant effect on the cycle. The improvement with respect to batch size, however, increases at a decreasing rate. Conveying distance will clearly have an influence on the value of the ratio, for with longer lines there is a larger volume both to pressurize and de-pressurize. In the work with barytes it was found that the ratio for a 0.6 tonne batch conveyed through a 53 mm

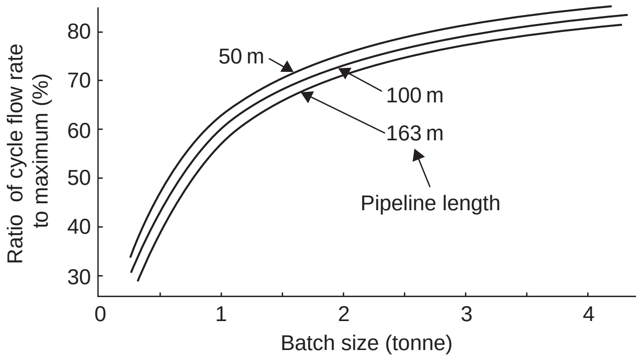


Figure 4.12 Influence of batch size and conveying line length on material flow rate for conveying cycle.

bore line was about 0.54 for a 50 m long pipeline, and 0.46 with a 163 m long pipeline. The results of a similar analysis for these pipelines are also presented in Figure 4.12.

4.4.2.2.5 Pipeline bore

With the barytes, tests were additionally carried out on 50 m long pipelines of 81 and 105 mm bore. The mean value of the ratio for the 81 mm bore pipeline, for which the batch size was increased to 1.2 tonne, was 0.65; and for the 105 mm bore pipeline, for which the batch size was 1.4 tonne, it was 0.66. These values, which allow for blow tank filling and valving times, correspond very closely to those predicted by the curve on Figure 4.12, and so it is possible that pipeline bore has little additional effect.

4.4.2.3 Blow tanks with a discharge valve

The ratio of the mean flow rate to the steady state material flow rate can be improved by reducing the time required for some of the stages in the conveying process.

4.4.2.3.1 Blow tank pressurizing

If there is a valve on the blow tank discharge line, and control valves on the supplementary and fluidizing air supply lines, the blow tank can be pressurized in a shorter space of time if all the air available is directed to the blow tank, and discharge is prevented until the steady state pressure is reached. This time can be shortened further if an additional air supply is available for the purpose, but the cost and complexity would be considerable, and the benefit obtained would probably be marginal.

When the blow tank discharge valve is opened the control valves on the supplementary and fluidizing air supply lines must be returned to their settings for conveying. This is essential, for the correct air flows must be maintained to achieve satisfactory blow tank discharge and material conveying at the desired rate. In the blow tank without a discharge valve these settings are never changed, and this is why it takes so long to achieve steady state conveying, particularly if the material is conveyed in dilute phase.

4.4.2.3.2 Blow tank venting

If there is a vent line between the blow tank and the supply hopper it will also be possible to reduce the time required for de-pressurizing the system. As soon as the blow tank is empty, the discharge valve should be shut and the vent line opened. It will also be necessary to shut the blow tank fluidizing air supply valve and fully open the supplementary air supply valve. By this means the blow tank can be isolated from both the air supply and the conveying line, and the processes associated with each can be carried out simultaneously.

By this means the blow tank can be de-pressurized very quickly in isolation from the conveying line. The total air supply will still be available to the pipeline so that this can be purged separately, and at the same time. This will also prevent the large volume of air in the blow tank from expanding rapidly through the conveying line, thereby causing very high air velocities and possible severe pipeline erosion during the venting process if the conveyed material is abrasive.

Isolation of the blow tank will also reduce the loading on the filtration unit at this time in the conveying cycle. It is important that this surge of air at the end of the cycle is taken into account when sizing the filters for the plant, regardless of the mode of blow tank operation, but particularly if the blow tank is not vented in isolation. If the blow tank is vented to the supply hopper it is equally essential that the filter on the supply hopper is also correctly sized for the anticipated volumetric flow rate.

4.4.3 Single blow tank control

With rotary valves and screw feeders, material flow rate can be controlled, over a limited range, simply by varying the drive speed. Blow tanks, as already mentioned in Chapter 3, have no moving parts, and yet turn-down ratios of 10:1 can be achieved quite successfully.

4.4.3.1 Air proportioning

Control of a blow tank is achieved by proportioning the total air supply between that which is directed to the blow tank and that which goes directly to the start of the conveying line. The total air supply is used to convey the material through the pipeline.

4.4.3.1.1 Blow tank air

The air directed to the blow tank is used to pressurize the blow tank. This air supply may also aerate or fluidize the material, depending upon the bulk characteristics of the material. The blow tank air discharges the material from the blow tank into the conveying line. The solids loading ratio of the material in the blow tank discharge line can be extremely high, and hence there is a pressure drop associated with this feeding. This is why supplementary air is necessary, unless the conveying line is very short and high pressure air is available.

4.4.3.1.2 Supplementary air

The supplementary air passes directly to the start of the conveying line at the blow tank discharge point. The supplementary air effectively dilutes the flow of material for conveying through the pipeline. It is essential that the correct solids loading ratio is achieved at this point in order to match the capability of the air mover in terms of pressure available. If the solids loading ratio is too low, for example, the pressure drop over the conveying line will be low and the pipeline will be under-utilized. If, on the other hand, the solids loading ratio is too high, the pressure drop required for conveying the material through the pipeline may exceed the capability of the air mover, and the pipeline will probably block.

4.4.3.2 Discharge rate control

Figure 3.28 was presented to show how the proportion of air that is used to fluidize the material in the blow tank can influence the discharge rate. The discharge characteristics presented are essentially a graph of material flow rate against total air mass flow rate, with data in terms of the ratio of fluidizing air to total air mass flow rate superimposed.

4.4.3.3 The influence of blow tank type

Both top and bottom types of blow tank are used in industry but the choice of configuration is often based on convenience rather than the merits of configuration and performance. In a programme of work carried out for the original Design Guide the performance of a blow tank, capable of being arranged in either top or bottom discharge, was compared with these two configurations [1].

A sketch of the two blow tank systems is given in Figure 4.13. The bottom section of the blow tank vessel was constructed so that it could be changed and either a membrane or a bottom discharge section could be used. In both cases the conveying line was identical, apart from slight changes at the start to accommodate differences in blow tank geometry.

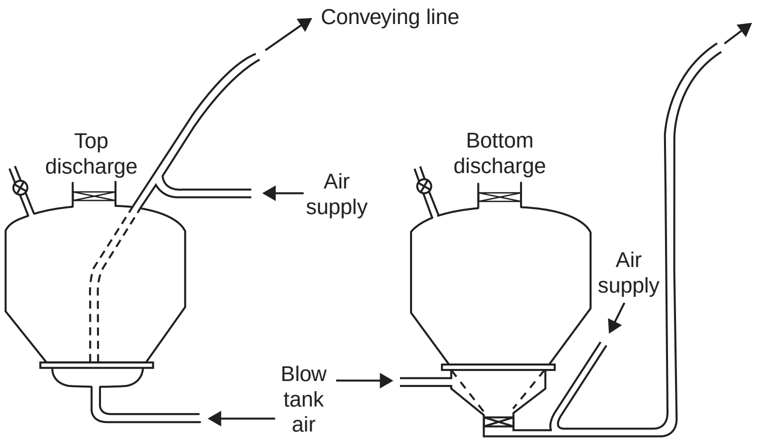


Figure 4.13 Sketch of top and bottom discharge blow tank arrangements tested.

4.4.3.3.1 Conveying line performance

The first point to note with respect to the differences between top and bottom discharge from blow tanks is that there is no difference in conveying line performance between the two. For a given material and pipeline, the conveying characteristics produced were identical such that for a given air flow rate and conveying line pressure drop the material flow rates were identical for the two blow tank systems.

This is perhaps not surprising since if a material is continuously fed into a pipeline there is not likely to be a difference in performance, regardless of the method by which the material was fed, provided that it is reasonably steady and continuous. Only if the material is pulsed into the pipeline, as with the pulse phase system of Figure 2.11 would a marked difference in performance be expected.

4.4.3.3.2 Blow tank discharge performance

As part of the research programme, the discharge characteristics of the two blow tank configurations were compared for the same material and the same pipeline. Extensive tests, therefore, were carried out with a fine grade of pulverized fuel ash conveyed through a 53 mm bore pipeline, 50 m long, containing nine 90° bends. In the top discharge mode material flow rates of up to 24 tonne/h were achieved, but in the bottom discharge mode this was almost halved. The two sets of blow tank characteristics are shown in Figure 4.14 for comparison.

There are three limits on these two plots. The one on the left, at low air flow rates, represents the minimum conveying limit for the material. This relates to the air flow rate necessary to achieve the minimum value of conveying air velocity. The two plots are very similar in this respect, as would be expected. The limit to the right, at high air flow rate, is simply set by the volumetric capability of the compressor used to supply

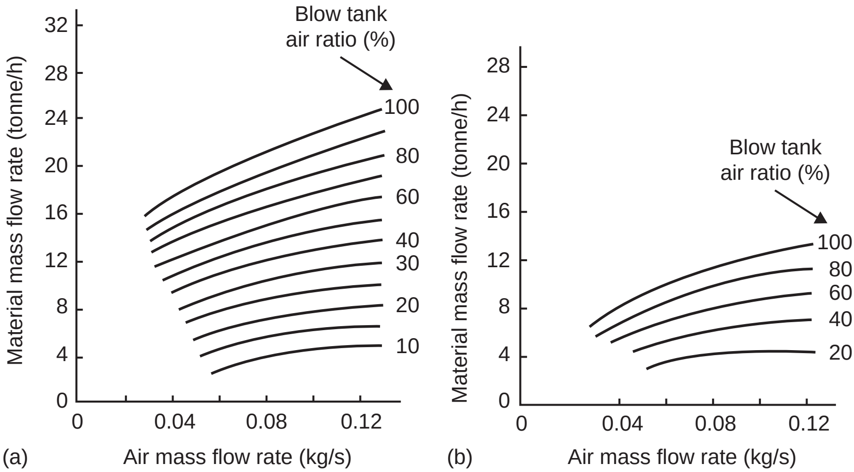


Figure 4.14 Blow tank characteristics for the discharge of pulverized fuel ash: (a) top discharge blow tank and (b) bottom discharge blow tank.

the air. The limit at high material flow rates, with all the air directed into the blow tank, represents the maximum discharge capability of the blow tank for the material being discharged.

It was mentioned at the end Section 4.4.1.1 above that as a generalization, the top discharge blow tank, with fluidization of the material, is most suitable for powdered materials. This would tend to be confirmed with Figure 4.14. It is suspected, however, that if fluidizing air was introduced more efficiently in the bottom discharge blow tank case, an improvement in performance would be obtained. This, however, would probably involve introducing a separate source of air into the centre of the flow with an aerated nozzle and this may cause obstruction by its presence. The work clearly demonstrates that blow tanks will work, but the discharge capability is not readily predictable.

The 100 per cent line on the blow tank characteristics represents the discharge limit of the blow tank. If a higher discharge rate is required from a blow tank, an improvement in the aeration of the material might help. Otherwise a larger discharge pipe will be needed. The discharge pipe does not have to be the same diameter as the conveying pipeline.

4.4.3.3.3 Material discharge performance

It is well known that different materials can have different conveying characteristics when conveyed through exactly the same pipeline, and this will be considered in detail in Chapter 12. The same also applies in terms of different materials with respect to their blow tank discharge characteristics. The property values of some materials tested in the top discharge blow tank are presented in Table 4.1 for reference.

Each of the materials presented in Table 4.1 was conveyed from the top discharge blow tank shown in Figure 4.13 and was conveyed through the 50 m long pipeline of 53 mm bore. The blow tank characteristics for the pulverized fuel ash were presented earlier in Figure 4.14a and those for the other four materials are presented in Figure 4.15. The materials considered cover a wide range of both densities and particle sizes. The materials show considerable diversity in their discharge characteristics and illustrate the difficulties of blow tank control. Fortunately most blow tanks are dedicated to a single material and so can readily be adjusted for the given material on commissioning.

The discharge characteristics for the granulated sugar and polyethylene pellets illustrate the problems of top discharge for granular materials compared with fine

Table 4.1 Property values of materials presented

Figure number	Material	Bulk density (kg/m^3)	Mean particle size (μm)	Particle density (kg/m^3)
4.14a	Pulverized fuel ash	980	40	2440
4.15a	Wheat flour	515	78	1470
4.15b	Granulated sugar	890	460	1580
4.15c	Pearlite	100	200	800
4.15d	Polyethylene pellets	540	4000	910

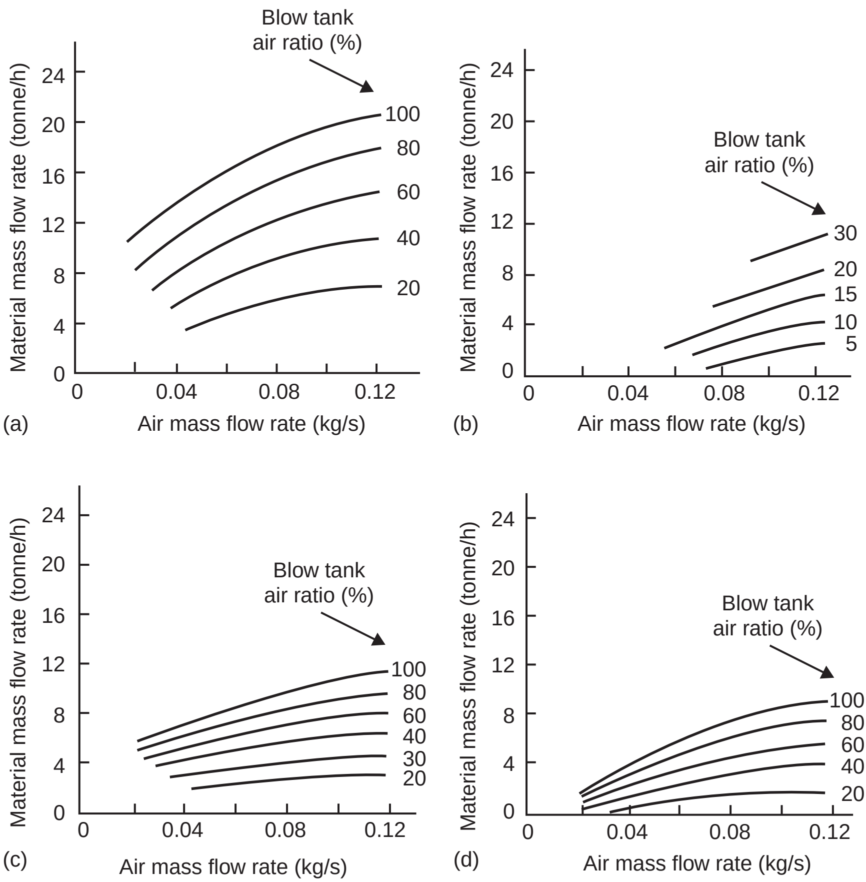


Figure 4.15 Top discharge blow tank characteristics for various materials: (a) for wheat flour, (b) for granulated sugar, (c) for pearlite and (d) for polyethylene pellets.

powdered materials. This is particularly the case with the sugar where control is over a limited proportion of blow tank air.

4.4.3.4 Blow tank control systems

If a blow tank is required to convey a variety of materials, or just one material over a range of distances, so that the material flow rate will need to be changed, an automatic control facility would be essential. Air supply pressure is the controlling parameter and so some form of feedback control should be provided on the air supply to the blow tank to ensure that the conveying line always works to the maximum capacity that the air supply pressure will allow.

The most effective way of controlling the blow tank discharge rate is to provide a modulating valve on one of the air supply lines. This will automatically proportion the total air supply between the blow tank and the supplementary line. A sketch of such

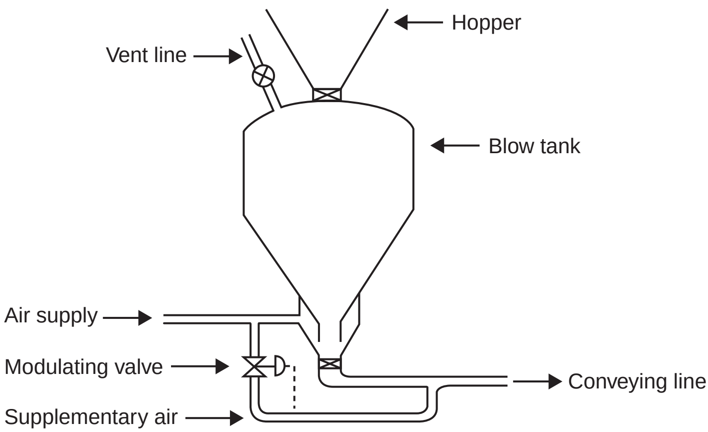


Figure 4.16 Blow tank control system.

a system, fitted to a bottom discharge blow tank, is shown in Figure 4.16. In this case the feedback signal is from the air pressure in the supplementary air supply line.

If the pressure monitored is below the operating value for the system, the modulating valve will restrict air flow to the supplementary line and so more will be directed to the blow tank. With a greater proportion of the air supply directed to the blow tank, the feed rate will increase. If the pressure rises too much, the modulating valve will open a little to allow more supplementary air, and hence the material flow rate will be reduced.

This type of control is particularly useful on the start-up and tail-out transients associated with the conveying cycle. During start-up, for example, all the air will be automatically directed to the blow tank to effect a rapid pressurization, and control will automatically be achieved with lines of different length. The sensing device for the valve is often positioned in the supplementary airline rather than in the air supply line. In the supplementary airline, changes in pressure will be monitored very quickly. In the air supply line the blow tank has a damping effect and consequently there will be a slight delay in sensing pressure changes.

4.4.4 Twin blow tank systems

If two blow tanks are used, rather than one, a significant improvement in performance can be achieved. There are two basic configurations of blow tanks. One is to have the two in parallel and the other is to have them in series. The series arrangement will be considered with feeding systems operating with lock hoppers.

4.4.4.1 Twin blow tanks in parallel

The ratio of the mean flow rate to the steady state material flow rate can be brought close to unity if two blow tanks in parallel are used. While one blow tank is being discharged

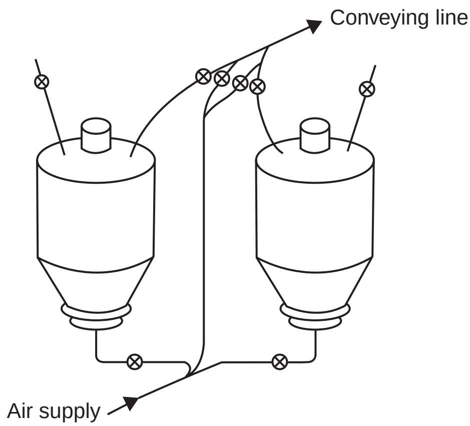


Figure 4.17 Typical parallel arrangement of twin blow tanks.

into the conveying pipeline, the other can be de-pressurized, filled, and pressurized, ready for discharging when the other one is empty. By this means almost continuous conveying can be achieved through a common pipeline. This arrangement, however, requires a full set of discharge, vent and isolating valves, and level switches for each blow tank, and an automatic control system to achieve the correct timing. A sketch of a typical parallel arrangement of twin blow tanks is given in Figure 4.17.

The sequence of events would be as follows:

	Blow Tank A	**Blow Tank B**
	fill **pressurize**	**discharge**
Change Over →		
	discharge	**vent** **fill** **pressurize**
Change Over →		
	vent **fill**	**discharge**

From this it can be seen that the blow tank pressurizing process in one blow tank has to be carried out while the material is being discharged from the other. This would require additional air and it would probably not be economically viable for the marginal improvement obtained. To achieve a high tonnage with a single blow tank, a fairly large blow tank would be needed, but with twin blow tanks the tank size can be smaller. The size can be based on a reasonably short blow tank cycle, provided that the two sets of sequences can be fitted into the time allowed.

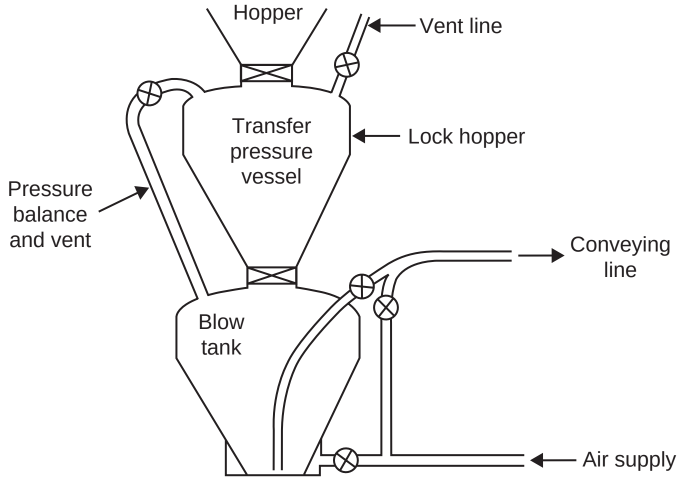


Figure 4.18 Blow tank system capable of continuous operation.

4.5 Lock hoppers

Lock hoppers provide a means of both allowing operation of many feeding devices that have only a low pressure capability, to operate at very much higher pressures, and allowing continuous conveying from a single blow tank feeder.

To illustrate the mode of operation the theme of blow tanks is continued, and a system often referred to as twin blow tanks operating in series is considered. The lock hopper is located between the supply hopper, which will generally be at atmospheric pressure to allow continuous loading of material, and the material feeding device, which can be at any pressure required, almost without limit. A typical layout with regard to a blow tank is illustrated in Figure 4.18.

The lock hopper, or pressure transfer vessel, is filled from the hopper above. The lock hopper is then pressurized to the same pressure as the blow tank, either by means of a pressure balance from the blow tank, which acts as a vent line for the blow tank while it is being filled, or by means of a direct line from the main air supply. With the transfer vessel at the same pressure as the blow tank, the blow tank can be topped up to maintain a continuous flow of material. The lock hopper will have to be pressurized slowly in order to prevent a loss in performance of the system while it is conveying material.

Once the material has been loaded into the blow tank the lock hopper will have to be vented to return it to atmospheric pressure. The lock hopper can then be loaded with another batch of material from the supply hopper.

The blow tank in Figure 4.18 is shown in a top discharge configuration, but without a fluidizing membrane. The air enters a plenum chamber at the base, to pressurize the blow tank and fluidize the material, and is discharged via an inverted cone into the conveying line. A vertically in-line arrangement of vessels, with one positioned above the other, does require a lot of headroom, and so the blow tank arrangement shown in Figure 4.18 is sometimes employed to minimize the head required.

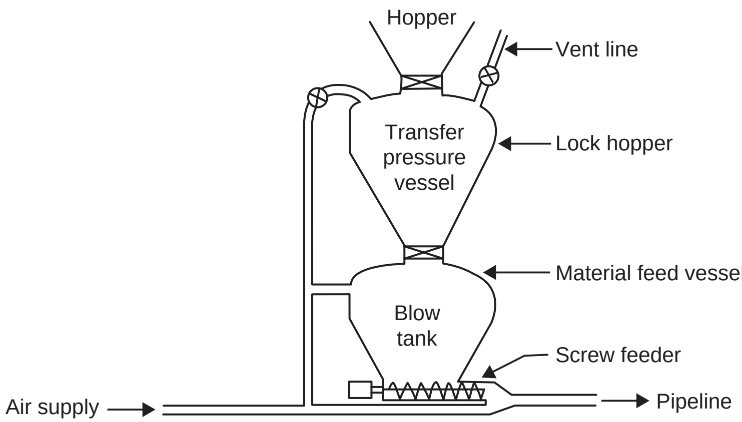


Figure 4.19 Twin blow tank system with screw feeding.

4.5.1 Alternative feeding arrangements

If a lock hopper arrangement is used, as shown in Figure 4.18, the pipeline feeding device need not be a blow tank at all, despite the use of high pressure air. With the transfer pressure vessel separating the hopper and the pipeline feeding device, the feeding device can equally be a rotary valve or a screw feeder, for there is virtually no pressure drop across the feeder. Any pressure drop will, in fact, be in the direction of material flow and so there are no problems of air leakage across the device, as there are with conventional feeders of this type.

4.5.1.1 Rotary valves and screws

A rotary valve or screw may be used in this situation to guarantee the feed of a steady flow of material into a pipeline. If a rotary valve or screw is to be employed, designs to cater for high pressure differentials do not have to be used. Erosive wear problems associated with abrasive materials are also significantly reduced with this type of system. A sketch of a screw feeder based on this lock hopper principle is given in Figure 4.19.

4.5.1.2 Venturi feeders

Venturi feeders can equally be operated at high pressure when located in a vessel under a lock hopper. At high pressure the influence of changes in pressure on the compressibility of air are not so great, and the generation of very high velocities within the venturi are not as necessary and so the device is very much easier to design and operate. An analysis of venturi flows and operation is given in Chapter 10.

4.5.1.3 Applications

In cases where there is a need for a high air supply pressure, either to convey a material in dense phase or over a long distance, and continuous operation is essential, a twin blow tank system is ideal. Although these systems do require more headroom than

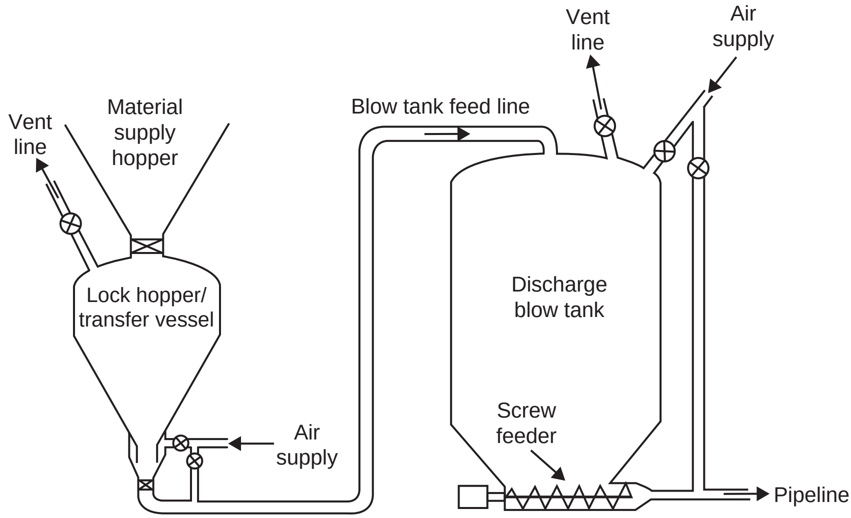


Figure 4.20 Side-by-side arrangement of blow tanks with screw feeding incorporated.

rotary valves, screw feeders and many single blow tank systems, this need not be excessive. It clearly depends upon the material flow rate to be achieved, but if a reasonable cycling frequency between the two pressure tanks is employed, the capacity of the vessels can be of a reasonable size and a compact system can be obtained.

A particular application of these systems is for the direct injection of pulverized coal (DIPC) into boilers and furnaces. In the case of furnaces the material often has to be delivered against a pressure. This, of course, presents no problem since high air supply pressures can be utilized. A general requirement of DIPC systems is that the material should be conveyed at a very uniform rate, and that it should also be capable of achieving a high turn-down ratio. An operating range of 10:1 on material flow rate is often requested in this respect. Blow tanks are capable of operating quite successfully over this range and so they are ideally suited to this type of application.

4.5.2 Alternative vessel configuration

Due to the head-room required, particularly for high tonnage duties requiring blow tanks, a side by side arrangement of blow tanks was devised. The driving force for this development was the possibility of replacing screw pump feeding systems with such blow tanks. The lock hopper fits into the existing space beneath the hopper, vacated by the screw pump, and the blow tank is placed alongside. This requires the material in the lock hopper to be conveyed to the blow tank, but it does allow continuous operation. A sketch of such an arrangement is given in Figure 4.20.

References

1. M G Jones, D Mills and J S Mason. A comparison of top and bottom discharge blow tank systems. Bulk Solids Handling. Vol 7, No 5. pp 701–706. October 1987.

Chapter 5

Pipelines and valves

5.1 Introduction

Decisions with regard to the specification of components for pneumatic conveying systems do not end with the feeder, air mover and filtration system. There are likely to be numerous valves on the plant, and the pipeline is just as important. This importance is significantly magnified if the material to be conveyed is abrasive.

5.2 Pipelines

Decisions do have to be made with regard to the pipeline. Material, wall thickness, surface finish, steps and bends to be used, all have to be given due consideration. One of the most critical parameters with regard to the successful operation of a pneumatic conveying system is maintaining a minimum value of conveying air velocity for the material to be handled. For the dilute phase conveying of granulated sugar, for example, this is about 16 m/s. If the velocity drops to 15 m/s the pipeline is likely to block.

5.2.1 Wall thickness

The volumetric flow rate of the air required is obtained by multiplying the conveying air velocity by the cross-sectional area of the pipeline, and making due note of both the pressure and temperature of the air. The diameter of a 4 in. nominal bore pipeline, however, is rarely 4 in. If a conveying air velocity is based on a diameter of 4 in., for example, and it is a schedule 10 pipeline, the actual bore will be 4.026 in. (106.1 mm) and not 4.000 in. (101.6 mm). This difference will mean that the conveying air velocity will be about 9 per cent lower. If 16 m/s is the velocity in a 101.6 mm bore pipeline, it will only be 14.6 m/s in a 106.1 mm bore line, and the pipeline is likely to block.

If an abrasive material is to be conveyed, wear of the pipeline must be expected. To give the pipeline a longer life, pipe having a greater wall thickness should be used. Schedule numbers are often used to specify wall thickness. Typical dimensions for 4 in. nominal bore pipeline are given in Table 5.1.

If the material to be conveyed is not abrasive at all, a thin walled pipeline should be suitable for the duty. Pipeline weight in kg/m could be added to Table 5.1 and this would show a marked difference. Lighter pipe sections will certainly make construction of the pipeline easier, particularly if there are vertical sections to erect.

Table 5.1 Pipe diameters and wall thicknesses for 4 inch nominal bore pipeline

Dimensions	Schedule number			
	10	40	80	160
Wall thickness (in.)	0.162	0.237	0.337	0.531
Pipe bore (in. (mm))	4.176 (106.1)	4.026 (102.3)	3.826 (97.2)	3.438 (87.3)
Outside diameter (in.)	4.5	4.5	4.5	4.5

5.2.1.1 Pipeline rotation

If a pipeline is to convey materials having a very large particle size, the particles will tend to 'skip' along lengths of horizontal pipeline. This is as a consequence of the greater influence of the gravitational force over the drag force on the particles. If the material being conveyed is abrasive, then a groove is likely to be worn along the bottom of the pipeline. Mild steel pipeline is particularly vulnerable to this type of wear. This is because erosive wear of ductile surface materials is very high at low, glancing, angles of impact. The subject of erosive wear is considered in detail in Chapter 23.

If this type of material does have to be conveyed, then a thick walled pipeline would be recommended, but if the pipeline was to be rotated periodically, this would also extend the life of the pipeline very considerably. For this purpose the pipeline should be located in a place where convenient access can be gained for the necessary changes to be made.

5.2.2 Pipeline material

Although steel is the most commonly used pipeline material, many other materials are available to suit the conveyed material and the conveying duty. It was mentioned above that thin walled pipe would be easier to handle and erect because it is lighter. Aluminium pipe is often used for this purpose.

5.2.2.1 Hygiene

Due to the problems of moisture and condensation in pipelines there is always the possibility of steel rusting, and contaminating the conveyed material. In cases where hygiene is important, such as with many food and pharmaceutical products, the pipeline will need to be made from stainless steel.

5.2.2.2 Hoses

Where flexibility is required in a pipeline, and this cannot be conveniently achieved with a combination of straight pipe and bends, flexible hose can be used. Where a single line needs to feed into a number of alternative lines, and a flow diverter is not wanted to be used, a section of flexible hose of the steel braided type can be used to provide the link.

Where road and rail vehicles and boats need to be off-loaded, flexible rubber hose is ideal. It is available in natural rubber and a variety of synthetic materials come in a wide range of sizes. The author has conveyed various drilling mud powders through hoses at pressures of up to 6 bar gauge to obtain data for transferring these materials from boats to oil rig platforms in the North Sea. The author has also tested flexible hose compounded from steel and rated at 250 atm, for erosive wear resistance.

Flexibility is generally needed in ship off-loading applications with vacuum systems, and hoses provide the necessary flexibility here. Care must be taken if the material is abrasive and has a large particle size, because the wear rate of rubbers can be excessive with such materials. Rubber hose is considered further in Section 5.4.

5.2.2.3 Erosive wear

If an abrasive material is to be conveyed in a pipeline, consideration must be given to the use of schedule 80 pipeline or higher. For very abrasive materials conventional mild steel pipeline is unlikely to be suitable, and spun alloy cast iron pipeline would be preferred. An alternative to this, which is commonly adopted, is to line a conventional steel pipeline with basalt.

If a more wear resistant material is required, then alumina ceramics can be used, but this is likely to be very much more expensive. A usual combination is to line the straight pipeline with basalt and to use alumina for the bends. Erosive wear of bends tends to be more severe than straight pipeline and so a much higher degree of protection needs to be given to them.

5.2.2.4 Material degradation

Friable materials need to be conveyed 'gently' and this is best achieved by controlling the conveying conditions. In terms of pipeline influences most of the problems of material degradation occur at the bends in the pipeline. It is the deceleration of particles on impact with bends that causes much of the damage. Decelerating forces are significantly lower with materials such as urethane and rubber, because of their resilience. It is generally a matter of compatibility with the conveyed product as to whether these materials can be incorporated into the pipeline. The subject of particle degradation is considered in some detail in Chapter 24.

5.2.3 Surface finish

Most pipelines are supplied having a satisfactory surface finish with regard to frictional resistance to flow. For some conveyed materials, such as polyethylene, however, a particular surface finish is required for the specific purpose of reducing the problem of 'angel hairs', or particle melting, with these materials. An artificially roughened surface is usually required.

5.2.4 Bends

Bends provide a pneumatic conveying pipeline with considerable flexibility in routing, but are the cause of many problems. Each bend will add to the overall resistance

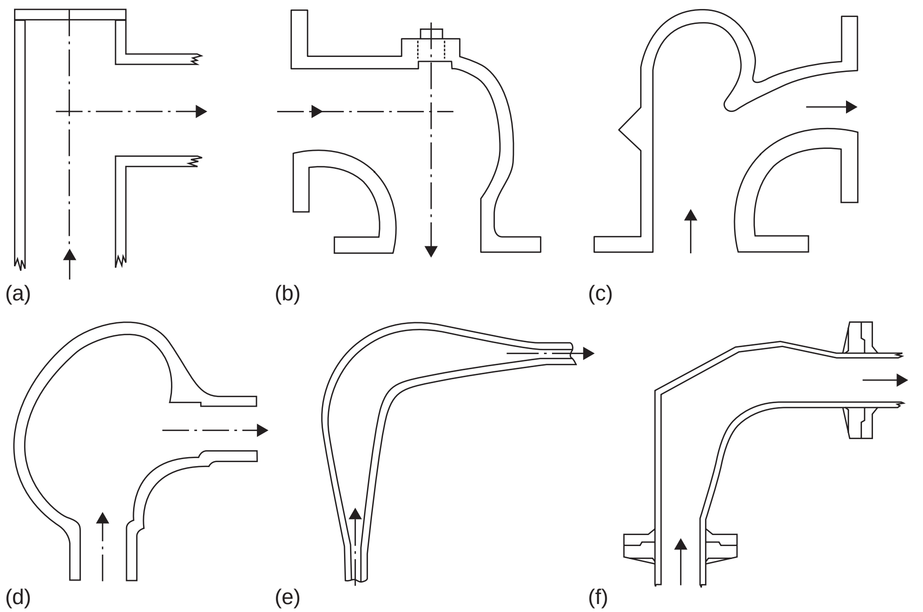


Figure 5.1 Some special bends developed for pneumatic conveying systems: (a) the blind tee, (b) the Booth bend, (c) the vortice ell, (d) the flow bow, (e) the expanded bend and (f) the gamma bend.

of the pipeline, and hence to the conveying air pressure required. If the conveyed material is abrasive an ordinary steel bend could fail within 2 h. An abrupt change in direction will add to the problem of fines generation with friable materials, and angel hairs will be generated in long radius bends with many synthetic materials.

Numerous different bends are available, to minimize each of the above problems. Many of these are made of, or lined with, basalt, cast iron, rubber, etc, and some have a constant bore and a constant radius, as with conventional bends. Another group of bends that have been developed, specifically for pneumatic conveying system pipelines, have neither constant bore nor constant radius. Some of these bends are shown in Figure 5.1. Care must be taken in selecting such bends, for account must be taken of their suitability for the material being conveyed and the pressure drop across the bend with that material.

5.2.4.1 Blind tee

With an abrasive material, the simple blind tee bend shown in Figure 5.1a will probably last 100 times longer than an equivalent radiused bend. It will ultimately fail around the inside corner due to turbulence. For abrasive materials, therefore, it is extremely effective, and can even be made out of scrap material. The blind end of the bend traps the conveyed material and so the oncoming material impacts against other material, instead of the bend, and thereby protects it. This is similar to the ‘dirt box’ used in many areas of bulk solids handling where surfaces have to be protected from sliding and impacting abrasive materials.

The penalty, however, is in the increased pressure drop that can result. In a programme of tests with a 50 m long pipeline of 53 mm bore conveying fly ash, the author changed seven radiused bends in the pipeline with blind tee bends. With the radiused bends and a 2 bar pressure drop the fly ash was conveyed at 20 tonne/h. With the blind tee bends in place only 10 tonne/h could be achieved with the same 2 bar pressure drop.

Another problem with this type of bend is that the material that is trapped in the dead end of the bend may take a long time to be purged from the bend at the end of a conveying run. It could not, therefore, be used in pipelines required for the conveying of perishable and other time limited materials.

5.2.4.2 Special bends

Figure 5.1b shows a more sophisticated version of the blind tee bend that was developed in the early 1970s and is known as the Booth bend after its originator. This is a very short radius cast bend that incorporates a shallow depression. This allows material to collect in the bend and so subsequent material flowing through the pipeline will impact against itself. At the end of a conveying cycle the trapped material will be readily purged from the shallow depression in this bend. A pipe plug is provided in the back of the bend as it was well recognized that it is usually at bends that pipelines become blocked.

Another, more recent version, shown in Figure 5.1c, is the short radius bend with a large recessed chamber in the area of the primary wear point. It is claimed that this acts as a vortice and that material is constantly on the move in this pocket, thereby providing a cushioning effect to oncoming material that should reduce problems of erosive wear and material degradation.

It is suggested that the expanded bend, shown in Figure 5.1e, will also help to reduce erosive wear and particle degradation [1]. Both of these operational problems are very significantly influenced by velocity. With the expansion to a larger section at the bend the air velocity is significantly reduced, with a consequent reduction in impact velocity of the particles against the bend wall. The turbulence in the bend is so great that even if the velocity falls well below the minimum value for the material, the pipeline is unlikely to block, but material may be deposited in the bend and this will be difficult to purge clear.

The gamma bend in Figure 5.1f was specifically developed to minimize the problems of angel hair formation that can occur with materials such as nylons and polymers when they slide around the wall of a conventional radiused bend.

5.2.4.3 Pressure drop

Due to the change in direction, impact of particles against bend walls, and general turbulence, there will be a pressure drop across every bend in any pipeline. The major element of the pressure drop, however, is that due to the re-acceleration of the particles back to their terminal velocity after exiting the bend. The situation can best be explained by means of a pressure profile in the region of a bend, such as that in Figure 5.2 [2].

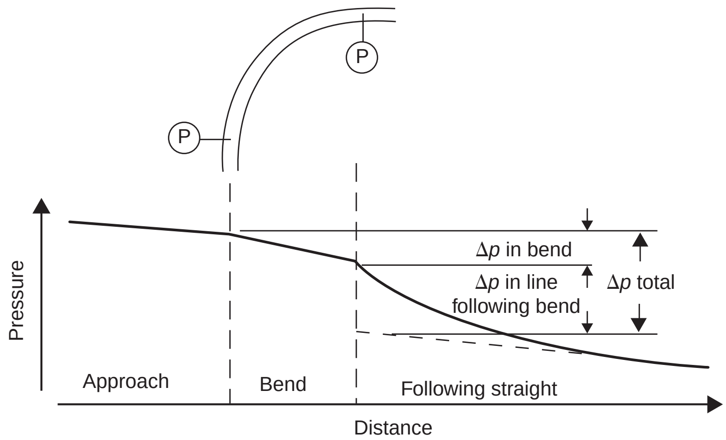


Figure 5.2 Pressure drop elements and evaluation for bends in a pipeline.

The pressure drop that might be recorded across the bend is quite small, and although this technique might be appropriate for single phase flows around bends, it is inappropriate for gas–solids flows. The particles leaving the bend will be at a lower velocity than that at entry and so they will have to be re-accelerated. The bend was the cause of the problem but the re-acceleration occurs in the straight length of pipeline following the bend, and so it is here that the associated pressure drop occurs, and not in the bend itself.

If pressure transducers are located along the length of the pipeline a steady pressure gradient will be recorded in the straight length of pipeline approaching the bend. A similar steady pressure gradient will also be recorded in the straight length of pipeline after the bend, but only after sufficient distance to allow for the particles to re-accelerate. The total pressure drop that can be attributed to the bend is determined in the way indicated in Figure 5.2.

5.2.5 Steps

If high pressure air, or a high vacuum, is used for conveying a material, it would generally be recommended that the pipeline should be stepped to a larger bore part way along its length. This is to cater for the expansion of the air that occurs with decrease in pressure, and so prevents excessively high conveying air velocities towards the end of the pipeline.

Figure 5.3 illustrates the case of a high pressure dilute phase conveying system. The minimum value of conveying air velocity that must be maintained is about 15 m/s and 60 m^3/s of free air is available to convey the air. The conveying line inlet air pressure is 4 bar gauge. From Figure 5.3 it will be seen that a 125 mm bore pipeline will be required for these conditions, and the resulting conveying line inlet air velocity will be 16.5 m/s. If a single bore pipeline is used, however, the conveying line exit air velocity will be about 81.5 m/s [3].

A velocity of 81.5 m/s will cause considerable damage to any conveyed material and very serious wear to the plant if the material is only slightly abrasive. By stepping

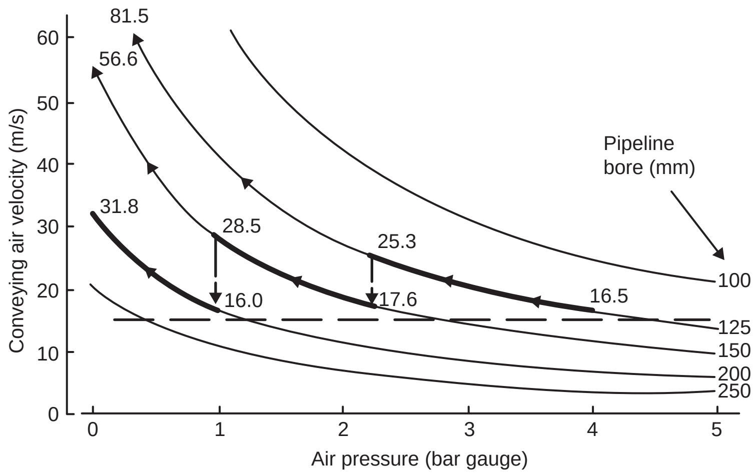


Figure 5.3 Stepped pipeline velocity profile for high pressure dilute phase system.

the pipeline twice, as shown in Figure 5.3, it will be seen that the velocity profile can be kept within reasonably low limits. The stepping of a pipeline to a larger bore would also be recommended for high vacuum conveying systems and high pressure dense phase conveying. The stepping of a pipeline is only dependent upon conveying air pressure and should be undertaken for any length of pipeline.

The stepping of a pipeline is also likely to lead to a significant improvement in performance of the conveying line. In a programme of tests undertaken by the author, fly ash was conveyed at 20 tonne/h through a 115 m long pipeline of 53 mm bore with a conveying line pressure drop of 2 bar. By stepping the pipeline up to 68 mm bore half way along and then to 81 mm towards the end, 40 tonne/h was achieved with the same air flow rate and 2 bar pressure drop [4].

In the above programme, one pipe was simply pushed inside the larger pipe and welded to make it airtight. For larger bore pipelines it would always be recommended that a tapered expansion section should be used to join pipeline of different bore. By this means the expansion can be achieved in a more controlled manner and should result in slightly better performance.

5.3 Valves

A number of different valves may need to be used on pneumatic conveying plant, and a wide variety of different valves are available in the market place. Rotary valves have been considered at length, and are ideal for controlling the feed of material into or out of a system at a controlled rate. There is, however, a requirement for many other types of valve, generally to be used for the purpose of isolating the flow. Many of these have been included on sketches of conveying systems in previous chapters and include, discharge valves, vent line valves and diverter valves.

5.3.1 Discharge valves

A valve in a conveying line that is required to stop and start the flow is an onerous duty. Although the valve is only used in either the open or closed position, and is not used for flow control purposes, particulate material must be able to pass freely through when it is open. If the control surfaces of the valve remain in the flow path, as they will with pinch valves and ball valves, they must provide a perfectly smooth passage for the flow of material through the valve when open.

Any small protuberances or surface irregularities that could promote turbulence in the area would result in a rapid deterioration in performance. This is particularly the case when the material to be conveyed is abrasive. This type of valve is also very vulnerable during the opening and closing sequences, and so these operations should be completed as quickly as possible.

5.3.1.1 Ball valves

The author has tested numerous ball valves in a 100 mm bore pipeline conveying silica sand in dilute phase at 2 bar pressure. They did not perform very well in such a harsh environment. As they have moving parts the very fine abrasive dust in the conveyed material wrecked havoc. The valves soon lost their airtightness, and the torque required to operate the valves gradually increased and soon exceeded that available by the automatic control facilities provided with the valves.

5.3.1.2 Pinch valves

Pinch valves are a much better proposition, as there is no relative movement between surfaces in which fine abrasive dust can lodge. These can also be opened and closed rapidly. Rubbers and urethanes also have very reasonable erosive wear resistance, and so are well worth considering for this kind of duty. They will not last forever, and so periodic maintenance is essential, and will be required. These valves must be located in an accessible position, and spares must be available.

5.3.1.3 Dome valves

The dome valve is a more recent addition to the list of valves available, but it has been specifically designed for this type of duty, and is now being widely used in the industry. The valve has moving parts, but these move completely out of the path of the conveyed material when the valve is open. On closing, the valve first cuts through the material and then becomes airtight by means of an inflatable seal. The valve can be water cooled and so it is capable of handling hot materials.

5.3.2 Isolating valves

There are many instances where material has to be transferred, usually under gravity, in batches. The valve is either open or closed and often has to provide an airtight seal. In the gate lock feeder, for example, a pair of valves is required to operate in sequence to feed small batches of material into a pipeline.

Where batches of material have to be fed into blow tanks, the valve has to be capable of withstanding the pressure subsequently applied to the blow tank. Of the valves considered above only the dome valve would be appropriate for this type of duty. It finds wide use in this application, particularly with the more difficult granular and abrasive materials.

5.3.2.1 Butterfly valves

If the material to be handled is not abrasive, the butterfly valve is ideal. They are reasonably priced, require very little headroom, are not too heavy, and are reasonably airtight. They are widely used in the food and related industries, and in gate lock feeders. They are, however, much too vulnerable for use with abrasive materials, since the valve remains in the flow when it is open.

5.3.2.2 Disc valves

Disc valves, like butterfly valves, require very little headroom, but like dome valves, they swing completely out of the way of the flow of material. They cut though the material on closing, but generally rely on the subsequent pressure in the vessel below to provide the necessary seal. Their suitability for use will depend very much upon the material to be handled and the application.

5.3.2.3 Slide valves

Slide valves are the oldest valves in the business, and although they have been improved over the years, the disc valve is a specific development from it. They take up little space and are cheap. A particular application is in terms of back-up. If any of the other more expensive and sophisticated valves fail, and need to be replaced, this can be a very difficult and time consuming task if the valve is holding several hundred tonnes of material in a hopper, and this must be drained out before the valve can be removed for repair or replacement.

5.3.3 Vent line valves

This is a deceptively easy duty, but if it is on a high pressure blow tank handling a material such as fly ash or cement, the valve will have to operate in a very harsh environment. With the venting of high pressure air the air velocity will be very high, albeit for a very short period of time. As a consequence of the turbulence in the blow tank, however, a considerable amount of abrasive dust is likely to be carried with the air. If the material is abrasive then the choice is between a pinch valve and a dome valve. If the material is non-abrasive, a diaphragm valve could be used.

5.3.4 Flow diversion

Flow diverting is a very common requirement with pneumatic conveying systems and can be achieved very easily. Many companies manufacture specific flow diverting valves for the purpose. Alternatively flow diversion can be achieved by using a set of isolating valves. The most common requirement is to divert the flow to one of two alternative routes, typically where material needs to be discharged into a number of alternative hoppers or silos. In this case the main delivery line would be provided with a diversion branch to each outlet in turn.

5.3.4.1 Diverter valves

There are two main types of diverter valves. In one, a hinged flap is located at the discharge point of the two outlet pipes. This flap provides a seal against the inlet to either pipe. The pipe walls in the area are lined with urethane, or similar material, to give an airtight seal, and this provides a very compact and light weight unit.

The author tested a Y-branched diverter valve of this design with silica sand in dilute phase, but it was a disaster. After conveying only 12 tonne of sand, the 4 mm thick bronze flap had a 15 mm diameter hole through it. The urethane lining, however, was in perfect condition. The problem was that the sand was always impacting against the flap. A straight through design with a branch off would have been better, but still not suitable for abrasive materials.

The other main design operates with a tunnel section of pipe between the supply and the two outlet lines. This unit would not be recommended for abrasive materials either. This design, however, should provide a more positive seal for the line not operating, which would probably make it a more suitable valve for vacuum conveying duties. A sketch of a parallel tunnel type diverter valve is presented in Figure 5.4 to illustrate the method of operation.

5.3.4.2 Isolating valves

Flow diversion can equally be achieved by using a pair of isolating valves, with one placed in the branch, close to the supply pipe, and the other in the supply pipe, just

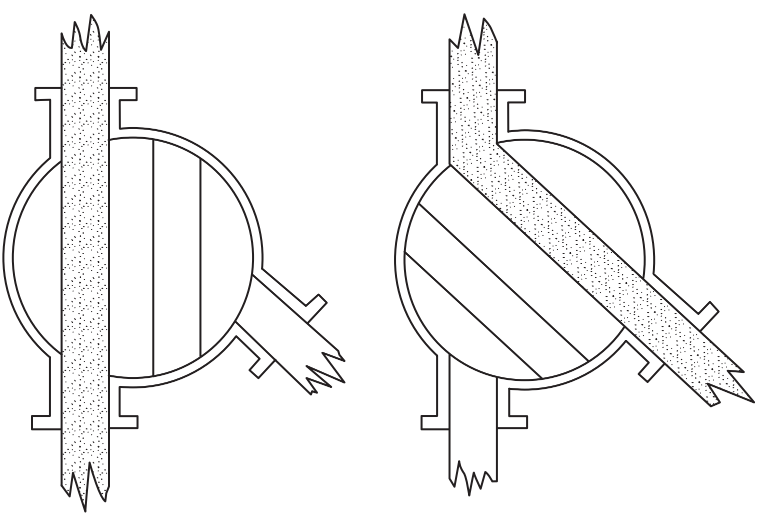


Figure 5.4 Sketch of parallel tunnel type diverter valve.

downstream of the branch. This can be repeated at any number of points along the pipeline. The main disadvantage with this arrangement is that a plug of material will be trapped in the short section of pipeline not in use, which will have to be blown through when the flow direction changes.

If the conveyed material is abrasive, this method of flow diversion would be recommended. Either pinch valves or dome valves would need to be employed for the purpose. With two separate valves, instead of one to operate, care would have to be exercised with the sequencing when changing flow direction.

5.3.5 Flow splitting

Multiple flow splitting is not a common requirement and so there are few devices available. They are often required on boiler plant, where coal dust might need to be sent to the four corners of a boiler, and on blast furnaces, where coal or limestone powder might need injecting at a dozen or more different points around its circumference.

The main requirement here is generally that all of the outlets should be supplied with material, and at a uniform rate to each, despite the fact that the distance to each point will be different. The splitting is best achieved in the vertical plane, with the line sizes very carefully evaluated to provide a uniform balance for each.

5.4 Rubber hose

Rubber hose is widely used in conveying systems for both pipeline and bends, and in systems where a degree of natural flexibility is required. Its particular properties also make it ideal for use in systems where the material being conveyed may be friable, abrasive or cohesive. Its natural flexibility makes it ideal for use in vacuum off-loading applications, mobile conveying systems and for joining pipeline sections in situations where standard pipeline bends will not match the geometry required [5].

5.4.1 Erosive wear and particle degradation

Rubber hose has the capability of withstanding erosive wear better than steel pipeline in certain situations. Although the hardness of the surface material is generally much lower than that of alternative metal surfaces, and of the particles impacting against the surface, it derives its erosive wear resistance from the fact that it is able to absorb much of the energy of impact by virtue of its resilience. By the same mechanism, the energy of impact of friable materials is also absorbed and so particle degradation can also be reduced appreciably.

5.4.2 Pressure drop

Problems of erosive wear and particle degradation are particularly severe in high velocity dilute phase conveying. Unfortunately the pressure drop for gas–solid flows through rubber hose also increases with increase in velocity, and more so than for steel pipeline. In a programme of tests with cement the author tested both steel and rubber hose and found that for low velocity, dense phase conveying, there was little difference

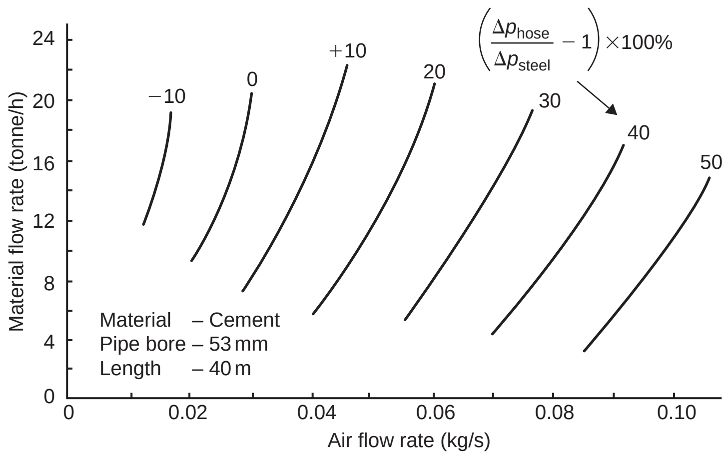


Figure 5.5 Comparison of pressure drop data for steel and rubber hose pipelines.

in pressure drop between the steel and rubber hose. As the air flow rate, and hence velocity was increased, however, the pressure drop through the hose increased significantly. A summary of the results is presented in Figure 5.5 [5].

The programme was repeated with barytes and a similar set of results was obtained. It is suspected that the coefficient of restitution between the particles and the pipeline wall plays an important part. Rubber, being resilient, will have a lower coefficient of restitution for impacting particles than steel. If the rubber absorbs more of the energy of impact of the particles than steel, a greater pressure drop, due to having to re-accelerate the particles from a lower velocity, will result for the rubber pipeline. This is why the pressure drop for flow through the rubber hose is greater than that through the steel pipeline; and since pressure drop increases with the square of velocity, this is why it increases with increase in conveying air velocity.

5.4.3 Conveying cohesive materials

In steel pipelines, cohesive and sticky materials have a tendency to adhere to the pipeline wall and form a coating. This coating can gradually increase in thickness until it builds up to such an extent that it results in the pipeline being blocked. This is particularly the case with ultra-fine powders and materials that have a fat content, or some other substance that makes the material sticky.

If such materials are conveyed through a thin walled rubber hose, the natural movement and flexing of the hose, resulting from the pulsations of the air under pressure and the material transfer, is generally sufficient to dislodge any material that has a tendency to adhere to the pipeline wall. The pipeline needs to be supported so that it is free to move, but having sufficient support so that it is maintained reasonably straight. With the requirement for a thin walled hose capable of flexing it is limited to low pressure dilute phase conveying, but it does provide a simple and effective means of conveying this type of material.

References

1. V K Agarwal, N Kulkarni and D Mills. Influence of expanded bends on wear and particle degradation in pneumatic conveying system pipelines. Proc IMechE Conf on Powder and Bulk Solids Handling. pp 307–317. London. June 2000.
2. D Mills. The value and use of measurements in pneumatic conveying. Part 1 – conveying air pressure. Material and Product Handling. Vol 2, pp 7–13. January–March 2002.
3. D Mills. Application of stepped pipelines in pneumatic conveying systems. Proc 15th Int Conf on Hydrotransport. pp 401–416. Banff, Canada. June 2002.
4. D Mills and J S Mason. An analysis of stepped pipelines for pneumatic conveying systems. Proc 12th Powder and Bulk Solids Conf. pp 696–704. Chicago. May 1987.
5. D Mills. Using rubber hose to enhance your pneumatic conveying process. Powder and Bulk Engineering. pp 79–87. March 2000.

Chapter 6

Air movers

6.1 Introduction

The air mover is at the heart of the pneumatic conveying system, and the success of the entire system rests on correctly specifying the duty of the air mover. The specification is in terms of the volumetric flow rate of free air required, and the pressure at which it must be delivered. The values of these two parameters are primarily dependent upon the material to be conveyed, its flow rate and the conveying distance, and this is considered in Chapter 9. The choice of an air mover to supply the air at the desired flow rate and pressure is equally important, and there is a wide range of machines that are potentially capable of meeting the duty.

Not all air movers are ideally suited to pneumatic conveying, however, and so the operating characteristics must be understood and interpreted. Plant air may be available, but it may not be economical to use it for pneumatic conveying. Some air movers have limitations, and some are more suited as exhausters than compressors, and so the correct choice must be made for vacuum and positive pressure duties.

There are also many peripheral issues associated with the supply of air for pneumatic conveying systems that need to be considered, in addition to the basic hardware. Power requirements for pneumatic conveying can be very high, particularly if it is required to convey a material at a high flow rate over a long distance, and so a first order approximation is presented to allow reasonably reliable estimates to be made early in the selection process.

With most compressors the air is delivered at a high temperature, but this may have to be cooled if high temperature air is not suitable for conveying the material. When compressed air is cooled to ambient temperature, however, it often becomes saturated with water, and this may cause problems. In addition, many compressors do not deliver oil free air.

6.2 Types of air mover

Air movers available for pneumatic conveying applications range from fans and blowers, producing high volumetric flow rates at relatively low pressures, to positive displacement compressors, usually reciprocating or rotary screw machines, capable of producing the higher pressures required for long distance or dense phase conveying systems. The main features of some air movers typically employed for pneumatic conveying duties are outlined, in particular the operating characteristics.

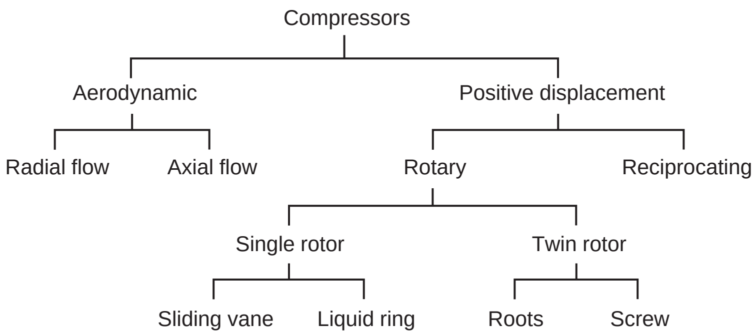


Figure 6.1 Classification of compressors.

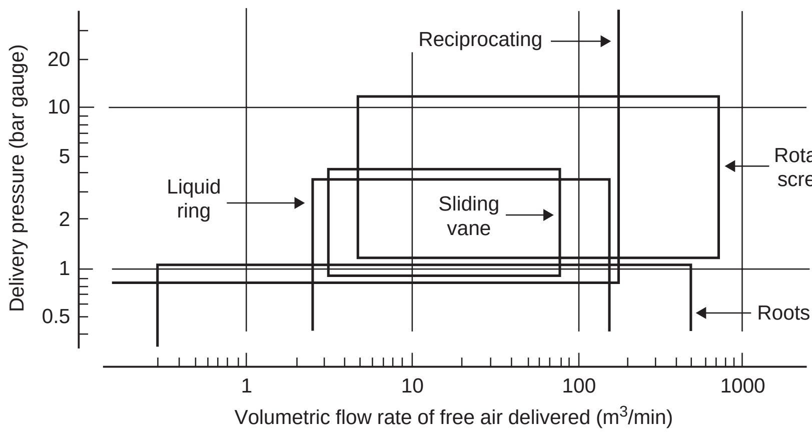


Figure 6.2 Approximate ranges of operation of various types of air mover for pneumatic conveying application.

The basic types of air mover are categorized in a chart of compressor types in Figure 6.1 and their approximate performance coverage, in terms of delivery pressure and volumetric flow rate of free air delivered, are illustrated in Figure 6.2. It should be emphasized that Figure 6.2 is intended only to give a guide to the range of operation of different types of machine. In most cases there are substantial overlaps in their performance coverage. In particular, the reciprocating compressor is available in a very extensive range of sizes and types, and models could be found to satisfy almost any operating conditions shown on Figure 6.2. Many compressors are capable of being staged to deliver air at higher pressures and so this will also be considered.

6.2.1 Aerodynamic compressors

For high pressure duties centrifugal compressors, and especially the multiple stage axial flow machines, are normally manufactured only in large sizes, handling very high volumetric flow rates, and so they rarely find application to pneumatic conveying installations. Axial flow compressors are widely used in aircraft engines. Multiple stage centrifugal compressors are also capable of delivering high flow rates at high pressure, and are often used to provide the air for testing aircraft engines in wind tunnels. Single stage machines find widespread use for short distance dilute phase systems, as these provide high volumetric flow rates at low pressures.

6.2.1.1 Fans

In pneumatic conveying applications, fans used are normally of the radial, flat bladed type. Fans are widely used on short distance, dilute phase systems, where the chance of blocking the line is small. Fans may be used on both positive and negative pressure systems and also on combined 'suck–blow' systems, where, with light or fluffy, non-abrasive materials, it is sometimes possible to convey the material through the fan itself, which is not a possibility with most of the positive displacement machines.

On vacuum duties they are often used for cleaning operations. With waste and stringy materials, such as straw and paper, plastic, film and textile trim, it is even possible to sharpen the blades of the fan so that they will cut or chop the material into pieces as it passes through the fan. Fans, however, are not suitable for higher pressure and heavy duty operation. This is because their operating characteristics are generally not satisfactory for the duty or application.

6.2.1.2 Constant speed characteristics

The main problem with fans is that they suffer from the disadvantage that the air flow rate is very dependent upon the conveying line pressure drop. The constant speed operating characteristic tends to flatten out at high operating pressure. This is a fundamental operating characteristic for pneumatic conveying, and so this class of compressor cannot be used reliably. With a compressor having this type of operating characteristic, it means that if the solids feed rate to the system should become excessive for any reason, causing the pressure drop to increase significantly, the air flow rate may become so low that the material will drop out of suspension, with the risk of blocking the line.

This is particularly a problem in dilute phase suspension flow systems where the conveying air velocity is relatively high. The mean value of conveying air velocity in a dilute phase system is typically about 20 m/s, and so for a 100 m long pipeline, for example, it will only take about 5 s for the air to traverse the entire length of the pipeline. A short surge in feed rate, therefore, can quickly have a significant effect on the pressure required. If the conveying air velocity falls below the minimum value as a consequence, the pipeline can become blocked in a short space of time. Positive displacement machines, for which the volumetric flow rate is largely independent of the discharge pressure, are less likely to cause this type of system failure. This point is illustrated in Figure 6.3.

In order to convey materials reliably in pneumatic conveying systems, a minimum value of conveying air velocity must be maintained. For dilute phase conveying systems this minimum velocity is typically of the order of 15 m/s, and if it drops by more than about 10 or 20 per cent the pipeline is likely to block. A small surge in the feed rate into a pipeline of only 10 per cent would cause a corresponding increase in pressure demand, and with either an axial flow or a radial flow machine, the reduction in the volumetric flow rate of the air would probably result in pipeline blockage.

6.2.1.2.1 Regenerative blowers

The performance curves for regenerative (side-channel) blowers are generally better than those of the aerodynamic compressors shown in Figure 6.3, but they are not as good as those for positive displacement machines. There is a natural tendency to operate a compressor at a pressure close to its maximum rating, but it is generally in this area that the operating characteristics deteriorate.

Since the cost of the air mover will represent a significant proportion of the total system cost, this is an area where potential savings can be made. Particular care should be taken if regenerative blowers are to be considered, therefore, and it is essential that the operating characteristics of the machine are related to the extreme requirements of the system. A beneficial feature claimed for these blowers is that they are less sensitive than most positive displacement machines to erosive wear from dust laden air.

6.2.2 Positive displacement compressors

The constant speed operating characteristic for positive displacement machines, shown on Figure 6.3, provides a basis on which the design of heavy duty conveying systems can be reliably based. A pressure surge in the conveying system will result in only a small decrease in the air flow rate delivered by the compressor, and this can be incorporated into the safety margins for the system. A pressure surge, of course, will additionally cause a reduction in air velocity because of the compressibility effects, and this must also be catered for in such safety margins. With a positive displacement compressor,

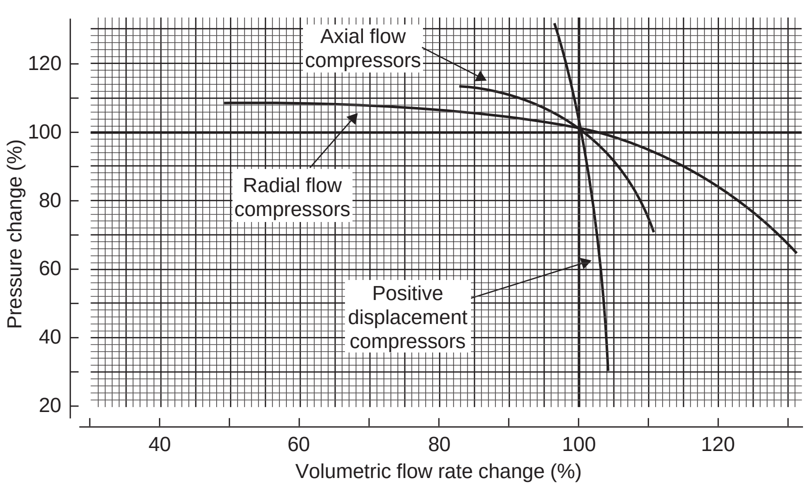


Figure 6.3 Constant speed characteristics of aerodynamic and positive displacement compressors.

however, the percentage reduction in conveying air velocity due to the constant speed characteristic will be no more than that caused by the compressibility effect.

In the classification of compressors presented in Figure 6.1, five different types of positive displacement compressor are included. The constant speed-operating characteristic of each of these is similar to that shown on Figure 6.3. A particular feature of most of these machines is that very fine operating clearances are generally maintained between rotating parts. As a result there is no possibility of the conveyed material passing through the compressor, with the limited exception of the liquid ring machine, as it can with a fan. Indeed, if the material being conveyed is abrasive, even dust must be prevented from entering most machines or they will suffer severe damage.

6.2.2.1 Roots (positive displacement) type blowers

In 1854 Roots invented the original rotary positive displacement blower. They are now widely used on pneumatic conveying applications where the operating pressure does not exceed about 1 bar gauge. Roots type, or positive displacement, blowers are probably the most commonly used type of compressor for dilute phase conveying systems. The principle of the blower is illustrated in Figure 6.4.

The blower provides an ideal match, in terms of pressure capability, with the conventional low pressure rotary valve, and this is a typical working combination on many plants operating in industry. Positive displacement blowers are generally bi-rotational, so that they can be used as vacuum pumps, or exhausters, as well as compressors. They are normally available in sizes handling up to about 500 m^3/min, although some manufacturers quote 1500 m^3/min.

As will be seen from Figure 6.4, twin rotors are mounted on parallel shafts within a casing, and they rotate in opposite directions. As the rotors turn, air is drawn into the spaces between the rotors and the casing wall, and is transported from the inlet to the outlet without compression. As the outlet port is reached, compression takes place when the air in the delivery pressure pipe flows back and meets the trapped air.

Due to this shock compression the thermodynamic efficiency of the machine is a little lower than that of other compressors, and is one of the reasons why these simple compressors are only used for low pressure applications. In order to reduce the pulsation level, and the noise, three lobed rotors, as well as twisted rotors, have been introduced, and they now operate at very much higher speeds.

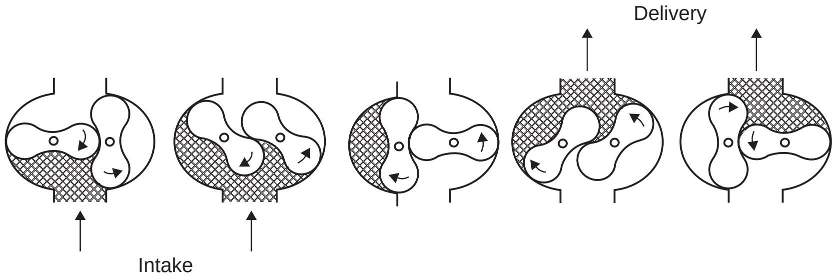


Figure 6.4 Operating principle of positive displacement blower.

The maximum value of compression ratio with these machines is generally 2:1 when operating oil free. This means that for blowing, the maximum delivery pressure is about 1.0 bag gauge, and for exhausting, the maximum vacuum is about 0.5 bar. For combined vacuum and blowing duties these pressures will naturally be much lower, and are typically between 0.7 bar absolute (0.3 bar of vacuum) and 1.4 bar absolute (0.4 bar gauge), as a maximum. Even with a lubricated machine little improvement on this operating range can be achieved for suck–blow conveying systems.

6.2.2.1.1 Compressors

Gears control the relative position of the two impellers to each other, and maintain very small but definite clearances. This allows operation without lubrication being required inside the air casing. The performance of the machine would be enhanced with lubrication, with a delivery pressure capability of about 1.25 bar gauge, but oil free air is a general requirement of these machines. Double shaft seals with ventilated air gaps are generally provided in order to ensure that the compressed air is oil free. Typical blower characteristics are shown in Figure 6.5 for a positive displacement blower operating as a compressor.

A further development with this type of machine is to operate at very much higher speeds than those indicated on Figure 6.5. Operating speeds for new machines are now approximately double those indicated on Figure 6.5, but the slope of the constant speed and power absorbed lines remain exactly the same. With an improvement in materials of manufacture, greater accuracy of machining, and higher speed operation, blowers have been developed into a more compact machine. The thermodynamic efficiency is improved, and as a result the operating temperature is lowered, and there is a corresponding reduction in power requirements.

Manufacturers of positive displacement blowers rarely present the operating characteristics in the form shown in Figure 6.5, but a plot of this kind does illustrate very clearly the constant speed characteristics of the machine. It is also very useful in terms

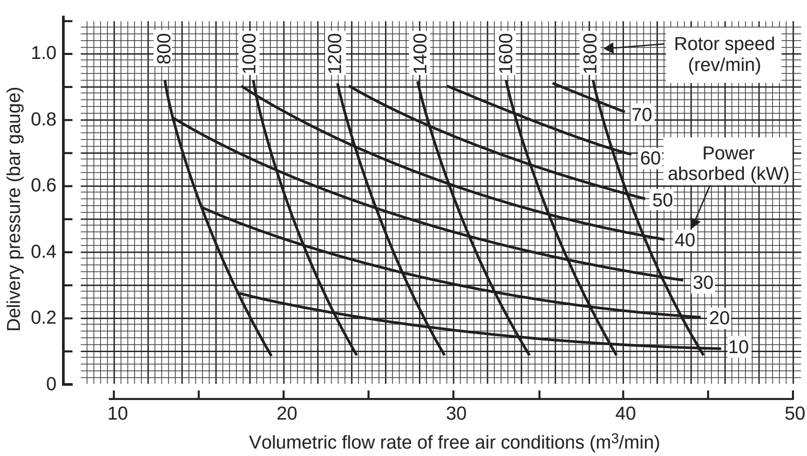


Figure 6.5 Typical characteristics for a positive displacement blower operating as a compressor.

of making changes in performance across the range of rotor speeds and operating duties that the particular model covers. Lines of constant power requirement are particularly useful as these will indicate whether the changes can be achieved with an existing drive.

6.2.2.1.2 *Exhausters*

Performance characteristics for a similar positive displacement blower operating as an exhauster are presented in Figure 6.6.

6.2.2.1.3 *Pressure capability*

The limit on the compression ratio of 2:1 for these machines, when running dry, is essentially dictated by the operating temperature. At pressures higher than 1 bar gauge, and vacuums below 0.5 bar, the discharge air temperatures generated can result in casing and impeller distortion. Oil lubrication can extend this range of operation for, apart from lubricating the machine, it will have a cooling effect, but it does mean that an oil filter and an oil cooler will have to be added.

Water injection will have a very significant effect on the cooling of the air, but this is not always desirable. Water or forced air cooling of the machine can also be employed, as this will allow the higher compression air temperatures to be achieved, while limiting the operating temperature of the machine itself. By these means positive displacement blowers are available that will deliver air at pressures of up to 2 bar gauge and at vacuums down to 0.65 bar with a single stage.

6.2.2.1.4 *Staging*

As with most aerodynamic and positive displacement machines, staging is also possible with positive displacement blowers, although it is probably less common, and is generally

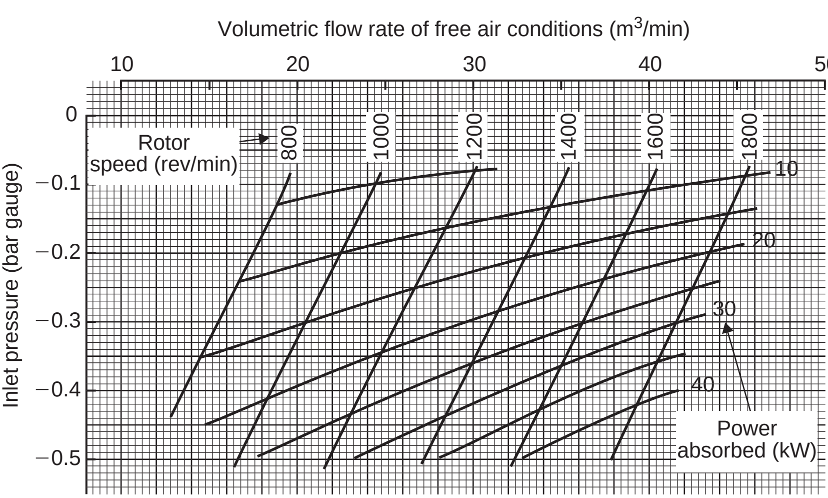


Figure 6.6 Typical characteristics for a positive displacement blower operating as an exhauster.

limited to a maximum of two machines in series. For blowing, the compression ratio is usually limited to about 1.7 for each machine, for oil free operation, and so a delivery pressure close to 2 bar gauge can be achieved by this means. With lubricated machines the compression ratio can be increased to about 1.95, which means that a delivery pressure of 2.8 bar gauge is a possibility.

If blowers are to be operated in series the air at outlet from the first stage must be cooled before the second stage. Although heat exchangers are generally used for this purpose, water sprays can also be used. Evaporation of water can have a very significant cooling effect, because of the very high enthalpy of evaporation, h_{fg}, which is typically over 2400 kJ/kg for water, and so the mass flow rate of water for this purpose would only need to be about 2 per cent of the air flow rate. Consideration, of course, must be given to any subsequent problems with the conveyed material and condensation.

6.2.2.2 Sliding vane rotary compressors

For medium and high pressure systems the sliding vane type of rotary compressor is well suited. These generally produce a smoother flow of air at a higher pressure than the positive displacement blower, and a single stage machine is capable of delivering in excess of 50 m^3/min at a maximum pressure of about 4 bar. Significantly higher operating pressures may be obtained from two stage machines. Oil injection also permits higher working pressures (up to about 10 bar), but this type of machine is generally not available in capacities greater than about 6 m^3/min.

Figure 6.7 illustrates the operating principle of a simple single stage sliding vane compressor. It is a single rotor device, with the rotor eccentric to the casing. Compression, as will be seen from Figure 6.7, occurs within the machine, unlike the positive displacement blower, and so the air is delivered without such marked pulsations. It will be seen that the machine will operate equally well as an exhauster for vacuum conveying duties.

It should be noted that some form of cooling is essential since quite high temperatures can be reached as a result of the combined effect of the vanes rubbing against the casing and the compression of the air between the rotor and the casing. The cooling

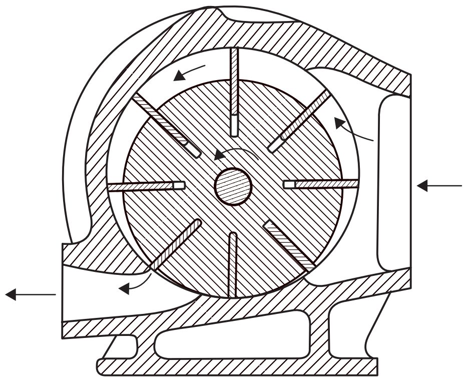


Figure 6.7 Sketch of sliding vane rotary compressor.

may be by water circulated through an external jacket, or by the injection of oil directly into the air stream just after the beginning of compression.

As mentioned previously, the direct injection of oil into the machine does permit higher working pressures, but an efficient oil separation system does add to the cost of the plant.

6.2.2.3 Liquid ring compressors

Most of the air movers described previously, or suitable variations of these, can be used on negative pressure conveying systems. However, the most commonly used are positive displacement blowers, operating as exhausters, which are capable typically of holding a continuous vacuum of about 400 mmHg gauge (360 mmHg absolute). Higher vacuums can be maintained by positive displacement blowers fitted with water injection, but it would be more usual to employ a liquid ring vacuum pump which can reach 600 mmHg gauge (160 mmHg absolute) in a single stage, and over 700 mmHg in two stages.

Liquid ring vacuum pumps having capabilities from about 1 m^3/min up to 70 m^3/min are available. The liquid ring compressor was developed around 1905 from a self-priming rotary water pump, first built in 1817. As a compressor it is used for applications up to about 4 bar. This type of compressor, however, is relatively inefficient and so is mainly used for low pressure applications, more generally as vacuum pumps. A particular advantage of the machine is that it produces oil free air. A typical form of liquid ring compressor is illustrated in Figure 6.8.

As with the sliding vane rotary compressor, this is also a single rotor machine in which the rotor is eccentric to the casing. As the impeller rotates, the service liquid (usually water) is thrown outwards to form a stable ring concentric with the pump casing. As the impeller itself is eccentric to the casing, the spaces between the impeller blades and the liquid ring vary in size so that air entering these spaces from the suction port is trapped and compressed before being discharged through the outlet port. Compression, therefore, occurs within the machine, as with the sliding vane compressor.

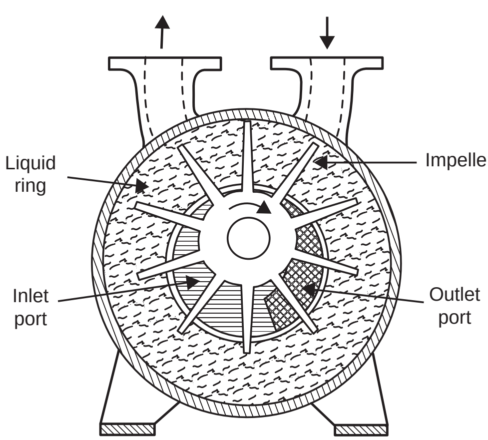


Figure 6.8 Sketch of liquid ring compressor.

The liquid ring also performs the useful functions of cooling the compressed air and washing out small quantities of entrained dust. The tolerance of the machine to dust is a particular advantage in vacuum conveying systems and is, therefore, widely used in this application.

6.2.2.4 Rotary screw compressors

A relatively recent innovation for medium to high pressure operation is the helical lobe rotary, or Lysholm, screw compressor. The rotary screw compressor was patented in 1878, but in a form similar to the Roots blower, that is, without internal compression. The mathematical laws for obtaining compression were developed by the Swedish engineer, A. Lysholm in the 1930s.

In 1958 rotor profiles giving a high efficiency were developed but these require oil injection into the compression chamber to reduce internal air leakage. The oil helps to cool the air during compression but, as with oil injected sliding vane machines, it is generally necessary to remove the oil from the compressed air. With large compressors the injection, separation and filtration equipment can represent a substantial proportion of the plant cost. In 1967 a much improved rotor profile was developed which allowed rolling motion between the rotor flanks with reduced air leakage, without the need for oil injection.

The machine consists essentially of male and female intermeshing rotors mounted on parallel shafts. Inlet and outlet ports are at opposite ends of the compressor. Air entering one of the cavities in the female rotor becomes trapped by a male lobe, and as the rotors turn, this trapped air is compressed and moved towards the discharge end. Continuing rotation of the lobes causes the discharge opening to be uncovered so that the trapped air, now at minimum volume, is released into the discharge line.

Screw compressors are manufactured with capacities ranging from 4 to 700 m^3/min. With oil injection they can develop maximum pressures of about 9 bar. Dry machines can reach 11 bar with two stages, and about 4 bar with a single stage. As these machines are generally free from pressure pulsations it is not usually necessary to operate with an air receiver, and they do not require special foundations for mounting.

6.2.2.5 Reciprocating compressors

The familiar reciprocating compressor, until recent years, was probably the most widely used machine for providing high pressure air for pneumatic conveying systems, but the screw compressor has been a serious competitor where large flow rates are required. Reciprocating compressors are available as single cylinder machines, or with multiple cylinders arranged to give one or more stages of compression. Reciprocating compressors probably have the best thermodynamic efficiency of any air mover.

Where it is essential that there should be no material contamination with oil, reciprocating compressors can be provided with carbon filled polytetrafluoroethylene (ptfe) rings, which eliminate the need for oil in cylinder lubrication, and hence additional separation equipment. A compressor of this type could thus be found to suit almost any pneumatic conveying application in the medium to high pressure range. Even the disadvantage of a pulsating air flow, usually associated with reciprocating machines, can be overcome by selecting one of the modern, small mobile cylinder compressors, such as that in which seven pairs of radially disposed opposing pistons are made to reciprocate by the motion of a centrally placed wobble plate.

6.2.3 Staging

Arranging two or more compressors in series, in order to achieve higher delivery pressures, is possible with most types of compressor, as mentioned earlier with respect to the staging of positive displacement blowers. To improve the efficiency of compression it is usual to cool the air between the stages. Due to the high delivery temperature of air from compressors, which is considered in detail in Section of 6.3.1, this cooling is essential.

The lower volumetric flow rate of the air, as a result of the increase in pressure, and the reduction in temperature, will mean that the size of the next compression stage can be reduced, apart from improving conditions with regard to lubrication as a result of the lower air temperature. Inter-cooling by means of an air blast, or a water-based heat exchanger, are the normal means of cooling the air between stages.

With regard to the staging of positive displacement blowers, considered above, it was mentioned that water sprays could also be used. Some compressors, however, are susceptible to damage by water drops and so it is generally recommended that the air between stages should not be cooled to a temperature below that of the prevailing dew point. This aspect of air requirements is considered in some detail in Chapter 25 on 'Moisture and condensation'. The elimination of water between stages will also minimize the problems caused by the possible rusting of materials in this area.

6.2.4 Specification of air movers

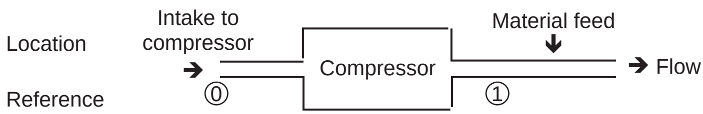
The operating performance of compressors and exhausters, for a particular model, is generally in terms of the volumetric flow rate of the air and the delivery pressure, or vacuum, for a range of rotational speeds, similar to those presented in Figures 6.5 and 6.6. Different models will cover a different range of duties, and there is likely to be an overlap in volumetric flow rate capability between different models.

As air is compressible, with respect to both pressure and temperature, it is necessary to specify reference conditions for air movers, that are internationally recognized. It is essential, therefore, that it should be realized that the volumetric flow rate to be specified for the air mover will not be same as the volumetric flow rate required to convey a material at the start of a pipeline.

It will be necessary to convert the volumetric flow rate required for the system to the volumetric flow rate to be specified for the air mover. The air mass flow rate will be exactly the same for the two, but this is not how air movers are specified. It would provide a useful check, however, if the air mass flow rate was to be evaluated for the two cases. All the models required for this type of analysis are presented in Chapter 9 on Air Flow Rate Evaluation.

6.2.4.1 *Blowers and compressors*

The specification of machines delivering air at positive pressures is in terms of the volumetric flow rate of the air drawn into the machine and the delivery pressure at which the air is required. The pressure and temperature of the air, for which the volumetric flow rate applies, is generally free air conditions. This is usually taken as being a pressure of 101.3 kN/m^2 absolute and a temperature of 288 K (15°C). The situation is summarized in the sketch below:



Parameter:		
Pressure	$p_0 = 101.3\ \mathrm{kN/m^2}$	p_1 – to be specified
Temperature	$T_0 = 288\ \mathrm{K}$	T_1 – will be given
Flow rate	$\dot{V}_0$ = to be specified	$\dot{V}_1$ – to be calculated
Air velocity	Not appropriate	C_1 – to be specified

6.2.4.1.1 *Pressure*

The pressure to be specified for the compressor is p_1. This is approximately the pressure of the air required at the material feed point into the pipeline. This will depend upon the flow rate of material to be conveyed, the conveying distance, pipeline routing and the conveying characteristics of the material. An allowance will need to be made for any losses in air supply lines, pressure drop across the feeder and filtration unit, possible surges in feed rate, and a margin for contingencies and safety.

6.2.4.1.2 *Volumetric flow rate*

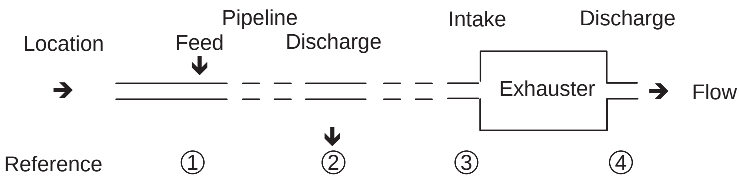
The volumetric flow rate to be specified is $\dot{V}_0$. This is the volumetric flow rate of free air that is drawn into the compressor. The critical design parameter for a pneumatic conveying system is the conveying line air velocity, C_1, at the material feed point into the pipeline. This is the starting point in evaluating $\dot{V}_0$ and so a value of C_1 must be specified. Equation (9.10) from Chapter 9 on air flow rate evaluation can be used to determine $\dot{V}_0$, knowing C_1, the pipeline bore, d, the air pressure, p_1, and the air temperature, T_1. This is reproduced here as Equation (6.1) for reference. The constant, 2.23, takes account of the reference, free air, values of pressure and temperature required at the compressor inlet:

$$\dot{V}_0 = 2.23 \times \frac{p_1 d^2 C_1}{T_1}\ \mathrm{m^3/s} \tag{6.1}$$

6.2.4.2 *Exhausters and vacuum pumps*

The specification of machines operating under vacuum conditions is also in terms of the volumetric flow rate of air at inlet to the machine, and the temperature here is also 288 K.

The vacuum capability of the machine is specified and this generally relates to the air being discharged from the machine to standard atmospheric pressure of 101.3 kN/m^2 absolute. The situation is summarized in the sketch below:



Parameter:

Pressure – atmospheric	p_3 – to be specified
Temperature – atmospheric	$T_3 = 288$ K
Flow rate – to be calculated	$\dot{V}_3$ – to be specified
Air velocity – C_1 to be specified	$p_4 = 101.3$ kN/m^2

6.2.4.2.1 Vacuum

The vacuum to be specified for the exhauster is p_3. This will depend mainly upon the pressure drop across the pipeline, $(p_1 - p_2)$, necessary to convey the material at the required flow rate over the given distance. An allowance will have to be made for any other losses and margins that might need to be included, as for the compressors considered above.

6.2.4.2.2 Volumetric flow rate

The volumetric flow rate to be specified is $\dot{V}_3$. This is the actual volumetric flow rate of air that will be drawn into the exhauster. The critical design parameter for a pneumatic conveying system is the conveying line air velocity, C_1, at the material feed point into the pipeline. This is the starting point in evaluating $\dot{V}_3$ and so a value of C_1 must be specified. Equation (9.10) can be modified slightly to determine $\dot{V}_3$, knowing C_1, the pipeline bore, d, the air pressures, p_1 and p_3, and the air temperature, T_1.

$$\dot{V}_3 = 226 \times \frac{p_1 d^2 C_1}{T_1 p_3} \ \text{m}^3\text{/s} \tag{6.2}$$

The constant is now 226 because p_1 is included in the equation, since the pressure at the feed point may be a little below 101.3 kN/m^2 absolute.

6.2.4.3 Air leakage and ingress

Note that for positive pressure conveying systems an allowance must be made for any air leakage across the material feeding device, or any other loss of air from the system. This will have to be added to the above $\dot{V}_0$ value from Equation (6.1), since this is only the quantity of air required for conveying the material.

In the case of negative pressure conveying systems an allowance must be made for any air leakage into the system that may occur across the material discharge device or any other gain of air into the system. This will have to be added to the above $\dot{V}_3$ value from Equation (6.2), as this is also the quantity of air required for conveying the material only.

6.3 Air compression effects

When compressed air is delivered into a pipeline for use, the air will almost certainly be very hot, and it may contain quantities of water and oil. Air delivery temperature and the problem of oil are considered in some detail at this point, but the specific subjects of moisture and condensation, and air drying, although introduced here, are considered generally and in more detail in Chapter 25. The power required to provide the compressed air, and hence the operating cost, can be very high, and this topic is also considered in some detail at this point.

6.3.1 Delivery temperature

Much of the work energy that goes into compressing air manifests itself in increasing the temperature of the air. For air compression to pressures greater than about 2 bar gauge air cooling is generally employed. The most efficient form of compression is to carry out the process isothermally, and so cylinders of reciprocating machines are often water cooled, and if staging is employed for achieving high pressures, inter-cooling is generally incorporated as well. For most high pressure machines that have some form of air cooling, therefore, the influence of air temperature can be neglected.

In the majority of dilute phase conveying systems, where a large volume of air is required at a relatively low pressure, positive displacement blowers are generally used. For this type of application they are not usually cooled and so the air, after compression, can be at a fairly high temperature. Thermodynamic equations are available that will allow this temperature to be evaluated. Compression can be based on an isentropic model for which the relationship between the absolute pressure and the absolute temperature is given by:

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{(\gamma - 1)/\gamma} \tag{6.3}$$

where γ is the ratio of specific heats, $C_p/C_v = 1.4$ for air and subscripts 1 and 2 refer to inlet and outlet conditions.

This is the ideal case. In practice the air will be delivered at a higher temperature than this due to thermodynamic irreversibilities. The compression process is adiabatic, partly because of the speed of the process, but it is far from being a reversible process. As a result, the temperature of the air leaving a compressor can be very high.

If, for example, air at a temperature of 20°C is compressed to 1 bar gauge in a positive displacement blower, the minimum temperature after compression, for a reversible process, would be about 84°C, and with an isentropic efficiency of 80 per cent it would be 100°C. Irreversibility is taken into account by means of an isentropic efficiency,

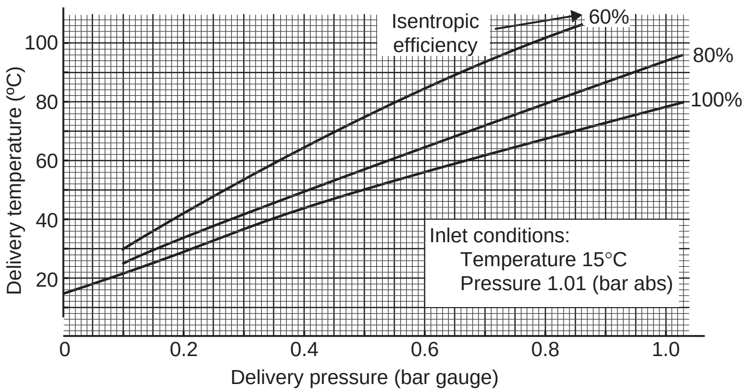


Figure 6.9 The influence of delivery pressure and isentropic efficiency of compression on delivery temperature.

which is defined as the ratio of the theoretical temperature rise to the actual temperature rise, as follows:

$$\eta_i = \frac{T_2 - T_1}{T_2^* - T_1} \tag{6.4}$$

where T_2^* is the actual isentropic delivery temperature.

A graph showing the influence of delivery pressure and isentropic efficiency on delivery temperature is given in Figure 6.9. This covers the range of pressures appropriate to positive displacement blowers.

If air at 20°C is compressed to 3 bar gauge in a screw compressor it will be delivered at a temperature of about 200°C, which is why for air compression to pressures greater than about 2 bar gauge, air cooling is generally employed. Whether the air can be used to convey a material without being cooled will depend to a large extent on the properties of the material to be conveyed.

6.3.2 Oil free air

Oil free air is generally recommended for most pneumatic conveying systems, and not just those where the material must not be contaminated, such as food products, pharmaceuticals and chemicals. Lubricating oil, if used in an air compressor, can be carried over with the air and can be trapped at bends in the pipeline or obstructions. Most lubricating oils eventually break down into more carbonaceous matter which is prone to spontaneous combustion, particularly in an oxygen rich environment, and where frictional heating may be generated by moving particulate matter.

Although conventional coalescing after-filters can be fitted, which are highly efficient at removing aerosol oil drops, oil in the super-heated phase will pass straight through them. Super-heated oil vapour will turn back to liquid further down the pipeline if the air cools. Ultimately precipitation may occur, followed by oil breakdown, and eventually a compressed air fire. The only safe solution, where oil injected compressors are used, is to employ chemical after-filters such as the carbon absorber type that are capable of removing oil in both liquid droplet and super-heated phases. The solution, however, is expensive and requires continuous maintenance and replacement of carbon filter cells.

6.3.3 Water removal

As the pressure of air is increased, its capability for holding moisture in suspension decreases. As the temperature of air increases, however, it is able to absorb much more moisture. If saturated air is compressed isothermally, therefore, the specific humidity will automatically be reduced. If the air is not initially saturated, isothermal compression will reduce the relative humidity of the air and it may well reach the saturation point during the compression process. Where air is compressed isothermally, therefore, quite large quantities of water vapour can be condensed, and in many cases the air leaving the compressor will be saturated. In adiabatic compression the temperature of the air will rise, and because of the marked ability of warmer air to support moisture, it is unlikely that any condensation will take place during the compression process.

6.3.3.1 Air line filters

As compression occurs very rapidly, it is quite possible that when condensation does occur, droplets of water will be carried through pipelines with the compressed air. Also, if additional cooling of saturated air occurs in the outlet line, further condensation will occur. The removal of droplets of water in suspension is a relatively simple process. Normal air line filters work on a similar principle to a spin drier. Air flowing through the filter is made to swirl by passing it through a series of louvers. This causes the water droplets to be thrown outwards and drain to a bowl where it can be drained off. It is important, therefore, that such filters, and compressor and air receiver drains, should be carefully maintained, and be protected from frost.

6.3.4 Air drying

If dry air is required for conveying a material a reduction in specific humidity can be obtained by cooling the air at constant pressure. This may be prior to compression or after. When air is cooled its relative humidity will increase, and when it reaches 100 per cent further cooling will cause condensation. Beyond this point the specific humidity will decrease. If the condensate is drained away and the air is then heated, its specific humidity will remain constant, but the relative humidity will decrease. This process is adopted in most refrigerant types of air dryer. Alternatively a desiccant dehumidifier can be used for the purpose. If the material to be conveyed is hygroscopic, some form of air drying is usually incorporated.

6.3.4.1 Refrigerants

Refrigeration drying is particularly effective when the air is warm and the humidity is high. Under these circumstances a cooling system can remove two to four times as much energy (temperature and moisture) from an air stream as the machine consumes in electrical power to accomplish this removal [1]. The air may be dried under atmospheric conditions, prior to being compressed or otherwise used, or it may be dried at pressure after it has been compressed. In the latter case refrigeration units are used for the dual purpose of both drying and cooling the air.

Refrigerant dryers usually have two stages of heat exchange. In the first the warm inlet air is pre-cooled by the cold, dry, outgoing air. It then passes to a refrigerant heat exchanger where it is cooled to the required dew point. This is usually about 2°C. Drying down to this level of moisture avoids problems of ice formation and freezing in the unit. If any further drying is required, much lower temperatures would have to be achieved, and this would make a refrigerant unit very expensive.

Such units, however, are now available and these have the capability of cooling the air down to −60°C. The process is generally staged, with three units arranged in series and parallel. The first is a conventional, continuously operating unit, which reduces the temperature to 2°C, as above. In series with this are two refrigeration units with the capability of cooling the air down to −60°C. As ice will form on these units they are arranged in parallel, with one operating, to dry the air, while the other is being de-frosted.

6.3.4.2 Desiccants

Desiccant dehumidifiers are particularly well suited to the removal of moisture from air at low temperature and low humidity. The driest possible air is obtained from a desiccant dryer. These are capable of reducing the moisture level to an equivalent dew point temperature of −70°C if necessary. They should not, however, be used for drying warm, humid air unless absolutely necessary, for they are costly to operate. A refrigeration system will generally add 10 per cent to the operating costs, but this may be as high as 30 per cent with a chemical type of dryer.

Typically 15 per cent of the compressed air being dried is lost to the system as it is required for purging the saturated desiccant in regenerative types. An additional problem with this type of system is that dust can be carried over into the conveying line. Water droplets often result in the bursting of the desiccant granules and so it is necessary to provide a filter for these fragments.

There are two main types of desiccant dryer. In one, desiccant tablets are charged, and when these decay they need to be topped up. In the other, a regenerative system is employed. For drying compressed air, two units operating in parallel are generally used. While the process air is passed through one unit for drying, the desiccant in the other unit is being dried by heated reactivation air ready for re-use. For the drying of atmospheric air a slowly rotating (typically at about six revolutions per hour) device is generally used in which the process and recirculation air streams are kept separate by means of seals.

It should be noted that this is entirely a chemical process, and although extremely low values of dew point can be achieved, there is no physical reduction in temperature of the air. The air temperature will rise in proportion to the amount of water removed [1]. For positive pressure conveying systems these are generally used to dry the air after it has been compressed and cooled.

6.3.5 The use of plant air

If plant air is available it may be possible to use this rather than purchase a separate compressor for the conveying system. If plant air is used it will certainly reduce the capital cost of the system, but careful consideration will have to be given to the operating cost of this arrangement. If plant air is available at 6 or 7 bar, and the system only requires air at 1 or 2 bar, the cost of using plant air will be significantly higher than that from an air mover dedicated to the conveying system.

In the long term it may well be more economical to provide the system with its own air mover. If air is required at 2 bar gauge, for example, a given flow rate of air compressed to 7 bar gauge will require approximately 90 per cent more energy than compressing the same flow rate of air to 2 bar gauge.

6.3.6 Power requirements

Delivery pressure and volumetric flow rate are the two main factors that influence the power requirements of a compressor, blower or fan. For an accurate assessment of the power requirements, it will clearly be necessary to consult manufacturer's literature. By this means different machines capable of meeting a given duty can be compared. For a quick, approximate assessment, to allow a comparison to be made of different operating variables, a simple model based on isothermal compression can be used:

$$\text{Power} = 202\dot{V}_0 \ln\left(\frac{p_4}{p_3}\right) \text{kW} \tag{6.5}$$

or

$$P = 165\dot{m}_a \ln\left(\frac{p_4}{p_3}\right) \text{kW} \tag{6.6}$$

where P is the power required (kW), $\dot{V}_0$, the air flow rate at free air conditions (m^3/s), $\dot{m}_a$, air mass flow rate (kg/s), p_3, the compressor inlet pressure (bar abs) and p_4, the compressor delivery pressure (bar abs).

This will give an approximate value of the actual drive power required. If this is multiplied by the unit cost of electricity it will give the cost of operating the system. Since power requirements for pneumatic conveying can be very high, particularly if it is required to convey a material at a high flow rate over a long distance, this basic model will allow an estimation of the operating cost per tonne of material conveyed to be made.

To give some idea of the power required for the compressor, for a pneumatic conveying system, a graph is included in Figure 6.10 which shows how drive power is influenced by delivery pressure and volumetric flow rate.

Air pressures of up to 5 bar gauge are considered in Figure 6.10, and so will relate to high pressure systems, whether for dilute or dense phase conveying. Figure 6.11 is drawn and included specifically for dilute phase conveying systems, with delivery pressures appropriate to positive displacement blowers. A conveying line inlet air

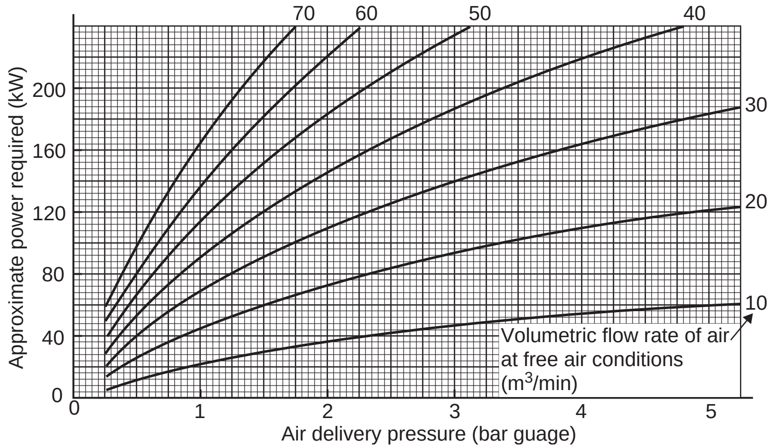


Figure 6.10 The influence of delivery pressure and volumetric flow rate on compressor power required.

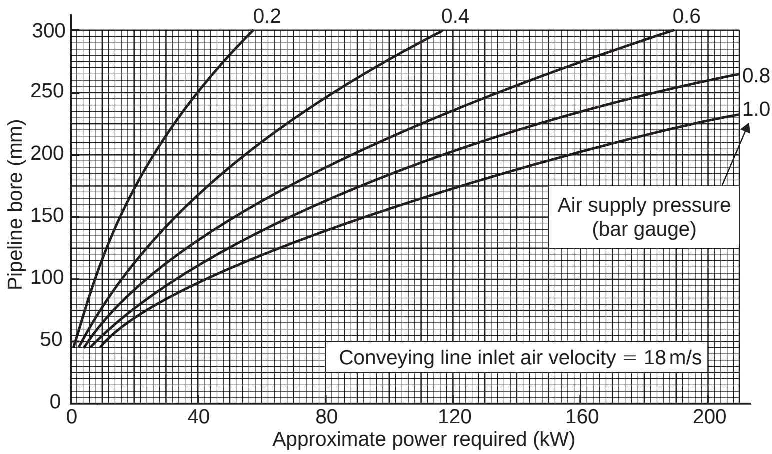


Figure 6.11 Approximate power requirements for low pressure dilute phase conveying.

velocity of 18 m/s has been considered and so the vertical axis has been drawn in terms of pipeline bore.

It must be emphasized that the models presented in Equations (6.5) and (6.6) are only for first approximation purposes.

The power required will vary from one type of compressor to another, and it will vary across the range of operating characteristics for each machine, such as those shown in Figures 6.5 and 6.6. For an accurate value, therefore, manufacturer's literature must be consulted, as mentioned above, both for the type of compressor and the operating conditions.

In comparison with a reciprocating compressor, for example, a screw compressor would require approximately 10 per cent more power to provide the same volumetric flow rate at a given pressure. In the case of positive displacement blowers, the power requirements indicated on operating characteristics provided by manufacturers, such as those shown in Figures 6.5 and 6.6, do not always include transmission losses, etc. Values given are generally of absorbed power for the bare shaft only, and so filtration and transmission losses must be allowed for when selecting a motor.

6.3.6.1 Idling characteristics

All types of compressor are available in a wide range of models in order to cover the range of volumetric flow rates indicated on Figure 6.2. The upper limit on flow rate is clearly dictated by the size of the machine but the lower limit, for any given model, is not so clearly defined. For the blower shown in Figures 6.5 and 6.6 it will be seen that limits are provided in terms of a range of rotor speeds, and the turn down ratio, in terms of volumetric flow rate delivered for the particular model, is about 2:1 on volumetric flow rate.

If a compressor is operated at a value of volumetric flow rate below its recommended lower limit, the efficiency of operation will fall. This will manifest itself by a marked change in the slope of the lines of constant power absorbed for the machine, such as those shown in Figures 6.5 and 6.6, at air flow rates below the lower operating limit. This is illustrated in Figure 6.12. These are operating curves for a screw compressor, which have been extended beyond the operating range for the machine, right down to zero flow rate, and hence idling conditions.

Compressors are often left to idle, when not required to deliver air, so that they do not have to be re-started, and so are instantly available for use when required. It will be seen from Figure 6.12, however, that there is a significant penalty to pay in terms of power required for this operating stand-by duty. Due to the change in slope of the lines

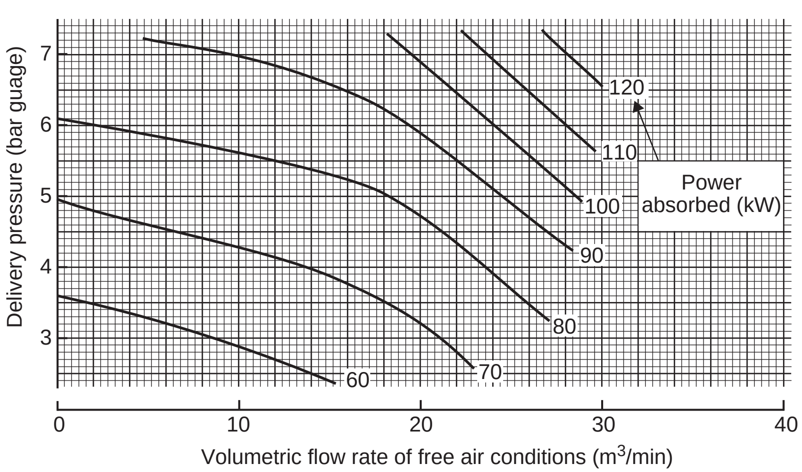


Figure 6.12 Typical idling characteristics for a screw compressor.

of constant power absorbed, below the recommended range of operating, the power absorbed when idling, and delivering no air, is almost 70 per cent of that required for full load operation. Thus when idling, at a given delivery pressure, there is a saving in power of only some 30 per cent.

6.4 Pre-cooling systems

In recent years, with increasing emphasis on power consumption, more consideration is being given to ways of reducing power. A European Union study has shown that 15 per cent of the world-wide energy consumption is used to produce compressed air. One proposal, with regard to reducing the power requirement for compressed air, is that the air should be cooled to −60°C before being compressed.

It was mentioned earlier, in relation to refrigeration drying of air, that units were available that were capable of cooling air to a temperature of −60°C. Such units form the basis of commercially available pre-cooling systems for compressors.

The idea is that all of the air to be compressed should be physically cooled to −60°C first. By this means the air will be extremely dry, so that there will be no need for a further dryer on the pressure side, and there will be no possibility of condensation occurring anywhere in the subsequent system. This will also eliminate the presence of water–oil emulsions that can occur in lubricated compressors.

For air at standard atmospheric pressure the density is 1.225 kg/m^3 at a temperature of 15°C but at −60°C it is 1.657 kg/m^3, which represents a 35 per cent increase. In terms of the volumetric flow rate it means that this is reduced to 74 per cent of the free air flow rate that would have to be compressed, and so a much smaller compressor can be used. Manufacturers of this type of system claim that up to a 30 per cent reduction in power consumption of compressors can be made by this means, and that plant maintenance is significantly reduced.

If atmospheric air at a temperature of 15°C is compressed to 2 bar gauge, the delivery temperature, assuming adiabatic compression and an isentropic efficiency of 70 per cent, will be about 165°C. For air at −60°C, similarly compressed, the delivery temperature will be about 50°C. In the first case the air would, for most applications, have to be cooled, and if it was not dried, condensation could well occur. With the pre-cooling system the air would probably not need to be cooled after being compressed, and being dry, there would be no possibility of condensation occurring.

6.5 Nomenclature

C	Conveying air velocity	m/s
C_p	Specific heat at constant pressure	kJ/kg·K
C_v	Specific heat at constant volume	kJ/kg·K
d	Pipe bore	m
h_{fg}	Enthalpy of evaporation	kJ/kg
$\dot{m}$	Mass flow rate	kg/s
p	Air pressure	kN/m^2 (bar)
	Note: 1 bar = 100 kN/m^2	

P	Power required	kW
t	Actual temperature	°C
T	Absolute temperature = t°C + 273	K
$\dot{V}$	Volumetric flow rate	$m^3 s$

6.5.1 Greek

γ	Ratio of specific heats = C_p/C_v	–
η	Efficiency	%

6.5.2 Subscripts

a	Conveying air
i	Isentropic value
0	Free air or reference conditions: $p_0 = 101.3\,kN/m^2$, $T_0 = 288\,K$
1	Pipeline inlet conditions
2	Pipeline outlet conditions
3	Compressor/exhauster inlet conditions
4	Compressor/exhauster outlet conditions

6.5.3 Superscripts

*	Actual isentropic value	–
·	Per unit time or rate	1/s

References

1. K Speltz. Dehumidification in manufacturing – methods and applications. Proc 23rd Powder and Bulk Solids Conf. pp 83–93. Chicago. May 1998.

Chapter 7

Gas–solid separation devices

7.1 Introduction

Gas–solid separation devices associated with pneumatic conveying systems have two functions. The first is to recover as much as possible of the conveyed material for the next stage of the handling or treatment process. The second is to minimize pollution of the working environment by the material. A number of devices are available that meet these requirements. Particle size is the main parameter to be considered here in terms of system selection and air flow rate in terms of system sizing.

7.1.1 Separation requirements

The first of these functions is principally a matter of economics, in that the more valuable the material, the more trouble should be taken to ensure total recovery. However, the avoidance of environmental pollution is potentially more important, particularly since the introduction of more stringent Health and Safety at Work Legislation. Where the material is known to be potentially dangerous, of course, extreme measures must be taken to prevent its escape into the atmosphere from the handling plant. This is particularly the case with toxic and explosive materials.

The choice of gas–solid disengaging system to be used on any given application will be influenced by a number of factors, notably the amount of bulk particulate material involved, the particle size range of the material, the collecting efficiency required, and the capital and running costs. In general, the finer the particles that have to be collected, the higher will be the cost of a suitable separation system.

7.1.2 Separation mechanisms

Where a bulk material consists of relatively large and heavy particles, with no fine dust, it may be sufficient to collect the material in a simple bin, the solid material falling under gravity to the bottom of the bin, while the gas is taken off through a suitable vent. However, with a bulk solid of slightly smaller particle size it may be advisable to enhance the gravitational effect, and the most common method of achieving this is to impart spin to the gas–solid stream so that the solid particles are thrown outwards while the gas is drawn off from the centre of the vortex. This is basically the principle on which the cyclone separator operates.

Where fine particles are involved, especially if they are also of low density, separation in a cyclone may not be fully effective, and in this case the gas–solid stream may be vented through a fabric filter. Many different types of fabric filter are in use and selection depends mainly upon the nature of the solid particles being collected and the proportion of solids in the gas stream.

For materials containing extremely fine particles or dust, further refinement in the filtration technique may be necessary, using wet washers or scrubbers, or electrostatic precipitators, for example. While this last group of gas–solid separation devices are used in industry, they are generally used in association with a process plant, and are very rarely used in conjunction with a pneumatic conveying system, and so no further reference will be made to any of these devices.

7.1.3 Pressure drop considerations

The separation device should not present a high pressure drop to the system if maximum material flow rate is to be achieved for a given overall pressure drop. This is particularly the case in low pressure fan systems, where the pressure drop across the separation unit could be a significant percentage of the total pressure drop available. Regular maintenance of separation equipment is important. The pressure drop across fabric filters will increase rapidly if they are not cleaned regularly, or if the fabric is not replaced when cleaning is no longer effective. If cyclones are used for separation, wear will reduce the separation efficiency.

7.2 Dust control

In addition to the economic reasons for efficiently removing solid material from a conveying gas stream, there are important considerations of product quality control, and health and safety. In this respect it is generally very fine particles or dust that pose the problem.

7.2.1 Particle degradation

In some manufacturing processes, a bulk solid is actually required in the form of ultrafine particles. In many cases, however, the presence of dust in the product is undesirable for practical and commercial reasons. Much of the dust results from particle degradation in the conveying process and, for a given material, this is a function of the conveying conditions, in terms of material concentration and conveying air velocity, and the pipeline geometry.

Plant operating difficulties can result if degradation causes a large percentage of fines to be produced, particularly if the filtration equipment provided is not capable of handling the fines satisfactorily. Filter cloths and screens will rapidly block if they have to cope with unexpectedly high flow rates of fine material. The net result is that there is usually an increase in pressure drop across the filter.

This means that the pressure drop available for conveying the material will be reduced, which in turn means that the mass flow rate of the material will probably have to drop to compensate. Alternatively, if the filtration plant is correctly specified, with particle degradation taken into account, it is likely to cost more as a result. This, therefore,

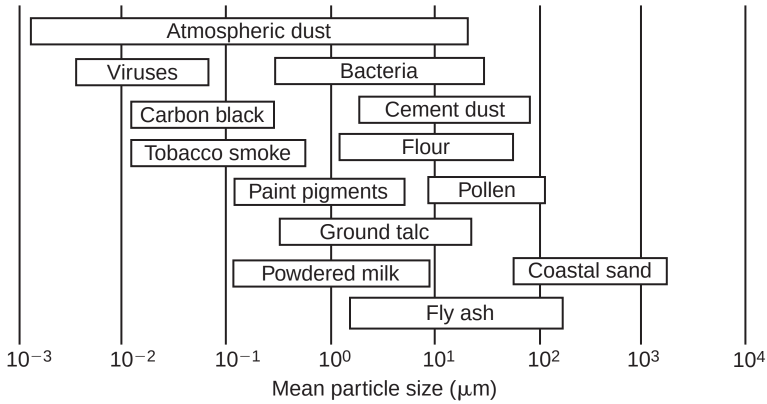


Figure 7.1 Approximate size range of some familiar types of airborne particulate material.

provides a direct financial incentive to ensure that particle degradation is minimized, even if it is not a problem with respect to the material itself.

7.2.2 Dust emission

Excepting the potentially explosive and known toxic materials, the most undesirable dusts are those that are so fine that they present a health hazard by remaining suspended in the air for long periods of time. Figure 7.1 illustrates comparative size ranges of some familiar airborne particles. Airborne dusts which may be encountered in industrial situations are generally less than about 10 μm in size.

Particles of this size can be taken into the body by ingestion, skin absorption or inhalation. The former is rarely a serious problem and, although diseases of the skin are not an infrequent occurrence, it is inhalation that presents the greatest hazard for workers in a dusty environment.

Particles falling in the size range of approximately 0.5–5 μm, if inhaled, can reach the lower regions of the lungs where they will be retained, and prolonged exposure to such dusts can cause permanent damage to the lung tissues (pneumoconiosis) symptomized by shortness of breath and increased susceptibility to respiratory infection. Prevention of the emission of these fine particles into the atmosphere is thus of paramount importance, whether they have been proven to be problematical or not.

7.3 Separation devices

An assessment of the magnitude of a potential dust problem can be made by examining the bulk material to be handled, paying special attention to the fines content of the material. When making a decision about the type of gas–solid separation device to be used in a pneumatic conveying plant for a particular material, it is clearly more important to know the particle size distribution of the bulk material after conveying than at the feed point. Tests are available to determine the 'dustability' of a material; that is, the propensity of particles from within the bulk to become airborne when subjected to external forces.

7.3.1 Gravity settling chambers

The simplest type of equipment for separating solid material from a gas stream is the gravity settling chamber in which the velocity of the gas–solid stream is reduced, and the residence time increased, so that the particles fall out of suspension under the influence of gravity. Such a device is shown in Figure 7.2.

7.3.1.1 Collecting efficiency

The rate at which solid particles settle in air, and hence the efficiency of the process of separation, is primarily dependent upon the mass of the particles. This effectively means a combination of their size and density. In general, settling chambers on their own would only be used for disengaging bulk solids of relatively large particle size. Typically this would mean particles greater than about 150 μm, but this obviously depends also upon the shape and density of the particles; hence the value of tests and experience gained. For particles larger than about 300 μm, a collecting efficiency in excess of 95 per cent should be possible.

To improve the collecting efficiency of the basic gravity settling chamber when working with materials of low density, or of a fibrous nature, a mesh separating screen could be fitted at an angle across the gas flow, as shown in Figure 7.2b. The screen should be provided with a rapping mechanism to shake collected particles free on a regular basis. Although the gravity settling chamber is basically a very simple device, care should be taken to ensure that its design allows, as far as possible, a uniform distribution of the gas as it enters and leaves.

Within the settling chamber the gas velocity should generally be less than about 3 m/s if excessive re-entrainment of collected particles is to be avoided. Where a material consists essentially of coarse particles, but also has some dust content, it may be satisfactory to use a settling chamber with the gas vented through a suitable fabric filter.

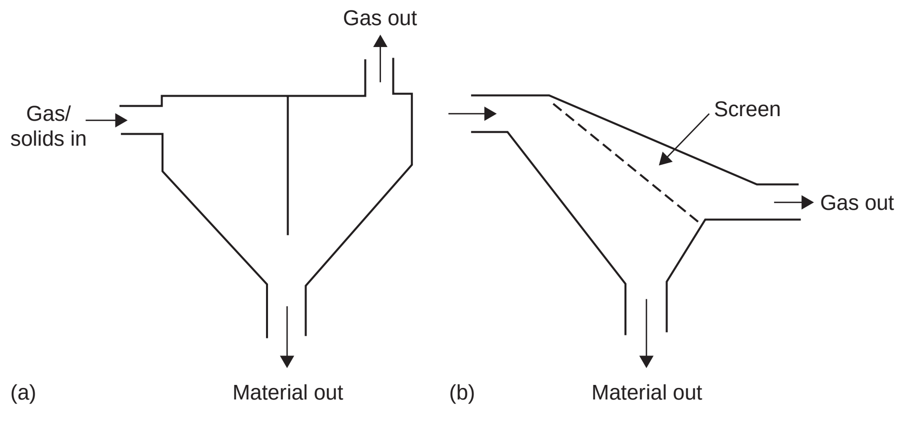


Figure 7.2 Gravity settling chambers: (a) basic system and (b) design incorporating screen.

This technique is commonly used for disengaging coarse material after conveying pneumatically in either a positive or a negative pressure system. In this arrangement of filter–receiver it is important that the filter is correctly sized to prevent over loading, and that an adequate cleaning routine is followed.

7.3.2 Cyclone separators

In pneumatic conveying plants handling medium to fine particulate material, the gas–solid separator is often a cyclone-receiver. This may be combined with a fabric filter unit if the bulk material is dusty. Like the simple gravity separating chamber, the cyclone separator is dependent upon the mass of the particles for its operation. The forces that disengage the solid particles from the conveying gas, however, are developed by imparting a spinning motion to the incoming stream so that the particles migrate outwards and downwards under the influence of centrifugal and gravitational effects.

7.3.2.1 Reverse flow type

The commonest form of cyclone is the so-called 'reverse flow' type, illustrated in Figure 7.3, in which the rotation of the gas is effected by introducing it tangentially to the cylindrical upper part of the device, thereby creating a spiral flow downwards. This spiral

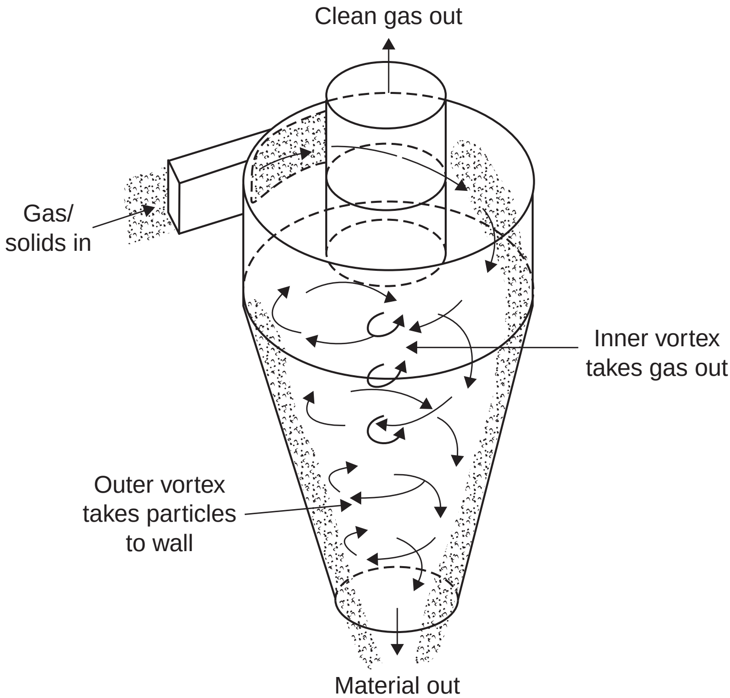


Figure 7.3 Principle of the cyclone separator.

continues down the outside of the unit until it reaches a point, near to the base of the cone, where it reverses its direction of flow. The solid particles are then collected from the outlet at the base of the conical lower part while the cleaned gas flows in the opposite direction through the top outlet.

Alternative designs of cyclone separator that have been proposed include the 'straight-through' type, in which the rotation of the gas–solids stream is imparted by fixed vanes mounted in a circular duct. The cleaned gas leaves through a concentric inner duct while the solid particles are extracted through an annular space between the inner and outer ducts.

7.3.2.2 Collecting efficiency

The size of particles that can be separated in a cyclone, and the collecting efficiency, depend principally upon the difference in density of the solid particles and the conveying gas, the solids concentration, the inlet gas velocity and the dimensions (notably the diameter) of the cyclone itself. Increasing the entry velocity or decreasing the cylinder diameter should normally result in an increase in the collecting efficiency of finer particles, but the practical lower limit on particle size is likely to be around 10 μm.

It should be noted that decreasing the cylinder diameter will reduce the gas–solids throughput, and consequently more cyclones will be needed for a given application, and at greater cost. Also, operating at a higher inlet gas velocity (up to a maximum of about 30 m/s) may cause difficulties when the conveyed particles are abrasive or friable. In contrast, operation at higher solids concentrations may be advantageous, as finer particles tend to be trapped and swept out by larger particles, resulting in an improved collecting efficiency.

7.3.2.3 Typical dimensions

The dimensions of a cyclone designed for optimum performance will therefore depend on its actual application, that is, on the nature of the solid material to be separated and the separation efficiency required. Typically the proportions would be as shown in Figure 7.4. It is general practice to avoid extremely large diameter cyclones and provide extra capacity by means of smaller units connected in parallel. Most commercial units, therefore, are typically less than 3 m in diameter.

For high collecting efficiency the shape of the cyclone would be modified by decreasing the cross-sectional area of the gas–solid inlet and the gas outlet, and reducing the depth to which the gas outlet duct extends into the cyclone cylinder. Also, for high efficiency, a cyclone of smaller diameter would be selected. Thus, while it would be usual to select a single cyclone of suitable capacity for a given application, multiple parallel units would give better collecting efficiency for fine particles. Two of more units in series might be preferable, where the material to be collected has a wide particle size range.

Many attempts have been made to develop theoretical expressions for the prediction of collecting efficiency, based on the dimensions of the cyclone and on the properties of the gas and solid material to be separated. None has really proved to be satisfactory and reliance must be placed on experimental data for cyclone performance.

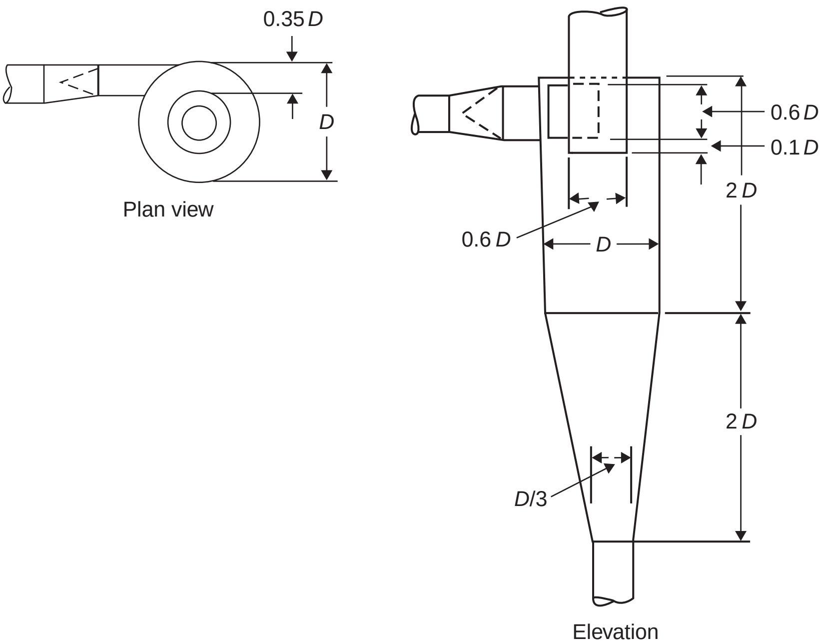


Figure 7.4 Typical proportions of a cyclone separator.

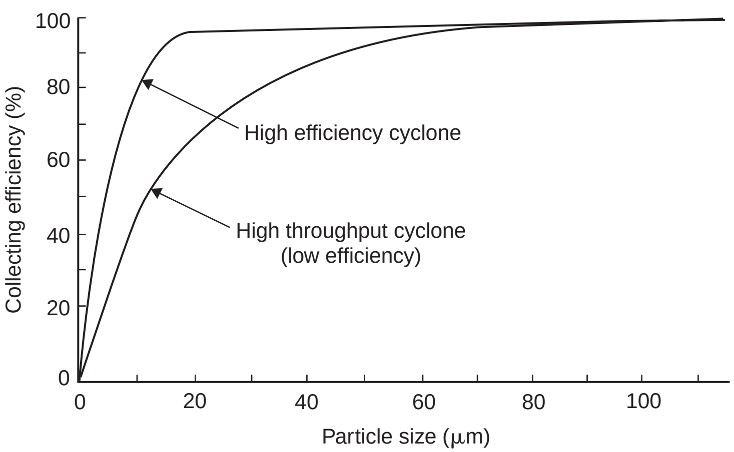


Figure 7.5 Performance curves for typical cyclone separators.

The data is normally presented in the form of a plot of collecting efficiency against particle size for cyclones tested with some 'standard' material. Such a plot for two possible design extremes is presented in Figure 7.5 [1]. One plot is for a high efficiency cyclone, and the other is for a low efficiency cyclone having a high throughput capability. Possibly two or more of the high efficiency cyclones would be needed to meet the flow rate capability of the low efficiency cyclone.

7.3.3 Filters

The fabric filter is now the 'industry standard' for gas–solid separation duties in pneumatic conveying systems. This is particularly the case where there is an element of dust in the conveyed material. Considerable development has taken place over recent years, with particular improvements in fabrics. In order to appreciate the principles on which filter units are designed or selected it is helpful to understand the manner in which they operate.

7.3.3.1 Filtration mechanisms

There are two fundamental mechanisms by which particles can be removed from a stream of gas passing through a porous fabric. The most obvious of these is a 'sieving' mechanism in which particles too large to pass through the mesh of the fabric are caught and retained on the surface of the filter. The caught particles gradually build up a cake on the fabric surface so that the labyrinthine nature of the gas flow path continually increases while the effective mesh size decreases. The collecting efficiency of the filter will therefore tend to be improved by use, but the pressure drop across the filter will increase, of course, and so regular cleaning is essential to maintain the pressure drop at an operational level.

The less obvious, but for very fine particles, more important, mechanism of filtration is that in which the particles are caught by impingement on the fibres within the filter fabric. This is often referred to as 'depth filtration' to distinguish it from 'sieving'. It is for this reason that filters usually consist of a fibrous mat, called needlefelt, rather than a single woven fabric screen. The actual flow paths followed by the gas passing through a depth filter are thus extremely tortuous, and a particle unable to follow these paths is given a trajectory which sooner or later brings it into contact with a fibre where it adheres, largely as a result of Van der Waal's forces.

7.3.3.2 Collecting efficiency

The collecting efficiency of a fabric filter is mainly influenced by the gas velocity through the fabric, and the size of particle to be collected. Where the particles are relatively large, which means greater than about 5 μm, they are likely, because of their greater inertia, to come frequently into contact with the filter fibres. The tendency to 'bounce' off the fibres and escape from the filter, however, is also greater, especially where the gas velocity is high. Where the solids loading is low, the performance of the filter may be improved by wetting the fabric to enhance the adhesive properties of the fibres. The method of cleaning the filter bags and their length also have an influence on collecting efficiency, as will be considered later.

7.3.3.3 Filter media

A wide range of materials is available for the manufacture of filter fabrics. Wool or cotton, the latter particularly having the advantage of low cost, may be used. For better resistance to abrasive wear or chemical attack, and a higher maximum operating temperature, however, either glass fibre or one of a number of alternative man-made fibres should be selected, such as Polyethylene, Polypropylene, Nylon (polyamide), Orlon (acrylic), Dacron (polyester), Teflon (PTFE), etc.

Apart from the properties of the fibres themselves, specifications for filter fabrics should include the 'weight per unit area', which gives an indication of the thickness, and therefore the strength and durability of the fabric, and an indication of its permeability.

The permeability of the material depends upon the construction of the fabric, which is a function of whether it is woven or felted, its thickness, tightness of weave, and so on. This information allows an estimate of the pressure drop across a filter to be made. Various surface treatments may also be carried out on filter fabrics by the manufacturer, the principal aim being to reduce the adhesion of caked solids to the fabrics, and thus render the cleaning process easier and more effective. Filter surfaces may also be treated to increase their resistance to combustion.

7.3.3.4 Selection criteria

The selection of a fabric filter for a given application should be made after consideration of a number of criteria. The first of these should be the particle size range, the nature of the solid material to be collected and the temperature of the conveying gas, which will dictate the types of fabric that would be acceptable. The size of unit required will depend principally upon the maximum gas flow rate to be handled, and the maximum allowable pressure drop.

The size will also be influenced by the proportion of solid material carried by the gas, the method of cleaning to be used, and the planned frequency of replacement of the filter fabric. Several of these criteria are clearly affected by cost factors, and so a careful balance must be struck between the capital cost of the equipment, normal running costs and the cost of routine maintenance.

7.3.3.5 Bag filters

In pneumatic conveying systems handling fine or dusty material, the method of filtration that has become almost universally adopted is a bag type fabric filter, either used on its own or as a 'back-up' to one of more cyclone separators. They may have application as bin vents in situations where all the solid material to be collected is blown into a hopper, and the clean air is vented off at the top through the filter unit, while the collected material is discharged from the base of the hopper through a suitable airlock.

The actual configuration of the filter bags within the unit, and the method of cleaning vary from one manufacturer to another. The bags are usually of uniform cross section along their length and the most common shapes are circular to or rectangular. Rectangular bags probably provide a filter unit with the largest fabric surface area to filter volume.

The cleaning process is of particular importance since it has a considerable influence on the size of filter required for a given application. Figure 7.6 illustrates diagrammatically a typical form of bag filter unit. Although the filter bags shown in Figure 7.6 are suitable for continuously operating systems, the method of cleaning is only suitable for batch conveying operations, for filter surfaces cannot be cleaned effectively by shaking unless the flow of air ceases.

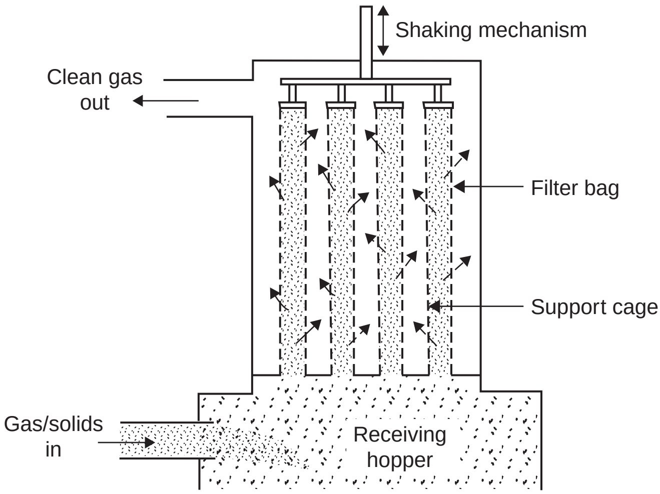


Figure 7.6 Typical shaken bag filter unit.

The gas–solid stream enters the device from beneath the fabric bags so that larger particles are separated by gravity settling, often aided by a cyclone action, although this is not necessary, provided that direct impingement of particles on the bags from the conveying line is prevented. Fine particles are then caught on the insides of the fabric bags as the gas flows upwards through the unit.

These filters are available in a very wide range of sizes, lengths, shapes and configurations. The shaking mechanism represented in Figure 7.6 is one of several methods of bag cleaning that may be employed.

7.3.3.6 Filter size

The basic measure of filter size is the effective surface area of fabric through which the gas has to pass. It is usual, in the case of pneumatic conveying systems, to specify the size of filter required on the basis of an assumed value of the so-called 'air to fabric ratio', which is defined as the ratio of the volumetric air flow rate divided by the effective area of the filter fabric. It should be noted that this parameter is not, in fact, a ratio but has the dimensions of velocity. It is perhaps best regarded as a superficial velocity of the air through the filter fabric.

The actual value of the air to fabric ratio to be used depends upon several factors, as indicated previously and, although there have been attempts to develop theoretical expressions for the prediction of this parameter in various situations, none is really satisfactory, and reliance must be placed on experience. The manufacturers of filter units should normally be able to advise on suitable air to fabric ratios for the bulk particulate material being handled.

Typical values for felted fabrics are in the region of about 0.025 m/s for fine particulate materials and up to about 0.050 m/s when handling coarser or granular materials.

For woven fabrics, however, these figures should be halved, since the free area actually available for gas flow is much less.

7.3.3.7 Filter cleaning

The design of present-day fabric filter units, with their multiple bags or envelopes and their complex cleaning mechanisms, has gradually evolved with increasing awareness of the need to conserve energy and to avoid atmospheric pollution. The use of multiple bags was simply a means of getting a larger area of fabric into a small space, but a more important aspect of filter design, concerned the method of minimizing the proportion of fabric area out of action at any one time for cleaning.

This consideration led to the introduction of filter units having two or more separate compartments, each containing a number of bags. By this means one compartment could be shut off for cleaning while the others remained in service, handling the full gas–solid flow. Modern filter units using pulsed air jets for fabric cleaning do not require the unit to be compartmentalized, but are still designed to ensure that only a small number of bags are out of service at the same time.

There are two basic types of cleaning action that can be employed. These are mechanical shaking and air pulsing. The former system, illustrated in Figure 7.6, tends to be cheaper, but its application is restricted to batch operations. The cleaning will not function properly when on load, and so the filter can only be shaken effectively at the end of a conveying cycle in the absence of air and material flow. It is also restricted to installations handling materials which readily form a caked layer on the surface of the filter fabric. Shaking the framework on which the bags are mounted causes a flexing or rippling movement of the fabric which results in the material being dislodged and falling into the collecting hopper.

7.3.3.8 Reverse air jet cleaning

An alternative method of causing the filter fabric to flex and so dislodge caked material is to arrange for a periodic reversal of the direction of gas flow through the fabric. This may be achieved either by diverting the total flow of cleaned gas back through one section of the filter, or by a system of high pressure jets, operating in sequence, which inject cleaned air downwards through the bag walls in the reverse direction to the normal air flow. Such a device is shown in Figure 7.7 and this is very much the industry standard at the present time.

The pulsed reverse air jets last for only a very short period of time, typically less than a second, and so continuous operation of the filter is possible, and maximum utilization of the fabric area can be achieved. The air is generally pulsed through a venturi positioned at the inlet to the bag, and the bags are usually supported by a wire cage. The high pressure air pulsed through the venturi creates a shock wave and it is this, in combination with the reverse flow of air, that results in the cleaning of the filter bag.

There is clearly a limit to the length of filter bag that can be effectively cleaned by this means, and a reduction in cleaning efficiency must be expected if very long bags are used. Neither the pulse of air in the reverse direction, nor the shock wave will be

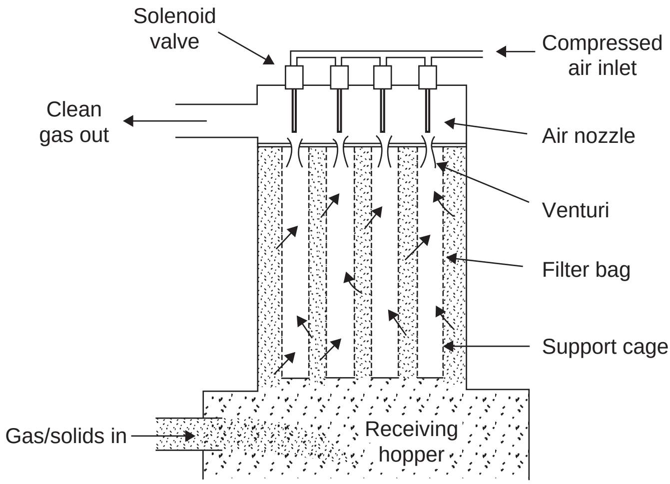


Figure 7.7 Bag filter unit with high pressure pulsed air jets.

effective at the base of long bags. This is more so with filters in the form of closely packed envelopes than it is with cylindrical bags.

7.3.3.9 Maintenance

From a maintenance point of view it is desirable to size a filter to have as low a value of face velocity as is economically possible. The particles are then not forced into the fabric, eventually to be permanently trapped in the fabric pores, but to stay near the outer surface for easy removal by the cleaning action. The permanent trapping of particles builds up the residual pressure drop of the fabric and once the pressure drop continually increases, despite more intensive cleaning, the fabric is said to be blinded.

Other particles are not necessarily trapped by the fabric but are driven by the high velocity right through the matrix of fibres to emerge on the clean side, having penetrated the fabric. Increased penetration and hence emission is one of the penalties for the excess velocity that results. It is at this stage that the filter bags should be replaced.

7.4 System considerations

Being at the end of the conveying process, its importance is often overlooked, but incorrect design and specification can cause endless problems in the conveying system. It is also important that the separation system is not considered in isolation. The influence that the system can have on the filter, and the influence that the filter can have on the system need to be considered in addition.

7.4.1 Blow tank systems

Although with batch systems both reverse air jet filters and mechanically shaken filters can be employed, care must be taken in sizing these units with respect to the volumetric flow rate of air. If, at the end of a conveying cycle the pipeline and blow tank have to be vented through the filter unit, the air flow rate will be considerably greater than the steady air flow rating of the air mover. This is particularly the case if the blow tank operates at a high pressure, for the transient nature of the air flow through the conveying cycle is significantly magnified.

This will result in a considerable increase in the air velocity through the filter, possibly resulting in blinded filters, giving higher filter resistance and subsequent difficulty with cleaning. This is particularly so in the case of mechanically shaken filters. It is essential in these circumstances to reduce the air supply at the end of the conveying cycle in order to keep the total air flow rate to as low a value as possible. To cater for these surges simply by increasing the filter size may be a more expensive solution.

7.4.2 Vacuum conveying systems

In vacuum conveying systems the clean air at outlet from the filter is drawn through an exhauster. Should a filter bag split, or otherwise fail, material will be carried over to the exhauster. Although a turbo blower can tolerate a certain amount of dusty air, provided that it is not abrasive, positive displacement blowers cannot, and so some form of protection must be provided. A cyclone is often used for this purpose, and although its efficiency with respect to fine particles is rather low, it will allow time for the system to be shut down before serious damage occurs to the blower.

The design parameter for sizing fabric filters is related to the superficial air velocity across the filter fabric. In a positive pressure conveying system the air flow rate that can be used in this evaluation is simply the volumetric rating of the air mover, unless the material conveyed is at a high temperature. In a negative pressure system the filter is under vacuum and this will have to be taken into account.

In comparison with a positive pressure system, employing the same 'free air' flow rate, a vacuum system operating under 0.5 bar of vacuum, for example, will need to have a filter approximately twice the size of one required for a positive pressure system. This is not a fair comparison, of course, since the pipeline bore for the vacuum system will be larger, but it does highlight the need to take account of both pressure and temperature in sizing. The modelling for this is considered in Chapter 9.

References

1. C R Woodcock and J S Mason. Bulk Solids Handling: An Introduction to the Practice and Technology. Glasgow: Blackie & Son Ltd. 1987.

Chapter 8

System selection considerations

8.1 Introduction

The selection of a pneumatic conveying system for a particular application involves the consideration of numerous parameters associated with the conveyed material, the conveying conditions and the system itself. The basic specification is usually that a material should be conveyed at a specified flow rate over a given distance. Unfortunately the conveying potential of a pneumatic conveying system is not easily defined or evaluated.

The influence that conveying distance has on material flow, for example, is particularly complex. For any given situation, however, a wide combination of pipeline bores and conveying line pressure drop values are usually available that will adequately meet the requirements. There is rarely a problem of not being able to achieve a given duty, therefore, but getting it right first time is a common problem.

Power consumption, and hence system operating costs are an obvious factor in the decision-making process. This, however, is not straightforward either, for problems of material and system compatibility also have to be taken into account. The inter-relating effects of all of these parameters are considered, both to provide information on the potential capability of pneumatic conveying systems, and as an introduction to the next section of the book, Part B, on System Design.

8.1.1 System economics

Generally the most economic system is required that will convey a material satisfactorily, with as few operational problems as possible. System economics are based on a combination of plant capital cost and operating costs. The operating costs take into account costs of power for operation, maintenance and staffing. Maintenance and staffing costs are partly dictated by the capital cost for the plant. Choice of components, such as feeders, filters and pipeline, and automatic controls and instrumentation will dictate to a certain extent the potential level of plant maintenance and manpower that will be required.

Capital costs of plant are generally provided as part of a tender, and so comparison can be made between competing pneumatic conveying systems, and possibly with alternative mechanical conveying systems, for a given duty. Operating costs, in terms of power requirements, however, are relatively easy to evaluate. These costs can often play a dominant role, particularly with pneumatic conveying systems, and so as it is such an important parameter, power requirements are also considered.

8.1.2 Material considerations

With so many different systems, requirements and possible variables to take into account it will only be possible to consider a relatively narrow range in this review. In order to illustrate the potential influence of as many of the main parameters as possible, several series of graphs are included. They are all concerned with continuously operating conventional systems, but they will provide a basis for comparison with other systems. The main emphasis is on conveyed material influences in both dilute and dense phase flow. For dense phase flow only sliding bed flow is considered in detail but reference to plug flow is made for comparison. In dilute phase flow the upper and lower extremes of conveying capability are considered which will cover almost any material.

8.2 Variables involved

When selecting a pneumatic conveying system for a particular application it is generally the conveying potential of the system that is of primary importance. The number of factors that have a potential influence on material flow rate, however, is quite considerable. They can be grouped into three broad categories: those associated with the conveyed material, the conveying conditions and the pipeline geometry.

8.2.1 The conveyed material

Properties of the conveyed material that can influence the conveying capability and potential flow rate that can be achieved include mean particle size, particle size distribution, particle shape, particle and bulk densities, air retention and permeability. The influence of material properties are dealt with in Chapter 12, with test methods for the determination of material properties relevant to pneumatic conveying being detailed in Appendix 1.

For the purpose of this introductory chapter, two representative materials are considered. These are materials that, in the experience of the author, cover the extremes of conveyability of powdered and granular materials. One is typical of powdered materials, such as bentonite and fly ash that have very good air retention properties. These materials are capable of being conveyed in dense phase and with low air velocities in conventional conveying systems, and are presented here in terms of material type A. The other material is typical of coarse granular materials having poor air retention properties, such as sand and granulated sugar. These materials are only capable of being conveyed in dilute phase suspension flow in conventional conveying systems, and are presented here in terms of material type B.

8.2.2 Conveying conditions

Material conveying conditions that have a direct influence on material conveying potential include solids loading ratio, conveying line pressure drop, and air flow rate or conveying air velocity. Of these conveying line pressure drop is the only fully independent variable since both solids loading ratio and conveying air velocity are additionally material dependent.

8.2.2.1 Conveying line pressure drop

Conveying line pressure drop is a primary variable. It is one of the main variables associated with the energy imparted to the conveying air by the air mover for the system. In order to show the influence of conveying line pressure drop on the flow rate that can be achieved for a given material in a given pipeline, values of conveying line pressure drop up to 3 bar are considered. This adequately covers the operating range of the majority of pneumatic conveying systems, and is sufficiently wide to illustrate the potential influence that higher values of pressure drop can have.

8.2.2.2 System influences

All the data presented here are based on continuously operating systems, since the main objects are to show the potential of pneumatic conveying systems and the relative effect that changes in system parameters can have on operating performance. If a choice is ultimately to be made between a system capable of continuous operation and one based on the intermittent conveying of batches, however, the relationship between the steady state flow rate achieved during batch conveying and the time averaged mean will have to be taken into account (see Figures 2.7 and 4.9).

8.2.2.3 Material influences

The solids loading ratio at which the material can be conveyed and the minimum conveying air velocity that can be employed are both dependent upon the properties of the material being conveyed. The influence of material properties features prominently and so the effect of solids loading ratio and minimum conveying air velocity are also considered in detail. Both conveying line pressure drop and conveying distance have an inter-relating effect on these parameters and so these influences are also incorporated.

8.2.3 Pipeline geometry

Pipeline geometry can be varied principally in terms of the length of the pipeline, the bore of the pipe and the number of bends in the pipeline. The influence of pipeline geometry is dealt with specifically in Chapter 14. For the purposes of this introductory chapter a basic pipeline geometry has been selected, and all pipelines considered are geometrically similar so that the influence of changes can be clearly seen.

8.2.3.1 Pipeline length

Pipeline length has to be considered in terms of its orientation, and account must be taken of the individual lengths of horizontal, vertically up and vertically down sections. For this introductory chapter all conveying distances are essentially for horizontal pipeline. Bends are automatically taken into account as discussed below. Any elements of vertical lift in a pipeline can be approximated by taking double the vertical rise and adding this to the total length of horizontal pipeline. Conveying distances that have been considered, on this basis, in general range from about 50 to 500 m, in order to cover as wide a range of applications as possible, and to show the potentials and limitations of pneumatic conveying for long distance conveying.

8.2.3.2 Pipeline bore

All pipelines considered here are single bore lines. When high air supply pressures are used for conveying a material the pipeline bore is often increased to a larger size part way along its length. This is particularly the case where high conveying air pressures are employed, when several such changes may be made. Stepped pipelines are considered in Chapters 9 and 14. The range of pipeline diameters considered here is from 50 to 250 mm.

8.2.3.3 Pipeline bends

Pipeline bends can have a significant influence on the performance of a pneumatic conveying system pipeline. The number of bends in a pipeline, therefore, is particularly important. In the data presented here the proportion of bends to pipeline length considered is approximately in the ratio of one bend to every 15 m of pipeline.

Bend geometry is another important factor and this is considered in detail in Chapter 14. This is usually considered in terms of the ratio of the bend diameter, D, to the pipe bore, d. Bends can range from those having a very large radius, to elbows and blind tees. In the data presented here the bends in the pipeline have a D/d ratio of about 8:1.

8.3 Variables investigated

Since the conveying capacity of a pneumatic conveying system is of primary concern, major consideration has been given to material flow rate. Material properties and the effects that they have on both conveying conditions and material flow rate are particularly important. Conveying distance is clearly of fundamental importance, and pipe bore and conveying line pressure drop are both major variables that must be considered.

With this small group alone there are five independent variables, and so universal relationships are quite impossible to represent in either tabular or graphical form. Mathematical models do not exist that will adequately cover even this small group of variables or the ranges that need to be considered. In order to demonstrate the capabilities of pneumatic conveying systems, and to illustrate the influence of the major variables, therefore, several sets of curves are presented and the relationships are developed individually.

8.3.1 The influence of material type

The vast differences that can exist between materials with respect to their conveying potential are illustrated in Figures 8.1 and 8.2.

For just these two plots a third material type has been added to complete the picture with regard to material types. This is material type C which covers materials that have very good permeability. To have such properties the material has to have a mean particle size above about 1 mm and for the particle size to be almost zero, so that it is effectively mono-sized. This group includes materials such as nylon and polyethylene pellets, and seeds and grains, such as peanuts. In terms of numbers of materials, this group is in a minority, compared with the other two, and so as not to confuse the issue

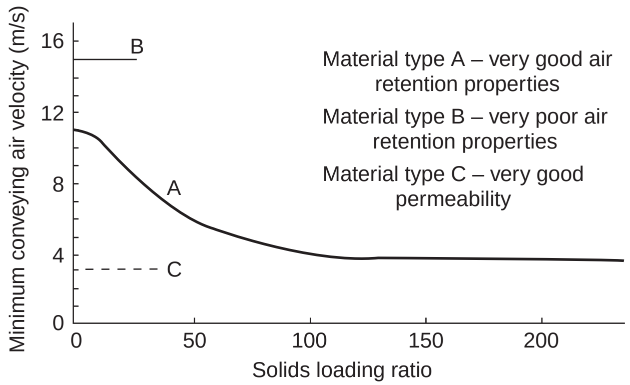


Figure 8.1 Comparison of materials with respect to minimum conveying air velocity relationships.

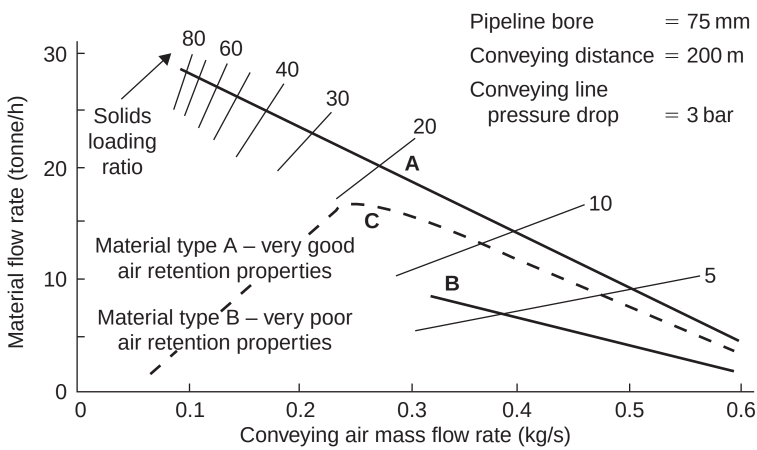


Figure 8.2 Comparison of materials with respect to material flow rate for given conveying conditions.

it is not added any further to the comparisons being made. This group of materials, however, is considered in detail in Part B of this Design Guide.

8.3.1.1 Minimum conveying air velocity

For fine powdered materials such as cement, barytes, fly ash and bentonite, that have good air retention properties, the relationship will generally be similar to that of material type A. With this group of materials a minimum conveying air velocity of about 10–12 m/s is usually sufficient to convey the material in dilute phase suspension flow. These materials are generally capable of being conveyed in dense phase, at low values of velocity, and at very high values of solids loading ratio if the pressure gradient is sufficiently high (see Figure 1.1). When conveyed at increasing solids loading ratios, these materials are generally capable of being conveyed quite successfully with air velocities very much lower than that necessary to convey the material in suspension flow.

For coarse granular materials such as sand, granulated sugar and alumina, that have poor air retention properties, the relationship will generally be similar to that of material type B. With these materials a minimum conveying air velocity of about 13–16 m/s is usually required to convey the material. These materials are not usually capable of being conveyed in any mode other than suspension flow with conventional pneumatic conveying systems. There is, therefore, little change in value of the minimum conveying air velocity that can be used to convey the material. Maximum values of solids loading ratio that can be achieved are generally quite low. A typical maximum value is about 15 but this can be as high as 30 if the pressure gradient is very high.

For very permeable materials conveying air velocities can also be very low, but solids loading ratios are also very low, with a typical maximum value of about 30. This is because the air flows readily through the interstices between the particles. For dilute phase conveying a minimum velocity similar to that for type B materials is required. At this point in time data on minimum conveying relationships of the type shown in Figure 8.1 can only be obtained reliably from actual conveying trials with the material. The means by which this data can be obtained is considered in Chapter 11.

8.3.1.2 Conveying air requirements

The differences in minimum conveying air velocity values that can be used for the three material types result in totally different conveying air requirements. These are shown in Figure 8.2. This is a plot of material flow rate against air mass flow rate and is drawn for a 200 m long pipeline of 75 mm bore with a pressure drop of 3 bar. With the plot being one of material flow rate against air flow rate, lines of solids loading ratio have also been added as these are simply straight lines through the origin.

Since material type A is capable of being conveyed in dense phase, conveying at a solids loading ratio of about 80 is possible with a pressure drop of 3 bar over 200 m, which agrees reasonably with Figure 1.1. With a minimum conveying air velocity of about 4 m/s, from Figure 8.1, a minimum air flow rate of about 0.08 kg/s is required. A minimum conveying air velocity of about 15 m/s is required for the type B material and so a minimum air mass flow rate of over 0.3 kg/s has to be employed. Despite the high value of conveying line pressure drop the maximum value of solids loading ratio that can be achieved with material type B is only about eight.

8.3.1.3 Conveying capabilities

In addition to the differences in air requirements for these three materials there are also differences in material flow rates that can be achieved at high air flow rates. For the materials considered here the difference is in the ratio of about 2:1. Materials A and B represent the two extremes of bulk solid materials with respect to pneumatic conveying and the majority of materials would be expected to lie between these two curves.

Major differences between materials occur because of the combined effect of the 2:1 ratio in material flow rate for a given air flow rate, and the fact that for materials that are capable of being conveyed at low velocity, the slope of the curves in the dense phase conveying region can be very different. Type C materials typically take a downward curve and material flow rate reduces with decrease in air flow rate. Type A materials often continue to give an increase in material flow rate with decrease in air flow rate, but many others give little or no change in material flow rate as the air flow rate is reduced. The phenomena is considered in detail in Chapters 12 and 13.

Relationships of the type shown in Figure 8.2 can only be obtained reliably from actual conveying trials with a material, in the same way as data on minimum conveying relationships mentioned above. The means by which such experimental data can be obtained is also considered in Chapter 11, with data for a number of materials being presented in subsequent chapters also.

8.3.2 The influence of conveying line pressure drop

In Figure 8.2 just one constant pressure drop curve for each material was included on the plot. Figures 8.3 and 8.4 are similar plots with a range of constant pressure drop lines included. Figure 8.3 compares the two materials (A and B) when conveyed through a 50 m long pipeline of 75 mm bore, and Figure 8.4 is a similar comparison for a 500 m long pipeline. In each case the influence of conveying line pressure drop on the material conveying potential can be clearly seen.

In addition to the individual figures illustrating the influence of conveying line pressure drop on material flow rate, Figures 8.3 and 8.4 together additionally show the influence of conveying distance on material flow rate, air flow rate and solids loading ratio for the two materials. These are comprehensive conveying characteristics for a given material in a given pipeline and are the basic data for the analysis presented in this Design Guide.

The determination and use of conveying characteristics are considered in detail in Chapter 11 and in many of the following chapters in Part B of the Design Guide. The

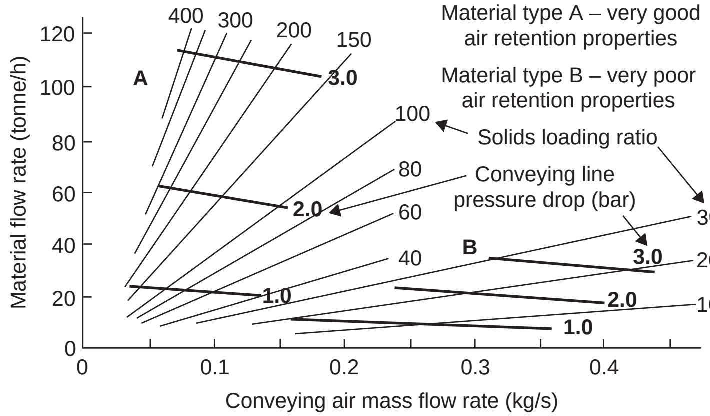


Figure 8.3 Comparison of conveying characteristics for materials conveyed over 50 m through a 75 mm bore pipeline.

minimum conveying conditions for a given material are defined on the conveying characteristics by relationships of the form presented in Figure 8.1.

8.3.3 The influence of conveying distance

Over the extremes of distance considered, the influence of conveying distance can be clearly seen by comparing Figures 8.3 and 8.4. Over the short distance of 50 m the type A material can be conveyed at extremely high values of solids loading ratios, even with low values of pressure drop. This means that the conveying limit relates to a minimum velocity of about 3½ m/s over the range of pressures considered. The minimum conveying velocity for the type B material is still 15 m/s, despite the fact that there is a very high pressure gradient.

The minimum values of air flow rate required for the type B material, therefore, are more than four (15/3½) times greater than those for the type A material, for any given value of pressure drop. As a consequence the minimum conveying conditions are so far apart that the conveying characteristics for the type A material can be presented in the 'no go area' for the type B material.

Over a distance of 500 m the pressure gradient is too low to convey the type A material in dense phase. The maximum value of solids loading ratio is less than seven and so the conveying limit now relates to a minimum conveying velocity of about 11 m/s. That for the type B material is still 15 m/s and so the two sets of conveying characteristics occupy a similar space. The significance of this is that there will have to be a significant increase in air flow rate to convey the type A material, but not for the type B material.

8.3.3.1 Solids loading ratio

The gradual change of solids loading ratio with respect to conveying distance is shown in Figures 8.5 and 8.6.

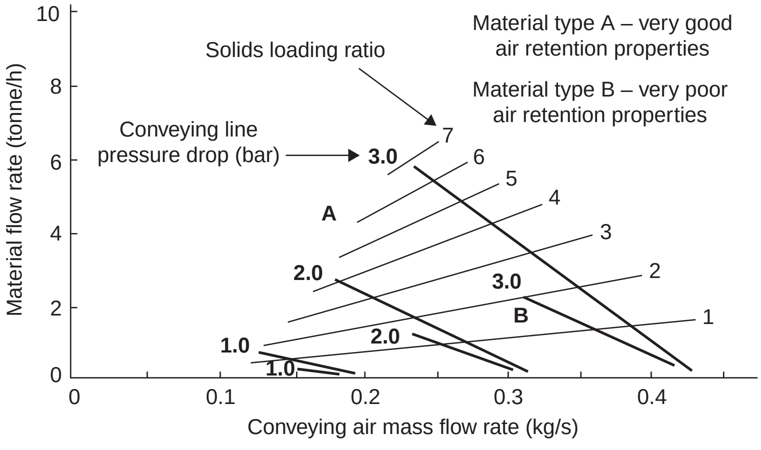


Figure 8.4 Comparison of conveying characteristics for materials conveyed over 500 m through a 75 mm bore pipeline.

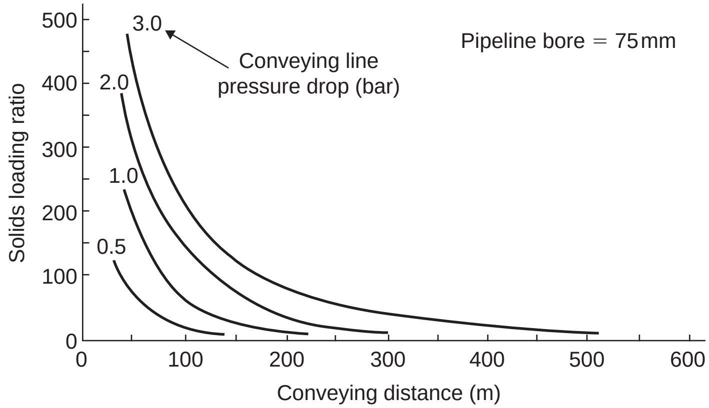


Figure 8.5 Influence of conveying distance and pressure drop on solids loading ratio at which a material with very good air retention properties can be conveyed.

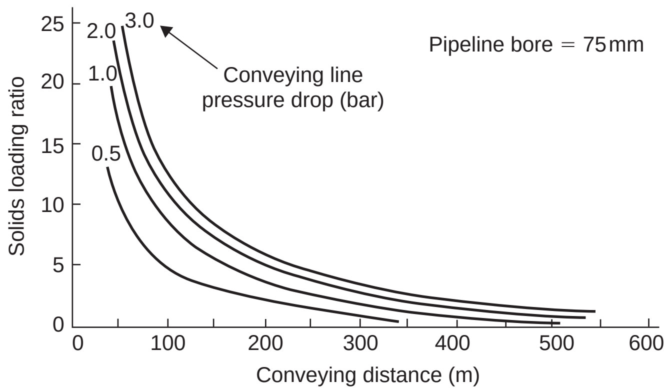


Figure 8.6 Influence of conveying distance and pressure drop on solids loading ratio at which a material with very poor air retention properties can be conveyed.

8.3.3.2 Material flow rate

The relationship between solids loading ratio and conveying distance in Figure 8.6 is an inverse law. That in Figure 8.5 is slightly steeper because of the increase in air flow rate required by the type A material with increase in conveying distance. In Figures 8.7 and 8.8 similar plots are presented in terms of material flow rate and these are very similar.

An important point here is that if there is an increase in conveying distance there will have to be a decrease in material flow rate to compensate, unless there is an increase in energy into the system. If the air flow rate and air supply pressure remain the same, the energy input will be the same. If the air pressure is increased there will be an increase in energy and, as will be seen from any of the Figures from 8.3 to 8.7, there will be an increase in material flow rate. There will, however, have to be a slight increase in air flow

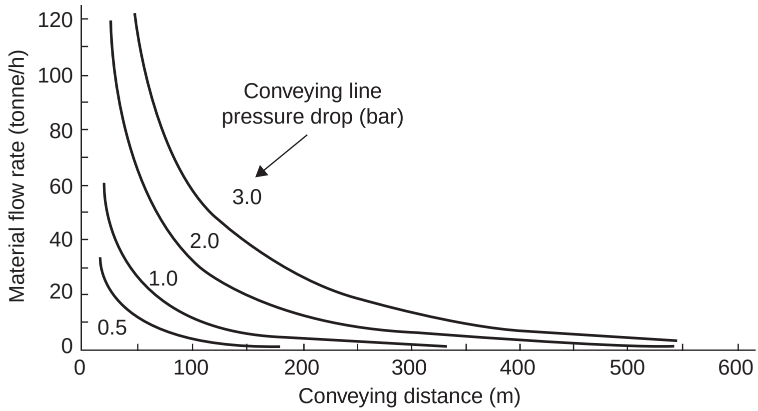


Figure 8.7 Influence of conveying distance and pressure drop on material flow rate through a 75 mm bore pipeline for a material having good air retention properties.

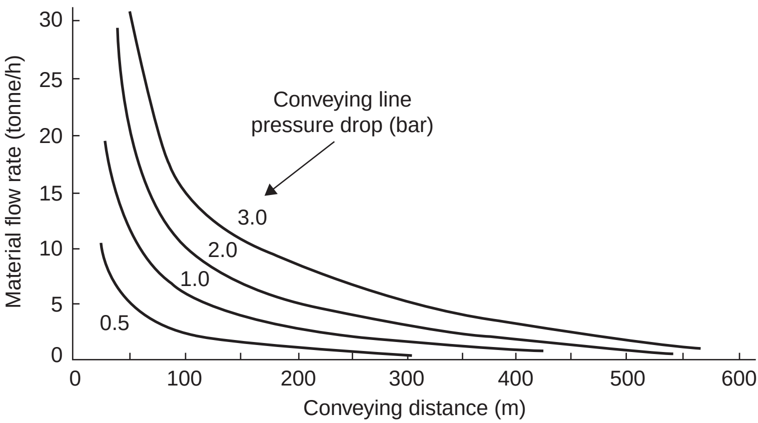


Figure 8.8 Influence of conveying distance and pressure drop on material flow rate through a 75 mm bore pipeline for a material having poor air retention properties.

rate in addition, to compensate for the compressibility of the air, and so maintain the correct value of velocity. This particular issue is considered in Chapter 9.

An increase in air flow rate alone is unlikely to give any benefit for, as will be seen from Figures 8.3 and 8.4, the lines of constant pressure drop generally tend to have a negative slope, and certainly in the dilute phase conveying area. This means that if more air is supplied, and hence more energy to the system, less material will be conveyed. At first sight this might be difficult to comprehend but this is explained further in Chapter 11.

It must also be realized that a 75 mm bore pipeline for a conveying distance of 500 m is not likely to be a realistic option. It is used here only for illustration purposes to avoid the introduction of additional variables. The air only pressure drop has to be taken into account in every pipeline because that value of the pressure drop is not available for conveying material. If it is high little will be left to convey material. Air only pressure drop is considered in detail in Chapter 10 and is applied in subsequent chapters.

8.3.3.3 Conveying line pressure drop

An alternative presentation of the data in Figures 8.7 and 8.8 is given in Figures 8.9 and 8.10. Conveying line pressure drop is presented on the horizontal axis and the family of curves are drawn for various conveying distances.

These two figures show that for short distance conveying a considerable increase in material flow rate can be achieved with an increase in conveying line pressure drop, and very high throughputs can be achieved with relatively small bore pipelines. If the conveying distance is very long, however, the potential of small bore pipelines is very

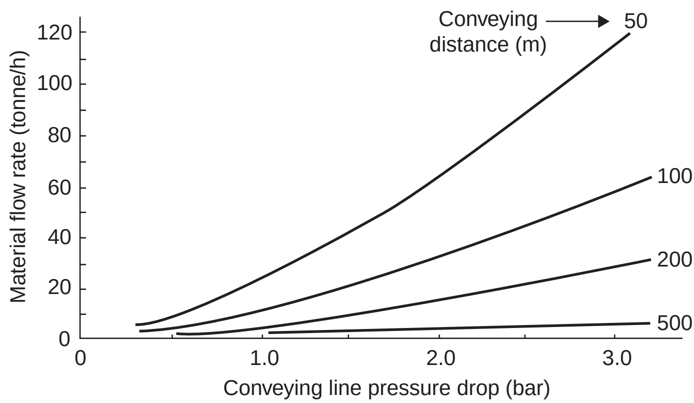


Figure 8.9 Influence of pressure drop and conveying distance on flow rate through a 75 mm bore pipeline for a material having good air retention properties (material type A).

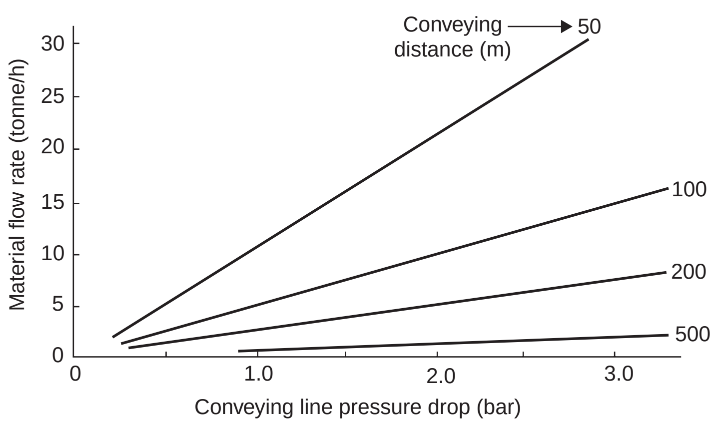


Figure 8.10 Influence of pressure drop and conveying distance on flow rate through a 75 mm bore pipeline for a material having poor air retention properties (material type B).

limited, even with high values of conveying line pressure drop. Also, if there is a limit on conveying line pressure drop, as there will be with negative pressure systems, and positive pressure systems using positive displacement blowers, the potential of small bore pipelines will be restricted automatically. In these cases consideration will have to be given to the use of larger bore pipelines.

8.3.4 The influence of pipeline bore

A larger bore pipeline is an obvious solution to increasing material flow rate and this clearly has much greater overall potential than air supply pressure in increasing flow rate. The potential influence of pipeline bore on the conveying performance of a pipeline is illustrated in Figures 8.11 and 8.12. These are both plots of material flow rate against pipeline bore for representative conveying conditions.

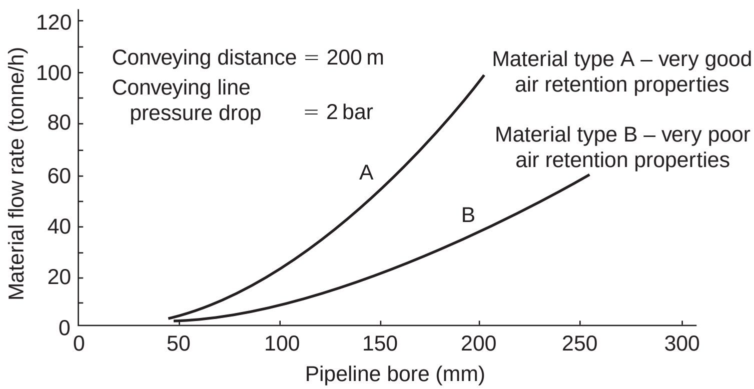


Figure 8.11 Comparison of materials with respect to the influence of pipe bore on material flow rate for given conveying conditions.

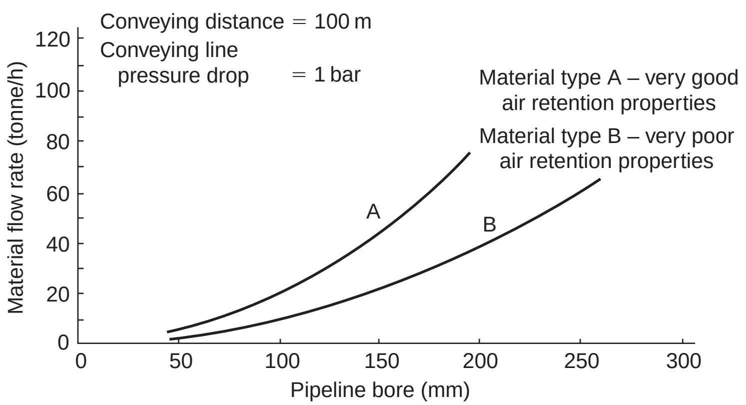


Figure 8.12 Comparison of materials with respect to the influence of pipe bore on material flow rate for given conveying conditions.

In Figure 8.11 the two materials are compared when conveyed over a distance of 200 m with a conveying line pressure drop of two bar. Figure 8.12 is a similar plot for the two materials conveyed over a distance of 100 m with a conveying line pressure drop of 1 bar.

These curves once again illustrate the differences that can exist between materials when pneumatically conveyed. They also show that quite high flow rates can be achieved with most materials, although line diameters have to be very much greater for materials having poor air retention properties. With larger bore pipelines proportionally more air is required to maintain the necessary conveying air velocities and so power will be significantly greater.

8.4 Material compatibility

The different conveying performances for the two materials with respect to both conveying distance and pipeline bore illustrate the problems to be encountered when a pipeline or conveying system has to be used for the conveying of more than one material. Totally different flow rates must be expected when different materials are conveyed through the same pipeline, even if the conveying line pressure drop is the same. The parameter that this last group of curves does not show is that of the conveying air requirements, although it was shown clearly in Figures 8.2–8.4.

If more than one material has to be conveyed through a given pipeline, the air supply has to be sufficient, in terms of volumetric capability, to convey the material with the requirement for the highest value of minimum conveying air velocity. When conveying other materials, however, the volumetric flow rate may need to be reduced, otherwise the conveying potential may also be reduced.

This effect can be illustrated by reference to Figure 8.2. If 0.38 kg/s of air is used to convey material type B, a flow rate of about 7 tonne/h could be expected in a 200 m long pipeline of 75 mm bore with a conveying line pressure drop of 3 bar. If this same air flow rate was to be used with material type A, a material flow rate of about 15 tonne/h would be obtained. If the air flow rate was to be reduced to 0.10 kg/s for material type A, however, a material flow rate of about 28 tonne/h could be expected in this same pipeline.

This aspect of system design is considered in detail in Chapter 19, together with similar influences of system design with respect to systems having multiple delivery points. Air requirements and consequent power requirements are also considered. This present chapter is concerned essentially with the performance of the pipeline. There will, of course, be problems with material feeding into these pipelines, and so the matching of the two will be taken into account in Chapter 19.

8.5 Design curves

One of the objects of this introductory chapter is to provide some basic data and information of the potential of pneumatic conveying systems for the conveying of various materials. As mentioned earlier, however, there are too many variables for a simple universal relationship to be applicable. Since only three variables can be represented on a single graph, a complete family of graphs is needed in order to represent a fourth variable. For this reason material type is considered as the fifth variable and only two material types are considered. This also necessarily means that only a limited number of incremental values of the fourth variable can be considered. To overcome this particular problem a second set of curves are presented in which the order of the first four variables are changed.

8.5.1 Conveying parameter combinations

In the first set of curves conveying line pressure drop is plotted against conveying distance and lines of constant pipeline bore are superimposed. Material flow rate is represented as the fourth variable in this set of curves and five values ranging from 5 to 100 tonne/h are considered. All five graphs are drawn for each material. The 10 graphs are presented in Figures 8.13–8.22.

With only 5 tonne/h being considered in Figures 8.13 and 8.14 the conveying line pressure drop was limited to 1.2 bar. This is extended to 3 bar for the other figures in this group.

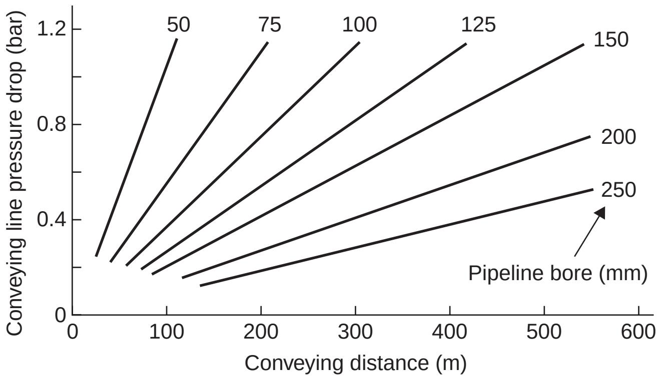


Figure 8.13 Conveying parameter combinations capable of achieving a flow rate of 5 tonne/h with a material having good air retention properties (material type A).

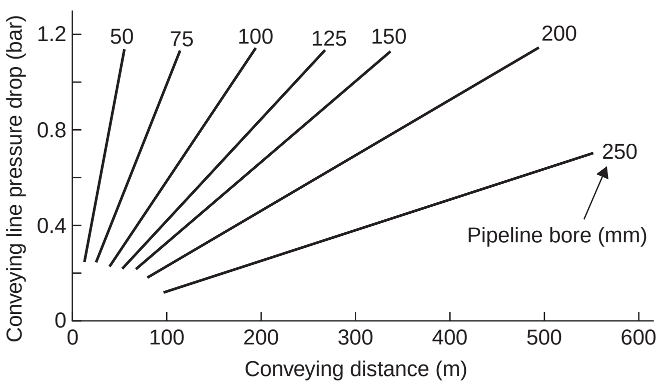


Figure 8.14 Conveying parameter combinations capable of achieving a flow rate of 5 tonne/h with a material having poor air retention properties (material type B).

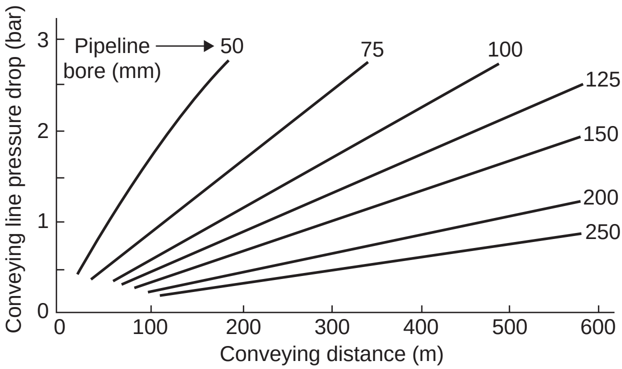


Figure 8.15 Conveying parameter combinations capable of achieving a flow rate of 10 tonne/h with a material having good air retention properties (material type A).

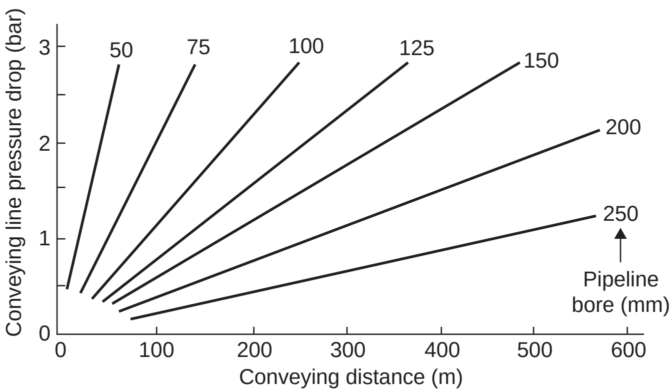


Figure 8.16 Conveying parameter combinations capable of achieving a flow rate of 10 tonne/h with a material having poor air retention properties (material type B).

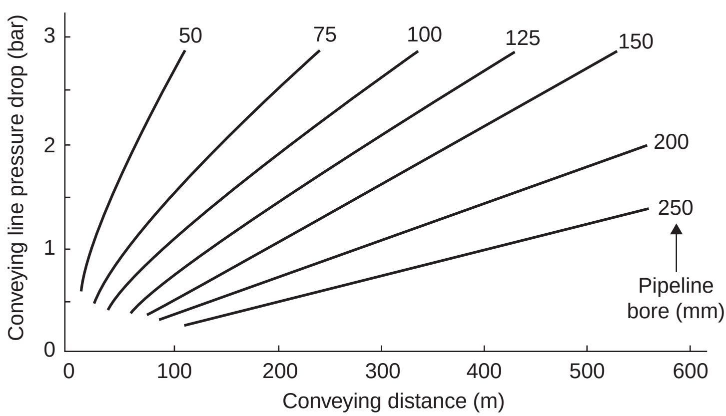


Figure 8.17 Conveying parameter combinations capable of achieving a flow rate of 20 tonne/h with a material having good air retention properties (material type A).

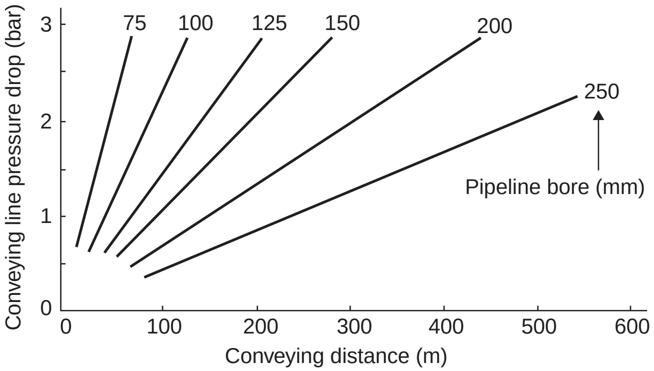


Figure 8.18 Conveying parameter combinations capable of achieving a flow rate of 20 tonne/h with a material having poor air retention properties (material type B).

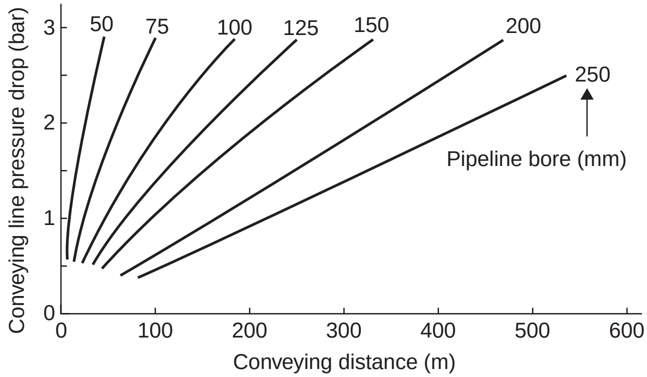


Figure 8.19 Conveying parameter combinations capable of achieving a flow rate of 50 tonne/h with a material having good air retention properties (material type A).

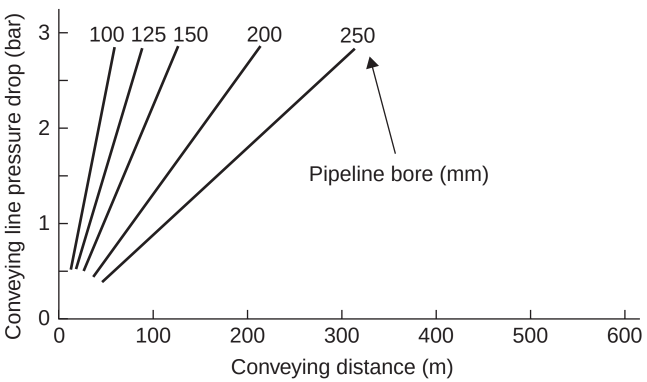


Figure 8.20 Conveying parameter combinations capable of achieving a flow rate of 50 tonne/h with a material having poor air retention properties (material type B).

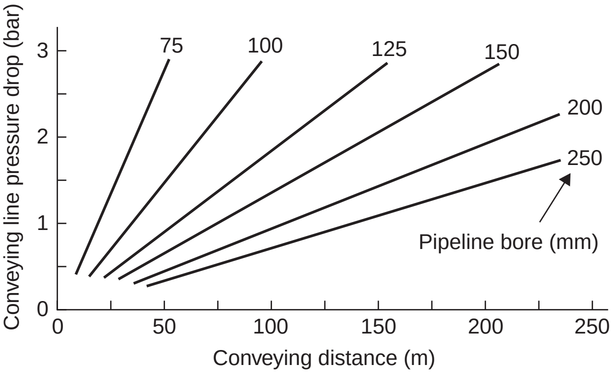


Figure 8.21 Conveying parameter combinations capable of achieving a flow rate of 100 tonne/h with a material having good air retention properties (material type A).

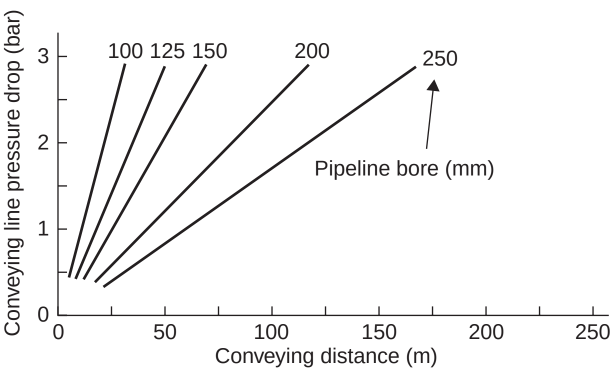


Figure 8.22 Conveying parameter combinations capable of achieving a flow rate of 100 tonne/h with a material having poor air retention properties (material type B).

With an increase to 20 tonne/h the 50 mm bore pipeline is no longer an option for the type B material.

With an increase to 50 tonne/h the 75 mm bore pipeline is no longer an option for the type B material.

With an increase to 100 tonne/h the conveying distance has been limited to 250 m because of the range of pipe bores and pressure drop values being considered.

With each one of these graphs being drawn for a given material flow rate, it will be seen that for any given conveying distance that a wide range of combinations of conveying line pressure drop and pipeline bore values are generally available that will satisfactorily meet the conveying requirement. If the conveying line pressure drop available for the system is limited, however, as it will be for a vacuum conveying system, the choice will be more restricted.

If there is no such limitation there is clearly a need to determine which of the possible combinations are best for the given duty. Operating costs, and hence power

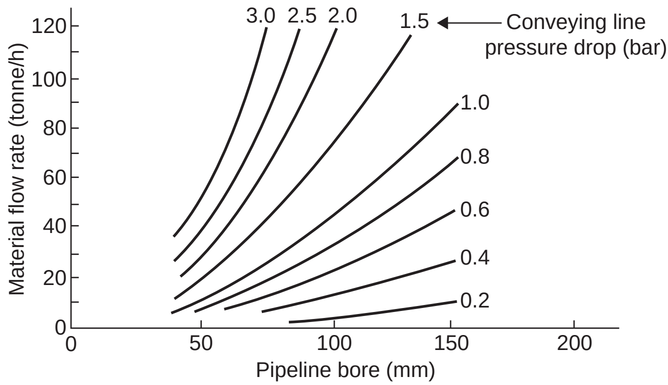


Figure 8.23 Potential of 50 m long pipelines for conveying a material having good air retention properties (material type A).

requirements are obviously the criterion for the basis of selection in this respect. This aspect of system selection is introduced in the next section of this chapter, in addition to being considered in detail in Chapter 11.

If a high pressure option is chosen, in order to achieve a high material flow rate in the smallest bore pipeline possible, over the range of air pressures being considered, consideration will have to be given to the conveying air expansion effects. High air supply pressures are often used for long distance conveying.

Over long distances, however, maximum values of solids loading ratio that can be achieved tend to be rather low, even for materials with very good air retention properties, as illustrated in Figure 8.5. As a consequence, conveying line inlet air velocities need to be quite high, and so with a high air supply pressure extremely high conveying line exit air velocities can result in a single bore pipeline.

If the material being conveyed is either abrasive or friable, such high conveying air velocities should be avoided. One means by which the general air velocity level can be lowered is to use a stepped pipeline. These are considered in relation to air flow rate evaluation in Chapter 9 and in a number of subsequent chapters with regard to the conveying of various materials.

Since the material has to be conveyed in suspension flow, however, conveying air velocities will still be relatively high. In this case the use of an alternative innovatory type of pneumatic conveying system would be worth considering, provided that one can be found to meet the required duty.

8.5.2 Pipeline conveying capacity

In the second set of curves presented, material flow rate is plotted against pipeline bore and lines of constant conveying line pressure drop are superimposed. Conveying distance is represented as the fourth variable here and four values ranging from 50 to 500 m are considered. All four graphs are drawn for each material. The eight graphs are presented in Figures 8.23–8.30.

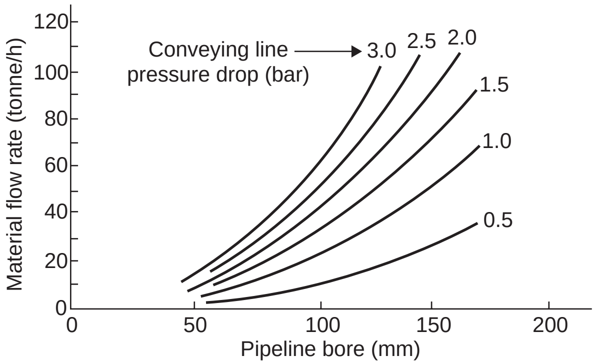


Figure 8.24 Potential of 50 m long pipelines for conveying a material having poor air retention properties (material type B).

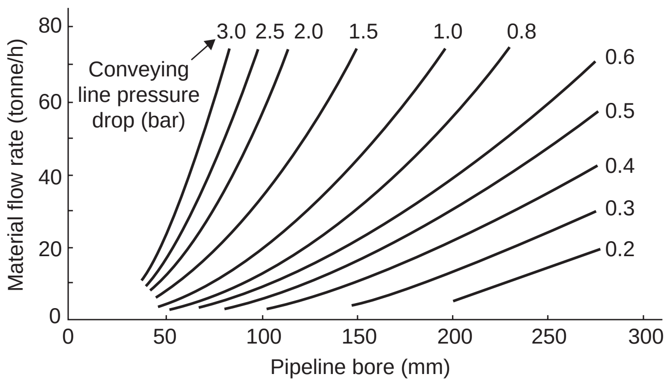


Figure 8.25 Potential of 100 m long pipelines for conveying a material having good air retention properties (material type A).

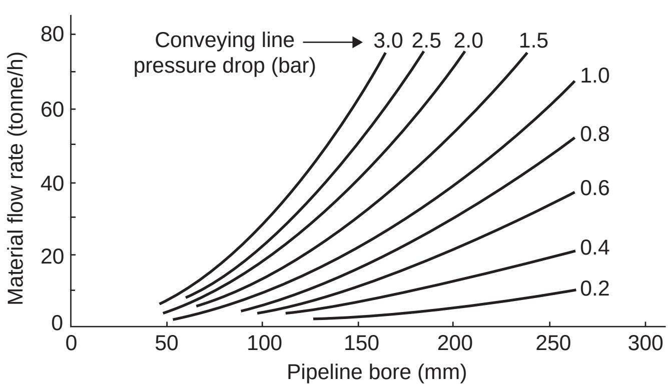


Figure 8.26 Potential of 100 m long pipelines for conveying a material having poor air retention properties (material type B).

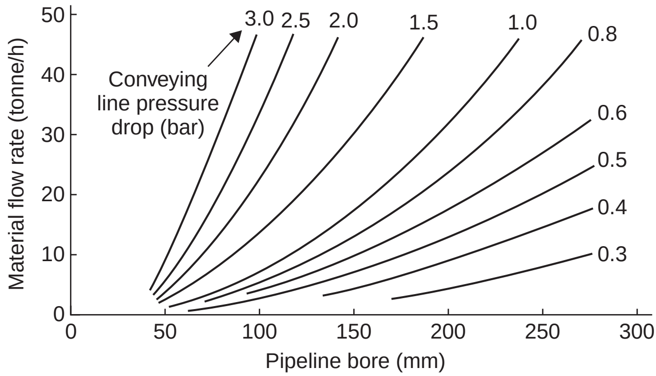


Figure 8.27 Potential of 200 m long pipelines for conveying a material having good air retention properties (material type A).

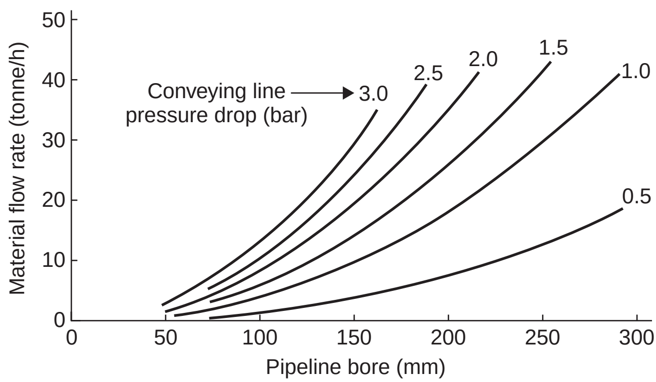


Figure 8.28 Potential of 200 m long pipelines for conveying a material having poor air retention properties (material type B).

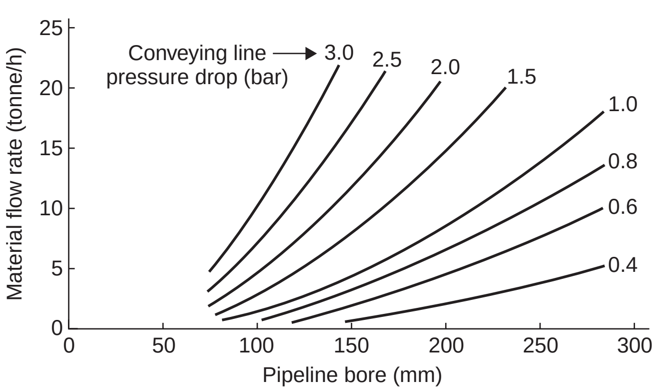


Figure 8.29 Potential of 500 m long pipelines for conveying a material having good air retention properties (material type A).

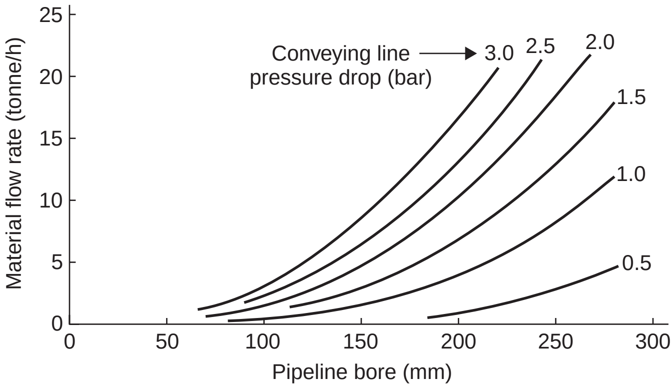


Figure 8.30 Potential of 500 m long pipelines for conveying a material having poor air retention properties (material type B).

With this form of presentation the influence of pipeline bore and conveying distance on the empty line pressure drop is shown. This is a topic that is considered in detail in Chapter 10. The pressure drop for the air in a conveying line is directly proportional to pipeline length and inversely proportional to pipeline diameter. This explains why the lines of constant pressure drop slope upwards to an increasing rate to higher material flow rates with increase in pipeline bore, for a given conveying distance.

For the short 50 m long pipeline material flow rates up to 120 tonne/h are considered with pipeline bores taken to only 150 mm.

For the 100 m long pipelines the material flow rate range considered has been reduced to 80 tonne/h and the pipeline bore has been extended to 250 mm.

For the 200 m long pipelines the material flow rate has been further reduced to 50 tonne/h since the same limit of 3 bar on conveying line pressure drop is considered.

For the 500 m long pipelines the material flow rate has been reduced to 20 tonne/h since the pressure gradient is down to 6 mbar/m and the maximum value of solids loading ratio that will be possible, even for a type A material will only be about 20 (see Figure 1.1).

8.6 Power requirements

Information on the power required for a pneumatic conveying system is just as important for its successful operation as design data for the selection of the correct pipeline bore and conveying line pressure drop for a given system. In cases where alternative combinations of parameters can be selected, an economic assessment of the best system will be well worthwhile carrying out, as mentioned earlier.

With so many cases to consider, and a wide range of air movers available (see Chapter 6), it is almost an impossible task to determine power requirements accurately. Quite clearly some air movers will be more efficient than others, and a smooth transition is unlikely to be made from one type of air mover into that for the next available. In order to overcome these problems, and to provide data that is both realistic and comparable, a simple mathematical model has been used to evaluate the compression work.

The model is based on the isothermal compression of air and for this, data is required on air flow rate (mass or volumetric), together with conveying line pressure drop values. This, of course, is the ideal case and does not take account of thermodynamic irreversibility or transmission losses. To allow for these the basic model is multiplied by a constant. A value of two has been used for this constant, and this has been found to provide reasonable agreement with manufacturers' literature for a wide range of air movers, air flow rates and delivery pressures (see Equations (6.5) and (6.6)). The main advantage of using such a model is that it provides a degree of uniformity when making comparisons between variables.

In this introductory chapter only a passing mention is made of power requirements as this is considered in more detail in Chapter 11. In order to supplement the earlier work presented here, and to illustrate the order of magnitude of the power requirements for pneumatic conveying, the influence of material type, conveying distance and pipeline bore are considered briefly here.

8.6.1 Influence of conveying distance

The influence of conveying distance on material flow rate is illustrated specifically in Figures 8.7 and 8.8, where it was shown that for a given pipeline bore and conveying line pressure drop there was a marked fall in material flow rate with increase in conveying distance. On this basis the power required to convey a material with very poor air retention properties will be approximately constant, since the conveying line inlet air velocity remains constant. For a material with very good air retention properties, however, there will have to be an increase in power with increase in conveying distance. This is due to the fact that as conveying distance increases, solids loading ratio decreases, and so conveying line inlet air velocity and hence air flow rate have to be increased.

The basis of comparison presented in Figures 8.31 and 8.32 is for conveying at a given flow rate over a range of distances. In Figure 8.31 a material flow rate of 10 tonne/h is considered and in Figure 8.32 it is 20 tonne/h. These are both plots of power required against conveying distance, and the two extremes of material type are represented on each. In order to achieve a constant material flow rate with respect to conveying distance, changes in both pipeline bore and conveying line pressure drop need to be made. The combination of parameters, within the ranges considered, have been selected that result in the lowest value of power required.

This provides possibly the best means by which materials can be compared. The change in relative spacing, with respect to conveying distance, between the two curves on each figure is due to the change in air requirements for materials with good air retention properties, as discussed above. The difference in power requirements for the two materials is approximately in the ratio of 3:1 over a distance of about 500 m. This is as close as they will get, for over this distance both materials have to be conveyed in suspension flow. For shorter distances the difference is of the order of 6:1, for the comparison is between suspension and non-suspension flow.

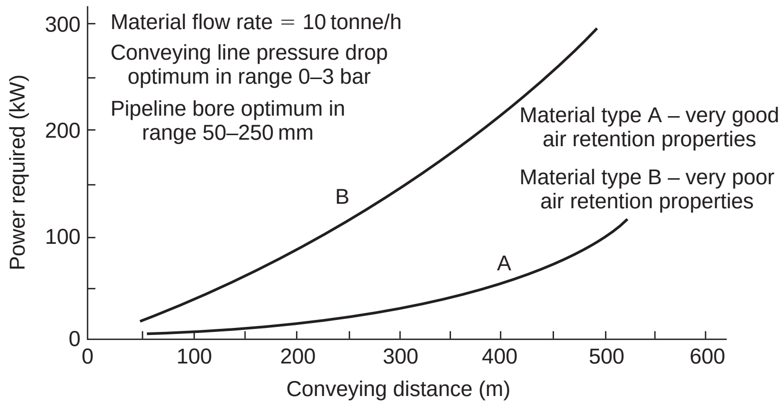


Figure 8.31 Comparison of materials with respect to the influence of conveying distance on power requirements for conveying 10 tonne/h.

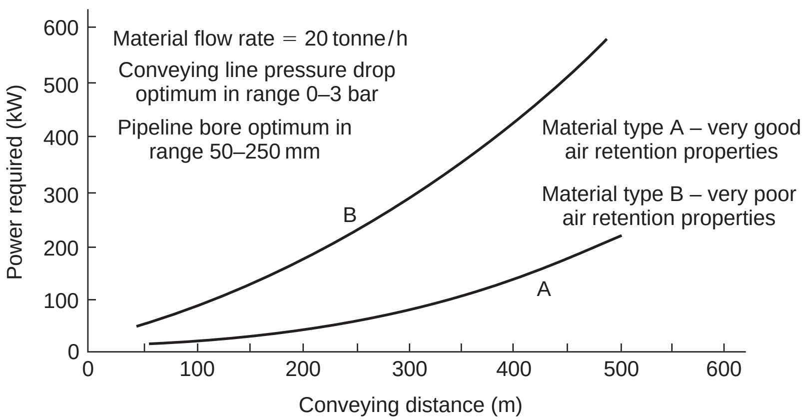


Figure 8.32 Comparison of materials with respect to the influence of conveying distance on power requirements for conveying 20 tonne/h.

Part of this difference can be attributed to the difference in conveying characteristics between the two materials. When conveyed under identical conveying conditions the difference is of the order of 2:1, as shown earlier with Figure 8.2. Any differences beyond this value can be attributed to the different velocity levels at which the materials are conveyed. The largest differences, therefore, occur with shorter conveying distances, where materials with very good air retention properties can be conveyed in dense phase and hence at low velocity.

8.6.1.1 System considerations

It is clear from this that if a material with very poor air retention properties could be conveyed in dense phase and at low velocity in an alternative pneumatic conveying

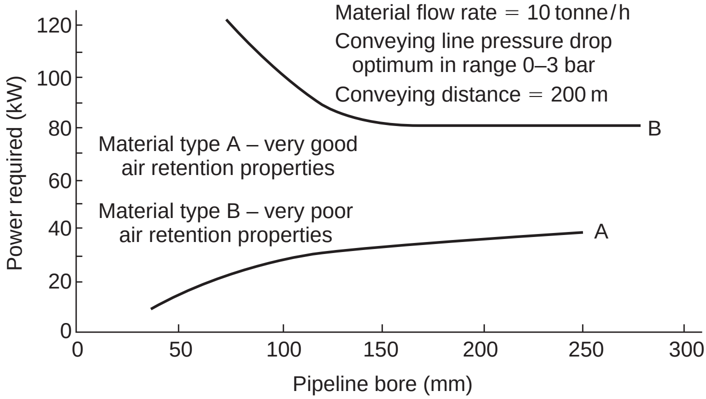


Figure 8.33 Comparison of materials with respect to the influence of pipe bore on power requirements for material conveyed at 10 tonne/h over 200 m.

system, such as a pulse phase or plug control system, it is possible that energy savings could be made over conventional conveying systems. The operating characteristics of such a system is presented in Figure 8.2 and so this throws some doubt on the possibility. Although the material will be conveyed at a lower velocity, the material flow rate reduces with decrease in velocity so that a larger bore pipeline would be needed to convey the material. This means that more air will be required, and hence more power, and so it is likely that the energy saving will be marginal.

8.6.2 Influence of pipeline bore

The influence of pipeline bore on material flow rate is illustrated specifically in Figures 8.11 and 8.12, where it was shown that for a given conveying distance and conveying line pressure drop there was a marked increase in material flow rate with increase in pipeline bore. The basis for comparison presented in Figures 8.33 and 8.34 is for conveying at a given flow rate with a range of pipeline bores.

In Figure 8.33 a material flow rate of 10 tonne/h is considered, conveyed over a distance of 200 m, and in Figure 8.34 the material flow rate is 20 tonne/h and the distance is 100 m. These are both plots of power required against pipeline bore, and the two extremes of material type are represented on each. In order to achieve a constant material flow rate with respect to pipeline bore an appropriate value of conveying line pressure drop was selected.

Once again this probably provides the best means by which materials can be compared. These particular curves also show very interesting, and different, trends for both materials considered.

8.6.2.1 Materials with good air retention properties

With respect to materials having good air retention properties it is clear that for minimum power requirements, small bore pipelines and high air supply pressures should

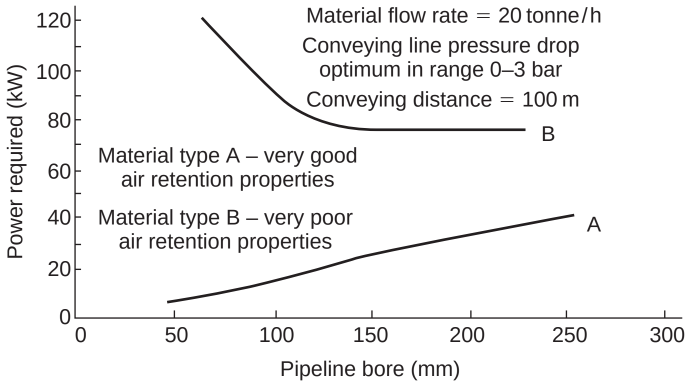


Figure 8.34 Comparison of materials with respect to the influence of pipe bore on power requirements for material conveyed at 20 tonne/h over 100 m.

be used. This is particularly the case for short distance conveying. In Figure 8.34, for example, with the material conveyed over 100 m, the power requirement for a 250 mm bore pipeline is about six times that for a 50 mm bore pipeline for the identical duty.

The reason for this is that in a small bore pipeline very little air is needed, although it is obviously required at a high pressure. This means that for a given material flow rate the solids loading ratio in a small bore pipeline will be very high, which in turn means that a low conveying line inlet air velocity can be employed. In a large bore pipeline a large quantity of air will be required, although at very low pressure.

This means that for a given material flow rate the solids loading ratio in a large bore pipeline will be very low, which means that a high conveying line inlet air velocity will have to be used. The combination of air flow rate and pressure required is far greater for the larger bore, dilute phase conveying case, and so for any material capable of being conveyed in dense phase, operating costs will be much lower in small bore pipelines using high pressure air.

This analysis is based on continuously operating systems. For systems employing air pressures of 3 bar and above, blow tanks are likely to be used. These are often batch conveying systems and in this case the relationship between the steady state flow rate achieved during batch conveying and the time averaged mean will have to be taken into account, as considered in Section 4.4.2.2. With high pressure systems it would be recommended that the pipeline should be stepped to a larger bore part way along its length and the potential influence of this is considered in Chapter 14.

8.6.2.2 Materials with poor air retention properties

In the case of materials having very poor air retention properties exactly the reverse situation applies. For these materials large bore pipelines and low air pressures should be used for minimum power requirements. In the cases presented in Figures 8.33 and 8.34 almost 50 per cent more power is required to convey the material in a small bore pipeline.

The reason for the poor performance of small bore pipelines is that high air supply pressures are required. In single bore pipelines very high mean conveying air velocities will result. High velocities, particularly in small bore pipelines result in high pressure drops, both for the empty line for the air only, and for the conveying of the material.

In large bore pipelines much lower conveying line pressure drops will be required to convey the material and so the mean conveying air velocity will be much lower. The air only pressure drop in a large bore pipeline is also lower than that for a small bore pipeline, even for the same value of conveying air velocity.

For the small bore pipeline an improvement in performance is possible. This is because a high air pressure is required and so a stepped pipeline could be employed. This would help to reduce the very high velocities that result and so improve the performance. This point is also considered further in Chapter 14.

8.6.2.3 Material compatibility

Material compatibility was considered earlier in relation to conveying air requirements at Section 8.3.1.2. Figures 8.33 and 8.34, however, show another aspect of this problem, for if such dissimilar materials have to be conveyed in a common pipeline, a bore selected for one material may not be suitable for another material. The difference in power requirements can also be very great, particularly with small bore pipelines. This problem can often be solved by using stepped pipelines and this is explored in Chapter 19.

8.7 System selection considerations

From the foregoing analysis it will be seen that with so many variables to consider, and with many alternative combinations of parameters capable of meeting most conveying requirements, a comprehensive logic diagram for the selection of a pneumatic conveying system would be too complex to be practicable. At a very basic level, however, systems can be considered simply in terms of dilute and dense phase and this is dictated either by material type or by conveying distance. This can be illustrated by reference to Figures 8.35 and 8.36.

8.7.1 Summary charts

In Figures 8.35 and 36 three values of each of the requirement parameters, material flow rate and conveying distance are considered. The design parameters, in terms of conveying line pressure drop and pipeline bore, for each combination of material flow rate and conveying distance, are presented in the boxes beneath. The boxes are in direct line from the appropriate values of material flow rate and conveying distance.

The design parameters in Figure 8.35 are for a material having very good air retention properties and in Figure 8.36 they are for a material having very poor air retention properties. Values of conveying line pressure drop and pipeline bore correspond to the combination resulting in the lowest operating power requirements, for each material, over the range of the variables considered.

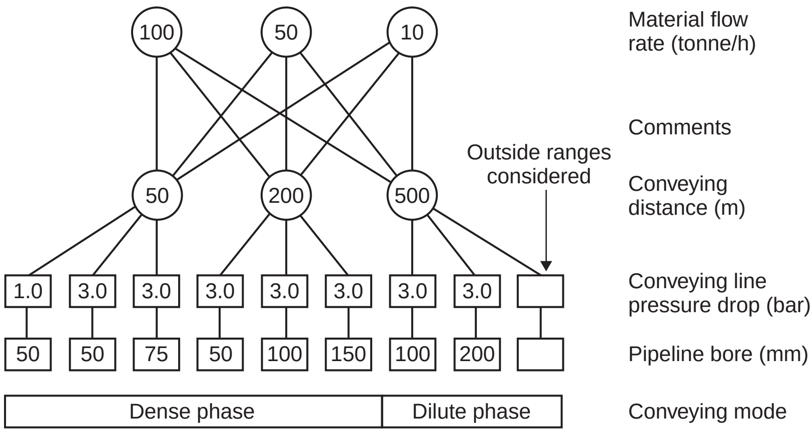


Figure 8.35 Summary chart for system capabilities and design parameters for materials having very good air retention (material type A).

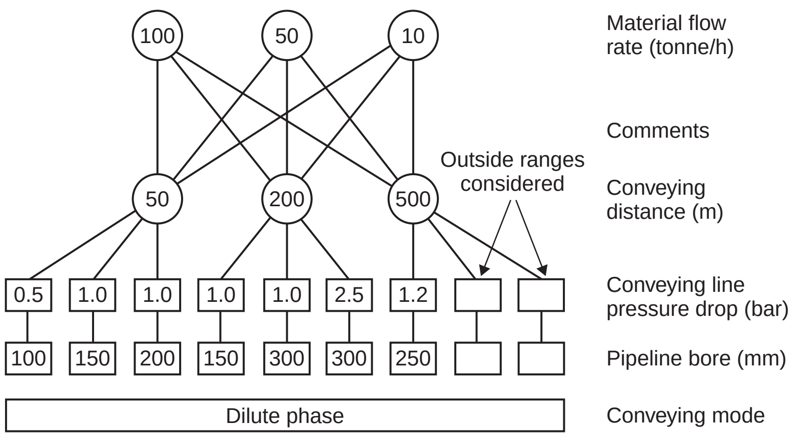


Figure 8.36 Summary chart for system capabilities and design parameters for materials having very poor air retention (material type B).

8.7.2 Materials capable of dense phase conveying

From Figure 8.35 it will be seen that for a material having very good air retention properties the choice of system is dependent upon conveying distance. For short distance conveying a dense phase system would be preferred, and for long distance conveying only dilute phase conveying is possible, with a conventional system. The transition from dense to dilute phase conveying occurs at a distance of 300–400 m with this material and with the limit of 3 bar on conveying line pressure drop that has been considered.

This represents the maximum, for the transition will occur at a shorter distance with a material not having such good air retention properties, or poorer conveying characteristics. For the material with very poor air retention properties in Figure 8.36 only dilute phase conveying is available over the range of conveying distances considered.

Although dense phase conveying is recommended when this is possible for a material, personal factors may dictate the selection of a dilute phase system. The decision presented here is simply based on operating costs. Plant capital costs, or a desire to use low pressure air movers or certain feeding devices, may result in a dilute phase system being preferred. As demonstrated in this chapter, a wide range of conveying parameter combinations are generally available for a material capable of being conveyed in dense phase, and so the material could be conveyed quite successfully in either dilute or dense phase in many cases.

8.7.3 Alternatives to dilute phase conveying

When the choice of conventional conveying system is restricted to dilute phase, either because of the distance conveyed or the properties of the material, the use of an alternative innovatory system, such as pulse phase, plug control or air addition system, may be well worth considering. If the material is capable of being conveyed in such a system over the distance required, and this is clearly the first point to establish, such a system should enable the material to be conveyed at much lower velocities, which will help with respect of plant erosion and particle degradation.

The next point to establish is whether the operating costs are lower, for the plant capital costs will almost certainly be higher. Operating costs will depend upon the conveying characteristics for the material. If these are similar to those of material A in Figure 8.2 then the operating costs will be significantly lower, but if they are similar to those of material C in Figure 8.2 any such benefit is likely to be marginal. The ultimate decision, therefore, needs to be made in relation to these various points.

This page intentionally left blank

Part B

System Design

This page intentionally left blank

Chapter 9

Air flow rate evaluation

9.1 Introduction

The selection of a fan, blower or compressor is probably one of the most important decisions to be made in the design of a pneumatic conveying system. It is often the largest single item of capital expenditure and the potential conveying capacity of the plant is dependent upon the correct choice being made. The rating of the fan, blower or compressor is expressed in terms of the supply pressure required and the volumetric flow to be delivered. Any error in this specification will result in a system that is either over-rated, is not capable of achieving the desired material flow rate, or will cause a pipeline blockage and convey nothing.

For an existing system it is often necessary to check the performance, particularly if operating problems are encountered, or changes in material or conveying distance need to be considered. Here it is the conveying line inlet air velocity that is important. Since the determination of conveying line inlet air velocity and the specification of air requirements is so important for the successful operation of pneumatic conveying systems, all the appropriate models are derived and presented for reference purposes.

Although it is air that is generally referred to, materials can be conveyed with any suitable gas. Constants are included in the equations that will correctly account for the type of gas used when evaluating the volumetric flow rate required. Air mass flow rate is also considered, as it is a useful working parameter with regard to solids loading ratio, and as its value remains constant it is particularly useful in equations of continuity.

9.1.1 Supply pressure

The delivery pressure, or vacuum, required depends essentially upon the working pressure drop needed over the length of the conveying pipeline. The pressure drop across the gas–solids separation device can usually be neglected, but if a blow tank is used for feeding the material into the pipeline then an allowance for the pressure drop across the feeding device will have to be made. Consideration will also have to be given to the pressure drop in any air supply and extraction lines, and to the need for a margin on the value of conveying line pressure drop required to convey the material through the pipeline at the specified rate.

The magnitude of the conveying line pressure drop, whether for a positive or a negative pressure system, depends to a large extent on the conveying distance and on the solids loading ratio at which the material is to be conveyed. For short distance dilute phase conveying a fan or blower would be satisfactory, but for dense phase conveying or long distance dilute phase conveying, a reciprocating or screw compressor would be required. The pressure drop is also dependent upon the conveying gas velocity and a multitude of properties associated with the conveyed material.

9.1.2 Volumetric flow rate

The volumetric flow rate required from the fan, blower or compressor depends upon a combination of the velocity required to convey the material and the diameter of the pipeline to be used. Pipes and fittings are generally available in a range of standard sizes, but velocity is not so clearly defined.

For convenience the velocity at the end of the pipeline could be specified, for in the majority of cases compressors are rated in terms of 'free air delivered', and the pressure at the end of a pipeline in positive pressure systems, in most applications, will be sufficiently close to atmospheric for this purpose. It is, however, the velocity at the start of the line that needs to be ascertained for design purposes.

The problem is that air, and any other gas that is used for the conveying of materials, is compressible and so its density, and hence volumetric flow rate, is influenced by both pressure and temperature. If the plant is not located at sea level, the influence of elevation may also have to be taken into account. As a result of the compressibility with respect to pressure, stepped bore pipelines are often employed and so these are given due consideration.

In negative pressure systems the air at the start of the conveying line is approximately at atmospheric pressure, and it decreases along the length of the conveying line to the exhauster. For this type of conveying system, therefore, the minimum velocity that needs to be specified occurs at the free air conditions. Exhausters, however, are generally specified in terms of the volumetric flow rate of the air that is drawn into the air mover, and not free air conditions, and so it is essentially the same problem in evaluating air flow rates as with positive pressure conveying systems.

9.1.3 The influence of velocity

A conveying plant is usually designed to achieve a specified flow rate. Material flow rate can be equated to the solids loading ratio and the air mass flow rate. The air flow rate, in turn, is proportional to air velocity and pipe bore. Since these three parameters also have an effect on the compressor rating, it is extremely important that the correct air mover specification is made. The relationship between the various parameters that link the compressor rating and material flow rate is demonstrated with the path analysis shown in Figure 9.1.

Figure 9.1 also illustrates the importance of conveying air velocity in this relationship, as it influences both the supply pressure and the volumetric flow rate of the compressor. This helps to explain why conveying air is one of the most important variables in pneumatic conveying, and why it needs to be controlled fairly precisely.

If, in a dilute phase conveying system, the velocity is too low, it is possible that the material being conveyed will drop out of suspension and block the pipeline. If, on the

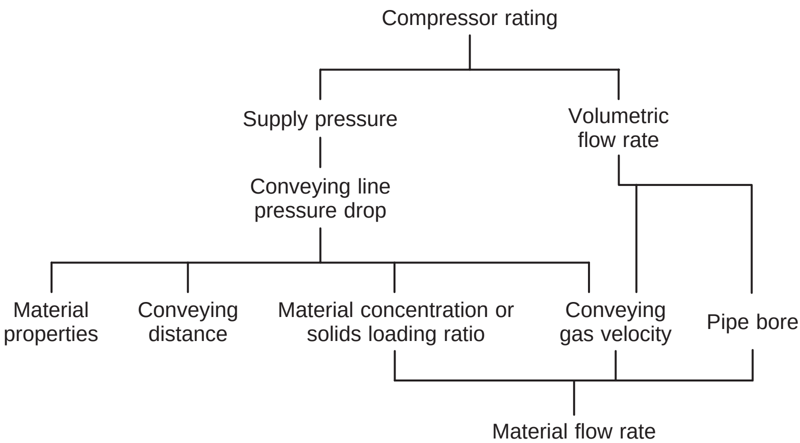


Figure 9.1 Parameters relating compressor rating with material flow rate.

other hand, the velocity is too high, bends in the pipeline will erode and fail if the material is abrasive, and the material will degrade if the particles are friable. Velocity also has a major influence on the conveying line pressure drop, and hence on the mass flow rate of the material conveyed through a pipeline. The range of velocity, therefore, is relatively narrow, particularly in dilute phase systems, varying from a minimum of about 15 m/s to a maximum of around 30 m/s.

For dense phase conveying the conveying line inlet air velocity can be as low as 3 m/s, but this depends upon the solids loading ratio at which the material is conveyed and the nature of the conveyed material. If the velocity drops below the minimum value the pipeline is likely to block. It is important, therefore, that the volumetric flow rate of air, specified for any conveying system, is sufficient to maintain the required minimum value of velocity throughout the conveying system.

9.1.3.1 Material influences

It should be noted that in evaluating conveying air velocities and volumetric air flow rates in pneumatic conveying applications, the presence of the material is disregarded in all cases. The conveying air velocity is essentially the superficial value, derived simply by dividing the volumetric flow rate by the pipe section area, without taking account of any particles that may be conveyed.

In dilute phase conveying, and at low values of solids loading ratio, the influence of the conveyed material will have negligible effect in this respect. At a solids loading ratio of 100, however, the material will occupy approximately 10 per cent of the volume at atmospheric pressure and so the actual air velocity will be about 10 per cent higher. At increased air pressures and solids loading ratios the percentage difference will be correspondingly higher.

It would be a very complex and time consuming process to evaluate actual air velocities and so for convenience the superficial air velocity is universally employed.

Critical values such as the minimum conveying air velocity and conveying line inlet air velocity are mostly derived from experience and experimental work. In such cases it is the superficial value of air velocity that is used.

9.1.4 Compressibility of air

As with the flow of air only in a pipeline, or single phase flow, the flow of a gas–solid mixture will also result if there is a pressure difference, provided that a minimum value of conveying air velocity is maintained. Material flow with the conveying air will be in the direction of decreasing pressure, whether it is a positive pressure or a vacuum conveying system.

Since air is compressible, the volumetric flow rate of the air will gradually increase from the material feed point at the start of the pipeline, to the material discharge point at the end of the pipeline. In a single bore pipeline the conveying air velocity will also gradually increase over the length of the pipeline.

This means that it is the value of the conveying air velocity at the material feed point, or the start of the pipeline, that is critical, since the value of the conveying air velocity will be the lowest at this point, in a single bore pipeline. In determining the necessary volumetric flow rate of air, therefore, it is the condition prevailing at the start of the pipeline, in terms of pressure and temperature that must be taken into account.

9.2 Volumetric flow rate

Volumetric flow rate in m^3/s has been chosen for all mathematical models presented as it is the basic SI unit. On graphical plots, however, m^3/min has been used as it is more widely quoted in trade literature for blowers and compressors. Conversion factors to and from m^3/s for other units are presented in Table 9.1.

Divide by the numbers given in Table 9.1 to convert the other way round.

This point will be considered further in the next section.

Table 9.1 Conversion factors for air flow rates

Multiply m^3/s by	To obtain
60	m^3/min
1000	l/s
1.225*	kg/s
73.53*	kg/min
35.31	ft^3/s
2119	ft^3/min (cfm)
2.701*	lb/s
162.1*	lb/min

*Where a conversion is from a volume to a mass, the conversion is based on free air conditions of temperature and pressure and the figures given relate to air only.

9.2.1 Presentation of equations

The majority of the equations that follow are presented in terms of both volumetric flow rate and conveying air velocity. The reason for this is the need to provide models that can be used for both the design of future systems and for checking the operation of existing systems.

In the design of a system a specific value of conveying air velocity will generally be recommended, together with a pipe bore, and it is the value of volumetric flow rate that is required for specification of the blower or compressor. In order to check an existing system it is usually necessary to determine the conveying air velocity for the particular conditions.

In addition to providing the appropriate models for the evaluation of air requirements and conveying air velocities, graphical representation of these models is also presented. With programmable calculators and computers, models such as these can be handled quite easily and quickly. Graphs, however, do have the advantage of showing visually the relative effects of the various parameters, and in some cases can be used very effectively to illustrate particular processes.

9.2.2 The influence of pipe bore

The diameter of a pipeline probably has the most significant effect of any single parameter on volumetric flow rate. The volumetric flow rate through a pipeline depends upon the mean velocity of flow at a given point in the pipeline and the pipe section area. The relationship is:

$$\dot{V} = C \times A \tag{9.1}$$

where $\dot{V}$ is the volumetric flow rate (m^3/s), C is the conveying air velocity (m/s) and A is the pipe section area (m^2) = $\pi d^2/4$ for a circular pipe, where d is the pipe bore (m) so that

$$\dot{V} = \frac{\pi d^2 C}{4} \text{ m}^3/\text{s} \tag{9.2}$$

or

$$C = \frac{4\dot{V}}{\pi d^2} \text{ m/s} \tag{9.3}$$

A graphical representation of the above models is presented in Figure 9.2. This is a plot of volumetric air flow rate against conveying air velocity, with a series of lines representing the relationship for different sizes of pipe. Conveying air velocities from about 2 to 40 m/s have been considered in order to cover the two extremes of minimum velocity in dense phase conveying and maximum velocity in dilute phase conveying. With pipeline bore as the family of curves this is a linear relationship.

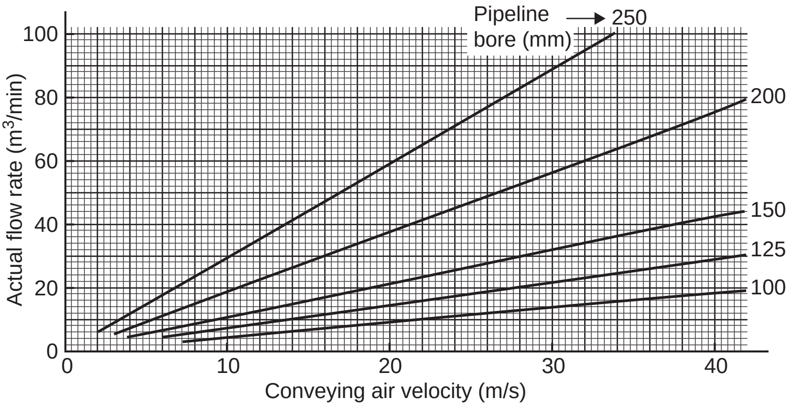


Figure 9.2 The influence of air velocity and pipeline bore on volumetric flow rate.

9.2.2.1 Reference conditions

It should be noted that the volumetric flow rate on this graph is not related to any reference conditions. It is the actual flow rate at any given condition of air pressure and temperature. Equations (9.1)–(9.3) and Figure 9.2 can be used either to determine the resulting velocity for a given flow rate in a given pipe size, or to determine the required volumetric flow rate knowing the velocity and pipe size.

Blowers and compressors are usually rated in terms of 'free air delivered'. This means that the volumetric flow rate is related to ambient conditions for reference purposes – usually a pressure of 1.013 bar absolute and a temperature of 15°C (288 K). The influence of pressure and temperature on volumetric flow rate, and hence velocity, is discussed in the following sections.

9.2.2.2 Pipeline influences

The air at the start of a conveying line will always be at a higher pressure than that at the end of the line because of the pressure drop necessary for air and material flow. Density decreases with decrease in pressure and so, in a constant bore pipeline, the air velocity will gradually increase from the start to the end of the pipeline. The air mass flow rate will remain constant at any section along a pipeline, but as the rating of blowers and compressors is generally expressed in volumetric flow rate terms, knowledge of the air mass flow rate is of little value in this situation.

9.2.3 The Ideal Gas Law

The relationship between mass and volumetric flow rate, pressure and temperature for a gas can be determined from the Ideal Gas Law:

$$p\dot{V} = \dot{m}RT \tag{9.4}$$

where p is the absolute pressure of gas (kN/m^2), $\dot{V}$ is the actual volumetric flow rate of the gas at the pressure p (m^3/s), $\dot{m}$ is the mass flow rate of gas (kg/s), R is the characteristic gas constant (kJ/kg · K) and T is the absolute temperature of gas (K) = t°C + 273.

Rearranging this gives:

$$\frac{p\dot{V}}{T} = \dot{m}R$$

For a given gas and constant mass flow rate:

$$\frac{p\dot{V}}{T} = constant$$

so that

$$\frac{p_1\dot{V}_1}{T_1} = \frac{p_2\dot{V}_2}{T_2} \tag{9.5}$$

where subscripts 1 and 2 can relate to any two points anywhere along the conveying pipeline or in terms of 'free air conditions'

$$\frac{p_0\dot{V}_0}{T_0} = \frac{p_1\dot{V}_1}{T_1} \tag{9.6}$$

where subscript 0 refers to reference conditions usually $p_0 = 101.3$ kN/m^2 absolute, $T_0 = 288$ K and $\dot{V}_0$ = free air delivered, and subscript 1 refers to actual conditions anywhere along the conveying pipeline.

9.2.3.1 *Working relationships*

Substituting reference values into Equation (9.6) and rearranging gives:

$$\dot{V}_0 = \frac{288 \times p_1}{101.3 \times T_1} \times \dot{V}_1 = 2.843 \times \frac{p_1\dot{V}_1}{T_1} \text{ m}^3/\text{s} \tag{9.7}$$

or alternatively

$$\dot{V}_1 = 0.352 \times \frac{T_1\dot{V}_0}{p_1} \text{ m}^3/\text{s} \tag{9.8}$$

9.2.3.2 *Gas constants*

The constant, R, in Equation (9.4) has a specific value for every gas and is obtained from:

$$R = \frac{R_0}{M} \text{ kJ/kg} \cdot \text{K} \tag{9.9}$$

Table 9.2 Values of characteristic gas constant

Gas	Equation	Molecular weight M	Gas constant R (kJ/kg · K)
Air		28.96	0.2871
Nitrogen	N_2	28.01	0.2968
Oxygen	O_2	32.00	0.2598
Carbon dioxide	CO_2	44.01	0.1889
Steam	H_2O	18.01	0.4616
Argon	Ar	39.95	0.2081

where R_0 is the universal gas constant kJ/kg (mol · K) $= 8.3143$ kJ/kg-mol · K and M is the molecular weight (mol).

Values for air and some commonly employed gases are presented in Table 9.2. Whichever gas is used, the appropriate value of R for that gas is simply substituted into Equation (9.4) and the design process is exactly the same.

9.2.3.2.1 The use of nitrogen

It will be noticed that there is little more than 3 per cent difference between the values of R for air and nitrogen, since about 78 per cent of air, by volume, is nitrogen. As a consequence little error would result if a system was inadvertently designed on the basis of air, and nitrogen was used for conveying the material instead. If carbon dioxide or superheated steam was to be used to convey the material, however, there would be a very significant error.

9.3 The influence of pressure

The influence that air pressure has on volumetric flow rate is shown graphically in Figures 9.3–9.5. These are plots of volumetric flow rate, at the reference atmospheric pressure of 1.013 bar absolute, against actual volumetric flow rate. To simplify the problem an isothermal situation has been assumed in order to isolate the influence of pressure, that is: $T_1 = T_0$. Once again this is a linear relationship.

A series of lines representing the relationship for different air pressures is given on each graph, and each one illustrates the relationship for a different type of system. One is a low positive pressure system, another is for the use of high pressure air, and the third relates to vacuum conveying.

9.3.1 System influences

In Figure 9.3 the pressure ranges from 0 (atmospheric) to 0.8 bar gauge and so is appropriate to low pressure, typically dilute phase, conveying systems. If an air flow rate of 25 m^3/min at free air conditions is considered it can be seen from Figure 9.3 that the actual volume at the material feed point at the start of the conveying line, will be reduced to about 14 m^3/min if the air pressure is 0.8 bar gauge. Alternatively, the

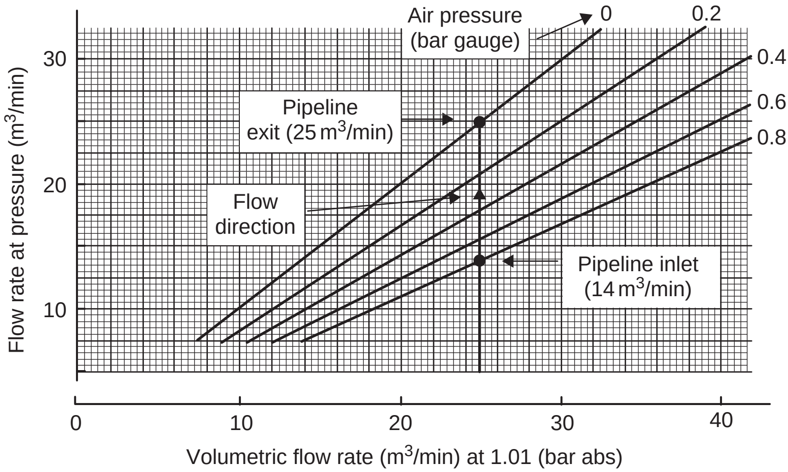


Figure 9.3 The influence of air pressure on volumetric flow rate low positive pressure systems.

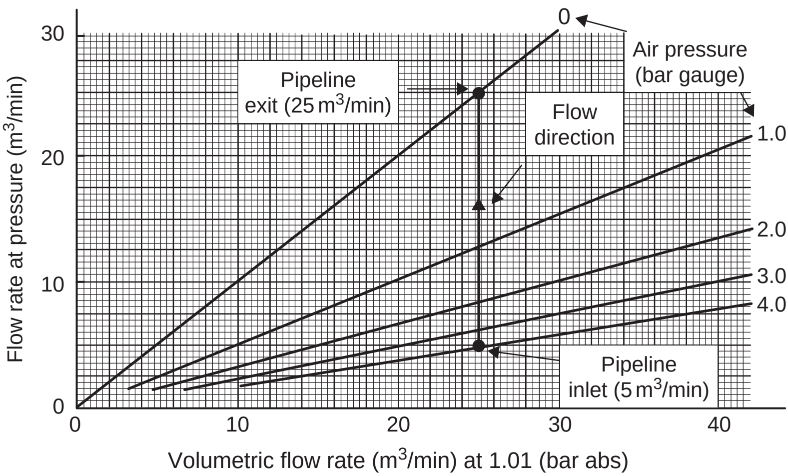


Figure 9.4 The influence of air pressure on volumetric flow rate high pressure systems.

flow rate can be determined from Equation (9.8):

$$\dot{V}_0 = \frac{0.352 \times 288 \times 25}{(1.013 + 0.8) \times 100} = 13.98 \text{ m}^3/\text{min}$$

In Figure 9.4 the pressure ranges from 1.0 to 4.0 bar gauge and so is relevant to high pressure conveying systems. If the air at the material feed point is 4.0 bar gauge a free air flow rate of 25 m^3/min will be reduced to about 5 m^3/min, as can be seen from Figure 9.4. In both of the above cases the air will expand through the conveying line

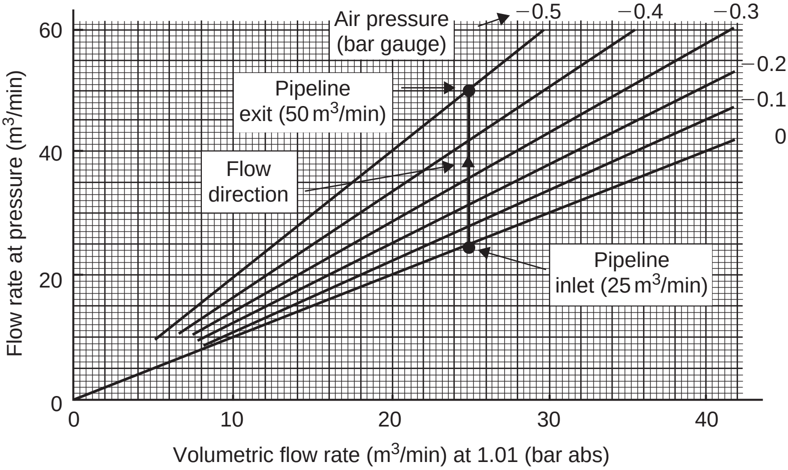


Figure 9.5 The influence of air pressure on volumetric flow rate negative pressure systems.

back, approximately, to the free air value, at the discharge hopper and filtration unit at the end of the pipeline.

In the case of a vacuum system, however, free air conditions prevail at the material feed point. The air then expands beyond this and so, if the exhaust is at −0.5 bar gauge, 25 m^3/min of free air will increase to about 50 m^3/min, as can be seen from Figure 9.5. Alternatively, the air flow rate can be determined from Equation (9.8) once again:

$$\dot{V}_1 = \frac{0.352 \times 288 \times 25}{(1.013 - 0.5) \times 100} = 49.4 \text{ m}^3\text{/min}$$

It can be seen from this range of values that it is extremely important to take this compressibility effect into account in the sizing of pipelines, and particularly so in the case of combined positive and negative pressure systems.

9.3.2 Velocity determination

If Figures 9.3 and 9.5 are used in conjunction with Figure 9.2 it will be possible to determine the resulting conveying air velocities for given conditions. An alternative to this procedure is to combine the models for actual volumetric flow rate and conveying air velocity.

9.3.2.1 Working relationships

From Equation (9.2) the actual volumetric flow rate:

$$\dot{V}_1 = \frac{\pi d^2 C}{4}$$

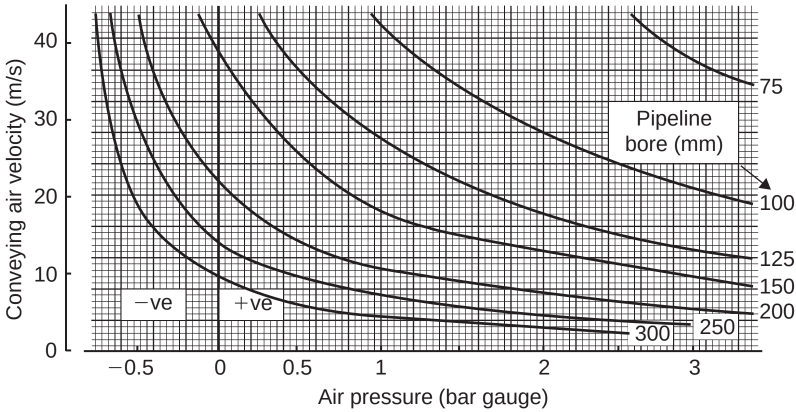


Figure 9.6 The influence of air pressure and pipe bore on conveying air velocity for a free air flow rate of 40 m^3/min.

and from Equation (9.7) free air delivered:

$$\dot{V}_0 = 2.843 \times \frac{p_1 \dot{V}_1}{T_1}$$

Substituting Equation (9.2) into Equation (9.7) gives:

$$\dot{V}_0 = 2.23 \times \frac{p_1 d^2 C}{T_1} \ \text{m}^3/\text{s} \tag{9.10}$$

which is the form required for system design. Rearranging to the form required for checking existing systems gives:

$$C = 0.448 \times \frac{T_1 \dot{V}_0}{d^2 p_1} \ \text{m/s} \tag{9.11}$$

9.3.2.2 Graphical representation

It will be seen from these models that a total of five variables are involved and so it is not possible to represent them diagrammatically on a single graph. By neglecting the influence of temperature at this stage the models can be reduced to four variables, and so if particular values of volumetric flow rate are chosen, the influence of the remaining three variables can be shown. This is presented for four values of volumetric flow rate in Figures 9.6–9.9, the volumetric flow rates being referred to ambient conditions of temperature and pressure.

These are all graphs of conveying air velocity drawn against air pressure, with pipe bore plotted as the family of curves. The reason for this is that both conveying air

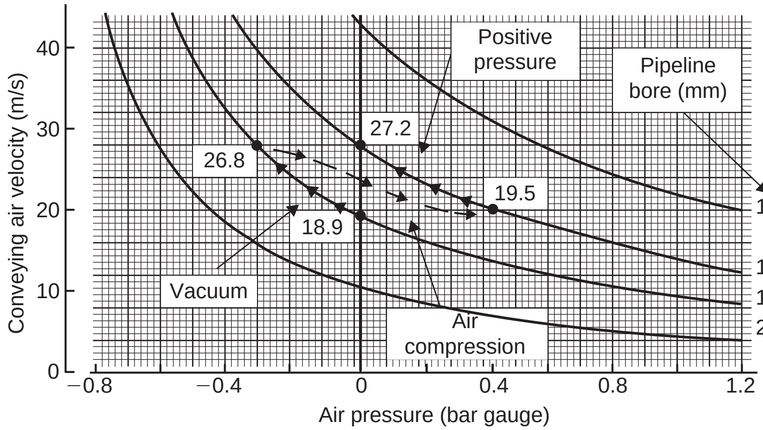


Figure 9.7 Velocity profile for a typical combined positive and negative pressure (suck-blow) system with a free air flow rate of $20\,m^3$/min.

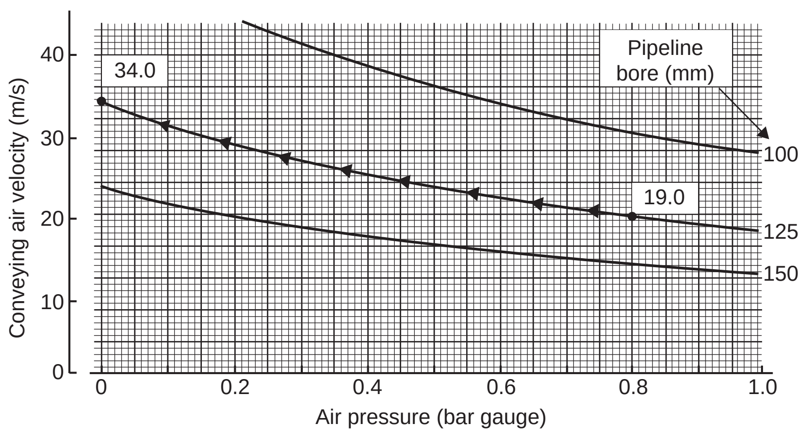


Figure 9.8 Typical velocity profile for a low pressure dilute phase system for a free air flow rate of $25\,m^3$/min.

velocity and air pressure are infinitely variable in the system, but pipelines are only available in a number of standard sizes. They are drawn once again to illustrate the performance of different types of system. Figures 9.6 and 9.9 cover the range of both positive and negative pressure systems and Figures 9.7 and 9.8 are drawn for positive pressure systems only.

Figure 9.6 clearly illustrates the influence of pressure on conveying air velocity in a single bore pipeline. The slope of the constant pipe bore curves increase at an increasing rate with decrease in pressure. The reason for this can be seen from Equation (9.11). Conveying line inlet air pressure, p_1, is on the bottom of the equation, and so as its value gets lower, small changes in its value have a more significant effect.

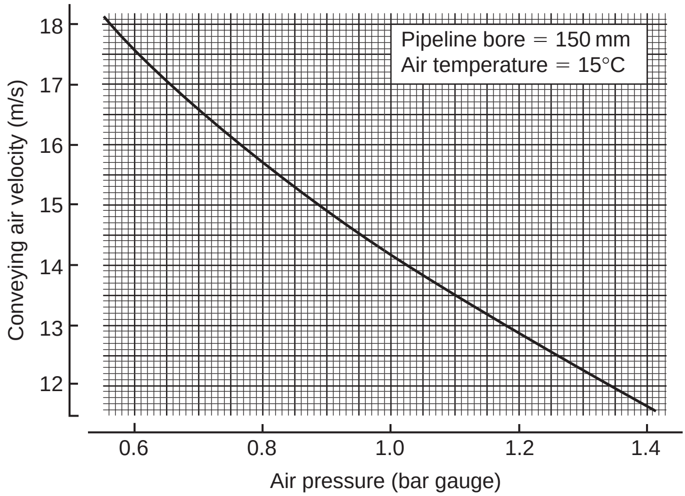


Figure 9.9 The influence of air pressure on conveying air velocity for a free air flow rate of 30 m^3/min.

This is particularly so for negative pressure systems, and is quite dramatic at high vacuum, as shown in Figure 9.6.

9.3.2.2.1 Suck-blow systems

On Figure 9.7 the expansion lines for a typical combined positive and negative pressure system are superimposed. This illustrates the problem of both pipeline sizing, with this type of system, and the relative expansion effects at different air pressures. With 20 m^3/min of free air a 150 mm bore pipeline would be required for the vacuum line. This would give an air velocity of 18.9 m/s at the material feed point and would expand to 26.8 m/s if the exhaust was at −0.3 bar gauge.

If the pressure on the delivery side of the blower was 0.4 bar gauge a 125 mm bore pipeline would be required. This would give pick-up and exit air velocities of 19.5 and 27.2 m/s, respectively. It will be noted that the pick-up and exit air velocities are very similar for the two parts of the system, but different size pipelines are required. The free air flow rate is clearly the same for the two parts of the system and so it will be seen that it is entirely due to the influence of the conveying line inlet air pressure on the compressibility of the air. In the above case it has been assumed that the material is conveyed in dilute phase suspension flow and that the minimum conveying air velocity for the material is about 15 m/s. If a 20 per cent margin is allowed when specifying a conveying line inlet air velocity, this would need to be about 18 m/s.

9.3.2.2.2 Low pressure systems

In Figure 9.8 a typical velocity profile for a low pressure dilute phase conveying system is shown. As with the previous system, a minimum conveying line inlet air velocity of 18 m/s is required, and so with a free air flow rate of 25 m^3/min and a conveying line inlet air pressure of 0.8 bar gauge, a 125 mm bore pipeline would be required. The resulting conveying line inlet air velocity is about 19 m/s, and it will be seen that the air velocity gradually increases along the length of the pipeline as the air pressure decreases. At the end of the pipeline the conveying line exit air velocity will be about 34 m/s.

The above is simply an example to illustrate the variation in conveying air velocity from feed point to material discharge in a pipeline. For the design of a conveying system Equation (9.10) would be used to evaluate the free air requirements.

For a 125 mm bore pipeline, and with a conveying line inlet air pressure of 0.8 bar gauge (181.3 kN/m^2 absolute) and a conveying line inlet air velocity of 18 m/s, this would come to 0.395 m^3/s or 23.7 m^3/min. If the influence of pressure was not taken into account, and the volumetric flow rate was evaluated on the basis of an air velocity of 18 m/s, effectively at the end of the pipeline, the conveying line inlet air velocity that would result at a pressure of 0.8 bar gauge would be about 10 m/s, and the pipeline would almost certainly block.

The influence of air pressure on conveying air velocity is illustrated further with Figure 9.9. This is a graph of conveying air velocity plotted against air pressure, and is drawn for a free air flow rate of 30 m^3/min in a 150 mm bore pipeline. During the operation of a pneumatic conveying system the conveying line inlet air pressure may vary slightly, particularly if there are variations in the feed rate of the material into the pipeline. If the feed rate increases for a short period by 10 per cent, the conveying line inlet air pressure will also have to increase by about 10 per cent in order to meet the increase in demand.

If the minimum conveying air velocity for the material was 15 m/s and it was being conveyed with a conveying line inlet air pressure of 0.8 bar gauge, an increase in pressure to only 1.0 bar gauge would probably be sufficient to result in a pipeline blockage. At low air pressures conveying air velocity is very sensitive to changes in air pressure and so due consideration must be given to this when deciding upon a safety margin for conveying line inlet air velocity, and hence the volumetric flow rate of free air, to be specified for the system.

9.4 Stepped pipeline systems

Figures 9.6–9.8 show quite clearly the nature of the problem of single bore pipeline conveying, with respect to air expansion and hence conveying air velocities, particularly where high pressures or vacuums are employed. For both long distance, and dense phase conveying, it is generally necessary to have a fairly high air pressure at the start of the conveying line. As the pressure of the conveying air decreases along the length of the line, its density decreases, with a corresponding increase in velocity, as illustrated above. A simple means of limiting the very high velocities that can occur towards the end of a pipeline is to step the pipeline to a larger bore once or twice along its length. By this means it will be possible to keep the conveying air velocity within reasonable limits.

The ultimate solution, of course, is to use a tapered pipeline, for in this the conveying air velocity could remain constant along the entire length of the pipeline. This, however, is neither practical nor possible, but it does provide the basis for a model of what is required. A stepped pipeline, therefore, should be designed to achieve a velocity profile that is as close as practically possible to a constant value.

9.4.1 Step location

The critical parameter in the design of any pipeline is the minimum value of conveying air velocity, for the given material and conveying conditions. In the design of a stepped pipeline system it is essential to ensure that the conveying air velocity does not fall below the minimum value anywhere along the length of the pipeline. In this respect it is the location of the step to each larger bore section of the pipeline that is crucial. With the air expanding into a larger bore pipe the velocity will fall, approximately in proportion to the change in pipe section area, at the step. The location of the step, therefore, must be such that the pressure is low enough to ensure that the velocity in the larger bore section at the step does not drop below the given minimum conveying air velocity.

A pipeline having two steps, and hence three sections of pipeline of different bore, is shown diagrammatically below in Figure 9.10. Reference numbers are assigned to the start and end of each section, and provided that there is no leakage of air into or out of the pipeline between the material feed point at ① and the discharge point at ⑥, the air mass flow rate will remain constant and the continuity equation can be used to equate conditions at any point along the length of the stepped pipeline.

By combining Equations (9.5) and (9.6) and substituting $\dot{V}$ from Equation (9.2) gives:

$$C_3 = \frac{4 p_0 \dot{V}_0 T_3}{\pi d_{3-4}^2 p_3 T_0} \text{ m/s} = 0.448 \, \frac{\dot{V}_0 T_3}{d_{3-4}^2 p_3} \tag{9.12}$$

This will give the conveying air velocity at the start of the second section of the stepped pipeline. By equating to the free air conditions in this way, the velocity at any section of the pipeline can be evaluated. If it is the pressure at a step in the pipeline that is required Equation (9.12) can be rearranged to give:

$$p_3 = \frac{4 p_0 \dot{V}_0 T_3}{\pi d_{3-4}^2 T_0 C_3} = 0.448 \frac{\dot{V}_0 T_3}{d_{3-4}^2 C_3} \tag{9.13}$$

It should be noted that since the end of one section of pipeline terminates at the point where the next section of pipeline starts, the pressure difference between these two points can be disregarded, and so in the above case $p_2 = p_3$ and $p_4 = p_5$. It would

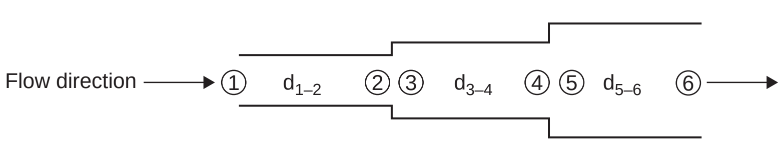


Figure 9.10 Stepped pipeline notation.

generally be recommended that a tapered expansion section should be used to join any two sections of pipeline at a step.

9.4.2 Dilute phase conveying

Figure 9.11 illustrates the case of a dilute phase conveying system, typically for a long distance conveying application.

The minimum conveying air velocity that must be maintained for the material is about 15 m/s, and 60 m^3/min of free air is available to convey the material. The conveying line inlet air pressure is 4 bar gauge. From Figure 9.11 it will be seen that a 125 mm bore pipeline will be required for these conditions, and the resulting conveying line inlet air velocity will be 16.5 m/s.

If a single bore pipeline was to be used for the entire length of the line the conveying line exit air velocity would be 81.5 m/s. The inlet air pressure is 4 bar gauge, which is approximately 5 bar absolute, and so if the discharge is to atmospheric pressure, a near fivefold increase in air velocity can be expected. If the material being conveyed is only slightly abrasive, severe wear will occur at any bend towards the end of the pipeline, because of the excessive velocity, and significant degradation of the conveyed material will also occur, even if the material is not particularly friable.

If the velocity was allowed to rise to 30 m/s in this 125 mm bore pipe a change to a 150 mm bore pipe would only reduce the velocity to 21 m/s. The velocity in a 200 mm bore pipe would be about 12 m/s, however, and this is unlikely to be acceptable. A 175 mm bore pipe would probably be satisfactory, but care must be taken that standard pipe sizes are selected. Even in a 175 mm bore pipeline the velocity at exit would be over 40 m/s and so it is clear that two steps and three different pipe sizes would be required.

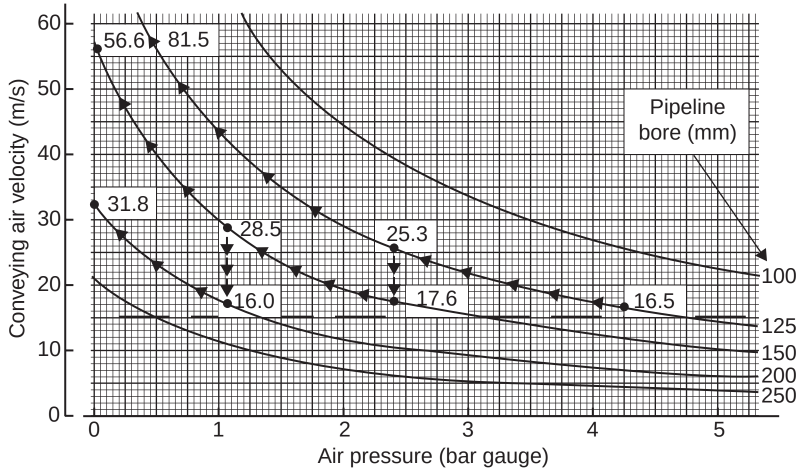


Figure 9.11 Stepped pipeline velocity profile for high pressure dilute phase system using 60 m^3/min of air at free air conditions.

The velocity profile for a possible combination of 125, 150 and 200 mm bore pipes is shown superimposed in Figure 9.11, but even with this the exit velocity is about 32 m/s. A plot similar to that shown in Figure 9.11, however, will give a clear indication of what is possible. The velocities at the six reference points along the pipeline are also presented on Figure 9.11 and these can be evaluated by using Equations (9.12) and (9.13).

9.4.3 Dense phase conveying

Figure 9.12 illustrates the case of a dense phase conveying system. The minimum conveying air velocity that must be maintained for the material is about 6 m/s, and 10 m^3/min of free air is available to convey the material. The conveying line inlet air pressure is 4 bar gauge. From Figure 9.12 it will be seen that a 100 mm bore pipeline will be required for these conditions, and the resulting conveying line inlet air velocity will be 7.6 m/s. If a single bore pipeline is used the conveying line exit air velocity will be 38.2 m/s.

Although this might be accepted in a dilute phase conveying system it is quite unnecessary in a dense phase system. Apart from reducing problems of erosive wear and particle degradation, by reducing conveying air velocities, a stepped pipeline is also likely to achieve an improved conveying performance, compared with a single bore pipeline, for the same air flow conditions. The velocity profile for a combination of 75, 100 and 125 mm bore pipes is shown superimposed in Figure 9.12. This has resulted in the conveying air velocity being confined to a relatively narrow band, with the maximum value being limited to only 13.8 m/s.

A maximum value of velocity (13.8 m/s) is below the minimum value of velocity that would be used for a dilute phase conveying system. In terms of conveying this is not a problem and comes as a direct consequence of the difference in properties between the two classes of material (see Figure 8.3). The only problem may be

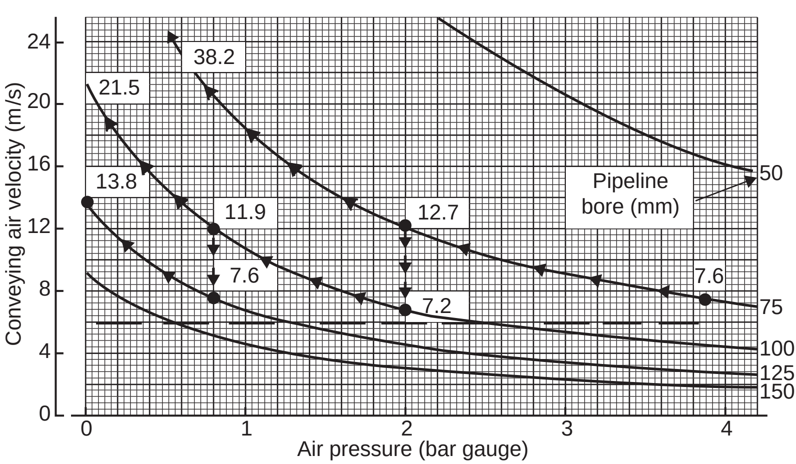


Figure 9.12 Stepped pipeline velocity profile for high pressure dense phase system using 10 m^3/min of air at free air conditions.

with regard to the purging of material from the pipeline and this is considered in Section 9.5.

9.4.4 Vacuum conveying

Although negative pressure systems are limited to a maximum conveying line pressure drop of less than 1 bar, stepping of the pipeline with vacuum conveying systems is just as important as it is with high positive pressure conveying systems. A typical vacuum conveying system is shown in Figure 9.13. It is drawn for a dilute phase system, where a minimum conveying air velocity of 16 m/s must be maintained, using 15 m^3/min of free air and exhausting to -0.6 bar gauge ($101.3 - 60 = 41.3$ kN/m^2 absolute).

If the vacuum was a little higher than 0.6 bar, a step to a third section of pipeline of 200 mm bore would be required. Even with a conveying line exit air pressure of -0.4 bar gauge a step could be usefully incorporated, as will be seen in Figure 9.13. As the slope of the constant pipe bore curves increase at an increasing rate with decrease in pressure, as discussed earlier in relation to Equation (9.11), steps are required more frequently at low air pressures.

9.4.4.1 Step position

A practical problem that arises from this is the actual positioning of the various steps along the length of the pipeline. As a first approximation, in the absence of any other information, pipeline lengths can be sized in proportion to the conveying line pressure drop for each section, provided that a reasonably uniform value of conveying air velocity is maintained along the length of the pipeline. It can be seen from Figures 9.11 to 9.13 that if there is a risk of the velocity being too low at the start of the next section, and the pipeline blocking, then the transition to the larger pipe size should be moved a little further downstream, where the pressure will be slightly lower.

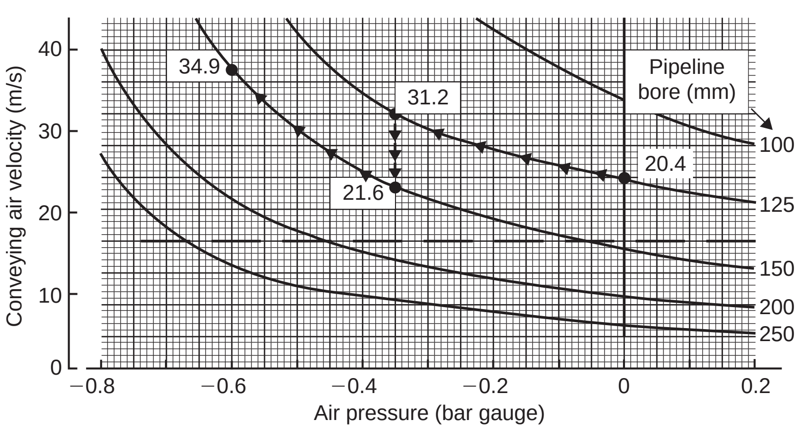


Figure 9.13 Stepped pipeline velocity profile for high vacuum system using 15 m^3/min of air at free air conditions.

9.4.5 Pipeline staging

With reference to Figure 9.6 and Equation (9.11) it will be seen that with increase in pressure the slope of the curves decrease. If a stepped pipeline system was to be designed on the basis of a doubling in conveying air velocity, for each section of pipeline, the working pressure for each section of pipeline would increase significantly with increase in pressure, as is shown in Table 9.3.

If it was required to convey a material over a distance of 100 km, it would only be economical if an air supply pressure much higher than 6 bar was to be used. It would also be necessary to divide the system into stages, such that the material was discharged from one system, when the pressure had fallen to a given value, and be fed into the next system with high pressure air.

With a conveying line inlet air pressure of 31 bar gauge, for example, the first step would not be necessary until the pressure had fallen to 15 bar gauge, which gives a working pressure difference of 16 bar. If the system discharged to atmospheric pressure, the pressure at entry to the last section of pipeline would be 1 bar gauge and the working pressure difference would only be 1 bar. This effect is illustrated in Figure 9.14, which illustrates the velocity profile for the latter sections of a very high pressure stepped pipeline system in which the material is conveyed in dilute phase.

It would be recommended, therefore, that for a very long distance conveying system, at the end of each stage along the pipeline, and at the very end of the pipeline, the

Table 9.3 Typical working pressures relating to a 2:1 conveying line air velocity expansion ratio

Air inlet pressure						
– Bar absolute	1	2	4	8	16	32
– Bar gauge	0	1	3	7	15	31
Air outlet pressure (bar gauge)	−0.5	0	1	3	7	15
Pressure difference (bar)	0.5	1	2	4	8	16

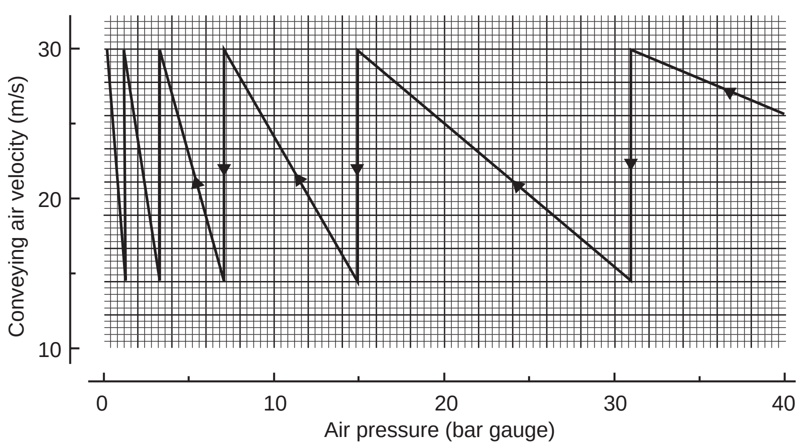


Figure 9.14 Velocity profile for very high pressure stepped pipeline system.

material should be discharged at a pressure no lower than about 3 bar gauge. By discharging at a high pressure, rather than atmospheric, the last two or three sections of the largest bore pipeline can be dispensed with. The reduction in working pressure drop would be very small in comparison and it would make for a very much simpler pipeline design and layout.

9.5 Pipeline purging

In many applications it is necessary to purge the pipeline clear of material at the end of a conveying run, particularly with perishable commodities and time limited products. In single bore pipelines this is rarely a problem, even if the material is conveyed in dense phase, because the velocity at the end of the pipeline is usually sufficiently high. There can, however, be problems with stepped pipelines. A comparison of the velocity profiles for flow in single and stepped bore pipelines is presented in Figure 9.15.

This is drawn for an air flow rate of 30 m^3/min at free air conditions. It relates to the dense phase conveying of a material for which the minimum conveying air velocity is about 5 m/s. This is similar to the plot shown in Figure 9.12, except that the air flow is presented from left to right with the new figure. Although this may be more conventional in terms of system sketching, it does mean that the air pressure axis is reversed, and is offered simply as an alternative means of presentation.

Figure 9.15 is developed further in Figure 9.16 with empty conveying line velocity profiles added. This also provides a comparison between single bore and stepped bore pipelines, with respect to purging, and illustrates the problem towards the end of a stepped pipeline.

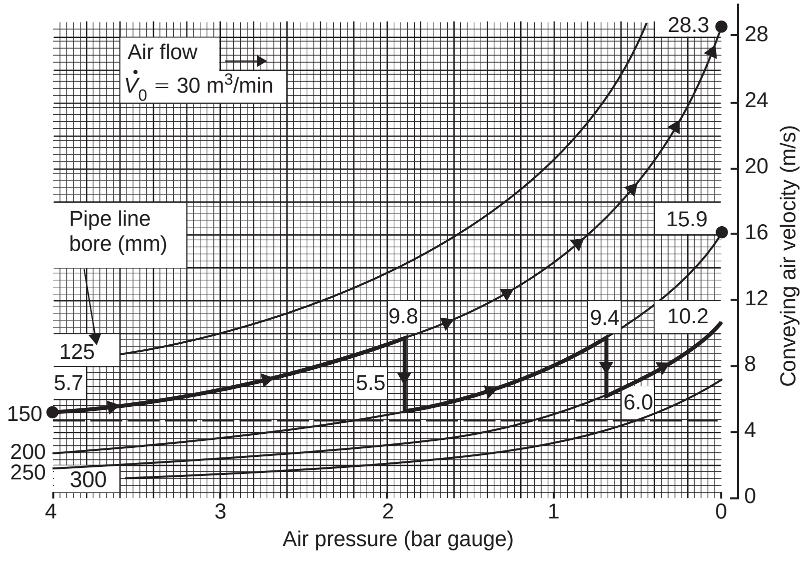


Figure 9.15 Comparison of velocity profiles in single and stepped bore pipelines.

At the end of a conveying run, with no material to convey, the pressure at the material feed point, at the start of the pipeline, will drop to that of the air only pressure drop value. For low velocity dense phase conveying the empty line pressure drop will only be a fraction of the pressure drop required for conveying. Thus the velocity of the air through a single bore empty pipeline will be very high throughout the entire length of the pipeline. At the end of the pipeline the air velocity will be exactly the same as in the conveying case, because the pressure here is always atmospheric.

At the material feed point the air velocity will only be slightly lower than that at the exit since the air pressure at the feed point is so much lower when material is not being conveyed. This will be seen with reference to Equation (9.11), for the air pressure, p, is in the denominator of the equation and there will be no significant change in the volumetric flow rate, $\dot{V}_0$, with reduction in pressure.

With the stepped bore pipeline this same volumetric flow rate of air has to expand into the larger bore section of pipeline, and so its velocity will reduce, as shown in Figure 9.16. At the end of the pipeline the situation is exactly the same as in the single bore pipeline case. The velocity for both conveying and purging will be the same, because the pressure here is always atmospheric. Since the purging velocity will not be constant throughout the pipeline the potential for clearing material from the latter sections of stepped pipelines by purging, therefore, will be severely limited.

9.6 The influence of temperature

In the above figures the influence of temperature was not included, so that the influence of pressure alone could be illustrated, and so it was assumed that all flows and

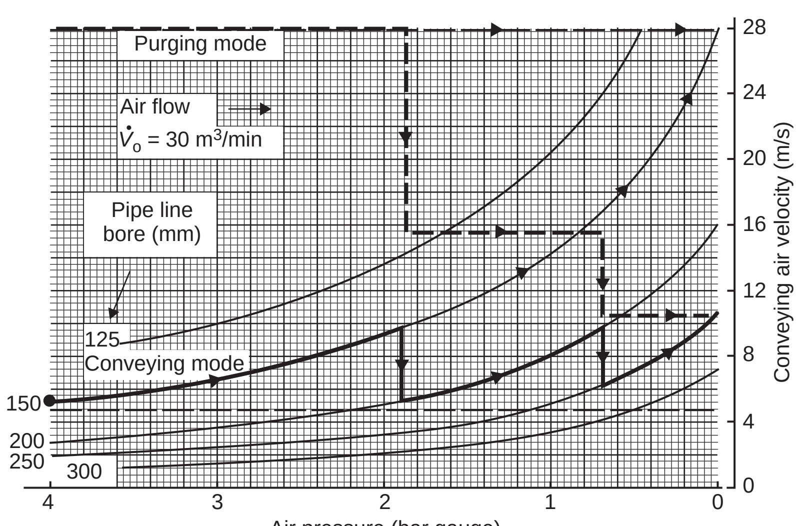


Figure 9.16 Comparison of velocity profiles in single and stepped bore pipelines in both conveying and purging modes.

expansions were isothermal and at the standard reference temperature. In Equations (9.7) and (9.8) the influence of pressure and temperature on actual volumetric flow rate is presented. If the influence of pressure is neglected, in order to separate the effect of temperature, the equation reduces to:

$$\dot{V}_1 = \frac{T_1 \dot{V}_0}{288} \text{ m}^3/\text{s} \tag{9.14}$$

The influence that air temperature can have on volumetric flow rate is shown graphically in Figure 9.17. This is a plot of volumetric flow rate at the reference temperature of 15°C, against actual volumetric flow rate at a given temperature. It should be noted that in Equation (9.14) and Figure 9.17 all pressures are standard atmospheric so that the influence of temperature can be considered in isolation from that of pressure.

It can be seen from Figure 9.17 that small changes in temperature do not have the significant effect on volumetric flow rate that changes in pressure can have. This is because the influence of temperature is in terms of the ratio of absolute temperatures and the 273 that has to be added to the Celsius temperature has a considerable dampening effect.

Air temperatures higher than 100°C can be experienced, however. Air at a temperature of 100°C will result from the compression of air in a positive displacement blower operating at about 1 bar gauge, but from a screw compressor delivering air at 3 bar gauge it could be more than 200°C. In some cases the material to be conveyed may be at a high temperature and this could have a major influence on the air flow rate, and hence conveying air velocity. This particular situation is considered in some detail below.

It will be seen from Equation (9.11) that if the temperature is reduced, then the velocity will fall. This is because the density of the air increases with decrease in temperature. The volumetric flow rate of air that is specified must be sufficient to maintain the desired conveying line inlet air velocity at the lowest temperature anticipated. Due

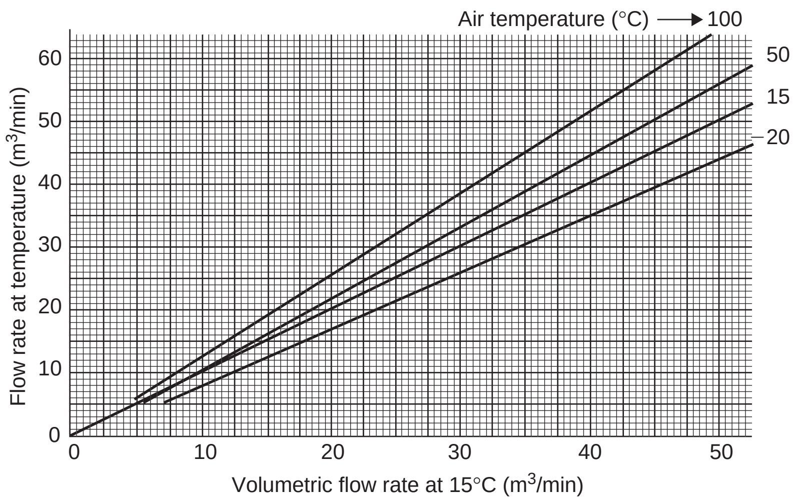


Figure 9.17 The influence of air temperature on volumetric flow rate.

account, therefore, must be taken of cold start-up and winter operating conditions, particularly with vacuum conveying systems that draw in atmospheric air. This point is illustrated quite forcefully in Figure 9.18.

Figure 9.18 is drawn for a 150 mm bore pipeline and a conveying line inlet air pressure of 1 bar gauge. It will be seen from this that conveying air velocity can be very sensitive to temperature. The average gradient on this plot is about 0.04 m/s per °C temperature change, and so if the temperature of the conveying air was reduced for some reason it could result in pipeline blockage in a system operating with a pick-up velocity close to the minimum conveying air velocity for the given material.

9.6.1 Conveyed material influences

The above analysis refers to the situation with regard to the air only. For the conveying line, however, the material also has to be taken into account, and although the air may be at 20°C, the material to be conveyed may be at 200°C or more. In order to determine the temperature of the conveyed suspension it is necessary to carry out an energy balance. If a control surface is taken around the material feeding device and the immediate pipelines an energy balance gives:

$$(\dot{m}C_{p}t)_{p} + (\dot{m}C_{p}t)_{a} = (\dot{m}C_{p}t)_{S} \tag{9.15}$$

where $\dot{m}$ is the mass flow rate (kg/s), C_p, is the specific heat (kJ/kg · K), t is the temperature (ºC) and the subscript p refers to conveyed material or particles, a is air, s is suspension.

If heat exchanges with the surroundings, kinetic energies and other minor energy quantities are neglected.

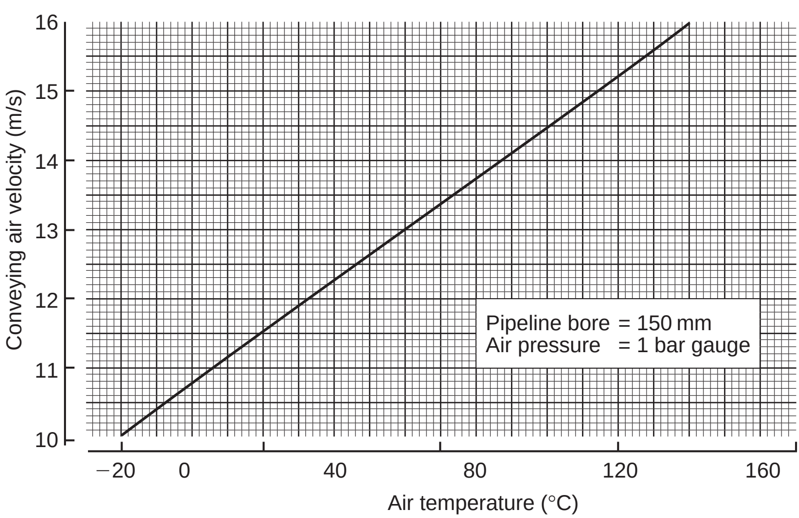


Figure 9.18 The influence of air temperature on conveying air velocity for a free air flow rate of 25 m³/min.

It is the temperature of the suspension, t_s, that is required and so a rearrangement gives:

$$t_{\mathrm{s}} = \frac{\dot{m}_{\mathrm{p}} C_{\mathrm{p_p}}}{\dot{m}_{\mathrm{s}} C_{\mathrm{p_s}}} t_{\mathrm{p}} + \frac{\dot{m}_{\mathrm{a}} C_{\mathrm{p_a}}}{\dot{m}_{\mathrm{s}} C_{\mathrm{p_s}}} t_{\mathrm{a}}$$

From continuity

$$\dot{m}_{\mathrm{s}} = \dot{m}_{\mathrm{a}} + \dot{m}_{\mathrm{p}} \tag{9.16}$$

and by definition

$$\dot{m}_{\mathrm{p}} = \phi \dot{m}_{\mathrm{a}} \tag{9.17}$$

where ϕ is the solids loading ratio of the conveyed material
and

$$C_{\mathrm{p_s}} = \frac{\dot{m}_{\mathrm{a}} C_{\mathrm{p_a}} + \dot{m}_{\mathrm{p}} C_{\mathrm{p_p}}}{\dot{m}_{\mathrm{a}} + \dot{m}_{\mathrm{p}}}$$

Substituting these gives:

$$t_{\mathrm{s}} = \frac{\phi C_{\mathrm{p_p}} t_{\mathrm{p}} + C_{\mathrm{p_a}} t_{\mathrm{a}}}{\phi C_{\mathrm{p_p}} + C_{\mathrm{p_a}}} \ {}^{\circ}\mathrm{C} \tag{9.18}$$

With so many variables it is difficult to illustrate the relationship graphically. One case has been selected, however, for a conveyed material at a temperature of 15°C, and having a specific heat of 1.0 kJ/kg · K. This shows the influence of conveying line inlet air temperature and solids loading ratio on the resulting suspension temperature. It relates to the dilute phase conveying of a material with a positive displacement blower, where the conveying line inlet air temperature might be up to about 100°C. This is shown in Figure 9.19.

Figure 9.19 shows that the solids loading ratio has a dominating effect on the suspension temperature, even with dilute phase conveying. Unless the conveyed material has a very low specific heat value, and is conveyed in very dilute phase, the temperature of the conveyed suspension will be close to that of the material to be conveyed.

If cold air is used to convey a hot material, therefore, the cooling effect on the material of the cold air will be minimal. This is illustrated in more detail in Figure 9.20 where material and air inlet temperatures of 500°C and 20°C respectively have been considered.

Figure 9.20 is also drawn for a material having a specific heat of 1.0 kJ/kg K and highlights the influence of solids loading ratio. It must be stressed that the suspension of material and air will only reach the equilibrium temperature at some distance from the pipeline feeding point, for thermal transient effects have to be taken into account.

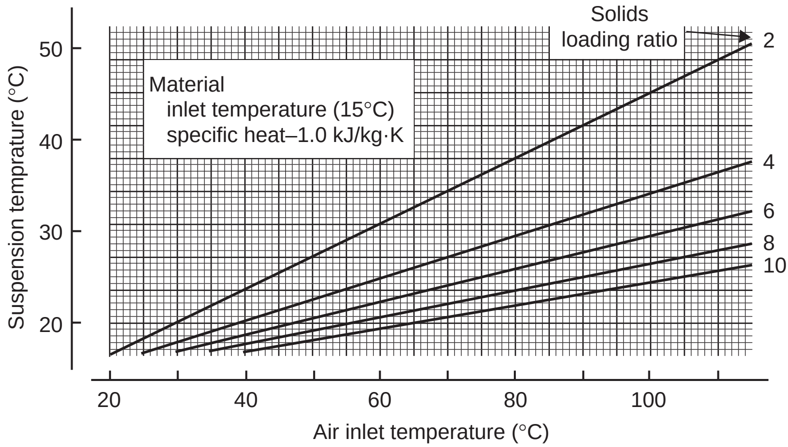


Figure 9.19 The influence of air inlet temperature and solids loading ratio on the equilibrium temperature of the suspension.

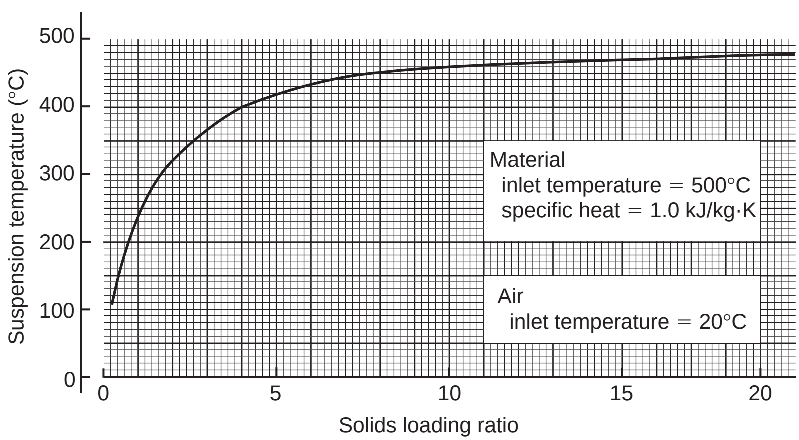


Figure 9.20 Influence of solids loading ratio on the equilibrium temperature.

The heat transfer process depends additionally upon the thermal conductivity of the material and the shape and size of the particles.

It is a time dependent process and with the high velocities required in dilute phase conveying, equilibrium will not be fully established at the end of the pipeline with many materials. Since volumetric flow rate decreases with decrease in temperature, if there is any doubt with regard to the temperature of the air at the start of a conveying line, the lowest likely value should be used for design purposes.

9.6.1.1 Specific heat

Specific heat is clearly an important property in this analysis and typical values are given in Table 9.4 for reference.

Table 9.4 Typical specific heat values

Material	Specific heat (kJ/kg·K)
Metals	
Copper	0.38
Nickel	0.45
Steel	0.47
Aluminium	0.89
Magnesium	1.01
Non-metals	
Sand, dry	0.80
Firebrick	0.96
Coal	1.30
Cotton	1.30
Bakelite	1.59
Cork	1.88
Note	
Air	1.00
Water	4.18

The specific heat values for air and water are also added for reference purposes, and that for air is a basic element in the model, of course. It will be noted, however, that water has a very much higher specific heat value than any of the other materials listed, and so if a material has a high moisture content this could have a considerable influence on the specific heat of the material.

9.7 The influence of altitude

As elevation increases, pressure naturally decreases, and so the elevation of a plant above sea level should always be noted for reference. With increase in elevation there is a corresponding drop in the value of the local atmospheric pressure and this will influence many of the velocities and volumetric flow rates in the calculations. There is, of course, a direct influence on the performance of vacuum conveying systems, since any reduction in atmospheric pressure automatically reduces the maximum available pressure difference. The variation of the local value of atmospheric pressure with the elevation of a plant above sea level is presented in Figure 9.21.

9.7.1 Atmospheric pressure

It will be seen from Figure 9.21 that for a plant located 1000 m above sea level there is a reduction of more than 10 per cent in atmospheric pressure, and equates to a reduction in pressure of about 11.4 kN/m^2 or 3.4 in Hg.

It will be seen from this that the influence of altitude should be considered in detail for plants located above about 300 m, particularly if a vacuum conveying system is to be considered. The normal atmospheric pressure at sea level can fluctuate quite naturally

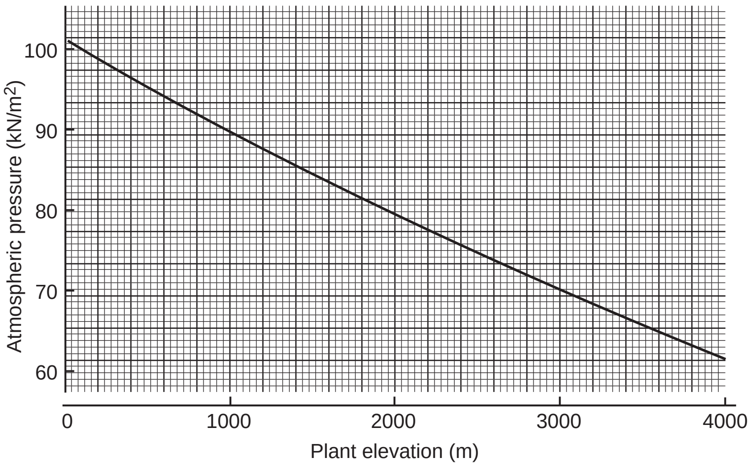


Figure 9.21 The influence of plant elevation on the local value of atmospheric pressure.

by ± 1 in. (25 mm) Hg on a day to day basis, which equates to a change in elevation of about 300 m. This fact might also have to be taken into account with vacuum systems operating on tight margins.

9.8 The use of air mass flow rate

When presenting data on the relationship between the main conveying parameters for a material in a given pipeline, air mass flow rate is generally used in preference to volumetric flow rate. Ideally air velocity should be used, as it is such an important parameter in pneumatic conveying. Due to the problems of compressibility, however, neither conveying line inlet air velocity nor volumetric flow rate are ideal for this purpose as they are not independent parameters. Air mass flow rate is an independent variable and is an ideal substitute in this work as its value remains constant along the length of a pipeline, whether single bore or stepped. Conveying air velocity and volumetric flow rate can be determined quite simply from air mass flow rate as follows:

From Equation (9.4)

$$\dot{V}_1 = \frac{\dot{m}_a R\,T_1}{p_1}\ \mathrm{m^3/s}$$

and substituting into Equation (9.3) gives:

$$C_1 = \frac{4\dot{m}_a R T_1}{\pi d^2 p_1}\ \mathrm{m/s} \tag{9.19}$$

which for air, with $R = 0.287\,\mathrm{kJ/kg \cdot K}$ gives:

$$C_1 = 0.365\frac{\dot{m}_a T_1}{d^2 p_1}\ \mathrm{m/s} \tag{9.20}$$

9.9 Nomenclature

A	Pipe section area (m^2)
C	Velocity (m/s)
Cp	Specific heat at constant pressure (kJ/kg·K)
Cv	Specific heat at constant volume (kJ/kg·K)
d	Pipe bore (m)
$\dot{m}$	Mass flow rate (kg/s and tonne/h)
M	Molecular weight (–)
p	Pressure (N/m^2, kN/m^2, bar). *Note*: 1 bar $=$ 100 kN/m^2 $=$ 10^5 N/m^2
R	Characteristic gas constant (kJ/kg·K)
R_0	Universal gas constant (kJ/kg-mol·K) $=$ 8.3143 kJ/kg mol·K
t	Actual temperature (°C)
T	Absolute temperature = t + 273 (K)
$\dot{V}$	Volumetric flow rate (m^3/s and m^3/min)

9.9.1 Greek

ϕ	Solids loading ratio $= \dot{m}_p/\dot{m}_a$

9.9.2 Subscripts

a	Air
p	Conveyed material or particles
s	Suspension
0	Reference conditions (free air)
	$p = 101.3$ kN/m^2
	$t = 15°C$
1, 2	Actual conditions, usually pipeline inlet and outlet.

Chapter 10

Air only relationships

10.1 Introduction

Although few reliable or universal models currently exist for predicting the pressure drop for gas–solid flows in pipelines, models for the single phase flow of a gas are well established. Although discussion will generally be in terms of air, the models presented will work equally well with the appropriate value of the specific gas constant for the particular gas being considered. Gas constants for a range of gases were presented in Section 9.2.3.2 with Table 9.2.

Empty conveying pipeline pressure drop values, for air only, will provide a useful datum for both the potential capability of a system for conveying material and the condition of the pipeline (considered in Chapter 20). Air only pressure drop values for the conveying pipeline also provide a basis for some first approximation design methods for the pneumatic conveying of materials (see Chapter 18).

Air supply and exhaust or venting pipelines can be of a considerable length with some systems, whether for positive pressure or vacuum systems, particularly if the air mover or the filtration plant is remote from the conveying system. In these cases it is important that the air only pressure drop values in these pipeline sections are evaluated, rather than just being ignored, for they could represent a large proportion of the available pressure drop if they are not sized correctly. Air flow control is also important, particularly if plant air is used for a conveying system, or if the air supply to a system needs to be proportioned between that delivered to a blow tank and that directed to the pipeline, for example.

10.2 Pipeline pressure drop

The pressure drop in the empty pipeline is a major consideration in the design of a pneumatic conveying system. If a positive displacement blower is used in combination with a long distance, small bore pipeline, for the suspension flow of a material, for example, it is quite possible that the entire pressure drop would be utilized in blowing the air through the pipeline and that no material would be conveyed. The pressure drop for air only in a pipeline is significantly influenced by the air velocity that is required for the conveying of the material. Bends and other pipeline features also need to be taken into account.

The value of the empty line pressure drop for any pipeline will provide a useful indicator of the condition of the pipeline. If a pressure gauge is situated in the air supply or extraction line, between the air mover and the material conveying pipeline, this will give an indication of the conveying line pressure drop. With an empty pipeline it will indicate the air only pressure drop. If this value is higher than expected it may be due to the fact that the line has not been purged clear of material. It may also be due to material build-up on the pipe walls or a partial blockage somewhere in the pipeline.

10.2.1 Flow parameters and properties

In order to be able to evaluate the pressure drop for the air flow in the empty pipeline, various properties of the air and of the pipeline need to be determined. Mathematical models and empirical relationships are now well established for this single phase flow situation, and so conveying line pressure drops can be evaluated with a reasonable degree of accuracy.

10.2.1.1 Conveying air velocity

This is one of the most important parameters in pneumatic conveying, with the air velocity at the material feed point, at the start of the pipeline, being particularly important. If the conveying air velocity is not specified, therefore, it will usually have to be evaluated from the volumetric flow rate, pipeline bore, and the conveying line inlet air pressure and temperature, as outlined with Equations (9.11) and (9.19).

10.2.1.2 Air density

The density, ρ, of air, or any other gas, is given simply by the mass of the gas divided by the volume it occupies:

$$\rho = \frac{m}{V} \text{ kg/m}^3$$

where m is the mass of gas (kg) and V, the volume occupied (m^3).

The Ideal Gas Law, presented with Equation (9.4) applies equally to a constant mass of a gas, as to a constant mass flow rate of a gas, and so:

$$\rho = \frac{m}{V} = \frac{p}{RT} \text{ kg/m}^3 \qquad (10.1)$$

where R is the characteristic gas constant (kJ/kg · K)

Gas constants for a number of gases were presented in Table 9.2.

A particular reference value is that of the density of air at free air conditions. For air $R = 0.2871$ kJ/kg · K and so at free air conditions of $p_0 = 101.3$ kN/m^2 and $T_0 = 288$ K, and its density $\rho = 1.225$ kg/m^3.

It will be seen from Equation (10.1) that air density is a function of both pressure and temperature, with density increasing with increase in pressure and decreasing with increase in temperature. The influence of pressure and temperature on the density of air is given in Figure 10.1 by way of illustration.

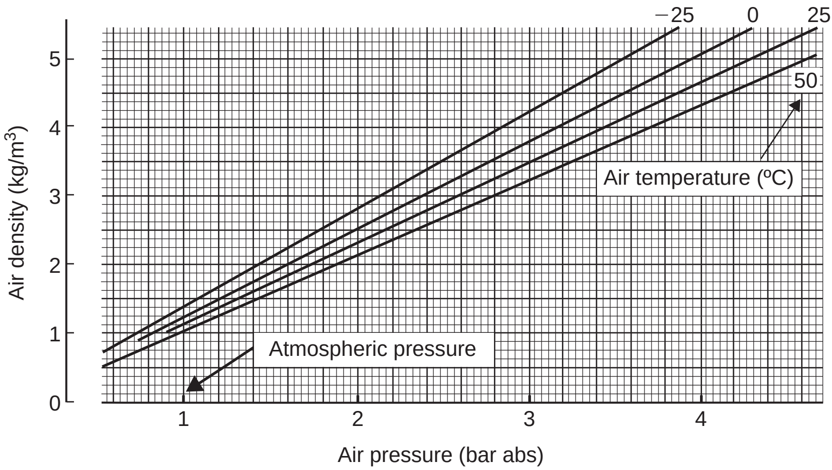


Figure 10.1 The influence of pressure and temperature on air density.

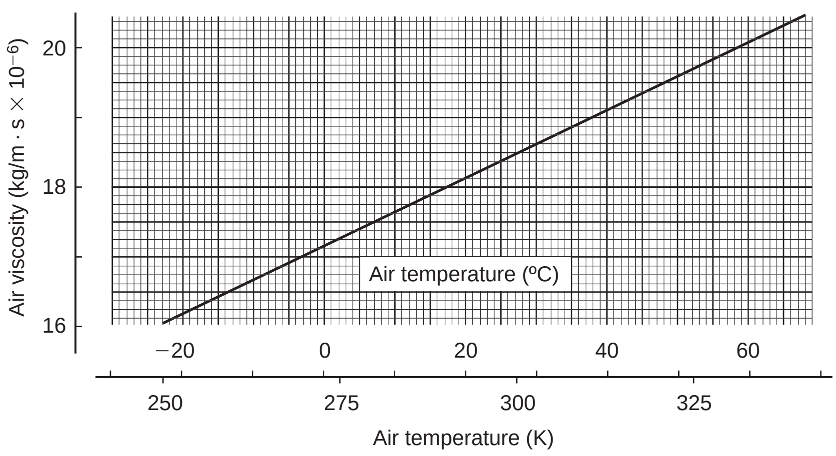


Figure 10.2 The influence of temperature on the viscosity of air.

10.2.1.3 Air viscosity

The viscosity, μ, of gases can usually be obtained from standard thermodynamic and transport properties tables. In general the influence of pressure on viscosity can be neglected. The influence of temperature on the viscosity of air is given in Figure 10.2 [1].

10.2.1.4 Friction factor

The friction factor, f, for a pipeline is a function of the Reynolds number, Re, for the flow and the pipe wall roughness, ε.

Note:
Reynolds number

$$\mathrm{Re} = \frac{\rho C d}{\mu}$$

where ρ is the density of air (kg/m^3); C, the velocity of air (m/s); d, the pipeline bore (m) and μ, the viscosity of air (kg/m · s).

Alternatively, by substituting ρ from Equation (10.1) and C from Equation (9.19), give an alternative form:

$$\mathrm{Re} = \frac{4\dot{m}_a}{\pi d \mu}$$

Values of friction coefficient can be obtained from a Moody chart, a copy of which is given in Figure 10.3.

Typical values of wall roughness, ε, are given in Table 10.1 [2].

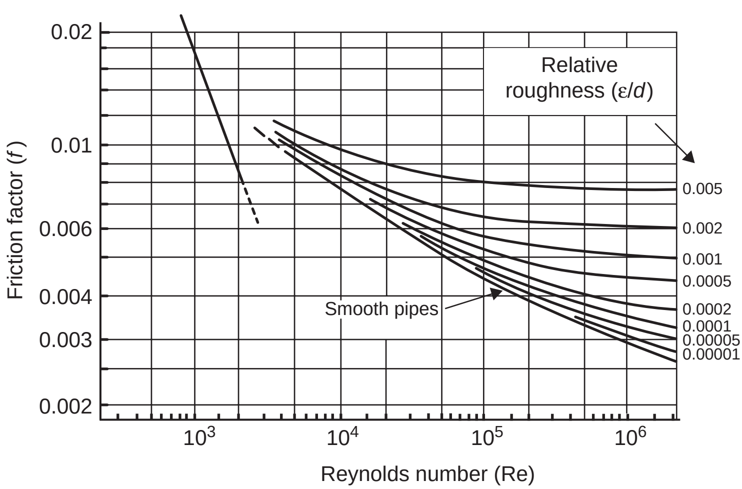


Figure 10.3 Friction coefficients for flow in circular pipe.

Table 10.1 Typical values of pipe wall roughness

Pipe material	Surface roughness $m \times 10^{-6}$ (μm)
Drawn tubing	1.5
Commercial steel and wrought iron pipes	4.5
Asphalted cast iron	120
Galvanized iron	150
Cast iron	300–3000

An accurate value of a surface roughness is clearly not critical, for a 100 per cent error in relative roughness will only result in a 10 per cent error in friction coefficient.

10.2.2 Pressure drop relationships

The pressure drop for straight pipeline, regardless of orientation, is derived in terms of the pipeline friction coefficient. The pressure drop for bends and other pipeline fittings and features is obtained in terms of a loss coefficient. For the total pipeline system the two are added together.

10.2.2.1 Straight pipeline

The pressure drop for a fluid flowing in a straight pipeline can be determined from Darcy's equation:

$$\Delta p = \frac{4fL}{d} \times \frac{\rho C^2}{2} \, \mathrm{N/m^2} \tag{10.2}$$

where Δp is the pressure drop (N/m^2); f, friction coefficient (–); L, the pipeline length (m); ρ, the density (kg/m^3); C, the velocity (m/s) and d, pipe bore (m).

For a compressible fluid such as air, the equation in this form is rather inconvenient, particularly if there is a large pressure drop, for average values of both density and velocity need to be specified, as they are both very pressure dependent. Both density and velocity, however, can be expressed in terms of constants and air pressure, which means that the expression can be easily integrated.

From Equation (10.1):

$$\rho = \frac{p}{RT}$$

and from Equation (9.19):

$$C = \frac{4\dot{m}_a RT}{\pi d^2 p} \, \mathrm{m/s} \tag{10.3}$$

Substituting these into Equation (10.2) and expressing in differential form gives:

$$p \, \mathrm{d}p = \frac{32 \, fL\dot{m}_a^2 RT}{\pi^2 d^5} \, \mathrm{d}L \tag{10.4}$$

Integrating gives:

$$p_1^2 - p_2^2 = \frac{64 \, fL\dot{m}_a^2 RT}{\pi^2 d^5} \tag{10.5}$$

where subscripts 1 and 2 refer to pipeline inlet and exit conditions.

This can be used to obtain the air only pressure drop for any straight pipeline since:

$$\Delta p = p_1 - p_2$$

and noting that:

if $\qquad p_1^2 - p_2^2 = \Gamma$

then $\qquad \Delta p_a = p_1 - \left(p_1^2 - \Gamma\right)^{0.5}$

and $\qquad \Delta p_a = \left(p_2^2 + \Gamma\right)^{0.5} - p_2$

For a positive pressure system p_2 will be specified (usually atmospheric pressure) and so a more useful form of Equation (10.5), which eliminates the unknown pressure p_1 is:

$$\Delta p_a = \left(p_2^2 + \frac{64\, fL\dot{m}_a^2 RT}{\pi^2 d^5}\right)^{0.5} - p_2 \ \mathrm{N/m^2} \tag{10.6}$$

Similarly for a negative pressure system p_1 will be specified (usually atmospheric) and so an alternative form of Equation (10.5), which eliminates the unknown pressure, p_2 is:

$$\Delta p_a = p_1 - \left(p_1^2 - \frac{64\, fLm_a^2 RT}{\pi^2 d^5}\right)^{0.5} \ \mathrm{N/m^2} \tag{10.7}$$

Note that R will have to be specified with units of J/kg·K in Equations (10.6) and (10.7).

10.2.2.1.1 The influence of air flow rate

The velocity of the conveying air will be approximately proportional to the air flow rate, whether on a mass or a volumetric flow rate basis. From Equation (10.2) it will be seen that pressure drop is proportional to the square of the velocity, and so air flow rate will have a very significant effect on conveying line pressure drop. The influence of velocity is considered in conjunction with pipeline length and bore below.

10.2.2.1.2 The influence of pipeline length

From Equation (10.2) it will be seen that pressure drop is directly proportional to pipeline length. Typical values of conveying line pressure drop for a 100 mm bore pipeline are given in Figure 10.4. This is a graph of the conveying line pressure drop for air flow through a pipeline, plotted against the air mass flow rate.

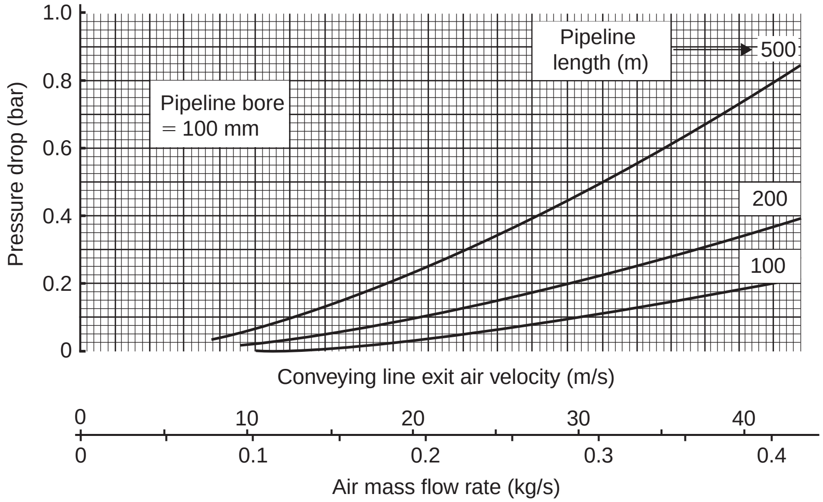


Figure 10.4 The influence of pipeline length and air flow rate on the empty pipeline pressure drop.

Conveying line exit air velocity values are also given on the air flow rate axis. This clearly shows the adverse effect of air flow rate on pressure drop. It also shows that if a material has to be conveyed over a long distance, the proportion of the total system pressure drop due to the air only in the pipeline will be very significant.

10.2.2.1.3 The influence of pipeline bore

From Equation (10.2) it will also be seen that pressure drop is inversely proportional to pipeline bore. Typical values of conveying line pressure drop for a 300 m long pipeline are given in Figure 10.5.

This is a similar plot to that of Figure 10.4. The air mass flow rate axis is proportional to pipe section area, and so conveying line exit air velocities are constant in each case. It can be clearly seen from this plot that the air only pressure drop reduces with increase in pipe bore. If an air mover with a pressure limitation, such as a positive displacement blower, has to be used to convey a material over a long distance, therefore, it should be possible to achieve reasonable flow rates with a large bore pipeline.

10.2.2.2 Bends

The pressure drop for bends in a pipeline can be expressed in terms of a 'velocity head':

$$\Delta p = k \times \frac{\rho C^2}{2} \, \mathrm{N/m^2} \qquad (10.8)$$

where k is the number of velocity heads lost for the particular bend geometry and configuration.

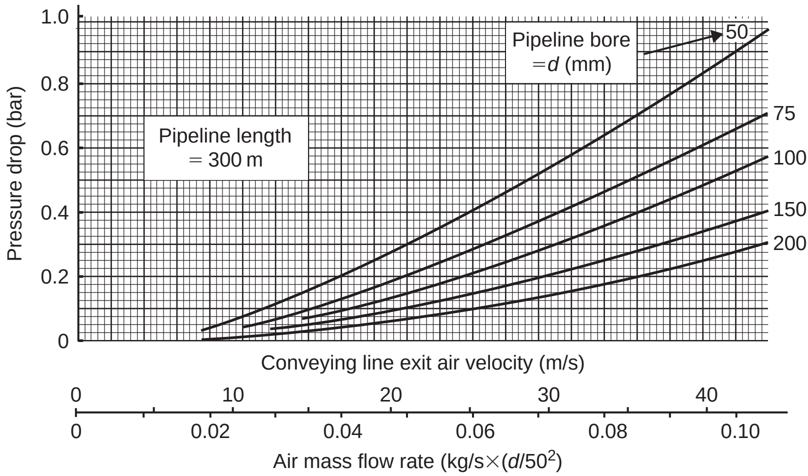


Figure 10.5 The influence of pipeline bore and air flow rate on the empty pipeline pressure drop.

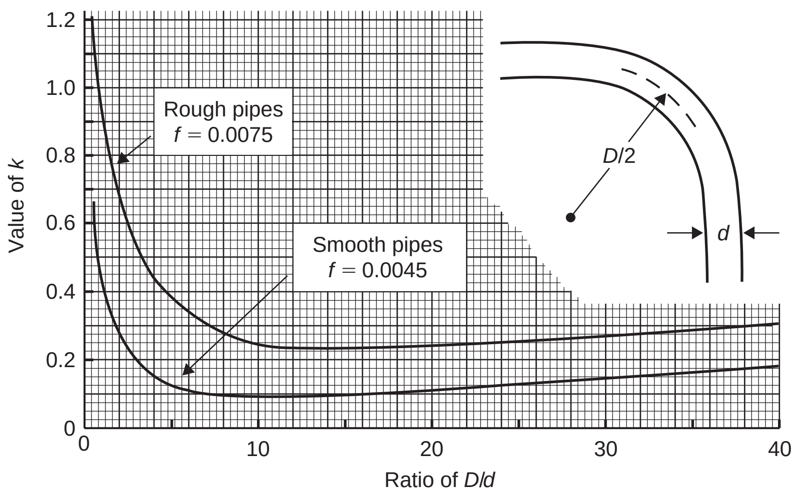


Figure 10.6 Head loss for 90° radiused bends.

Ninety-degree radiused bends are probably the most common pipeline bend. The pressure loss in such a bend will depend upon the ratio of the bend diameter, D, to the pipe bore, d, and the surface roughness. Typical values are given in Figure 10.6 [3]. From this it can be seen that very short radius bends will add significantly to the empty line pressure drop. Minimum pressure drop occurs with bends having a D/d ratio of about 12. This is not a critical value, however, for a reasonably low value of head loss will be obtained with a D/d range from about 5 to 30.

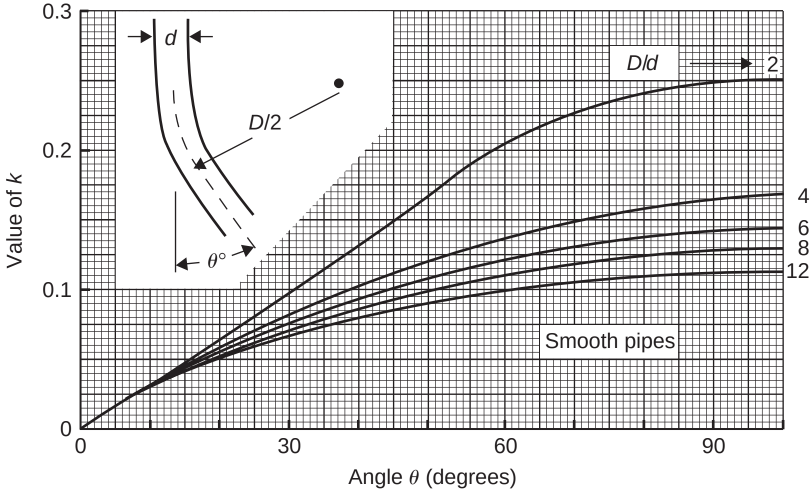


Figure 10.7 Head loss for radiused bends.

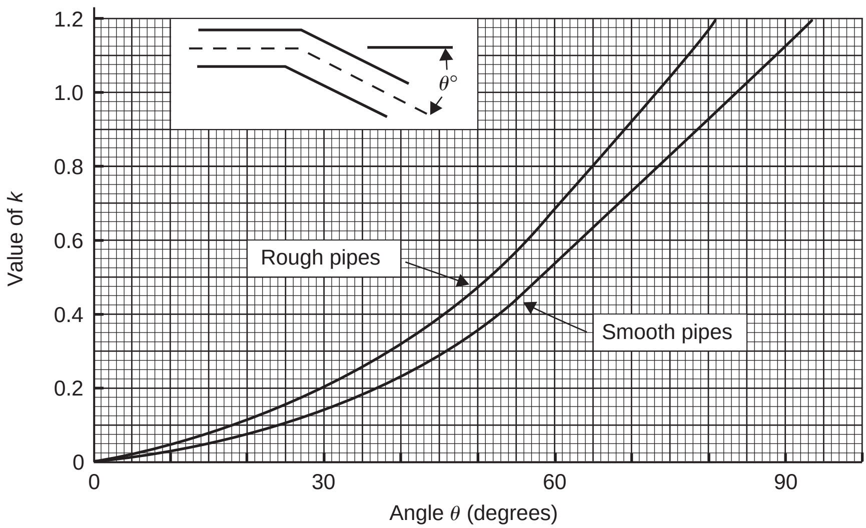


Figure 10.8 Head loss for mitred or sharp angle bends.

Head losses for radiused bends having a range of bend angles, over a range of *D/d* ratios, are given in Figure 10.7. A similar plot for sharp angled or mitred bends is given in Figure 10.8 [3]. This shows that the mitred bend will result in the highest value of air only pressure drop for a 90° bend, particularly for smooth pipes.

10.2.2.2.1 Equivalent length

The head loss for straight pipeline, as will be seen from Equation (10.2) is given by:

$$\frac{4fL}{d}$$

The equivalent length, L_e, of a bend with a head loss of k will therefore be:

$$L_e = \frac{kd}{4f} \text{ m} \tag{10.9}$$

Taking a typical pipeline friction coefficient, f, of 0.005, the equivalent length of a 100 mm bore 90° mitred bend of smooth pipe will be about 5.5 m. If there are a number of such bends in a short pipeline, the bends will add significantly to the total air only pressure drop value.

10.2.2.3 Other pipeline features

These are treated in exactly the same way as pipeline bends, and in Figures 10.9–10.11 head loss values are given for various pipeline fittings. Expansion fittings are required in stepped pipelines, where the diameter of a line is increased part way along its length in order to reduce the conveying air velocity. Figure 10.9 shows that the air only pressure drop will be a minimum if a tapered section were used having an included angle of about 6°.

Expansion and contraction sections often occur in association with pipeline feeding systems such as rotary valves, screws and venturis, and at discharge into reception

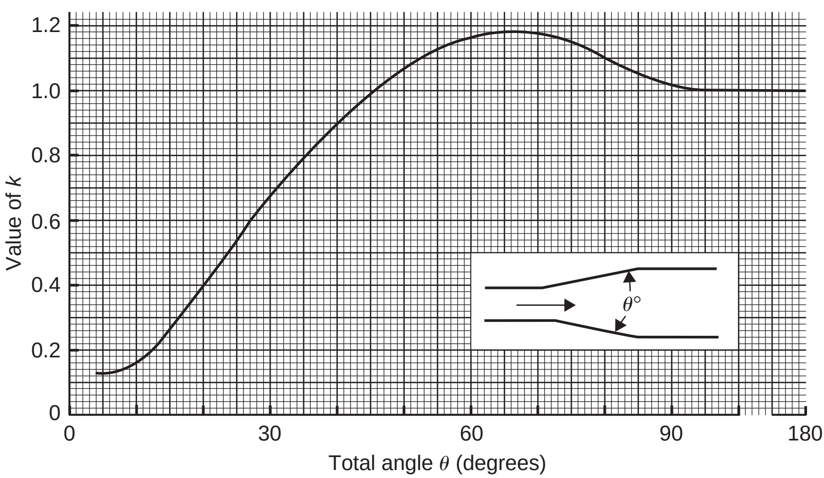


Figure 10.9 Head loss for enlarging pipeline sections.

vessels. Figures 10.9 and 10.10 illustrate the importance of careful design in such devices.

The head loss for various diverter sections, fabricated bends and ‘dog-leg’ sections, that are often used in air supply and exhaust pipelines, are given in Figure 10.11. A comparison of the two ‘dog-leg’ sections shows just how important careful pipeline design and layout are in minimizing pressure drop.

10.2.2.4 Total pipeline

The pressure drop for the total pipeline is simply given by a summation of all the component pressure drop values, so that:

$$\Delta p_a = \left(\frac{4fL}{d} + \Sigma k\right) \times \frac{\rho C^2}{2} \ \mathrm{N/m^2} \tag{10.10}$$

where Σk is the sum of the head loss for all the bends and fittings in the pipeline.

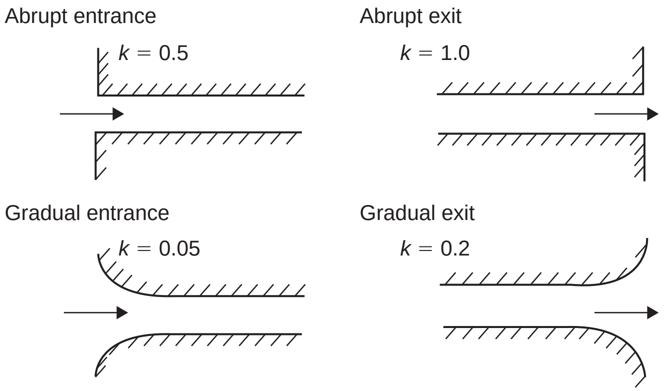


Figure 10.10 Entrance and exit head losses.

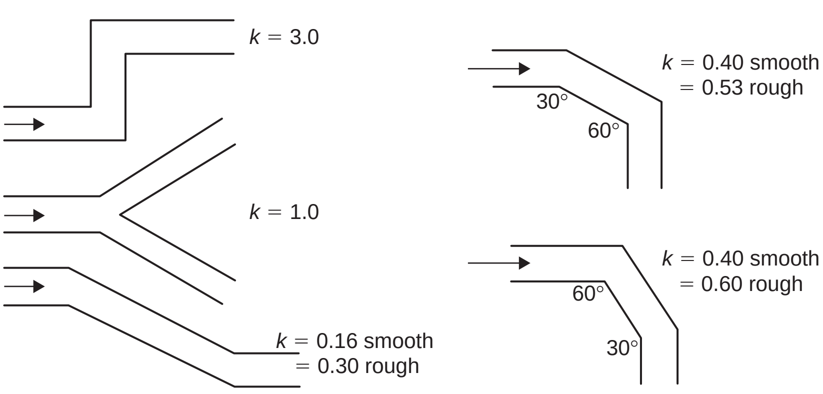


Figure 10.11 Head loss for various pipe fittings.

For convenience the head loss for the pipeline, bends and fittings can be grouped together using the term ψ such that:

$$\psi = \frac{4fL}{d} + \Sigma k \text{ (dimensionless)} \tag{10.11}$$

Substituting for ρ and C, as with Equation (10.4), and integrating gives:

$$p_1^2 - p_2^2 = \frac{16\psi \dot{m}_a^2 RT}{\pi^2 d^4} \tag{10.12}$$

This can be used to obtain the air only pressure drop in any pipeline situation.

10.2.2.4.1 Positive pressure systems

For a positive pressure system p_2 will be specified, as mentioned earlier in connection with Equation (10.6), and so a more useful form of Equation (10.12) is:

$$\Delta p_a = \left(p_2^2 + \frac{16\psi \dot{m}_a^2 RT}{\pi^2 d^4} \right)^{0.5} - p_2 \text{ N/m}^2 \tag{10.13}$$

For air $R = 287$ kJ/kg · K and if $T = 288$ K and taking $p_2 = 1.0$ bar (atmospheric pressure).

This gives:

$$\Delta p_a = \left[\left(1.0 + \frac{1.34\psi \dot{m}_a^2}{d^4 \times 10^5} \right)^{0.5} - 1.0 \right] \text{bar} \tag{10.14}$$

In many cases a value of the conveying line exit air velocity, C_2, can be determined. One such derivation was presented as Equation (9.19) and was introduced earlier as Equation (10.3):

$$C = \frac{4\dot{m}_a RT}{\pi d^2 p} \text{ m/s} \tag{10.3*}$$

A substitution of C_2 for $\dot{m}_a$ made from Equation (10.3) gives:

$$\dot{m}_a = \frac{\pi d^2 C_2 p_2}{4RT_2} \text{ kg/s} \tag{10.15}$$

*Reintroduced here.

Substituting this into Equation (10.12) gives:

$$p_1^2 - p_2^2 = \frac{\psi C_2^2 p_2^2}{RT_2} \tag{10.16}$$

From which:

$$\Delta p = p_2\left[\left(1 + \frac{\psi C_2^2}{RT_2}\right)^{0.5} - 1\right] \mathrm{N/m^2} \tag{10.17}$$

Thus in a situation where the downstream pressure, p_2, is known (commonly this would be atmospheric pressure in a positive pressure system) and the conveying line exit air velocity can be determined, this expression allows the pressure drop for the air alone to be estimated quite easily.

Alternatively, if the conveying line inlet air velocity, C_1, is known, this can be used instead. A substitution of C_1 for $\dot{m}_a$, from Equation (10.3), into Equation (10.12) gives:

$$p_1^2 - p_2^2 = \frac{\psi C_1^2 p_1^2}{RT_1} \tag{10.18}$$

From which:

$$\Delta p_a = p_2\left[\left(\frac{RT_1}{RT_1 - \psi C_1^2}\right)^{0.5} - 1\right] \mathrm{N/m^2} \tag{10.19}$$

Note:
The velocity, C_1, in Equations (10.18) and (10.19), is not the conveying line inlet air velocity which is specified for gas–solid flows in pneumatic conveying. It is the conveying line inlet air velocity that will result when no material is conveyed. C_2 in Equations (10.16) and (10.17), of course, is the same whether material is conveyed or not, since the pressure will always be the same at the end of the pipeline.

10.2.2.4.2 Negative pressure systems

For a negative pressure system, p_1, will be specified (usually atmospheric). A re-arrangement of Equation (10.18) gives:

$$\Delta p_a = p_1\left[1 - \left(1 - \frac{\psi C_1^2}{RT_1}\right)^{0.5}\right] \mathrm{N/m^2} \tag{10.20}$$

Note:
In this case the conveying line inlet air velocity, C_1, will be the same whether the material is conveyed or not, since the pressure, p_1, will be atmospheric in both cases. This is similar to Equations (10.16) and (10.17) for positive pressure systems.

10.2.3 Air only pressure drop datum

The empty pipeline pressure drop relationships for a pipeline, such as those shown in Figures 10.4 and 10.5, provide a datum for material conveying characteristics and capability. At a given value of air flow rate the pressure drop available must be greater than the air only pressure drop value, otherwise it will not be possible to convey material.

At any value of conveying line pressure drop there will be a corresponding value of air flow rate at which the air only pressure drop will equal the conveying line pressure drop. This value can be determined from Equation (10.13) by making $\dot{m}_a$ the subject of the equation. Such a re-arrangement gives:

$$\dot{m}_a = \left[\frac{\pi^2 d^4 (p_1 + p_2) \Delta p_a}{16 \psi R T} \right]^{0.5} \quad \text{kg/s} \tag{10.21}$$

This is quite a useful relationship, for it allows an estimate to be made of where the various lines of constant conveying line pressure drop on material conveying characteristics will reach the horizontal axis.

For air $R = 287\,\text{J/kg} \cdot \text{K}$ and if $T = 288\,\text{K}$,

$$\dot{m}_a = 273 \left[\frac{d^4 \Delta p_a (p_1 + p_2)}{\psi} \right]^{0.5} \quad \text{kg/s} \tag{10.22}$$

where all pressures are in bar.

10.3 Venturi analysis

Particular advantages of using venturi feeders for positive pressure conveying lines are that minimum headroom is required, there are no moving parts and, if the device is correctly designed, there need be no air leakage from the feeder, as there is with nearly all other types of feeder. A venturi basically consists of a controlled reduction in pipeline cross section in the region where the material is fed from the supply hopper, as shown in Figure 10.12.

A consequence of this reduction in flow area is an increase in the entraining air velocity, and a corresponding decrease in pressure, in this region. With a correctly designed venturi the pressure at the throat should be just a little lower, or about the same, as that in the supply hopper which, for the majority of applications, is atmospheric pressure. This then encourages the material to flow readily under gravity into the pipeline, and under these conditions there will be no leakage of air from the feeder in opposition to the material feed.

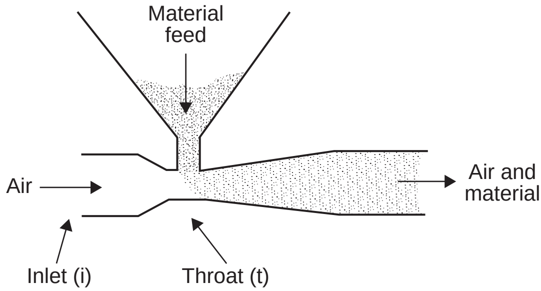


Figure 10.12 Basic type of venturi feeder.

For low pressure applications, in order to keep the throat at atmospheric pressure, and also of a practical size such that it will allow the passage of material to be conveyed, a relatively low limit has to be imposed on the air supply pressure. These feeders, therefore, are usually incorporated into systems that are required to convey free-flowing materials at low flow rates over relatively short distances.

Since only low pressures can be used with the basic type of venturi operating at atmospheric pressure, a positive displacement blower or a standard industrial fan is all that is needed to provide the air. To fully understand the limitations of this type of feeder, the thermodynamic relationships are presented below. The two parameters of interest in venturi feeders are the velocity at the throat and the area, or diameter, of the throat. From the steady flow energy equation, equating between the inlet (i) and the throat (t) gives:

$$C_p T_i + \frac{C_i^2}{2} = C_p T_t + \frac{C_t^2}{2} \tag{10.23}$$

where C_p is the specific heat (J/kg · K); T, the absolute temperature (K) and C, the velocity (m/s). From which:

$$C_t = \left[2C_p(T_i - T_t) + C_i^2\right]^{0.5} \text{ m/s} \tag{10.24}$$

If an isentropic model of expansion is assumed for the venturi then:

$$\frac{T_t}{T_t} = \left(\frac{p_t}{p_i}\right)^{\frac{\gamma-1}{\gamma}} \tag{10.25}$$

Substituting Equation (10.25) into (10.24) gives:

$$C_t = \left\{2C_p T_i \left[1 - \left(\frac{p_t}{p_i}\right)^{\frac{\gamma-1}{\gamma}}\right] + C_i^2\right\}^{0.5} \text{ m/s} \tag{10.26}$$

From the continuity equation:

$$\dot{m}_a = \rho_i A_i C_i = \rho_t A_t C_t \text{ kg/s} \tag{10.27}$$

where A is the section area $= \pi d^2/4$ (m^2) and ρ, the density of gas (kg/m^3)

$$\frac{p}{RT} \tag{10.28}$$

Substituting Equation (10.28) into (10.27) gives:

$$d_t = \left(\frac{C_i}{C_t} \times \frac{p_i}{p_t} \times \frac{T_t}{T_i}\right)^{0.5} \times d_i \text{ m} \tag{10.29}$$

Substituting Equation (10.25) into (10.29) gives:

$$d_t = \left[\frac{C_i}{C_t} \times \left(\frac{p_t}{p_i}\right)^{-\frac{1}{\gamma}}\right]^{0.5} \times d_i \text{ m} \tag{10.30}$$

If, for example,

$C_i = 20$ m/s
$d_i = 100$ mm
$T_i = 293$ K
$p_t = 101.3$ kN/m^2 abs
$p_i = 0.2$ bar gauge $= 121.3$ kN/m^2 abs

Note that for air $C_p = 1000$ J/kg and $\gamma = 1.4$. Substituting into Equation (10.26) gives:

$$C_t = \left\{2000 \times 293\left[1 - \left(\frac{101.3}{121.3}\right)^{0.286}\right] + 20^2\right\}^{0.5}$$

$$= 173 \text{ m/s}$$

and substituting into Equation (10.30) gives:

$$d_t = \left[\frac{20}{173} \times \left(\frac{101.3}{121.3}\right)^{-0.714}\right]^{0.5} \times 100$$

$$= 36.3 \text{ mm}$$

10.3.1 Atmospheric pressure applications

Although venturis capable of feeding materials into conveying pipelines with operating pressure drops of 0.4 bar are commercially available, the additional pressure drop across the venturi can be of the same order. This means that the air supply pressure will have to be at about 0.8 bar gauge and consequently, for this type of duty, it would be recommended that the air should be supplied by a positive displacement blower.

10.3.2 High pressure applications

It was mentioned in Chapters 3 and 4, dealing with feeding devices for pneumatic conveying systems that with the use of lock hoppers (see Section 4.5) venturis could also be used in high pressure systems. Although the above analysis was used to illustrate the atmospheric pressure application, the same models can be used to analyse high pressure applications simply with an alternative value of the pressure at the throat, p_t.

10.4 Air flow rate control

If the air to be used for conveying, is taken from a plant air supply, or some central source, it will probably be necessary to put a flow restriction into the pipeline. This will be needed in order to limit the quantity of air drawn to that of the volumetric flow rate actually required. If this is not done an uncontrolled expansion will occur and very much more air than necessary will be used. It will only be limited by the volumetric capability of the supply, or by the increased frictional resistance of the flow in the pipeline. The increased air flow rate will almost certainly result in a decrease in the material flow rate through the pipeline. It will also add significantly to problems of erosive wear and particle degradation.

Flow restrictors may also be required in situations where the air supply needs to be divided, as in blow tank systems. For the control of many types of blow tank it is necessary to proportion the air supply between the blow tank and the conveying line. If the total air supply is set, a flow restrictor can be placed in one or both of the divided lines. This, however, can only be done if the blow tank is dedicated to a single material conveyed over a fixed distance. For systems handling more than one material, or conveying to a number of hoppers over varying distances, a variable flow control would be needed. In these cases special control valves would be required rather than fixed restrictors.

Nozzles and orifice plates are most commonly used for restricting the air flow in a pipeline. Under certain flow conditions they can also be used to meter and control the air flow.

10.4.1 Nozzles

For the single phase flow of fluids through nozzles the theory is well established, and for a gas such as air it is based on the use of many of the equations already presented. Nozzles are either of the convergent–divergent type, as shown in Figure 10.13a, or are convergent only, as shown in Figure 10.13b. Both types restrict the flow by means of a short throat section at a reduced diameter.

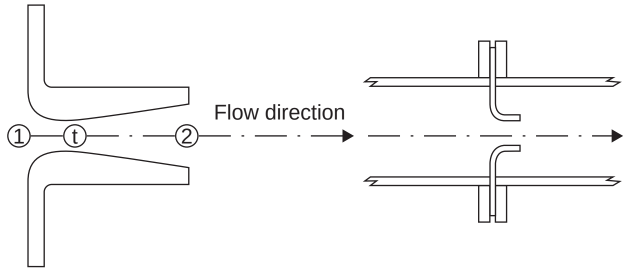


Figure 10.13 Sketch of nozzle types: (a) convergent–divergent nozzle and (b) convergent nozzle in pipeline.

10.4.1.1 Flow analysis

Assuming a steady one-dimensional flow, and equating the steady flow energy equation between inlet (1) and throat (t) gives:

$$C_pT_1 + \frac{C_1^2}{2} = C_pT_t + \frac{C_t^2}{2} \quad (10.24^*)$$

Neglecting the inlet velocity, C_1, and re-arranging gives:

$$C_t = \left[2C_pT_1\left(1 - \frac{T_t}{T_1}\right)\right]^{0.5} \text{ m/s} \quad (10.31)$$

Assuming isentropic flow, for which Equation (10.25) applies, the unknown temperature at the throat, T_t, can be expressed in terms of the pressure at the throat, p_t. Such a substitution gives:

$$C_t = \left\{2C_pT_1\left[1 - \left(\frac{p_t}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{0.5} \text{ m/s} \quad (10.32)$$

Also for isentropic flow:

$$v_t = v_1 \times \left(\frac{p_1}{p_t}\right)^{\frac{1}{\gamma}} \text{ m}^3\text{/kg} \quad (10.33)$$

where v is the specific volume (m^3/kg).

Now, from the Ideal Gas Law (Equation (9.4)):

$$p_1v_1 = RT_1$$

*Reintroduced here.

and substituting this into Equation (10.33) gives:

$$v_t = \frac{RT_1}{p_1} \times \left(\frac{p_1}{p_t}\right)^{\frac{1}{\gamma}} \text{ m}^3/\text{kg} \tag{10.34}$$

From the continuity equation (Equation (10.27)):

$$\dot{m}_a \times \frac{A_1 C_1}{v_1} = \frac{A_t C_t}{v_t} \text{ kg/s}$$

Substituting C_t from Equation (10.32) and v_t from Equation (10.34) into this gives:

$$\dot{m}_a = \frac{A_t\left\{2C_p T_1\left[1 - \left(\frac{p_t}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{0.5}}{\frac{RT_1}{p_1} \times \left(\frac{p_1}{p_t}\right)^{\frac{1}{\gamma}}} \text{ kg/s} \tag{10.35}$$

Re-arranging this gives:

$$\dot{m}_a = \frac{\pi d_t^2}{4} \times \frac{p_1}{R}\left\{\frac{2C_p}{T_1}\left[\left(\frac{p_t}{p_1}\right)^{\frac{2}{\gamma}} - \left(\frac{p_t}{p_1}\right)^{\frac{\gamma+1}{\gamma}}\right]\right\}^{0.5} \text{ kg/s} \tag{10.36}$$

where d_t is the nozzle throat diameter (m).

10.4.1.2 Critical pressure

A peculiarity of the expansion of the flow of a fluid through a nozzle is that as the downstream pressure, p_2, reduces, for a given upstream pressure, p_1, the pressure at the throat, p_t, will not reduce constantly with downstream pressure. The pressure at the throat will reduce to a fixed proportion of the inlet pressure, and any further reduction of the downstream pressure will not result in a lowering of the pressure at the throat.

Under these conditions the nozzle is said to be ‘choked’. When critical flow conditions exist, the velocity at the throat will be equal to the local sonic velocity. The air mass flow rate through a nozzle is a maximum under choked flow conditions and no reduction of the downstream pressure, below the critical throat pressure, will result in any change of the air mass flow rate.

It can be shown (e.g. [4]) that the ratio between the throat pressure and the supply or inlet pressure is given by:

$$\frac{p_t}{p_1} = \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma-1}} \tag{10.37}$$

For air $\gamma = 1.4$, $R = 287\,\text{J/kg}\cdot\text{K}$ and $C_p = 1000\,\text{J/kg}\cdot\text{K}$ and so

$$\frac{p_t}{p_1} = 0.528$$

10.4.1.3 Nozzle size and capability

Substituting the above data for air into Equation (10.36) gives:

$$\dot{m}_a = 0.0317 \frac{p_1 d_t^2}{T_1^{0.5}} \text{ kg/s} \tag{10.38}$$

where p_1 is the inlet or supply pressure (N/m^2 abs).

For the air flow rate in volumetric terms, the Ideal Gas Law gives:

$$\dot{V} = \frac{\dot{m}_a RT}{p} \text{ m}^3\text{/s}$$

For the volumetric flow rate at free air conditions, substitution of this into Equation (10.38) gives:

$$\dot{V}_0 = 0.0317 \frac{p_1 d_t^2}{T_1^{0.5}} \times \frac{RT_0}{p_0} \text{ m}^3\text{/s} \tag{10.39}$$

and substituting for R and free air conditions gives:

$$\dot{V}_0 = 0.0259 \frac{p_1 d_t^2}{T_1^{0.5}} \text{ m}^3\text{/s} \tag{10.40}$$

Alternatively, for a given air flow rate:

$$d_t = 5.62 \left(\frac{\dot{m}_a T_1^{0.5}}{p_1}\right)^{0.5} \text{ m} \tag{10.41}$$

A typical relationship between d_t, p_1 and both $\dot{m}_a$ and $\dot{V}_0$, for air at a temperature, t_1, of 15°C ($T_1 = 288$), for a range of air supply pressures, air flow rates and nozzle sizes, is given in Figure 10.14.

10.4.1.4 Nozzle types

The above analysis applies to either convergent–divergent or to convergent nozzles. For convergent nozzles, however, the range of operation is limited to downstream pressures less than 52.8 per cent of the upstream pressure, that is, below the critical pressure ratio. With convergent–divergent nozzles this range can be extended significantly, and for a well-made nozzle it can be as high as 90 per cent of the upstream pressure, with little deviation from the predicted flow rate.

10.4.2 Orifice plates

These are frequently used for measuring the flow rate of gases through pipelines but can also be used to choke the flow and so limit the throughput. The orifice consists of a thin plate which is usually fitted into a flanged joint in the pipeline. It has a sharp edged opening which is concentric with the pipe.

The above analysis also applies to orifice plates. There is, however, a coefficient of discharge associated with orifice plates and this has the effect of reducing the flow rate to about 61 per cent of the theoretical value. This means that the constants in Equations (10.35)–(10.40) would have to be multiplied by $\sqrt{0.61}$ a factor of 0.61 and the constant in Equation (10.41) would have to be divided by to take account of this coefficient of discharge. As with the convergent nozzle, the range of operation is limited to downstream pressures below the critical pressure ratio.

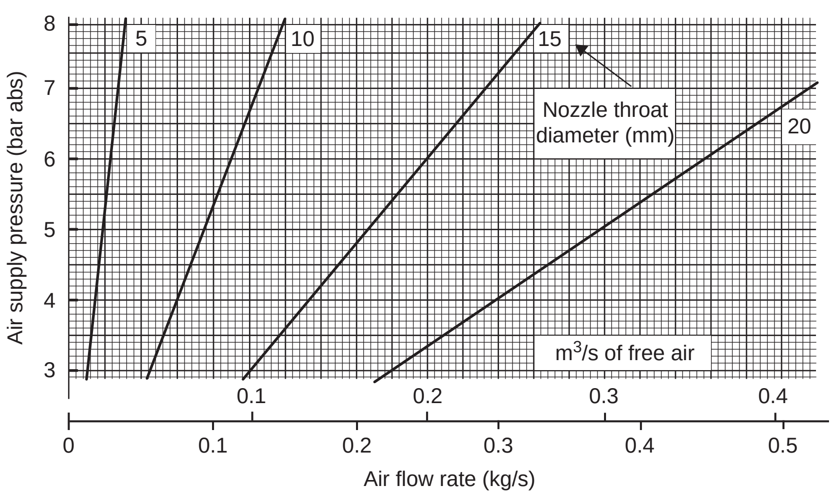


Figure 10.14 Influence of throat diameter and air supply pressure on choked air flow rate for nozzles.

10.4.3 Flow rate control

It will be seen from Figure 10.14 that, for a given nozzle, the air flow rate can be varied over a wide range simply by varying the air supply pressure. In a pipeline from a service supply, a diaphragm valve could be positioned upstream of the flow restrictor, and this could be used to vary the inlet pressure and hence the air flow rate. Provided that critical flow conditions exist, only the inlet air pressure and temperature, and the throat diameter, are needed to evaluate the air flow rate, as will be seen from Equation (10.38).

It will be noticed that, apart from including a representative coefficient of contraction for orifices, no other coefficients have been included in the analysis to allow for friction and other irreversibility in the flow. For most pneumatic conveying applications it will not be necessary, as these losses are generally quite small. If these devices are to be used for flow measurement purposes, however, with a need for a high degree of accuracy, either the loss factors will have to be taken into account or the device will have to be calibrated before being used.

10.5 Stepped pipelines

Stepped pipelines were discussed earlier in Section 9.4 to illustrate the problems of air expansion and velocity control along a pneumatic conveying system pipeline. The models necessary to evaluate the air only pressure drop have been developed since this introduction and so it is now possible to consider stepped pipelines further. A sketch of a two-section stepped pipeline is given in Figure 10.15.

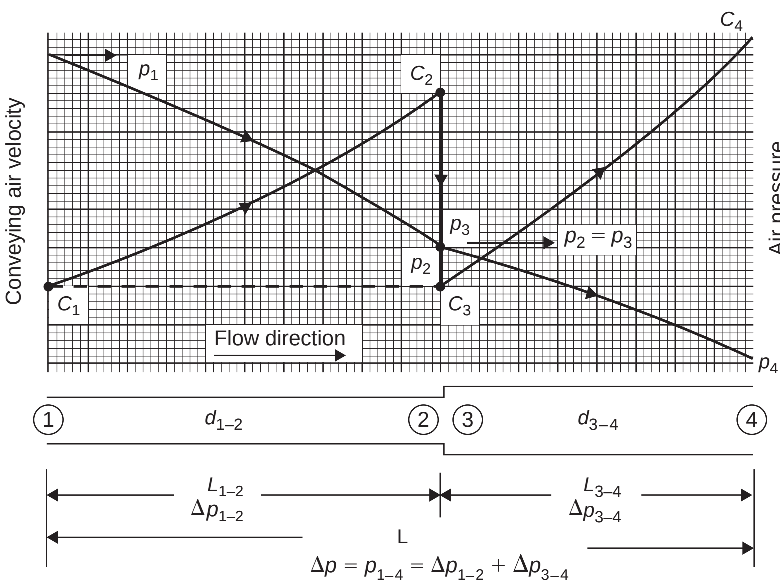


Figure 10.15 Velocity and pressure profiles for a stepped pipeline.

10.5.1 Air only pressure drop

From Equation (10.12), for a single bore pipeline, the following expression was developed:

$$p_1^2 - p_2^2 = \frac{16\psi \dot{m}_a^2 RT}{\pi^2 d^4} \text{ N/m}^2 = \Gamma \tag{10.42}$$

which gives either

$$\Delta p_a = p_1 - \left(p_1^2 - \Gamma\right)^{0.5} \text{ N/m}^2 \tag{10.43}$$

which is an expression in terms of the inlet pressure, p_1 or

$$\Delta p_a = \left(p_2^2 + \Gamma\right)^{0.5} - p_2 \text{ N/m}^2 \tag{10.44}$$

which is an expression in terms of the outlet pressure, p_2.

For a stepped pipeline the total pressure drop will be equal to the sum of the individual pressure drops for each section. For a two-section pipeline the unknown pressure at the step can be eliminated by using both of the above expressions, noting that $p_2 = p_3$.

$$\Delta p_a = p_1 - p_4 = \Delta p_{1-2} + \Delta p_{3-4}$$

For the first section:

$$\Delta p_{1-2} = p_1 - \left(p_1^2 - \Gamma_{1-2}\right)^{0.5}$$

and for the second section:

$$\Delta p_{3-4} = \left(p_4^2 + \Gamma_{3-4}\right)^{0.5} - p_4$$

adding these two expressions gives:

$$p_1 - p_4 = p_1 - p_4 - \left(p_1^2 - \Gamma_{1-2}\right)^{0.5} + \left(p_4^2 + \Gamma_{3-4}\right)^{0.5}$$

which reduces to:

$$p_1^2 - p_2^2 = \Gamma_{1-2} + \Gamma_{3-4} \text{ N/m}^2 \tag{10.45}$$

This equation is of the same form as Equation (10.42) and so the solution can either be in terms of the inlet pressure, p_1, as in Equation (10.43), or in terms of the exit pressure, p_4, as in Equation (10.44). The choice will depend upon which value is known, and whether the stepped pipeline is for a positive pressure or a vacuum system.

It should be noted that if the pipeline comprises more than one step, additional equations will be needed to solve the additional unknown pressures at the steps.

10.5.2 Position of steps

The position of the transition to a larger bore line must be such that the conveying air velocity does not drop below that of the conveying line inlet air velocity employed at the start of the pipeline. As the pressure drops along the length of the pipeline the velocity will increase, but a change in pipeline bore will significantly alter the situation, as illustrated in Figure 10.15, and with the examples shown in Figures 9.11 to 9.16 in Chapter 9 on Air flow rate evaluation.

It was also mentioned, in Section 9.4.4.1, that as a first approximation, pipeline lengths could be sized in proportion to the conveying line pressure drop for each section of pipeline, provided that a reasonably uniform value of conveying air velocity is maintained along the length of the pipeline. With reference to Figure 10.15, the length of the first section of pipeline, L_{1-2}, would be:

$$L_{1-2} = \frac{p_1 - p_2}{p_1 - p_4} \times L \text{ m} \tag{10.46}$$

The pressure at the step can be evaluated from Equation (9.13), developed in Section 9.4.1, from which the velocity at the end of each section along the length of the pipeline can be determined from either Equation (9.11), in terms of volumetric flow rates or Equation (9.20), in terms of air mass flow rate, to check on the uniformity of the velocity profile.

10.5.3 Transition sections

A tapered transition from one section to another would be recommended, in order to recover as much of the energy as possible in the preceding high velocity flow. The included angle of the transition would need to be about 5–10°, as shown in Figure 10.9.

10.6 Nomenclature

A	Pipe section area	m^2
C	Conveying air velocity	m/s
C_p	Specific heat at constant pressure	kJ/kg·K
C_v	Specific heat at constant volume	kJ/kg·K
d	Pipe bore	m
f	Friction coefficient	–
k	Bend loss coefficient	–
L	Pipeline length	m

m	Mass	kg	
$\dot{m}$	Mass flow rate	kg/s	
p	Air pressure	kN/m^2	N/m^2
	Note: 1 bar $= 100\,kN/m^2$		
R	Characteristic gas constant	$kJ/kg\cdot K$	
t	Actual temperature	°C	
T	Absolute temperature	K	
	$= t + 273$		
$\dot{V}$	Volume	m^3	
	Volumetric flow rate	m^3/s	

10.6.1 Greek

γ	Ratio of specific heats	C_p/C_v
ε	Pipe wall roughness	m
μ	Viscosity	$kg/m\cdot s$
ν	Specific volume	$m^3/kg = 1/\rho$
ρ	Density	kg/m^3
ψ	Total pipeline head loss coefficient	–

10.6.2 Subscripts

a	Conveying air
e	Equivalent value, usually length
i	Inlet conditions
t	Throat conditions
0	Reference conditions, free air values
	$P_0 = 101.3\,kN/m^2$
	$T_0 = 288\,K$
1, 2	Actual conditions, usually at inlet and outlet
3, 4, etc.	Actual conditions, usually at steps along pipeline or air mover inlet and outlet

10.6.3 Prefixes

Δ	Difference in value
Σ	Sum total

References

1. Y R Mayhew and G F C Rogers. Thermodynamic and Transport Properties of Fluids. Basil: Blackwell. 1968.
2. J M Gasiorek and W G Carter. Mechanics of Fluids for Mechanical Engineers. Blackie and Son. 1967.
3. J R D Francis. Fluid Mechanics for Engineering Students – 4th Ed. Edward Arnold. 1975.
4. V M Faires. Applied Thermodynamics – 3rd Ed. MacMillan. 1957.

Chapter 11

Conveying characteristics

11.1 Introduction

The capability or a pneumatic conveying system for conveying bulk particulate materials depends mainly upon five parameters. These are pipe bore, conveying distance, pressure available, conveying air velocity and material properties. The influence of many of these variables is reasonably predictable but that of the conveyed material is not, at present. For this reason the conveying characteristics of many different materials are presented and featured in order to illustrate the importance and significance of material properties.

11.1.1 Conveying characteristics

If a pneumatic conveying system is to be designed to ensure satisfactory operation, and to achieve maximum efficiency, it is necessary to know the conveying characteristics of the material to be handled. The conveying characteristics will tell a designer what the minimum conveying velocity is for the material, whether there is an optimum velocity at which the material can be conveyed, and what pipeline diameter and air mover rating will be required for a given material flow rate and conveying distance.

Alternatively, for an existing pneumatic conveying plant, the appropriate conveying characteristics will tell a designer what flow rate to expect if it is necessary to convey a different material, and whether the air flow rate is satisfactory. Conveying characteristics can also be used to check and optimize an existing plant if it is not operating satisfactorily. This aspect is considered in Chapter 21.

In order to be able to specify a pipe size and compressor rating for a required duty it is necessary to have information on the conveying characteristics of the material. If sufficient previous experience with a material is available, such that the conveying characteristics for the material are already established, it should be possible to base a design on the known information.

If previous experience with a material is not available, or is not sufficient for a full investigation, it will be necessary to carry out pneumatic conveying trials with the material. These should be planned such that they will provide data on the relationships between material flow rate, air flow rate and conveying line pressure drop over as wide a range of conveying conditions as can be achieved with the material.

The trials should also provide information on the minimum conveying air velocity for the material and how this is influenced by conveying conditions. This is particularly important in the case of dense phase conveying, for the differences in conveying characteristics between materials can be very much greater than those for dilute phase conveying.

If the investigation is to cover the entire range of conveying modes with the material, then the previous experience must be available over a similar range or conveying conditions. Scale up in terms of air supply pressure, pipe bore, conveying distance and pipeline geometry from existing data is reasonably predictable, provided if the extrapolation is not extended too far. Scale up in terms of mode of conveying, into regions of much higher solids loading ratios and lower conveying air velocities, however, should not be attempted unless evidence of the potential of the material for such conveying is available.

11.1.2 Conveying mode

If the pressure gradient available is sufficiently high, conveying is possible in the dense phase mode, provided that the material is capable or being conveyed in this mode. It is the influence of material properties on the possible mode of conveying, as well as differences in material flow rates achieved for identical conveying conditions that makes it essential for conveying trials to be carried out with an untried material. In conveying tests where the operating pressure gradient is high there is an additional need, therefore, to establish the limits of conveying and this may be over a very wide range of conveying conditions.

In addition to material properties, conveying distance can have a significant influence on the solids loading ratio, at which a material can be conveyed, and hence mode of conveying that is possible. The influencing factor here is simply pressure gradient, and this will limit conveying potential regardless of the capabilities of the material. Pressure gradient is simply the conveying line pressure drop available divided by the equivalent length of the pipeline. This was introduced in Chapter 1, and in Figure 1.1 an approximate relationship was presented between pressure gradient and the solids loading ratio that might be achieved with a material capable of dense phase flow in a sliding bed mode of flow.

11.2 Single phase flow

The flow of air only through a pipeline was considered in some detail in Chapter 10. This information is required since the pressure drop required to transport the air through the pipeline, without material, represents the datum for the pipeline. The air supply pressure available, minus the air only pressure drop for the pipeline, represents the pressure drop available for the conveying of material through the pipeline.

11.2.1 The Darcy equation for pressure drop

In order to illustrate how conveying characteristics can be used it is necessary to show first how they are built up and to examine the influence of the main variables. The simplest starting point is to consider the air only flowing through the pipeline. If a graph is drawn of pressure drop against air flow rate for the conveying line the result will be similar to that shown in Figure 11.1.

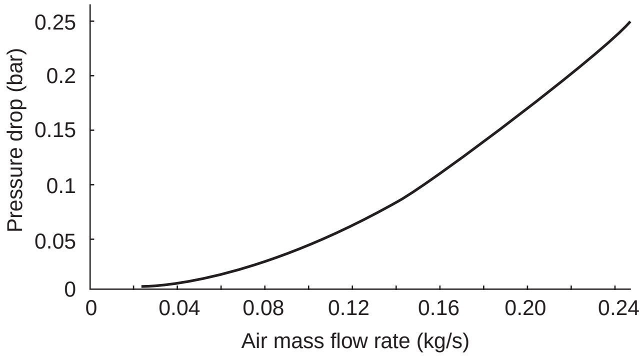


Figure 11.1 Air only pressure drop relationship for 95 m long pipeline of 81 mm bore having nine 90° bends.

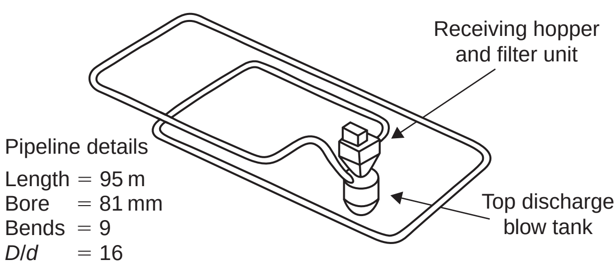


Figure 11.2 Sketch of 81 mm bore pipeline used.

The data in Figure 11.1 relates to a 95 m long pipeline of 81 mm (3 in. nominal) bore that includes nine 90° bends. A sketch of the pipeline is given in Figure 11.2. This pipeline was used for conveying many of the materials for which conveying characteristics are presented here and so both the pipeline and Figure 11.1 will serve as a reference to much of the data that follows.

This is single phase flow and the analysis of such flows is well established and quite straightforward. The pressure drop, Δp_a, for a fluid (typically air) of density, ρ, flowing through a pipeline of a given diameter, d, and length, L, can be determined from Darcy's Equation. This was presented in Equation (10.2) and is reproduced here for reference because of its importance:

$$\Delta p_a = \frac{4fL\rho C^2}{2d}\ \text{N/m}^2 \qquad (11.1)$$

where f is the pipeline friction factor (–) and C, the mean velocity of air (m/s).

It can be seen from this mathematical model that pressure drop follows a square law relationship with respect to velocity. This means that if the velocity is doubled the pressure drop will increase by a factor of four. Velocity, therefore, is a very important parameter in this work and constant reference will be made to this fact. As a consequence, in graphical representations of experimental results and data, velocity needs to be represented on one of the axes.

11.2.2 The use of air mass flow rate

A major problem with using velocity, however, is that it is not an independent variable. Gases are compressible and their densities vary with both pressure and temperature, as considered in some detail in Chapter 9. In Figure 11.1, it will be noticed that air mass flow rate has been used instead of velocity. Air mass flow rate is an independent variable and is an ideal substitute for velocity in this work.

Since density decreases with decrease in pressure, the velocity of the conveying gas will gradually increase along the length of a constant bore pipeline, but the mass flow rate of the gas will remain essentially constant. Velocity, C, can be determined quite easily from the mass flow rate, $\dot{m}_a$, using the Ideal Gas Law. This was presented in Equation (9.4) and is reproduced here for reference because of its importance:

$$p\dot{V} = \dot{m}_a RT \tag{11.2}$$

where p is the absolute pressure of gas (kN/m^2); $\dot{V}$, the volumetric flow rate (m^3/s); $\dot{m}_a$, the mass flow rate of gas (kg/s); T, the absolute temperature (K) and R, the characteristic gas constant (kJ/kg·K).

This was developed into an expression from which the conveying line inlet air velocity, C_1, could be evaluated, for a circular pipe with air as the conveying gas, in Equation (9.20) and this is reproduced below for reference:

$$C_1 = 0.365 \frac{\dot{m}_a T_1}{d^2 p_1} \text{ m/s} \tag{11.3}$$

Conveying line exit air velocity, C_2, can be similarly evaluated with values of T_2, and p_2.

This shows quite clearly how velocity is influenced by both gas pressure and temperature for a constant mass flow rate, and that for any given set of conveying conditions the air velocity can be evaluated quite easily.

11.3 Gas–solid flows

Figure 11.1 represents the relationship between air flow rate and pressure drop for the pipeline in Figure 11.2. If a small quantity of a granular or powdered material is fed into the air in the pipeline at a steady rate there will be an increase in the conveying line pressure drop, if the mass flow rate of the air remains constant. The magnitude of this increase depends upon the concentration of the material in the air.

11.3.1 The influence of conveyed solids on pressure drop

In a two phase flow system consisting of air and solid particles conveyed in suspension, part of the pressure drop is due to the air alone and part is due to the conveying of the

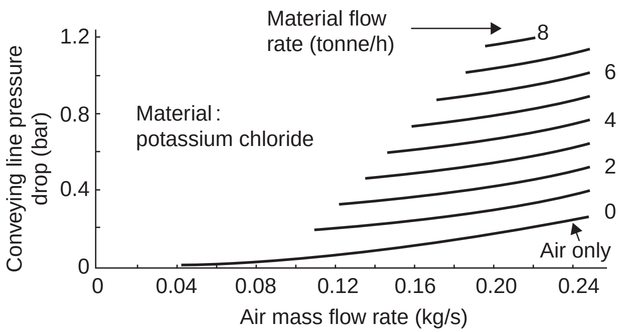


Figure 11.3 Pressure drop relationship with material flow.

particles in the air stream. In such a two phase flow the particles are conveyed at a velocity below that of the conveying gas, as considered in Section 1.2.3.4. There is, therefore, a drag force exerted on the particles by the air.

The influence of particle concentration on conveying line pressure drop over a wide range of conveying air mass flow rates, and hence velocities, is illustrated in Figure 11.3. The material conveyed here is potassium chloride having a mean particle size of about 500 μm. Conveying line pressure drop is plotted against air mass flow rate and lines of constant material flow rate are drawn on the graph.

The zero line at the bottom of the graph is the curve representing the variation of conveying line pressure drop with air flow rate for air only that comes from Figure 11.1. This, therefore, represents the lower limit with respect to material conveying capacity for the given system. It has been reported that the air only pressure drop curve can be reduced below the value shown on Figure 11.1 with 'seeding' of the pipeline. This is a boundary layer effect that can be achieved with low flow rates of particles. The material flow rates, however, are very low and are not appropriate to pneumatic conveying.

The curves drawn on Figure 11.3 were obtained from tests carried out with the material conveyed through the 81 mm bore conveying line shown in Figure 11.2. The data on Figure 11.3, therefore, relates only to the material tested and to this particular pipeline. This aspect of the problem is considered in more detail later.

11.3.2 Evaluation of velocity

If the superficial conveying air velocity is required for any condition this can be determined for any given air mass flow rate quite simply from the model in Equation (11.3). For the 81 mm bore pipeline over the range of air mass flow rates and pressures on Figure 11.3 this is shown in Figure 11.4. The relationships presented are for air at a temperature of 20°C.

For low pressure dilute phase conveying systems positive displacement blowers are often used, but their maximum delivery pressure capability is typically about 1 bar gauge. These are essentially adiabatic machines and so the air can reach quite high temperatures at outlet. The influence of temperature on conveying air velocity, for both air and material, is considered at Section 9.6.

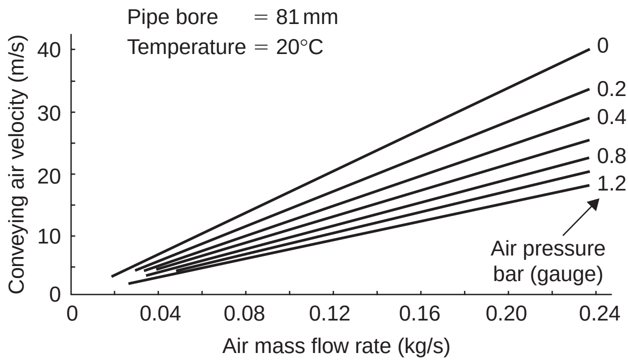


Figure 11.4 Variation of conveying air velocity with air mass flow rate and pressure.

11.3.3 Conveying limitations

Apart from the lower limit of zero for material conveying capacity, there are three other limitations on the plot in Figure 11.3. The first is the limit on the right hand side of the graph. This is not, in fact, a limit at all and conveying is possible with much higher air flow rates. In the case presented it was set by the volumetric capacity of the compressor used. By reference to Figure 11.4, however, it will be seen that conveying air velocities are up to about 40 m/s and for the majority of pneumatic conveying systems this is considered to be the upper limit.

The upper limit on air flow rate is influenced partly by problems of particle degradation and bend erosion in the conveying line, but it is mainly due to the adverse effect on the conveying line pressure drop and hence material flow rate. This relates to the influence of the (velocity)^2 term on pressure drop in Equation (11.1), that also applies approximately to gas–solid flows at high values of velocity. In terms of the overall conveying characteristics, the shape of the curves is quite clearly established within this maximum limit.

The second limit is that at the top of the graph. Once again, this is not a limit at all and conveying will be possible with very much higher pressures. In the case presented it was set by the pressure rating of the compressor used. For the type of material conveyed, however, it is also set by the flow rate of the air. Since the material can only be conveyed in suspension flow, at high velocity, the air flow rate available is close to its limit at a pressure of 1.2 bar gauge.

The third limit is that on the left hand side of the graph and this represents the approximate safe minimum conditions for successful conveying with the material. The lines actually terminate and conveying is not possible in the area to the left at lower air mass flow rates.

This limit is influenced by a complex combination of material properties, material concentration and conveying distance. In Figure 11.3 the potassium chloride is conveyed in dilute phase or suspension flow partly because the conveying line pressure gradient is very low, that is the ratio of the conveying line pressure drop to the pipeline length. As a result, a relatively high minimum conveying air velocity is required for this material.

Any attempt to convey with a lower air flow rate would result in blockage of the pipeline, in a conventional conveying system. This is because the air flow rate would be below the minimum required to keep the material in suspension. The terminology employed for these situations is choking, when conveying vertically up, and saltation when conveying horizontally.

It will be noted in Figure 11.3 that the lines of constant material flow rate terminate at progressively higher air mass flow rates as the material flow rate increases. This does not mean that the minimum conveying air velocity increases. This is entirely due to the influence of air pressure and, by reference to Figure 11.4, it will be seen that the minimum conveying air velocity for this material is about 15 m/s and that it changes little over this range of material flow rates.

At much higher material concentrations, or solids loading ratios, the minimum conveying velocity can be very much lower for materials having good air retention properties. This, however, is non-suspension flow, or the dense phase region, where the mode of conveying is very different.

11.3.4 Conveying air velocity effects

An alternative way of presenting the data is to plot the material flow rate against the air flow rate and to have a series of curves at a constant value of the conveying line pressure drop. Such a plot is shown in Figure 11.5a. This shows the influence of excessively high conveying air velocities which result in the lines of constant pressure drop sloping quite steeply to the air flow rate axis, and hence to zero material flow rate, at very high velocities.

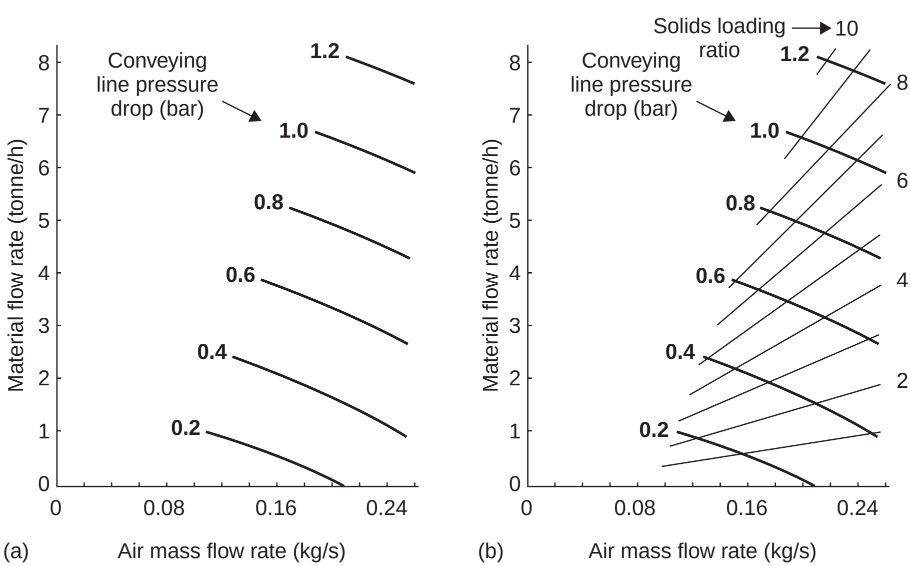


Figure 11.5 Alternative presentations of conveying data for potassium chloride: (a) pressure drop change and (b) conveying characteristics.

This is because of the square law relationship of pressure drop with respect to velocity, as mentioned above. If the conveying system has a compressor or blower with a maximum rating in terms of delivery pressure, a considerable amount of this available pressure will be taken up by moving the air through the line if the air flow rate, and hence velocity, is too high.

Part of the pressure drop is due to the material being conveyed and the greater the concentration of the material in the air, the greater the pressure drop. If the conveying air velocity is too high, therefore, the concentration of the material in the air will have to be reduced in order to match the available pressure drop, and so the resulting material flow rate will be much lower.

11.3.5 Solids loading ratio

Solids loading ratio is the term generally used by pneumatic conveying engineers to describe the conveyed gas–solids flow. Solids loading ratio is the ratio of the mass flow rate of the solids conveyed to the mass flow rate of the air used (see Equation (1.3)). The particular advantages over particle concentration are that it is a dimensionless quantity and its value does not vary with the conveying gas pressure. With the graphs in Figure 11.5 being plots of material flow rate against air flow rate, lines of constant solids loading ratio can be superimposed quite easily as they are straight lines through the origin. Such a plot is shown in Figure 11.5b.

11.4 The determination of conveying characteristics

Although the analysis of single phase flow is well established, that for the two phase flow of solid particles in a gas is not. Mathematical and empirical models have been derived to predict the influence of the many variables, but their use is generally very limited. Where models are available they are likely to be restricted to a narrow range of operating conditions, and nothing is currently available that will cover the entire range of the conveying characteristics shown in Figure 11.5b. It is necessary, therefore, to carry out tests with the actual material in a pneumatic conveying test facility.

The necessity for carrying out tests with the actual material for which the data is required is essential, for conveying characteristics can vary significantly from one material to another, and even between different grades of the same material. Carrying out tests in a similar pipeline, however, is not as critical as it is possible to use scaling parameters to scale the conveying characteristics from a test line to an actual plant pipeline. This aspect of system design is considered in Chapter 14.

11.4.1 Instrumentation and control

In order to determine the conveying characteristics for a material it is necessary to have a conveying plant that has sufficient controls and instrumentation to enable conveying trials to be carried out over as wide a range of conditions as possible. Air flow rate, material flow rate and conveying line pressure drop are the main parameters that have to be measured, and air flow rate and material flow rate need to be varied over as wide range as possible, within the limits imposed by the conveying air supply.

Rotameters, orifice plates and choked flow nozzles are among some of the devices that can be used for the measurement of air flow rate. The choice depends upon the magnitude of the flow rate, the pressure at which it has to be measured, and whether the flow is subject to pulsations.

Load cells are ideal for the measurement of material flow rate. These are used either on the supply hopper or the reception hopper. On the supply hopper to the feeding device, or on a blow tank if this is used, loss in weight will be measured. On the reception hopper, gain in weight will be recorded. Whichever is more convenient can be used. Load cells on both hoppers would only be required if it were necessary to observe material deposition in the pipeline.

Conveying line pressure drop for a given pipeline system can be measured quite simply with a pressure gauge, although a pressure transducer would be preferred. If this is positioned in an air supply or extraction line, a bourdon type gauge can be reliably used. This is because there should be no material in the flow to interfere with the recording. It will also give a very reasonable indication of the pressure drop since losses prior to the conveying line and that across the filtration system will generally be negligible in comparison with that across the pipeline.

If individual elements of a pipeline need to be assessed in isolation, such as bends or straight horizontal or vertical sections of pipeline, however, recordings will need to be monitored from a series of pressure tappings in the conveying line itself. In this type of situation pressure transducers will be essential and pressure tappings will have to be carefully designed to eliminate the possibility of dust affecting the accuracy of the readings. Such recording techniques are particularly necessary for changes in section and direction in the pipeline, such as step changes and bends. These will result in a deceleration of the particles, and the effects of these will be seen for many metres of straight pipeline following the change.

11.4.2 Experimental plan

If full controls are available on a conveying plant it should be possible to convey a material at any required flow rate, at any conveying air velocity and with any conveying line pressure drop within the capabilities of the system. Individual tests on this basis, however, take a long time to carry out since, with so many variables, very precise conveying conditions have to be established and then maintained each time. Precise material flow rate is also difficult to achieve with a blow tank, if this is used, since their discharge characteristics are also dependent upon the properties of the material being conveyed (see Section 4.4.3.3.2).

The method usually adopted is to set the plant in operation and record the necessary results when steady state conditions are obtained. If material and air flow rates are each progressively changed over as wide a range as possible a large amount of data can be obtained very quickly. Subsequent analysis of the results is then reasonably straightforward since so much information is available.

A few tests are generally conducted without the material so that the pressure drop for the empty line can be determined, and thereby establish a datum for the conveying line as illustrated in Figure 11.1. Tests should also be repeated periodically to provide a check on the condition of the conveyed material, if this is being re-circulated.

11.4.3 Presentation of results

Graphical representation of the results is probably the best method of displaying the interrelating effects of the many variables in the problem. With a number of major variables and a large number of test results, the drawing of families of curves provides an ideal means of both handling the data and presenting results. If two of the variables are chosen for the x- and y-axes of a graph, all the test results for a third variable can be marked on this graph. They can be appropriately rounded for convenience, with the decimal point representing the actual location of the test results on the graph. Lines of constant value of this variable can then be drawn through the data to provide a family of curves.

Results obtained from tests carried out with cement conveyed through the 95 m long pipeline of 81 mm bore shown in Figure 11.2 are presented in Figure 11.6. Figure 11.6a is a graph of conveying line pressure drop against air flow rate and Figure 11.6b is a graph of material flow rate against air flow rate. In each case experimental values of the third variable are plotted. Lines of constant value of the given parameter have been drawn through the data and it will be noticed that the family of curves drawn can be clearly identified from the data, despite the fact that no two tests were carried out at the same pressure and with the same material flow rates.

In Figure 11.7a the curves have been drawn without hindrance of the test results and lines of constant solids loading ratio have also been superimposed to produce the conveying characteristics for the cement in the given pipeline.

It must be emphasized that these conveying characteristics relate only to this material in this pipeline. The conveying characteristics for another material, or for this material in

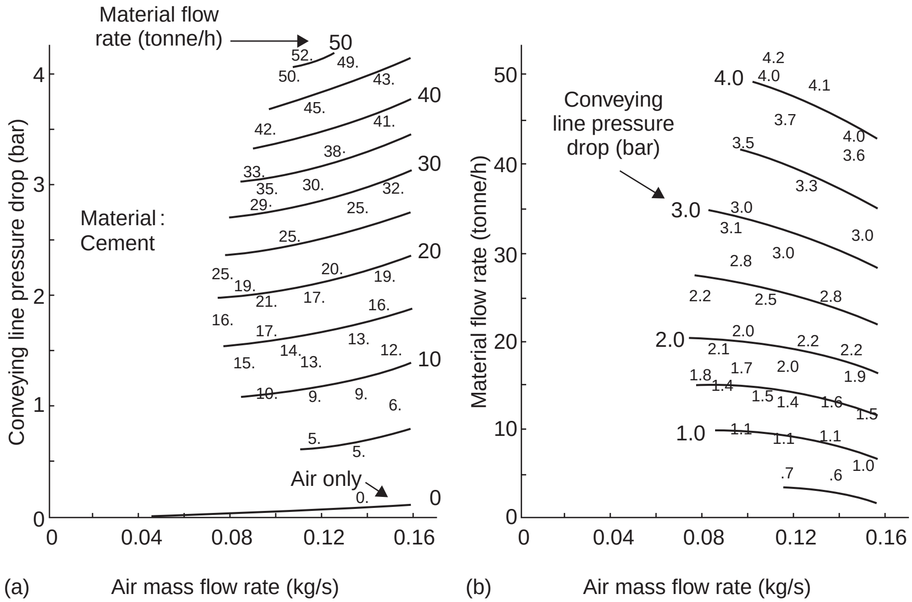


Figure 11.6 Analysis of data from the conveying of cement in 81 mm bore pipeline: (a) material flow rate data and (b) pressure drop data.

another pipeline, could differ very significantly from that for the cement shown in Figure 11.7a. The lines of constant conveying line pressure drop could be in different positions relative to the material flow rate axis, have a different shape and slope, and terminate at totally different values of air flow rate. It is for this reason that it is necessary to determine the conveying characteristics of the actual material to be conveyed.

From the conveying characteristics for the cement in Figure 11.7a the adverse effect of conveying the material with too high an air flow rate can be clearly seen. Although the cement can be successfully conveyed over the entire range that the conveying characteristics cover, and beyond at even higher air flow rates, the trend for this particular material, in the pipeline tested, is to decrease in material flow rate with increase in air flow rate for a constant value of conveying line pressure drop. This applies over the entire range of air flow rates investigated. A more detailed analysis of the influence of air flow rate, and hence the choice of conveying parameters, is considered in more detail later.

11.4.4 Determination of minimum conveying conditions

In order to determine the minimum conveying conditions for the cement, a graph of conveying line inlet air velocity drawn against solids loading ratio is presented in Figure 11.7b. On this graph some of the low velocity test results have been plotted. The spread of results was obtained because a wide range of conveying conditions was required for the characteristics to be drawn, but they do show a distinct trend, and a curve representing the possible minimum conveying conditions is drawn.

It has been found that the minimum conveying conditions for most materials can be correlated in this manner. This is a major parameter in system design, and although

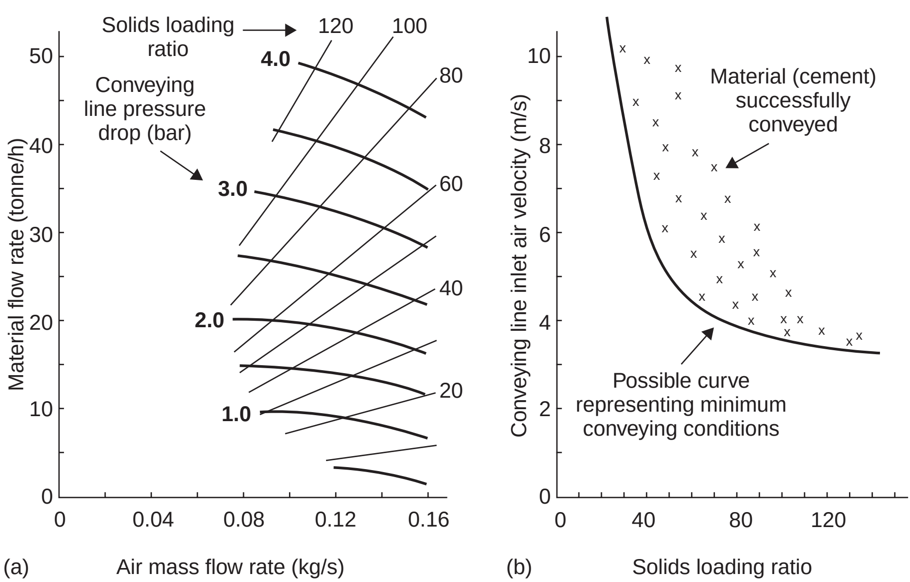


Figure 11.7 Design data for the pneumatic conveying of cement: (a) material conveying characteristics and (b) minimum velocity relationship.

the data can be obtained from Figure 11.7a, it is a much more complex relationship in this form because of the additional influence of pressure on conveying air velocity. Plots such as those in Figure 11.7b, therefore, provide a very useful means of identifying minimum conveying conditions for materials. The exact position of the curve on Figure 11.7b, which represents the minimum conveying conditions, is rather difficult to locate. If the pipeline is blocked no experimental results are obtained for the test, although in some cases it might be possible to estimate the approximate location on the graph from tests which preceded it.

As this is the design parameter that dictates the air requirements in terms of volumetric flow rate for a conveying system it would obviously be expedient to specify an air mover having a capacity with a reasonable margin, in order to allow for any differences in this relationship that might occur if a material with a slightly different specification has to be conveyed. Although an optimum design would normally be based on the system operating as close as possible to the minimum conveying conditions, a margin in air flow rate would be advisable in case the solids loading ratio specified in the design was, for some reason, on the low side.

11.4.5 The use of conveying characteristics

With conveying line pressure drop, solids loading ratio and both material and air flow rates all represented on the one graph, all the data necessary for the design of a pneumatic conveying system is available. If a system has to be designed to achieve a given flow rate, a point on the conveying characteristics must be chosen just above the minimum conveying conditions to ensure that the pipeline will not block. This point gives the compressor rating required, in terms of delivery pressure and volumetric flow rate (evaluated from the air mass flow rate), and the solids loading ratio of the conveyed material.

Alternatively, if a compressor or conveying system is already available with a given air supply pressure, the conveying characteristics can be used to determine the volumetric flow rate required to achieve optimum conveying conditions. They will also give the expected material flow rate and solids loading ratio. A particularly advantageous feature of presenting design information in this form is that it can be scaled quite easily. Conveying characteristics for a given material in one pipeline can be scaled to that of another pipeline of a different length, bore and configuration. The conveying characteristics themselves are scaled and so design data is obtained directly for the new pipeline. This process is considered in Chapter14.

11.5 Energy considerations

Apart from showing the relationship between the main design parameters for the conveying of a material through a pipeline, the conveying characteristics can be further developed to provide data on power requirements so that energy considerations can also be taken into account at the design stage of a system.

Two further materials, conveyed through the pipeline presented in Figure 11.2, are used to illustrate these points. One is cryolite, a coarse granular material with a very wide particle size distribution. The other is a dicalcium phosphate, a fine powdered material with good air retention properties.

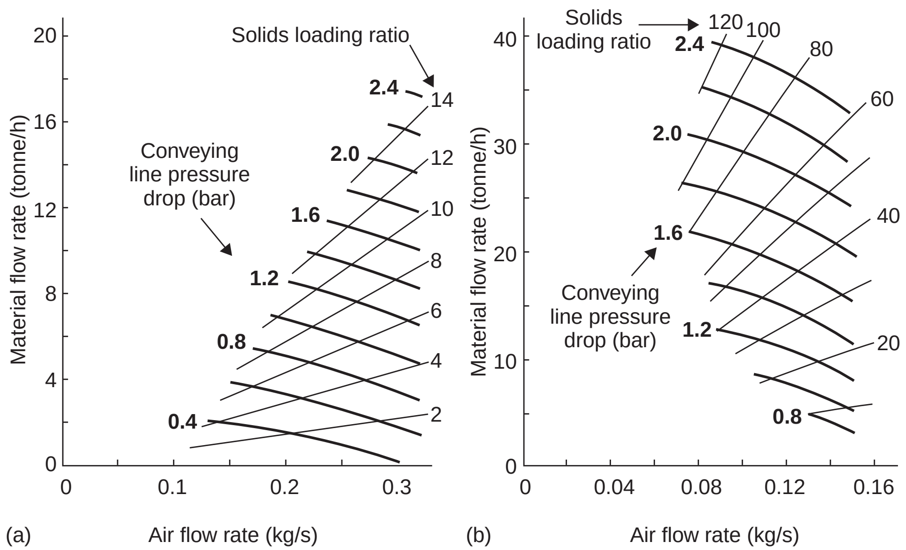


Figure 11.8 Conveying characteristics for materials conveyed through 95 m long pipeline of 81 mm bore: (a) cryolite and (b) dicalcium phosphate.

The cryolite could only be conveyed in dilute phase suspension flow through the pipeline, even though high pressure air was used. The dicalcium phosphate, however, could be conveyed in dense phase, and solids loading ratios well in excess of 100 were achieved. The conveying characteristics for these two materials are presented in Figure 11.8 for reference.

It will be noticed that for the dicalcium phosphate the material flow rate axis has been doubled, because it was possible to convey the material at a very much higher flow rate for the same conveying line pressure drop. It will also be seen that the air flow rate axis has been halved for the dicalcium phosphate, because it was possible to convey the material with very much less air. These are two very obvious differences between these two materials that were conveyed through exactly the same pipeline (Figure 11.2).

11.5.1 The influence of conveying air velocity

The adverse effect on material flow rate of conveying with an unnecessarily high air flow rate can be explained in terms of conveying air velocities. Two values need to be considered. These are the conveying line inlet and exit air velocities, and they can be determined by applying Equation (11.3). If the exit from the conveying line is taken as atmospheric pressure, the velocity here will be directly proportional to the air flow rate.

The conveying line inlet air velocity is a function of both pressure and air flow rate and so needs to be plotted for presentation. The conveying characteristics for the cryolite and dicalcium phosphate are redrawn in Figure 11.9. Lines of constant conveying line inlet air velocity have been superimposed on the conveying characteristics, and the air flow rate axis has been drawn in terms of conveying line exit air velocity.

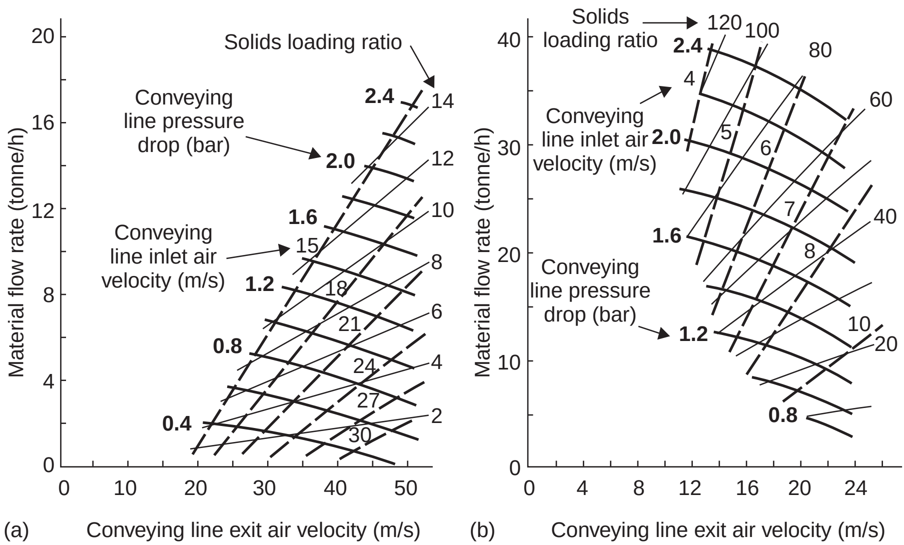


Figure 11.9 Conveying characteristics with lines of constant conveying line inlet air velocity added: (a) cryolite and (b) dicalcium phosphate.

Figures 11.9a and b show the differences between dilute and dense phase conveying quite clearly. The cryolite could not be conveyed with a conveying line inlet air velocity below about 14 m/s. Dicalcium phosphate, however, as will be seen from Figure 11.9b, could be conveyed with conveying line inlet air velocities as low as 4 m/s.

At one extreme a flow rate of 30 tonne/h can be obtained with inlet and exit velocities of 4 and 12 m/s, respectively. At the other extreme, the same flow rate can be obtained with the velocity expanding from 8 to 26 m/s. In the first case the dicalcium phosphate will be conveyed at a solids loading ratio of about 110 and in the second case the solids loading ratio will be about 50. If conveying air velocity alone is not a deciding factor between the two alternatives, power requirements might well be.

11.5.2 Power requirements

In the above example 30 tonne/h of dicalcium phosphate was conveyed through the pipeline. In the second case, however, the air flow rate required was considerably more and the conveying line pressure drop was also slightly higher. A more useful comparison of these two cases, and others, is to compare them on the basis of power requirements. Having evaluated all the parameters necessary for the system, it is now possible to determine the power required, and hence the approximate cost associated with operating the system.

For an accurate assessment of the power it will be necessary to consult manufacturers' literature. By this means, different machines capable of meeting the duty can be compared. For a quick, approximate assessment, to allow a comparison to be made of different variables, a simple model based on isothermal compression can be used.

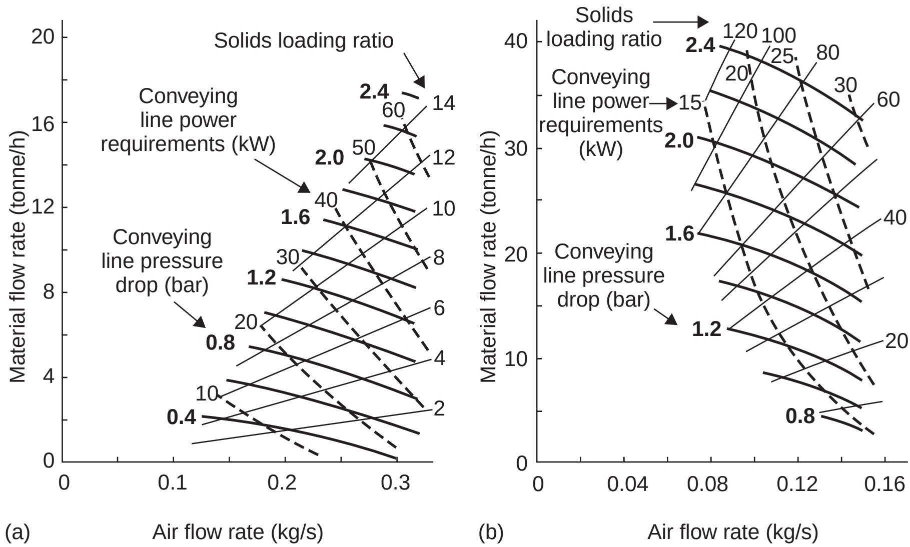


Figure 11.10 Conveying characteristics with lines of constant power requirements added: (a) cryolite and (b) dicalcium phosphate.

Such a model was presented at Section 6.3.6:

$$P = 2\dot{m}_a RT \ln\left(\frac{p_1}{p_2}\right) \text{kW} \tag{11.4}$$

where $\dot{m}_a$ is the air mass flow rate (kg/s); R, the characteristic gas constant (kJ/kg · K); T, the absolute temperature (K); p_1, the air inlet pressure to pipeline (bar abs); p_2, the air outlet pressure from pipeline (bar abs) and P, the power required (kW)
and with $R = 0.287$ kJ/kg · K for air and $T = 288$ K:

$$P = 165\dot{m}_a \ln\left(\frac{p_1}{p_2}\right) \text{kW} \tag{11.5}$$

A value of two was taken for the constant, to allow for the fact that the ideal model does not take account of thermodynamic irreversibility and transmission losses.

Using this model, it is a relatively straightforward operation to superimpose lines of constant power requirement onto the conveying characteristics. This has been done for the material conveying characteristics in Figure 11.8, and the results are presented in Figure 11.10. Although the data is not particularly accurate it does show quite clearly the adverse effect of conveying a material with an unnecessarily high air flow rate in terms of power consumption. In the above example of conveying dicalcium phosphate at 30 tonne/h it can be seen from Figure 11.10b that if the material is conveyed at a solids loading ratio of

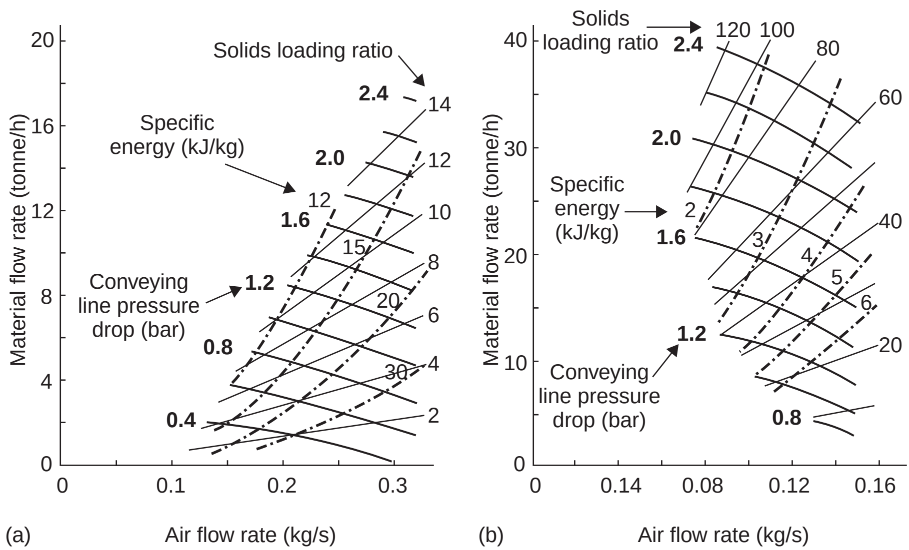


Figure 11.11 Conveying characteristics with lines of constant specific energy added: (a) cryolite and (b) dicalcium phosphate

110 the power required will be about 14 kW, whereas if the dicalcium phosphate is conveyed at a solids loading ratio of 50 the power required will be about 33 kW.

11.5.3 Specific energy

Although the data on power requirements clearly shows the effects of air flow rate, it does not present a clear picture if a comparison is to be made with respect to system air supply pressure or if a better comparison of different materials is required. To do this it is necessary to superimpose a family of curves in terms of specific energy onto the conveying characteristics. By this means, a fully comprehensive comparison will be possible. Lines of constant specific energy can be plotted quite simply by dividing the power requirements data on Figure 11.10 by the corresponding material flow rates. The results, in terms of specific energy in kJ/kg, are presented in Figure 11.11.

This shows quite conclusively that the most efficient conveying is achieved with the lowest possible air flow rate, and hence lowest conveying air velocity. The specific energy curves on Figure 11.11 follow a similar pattern to those of constant conveying line inlet air velocity on Figure 11.9, and so show that low velocity, dense phase conveying is more efficient than dilute phase conveying.

In the case cited earlier, with the dicalcium phosphate conveyed at 30 tonne/h, only 1.6 kJ/kg would be required if the material was conveyed at a solids loading ratio of 110, but at a solids loading ratio of 50 the specific energy would be more than doubled. This also illustrates why it is necessary to obtain such data, for it is essential to know whether a material is capable of being conveyed at high values of solids loading ratio before a low velocity system is recommended. Indeed, many materials could not even be conveyed at a solids loading ratio of 20 over this distance.

Cryolite is typical of materials that cannot be conveyed in dense phase with a conventional pneumatic conveying system. A minimum value of conveying line inlet air velocity of at least 14 m/s would always have to be maintained. A high value of solids loading ratio could not be achieved even if a very high air supply pressure was used. As a result specific energy levels are not likely to be reduced for the cryolite below those indicated on Figure 11.11a. These figures show quite clearly that low velocity dense phase conveying is more economical than dilute phase conveying. For a material that is not capable of being conveyed in dense phase, the lowest possible value of conveying line inlet air velocity should be employed.

11.6 Component pressure drop relationships

In order to determine the influence of vertical sections in a pipeline it is generally necessary to use pressure tappings along the length of the section to be considered. By this means, data can be obtained for vertical sections in isolation from the rest of the pipeline. In horizontal pipelines pressure tappings are not required since there is no change in orientation. The data obtained, however, will be in a different form, but if tests are carried out over a range of conveying conditions, the results can be presented in a similar way to those of the conveying characteristics for the pipeline.

Data obtained from a PhD programme [1] on vertical pneumatic conveying, supervised by the author, is included here to illustrate the nature of the relationships. A sketch of the pipeline specifically built for the test work, together with typical pressure gradient results are presented in Figure 11.12 [2]. Two pipelines were built, one of 53 and another

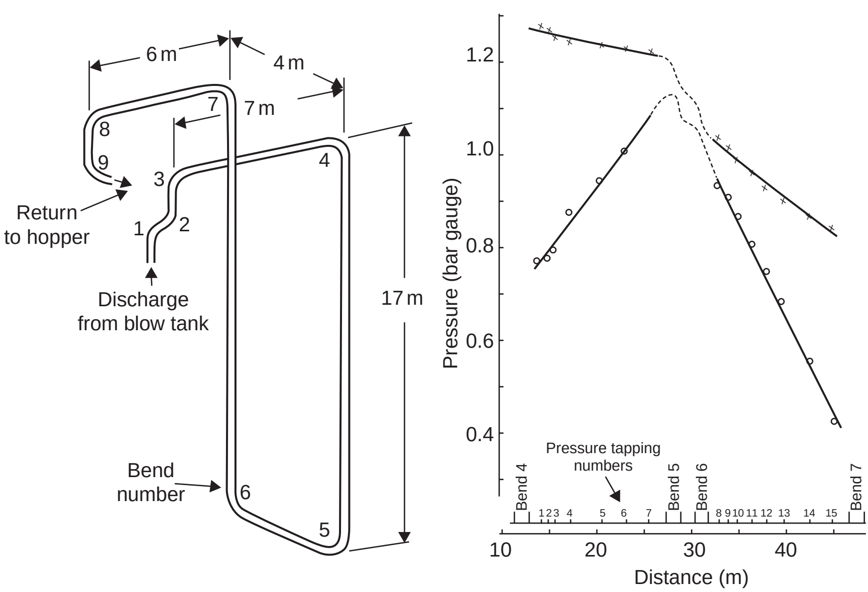


Figure 11.12 Vertical pipeline facility and test results with fine fly ash: (a) sketch of 53 mm bore pipeline and (b) typical pressure gradient data.

of 81 mm bore, both with essentially the same geometry as that in Figure 11.12a. In the vertically down sections of pipeline, there were seven sets of pressure tappings and in the vertically up sections there were eight sets. A ring of four pressure tappings was provided at every location and these were inter connected. Every pressure tapping was fitted with a filter pad and provided with a high pressure air purging facility, which was routinely operated after each and every test run.

Two typical sets of pressure measurement data for the vertically down and vertically up sections of pipeline are presented in Figure 11.12b. This shows the location of the pressure tappings and their proximity to the various bends in the pipeline. The data relates to the pneumatic conveying of a fine grade of pulverized fuel ash, and many other materials were tested [2].

11.6.1 Conveying vertically down

Results for the vertically downward conveying of a fine grade of pulverized fuel ash through the 53 mm bore pipeline are presented in Figure 11.13a. The same axes have been employed, as for the conveying characteristics, but lines of constant pressure gradient in mbar/m have been drawn from the experimental data. Solids loading ratio values of well over 100 were achieved for the flow of material.

The negative values of line pressure gradient on Figure 11.13a indicate that there is an increase in pressure through the pipeline. From Figure 11.13a, it will be seen that at a solids loading ratio of about 35 the fly ash could be conveyed through this pipeline with zero pressure drop. At lower values of solids loading ratio there will be a pressure

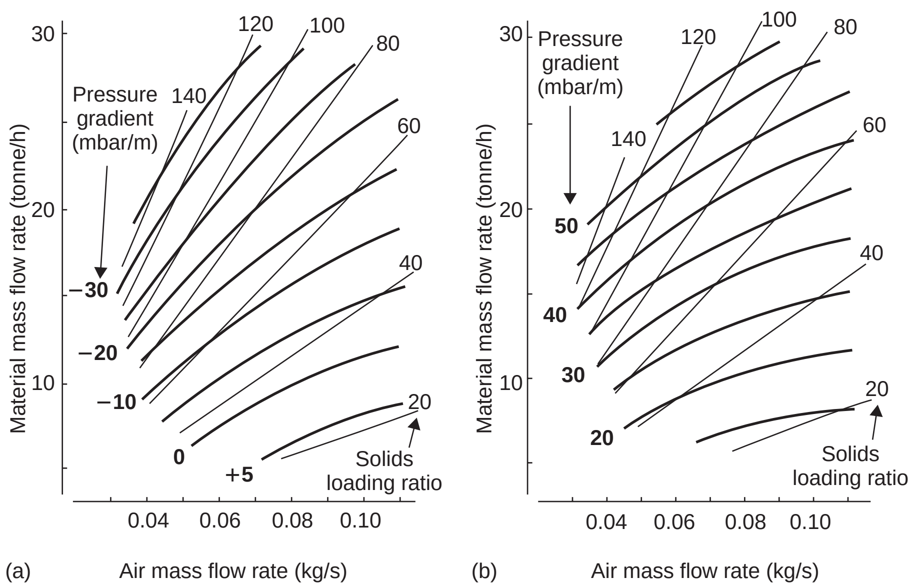


Figure 11.13 Pressure gradient data for the vertical conveying of a fine grade of fly ash in a 53 mm bore pipeline: (a) conveying vertically down and (b) conveying vertically up.

loss, but at higher solids loading ratios there will be an increase in pressure along the length of the pipeline. With a line pressure gradient of −25 mbar/m this would amount to a gain in pressure of about 1.0 bar for a 40 m length of vertical pipeline when conveying downwards.

If a pipeline having a significant proportion of the routing vertically downwards has to be designed, data such as that in Figure 11.13a is essential. This would be the case in situations where materials have to be conveyed down mine shafts. With a large vertical fall a very high pressure could result if the material was conveyed at a high value of solid loading ratio. It is possible that the pressure generated in this way could be used to convey the material to mine workings some distance from the bottom of the shaft. Such a system would have to be carefully designed, with due consideration to conveying air velocities in horizontal sections following vertical falls, but it is possible that it could operate with a low air supply pressure and require little power [3].

11.6.2 Conveying vertically up

Results for the vertically upward conveying of a fine grade of fly ash are presented in Figure 11.13b. Similar data for the vertically upward conveying of cement is presented in Figure 11.14. In Figure 11.14a the data if for a 53 mm bore pipeline and in Figure 11.14b the data is for an 81 mm bore pipeline. In all three cases, values of solids loading ratios well in excess of one hundred were achieved for the flows.

A comparison of these figures will show the influence of the two materials and the two pipeline bores on the relationships. A further comparison of these figures with

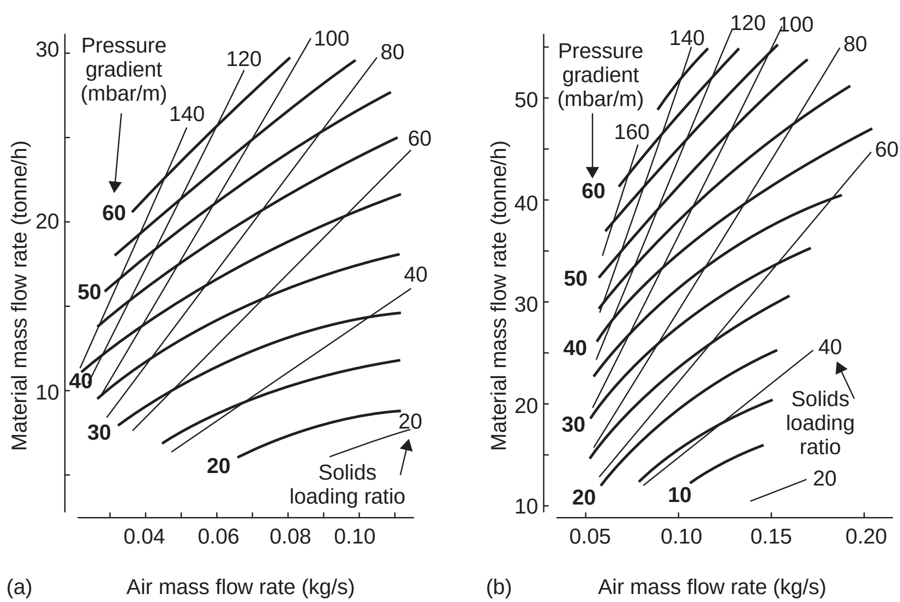


Figure 11.14 Pressure gradient data for the vertically upward conveying of cement: (a) for 53 mm bore pipeline and (b) for 81 mm bore pipeline.

those for a total pipeline system (including bends) in Figures 11.5b, 11.7a and 11.8 will show that the slope of the lines of constant pressure are totally different from those of constant pressure gradient drawn on Figures 11.13 and 14. Figures 11.13 and 14 show that material flow rate will increase with increase in air flow rate for a constant line pressure gradient.

Lines of constant conveying line pressure gradient will ultimately reach the horizontal axis and so the slope must, at some point, reverse. In the area appropriate to pneumatic conveying, however, it would appear that a significant increase in material flow rate can be obtained by increasing the air flow rate. This is possibly a feature of straight pipeline lengths as it applies to both vertically up and vertically down lines. An increase in air flow rate at a constant line pressure gradient will result in a corresponding increase in power requirements, but it does mean that much of the extra power is being used to convey additional material. This point is considered further in relation to both horizontal pipeline and bends that follows.

11.6.3 Horizontal pipelines

In work carried out to determine scaling parameters for horizontal conveying distance, tests were carried out on pipelines of various lengths but with each having the same number of bends. From an analysis of the results obtained the influence of the bends was isolated. The results for barytes in a 53 mm bore pipeline are presented in Figure 11.15. This is a similar plot to that for the vertical lines in Figures 11.13 and 11.14. It will be noticed that, although these pressure gradient values are much lower than those presented for the vertically up lines, the trend of the curves is very similar. Despite the fact that barytes has a particle density of about 4200 kg/m^3, solids loading ratios in excess of 100 were obtained once again. In terms of dense phase conveying capability it is the air retention property that is the dominating parameter.

Figure 11.15 shows once again that for straight pipeline sections there will be an increase in material flow rate with increase in air flow rate, in the area of the conveying

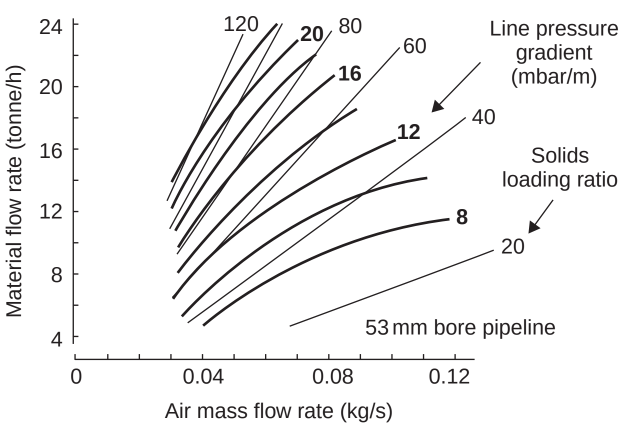


Figure 11.15 Influence of conveying conditions on horizontal line pressure gradient for barytes.

characteristics appropriate to dense phase conveying. With the horizontal pipeline section and both vertical sections showing the same trend, it must be the bends that have the over-riding effect on the total pipeline conveying characteristics.

11.6.4 Pipeline bends

In work carried out to determine scaling parameters for pipeline bends, tests were carried out on two lines of approximately the same length but having a different number of bends. From an analysis of the results obtained from these two pipelines, the influence of the bends was determined. By using the results of this analysis, it is possible to separate the effects of bends from the straight horizontal conveying, without having to use pressure tappings.

A plot similar to those presented in Figures 11.13 to 15 is given in Figure 11.16 for the pipeline bends. The data in this case is presented in terms of a pressure loss in mbar/bend, and relates to bends having a bend diameter to pipe bore ratio of about 24:1. It can be seen from Figure 11.16 why the conveying characteristics for a pipeline system are so different from those of the straight sections of pipeline.

In terms of pipeline conveying performance, therefore, bends can have a very significant effect. Losses associated with bends are expressed as either a pressure drop or an equivalent length of straight horizontal pipeline. The number of bends, their geometry and their location in the pipeline are all important. It is also possible that the type of conveyed material has a significant effect, as well as conveying parameters. These issues are considered further in Chapter 14.

Part of the problem lies in the complexity of the flow in the region of a bend. The conveyed particles approaching a bend, if fully accelerated, will have a velocity of about 80 per cent of that of the air. The velocity, of course, will depend upon the particle shape, size and density, and the pipeline orientation. At outlet from a bend the velocity of the particles will be reduced and so they will have to be re-accelerated back to their terminal velocity in the straight length of pipeline following the bend.

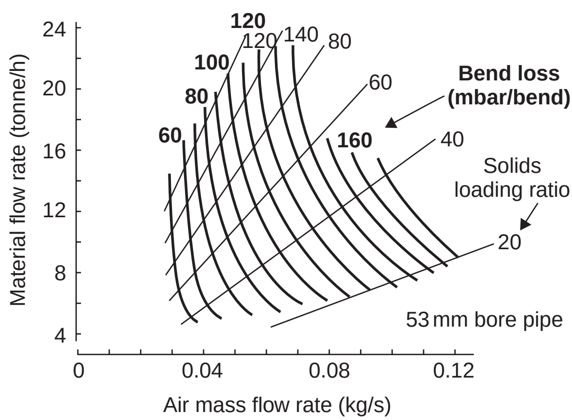


Figure 11.16 Influence of conveying conditions on bend losses for barytes.

11.7 Nomenclature

A	pipe section area	m^2	
C	conveying air velocity	m/s	
d	pipeline bore	m	
f	pipeline friction factor	–	
L	pipeline length	m	
$\dot{m}$	mass flow rate	kg/s	for air
		tonne/h	for material
P	power	kW	
p	air pressure	kN/m^2	
R	characteristic gas constant	kJ/kg·K	
T	air temperature (absolute)	K	
$\dot{V}$	volumetric flow rate	m^3/s	

11.7.1 Greek

ρ	air density	kg/m^3
ϕ	solids loading ratio	–

$$= \frac{\dot{m}_p}{3.6\,\dot{m}_a}$$

11.7.2 Subscripts

a	air
p	conveyed material or particles
1	inlet conditions and reference
2	exit conditions and reference

11.7.3 Prefixes

Δ	difference in value

References

1. P Marjanović. An investigation of the behaviour of gas–solids mixture flow properties for vertical conveying in pipelines. PhD Thesis. CNAA. Thames Polytechnic (now the University of Greenwich), London, UK. 1984.
2. D Mills. A review of the research work of Professor Predrag Marjanović. Proc 4th Int Conf for Conveying and handling of particulate solids. Budapest. May 2003.
3. D Mills. Application of stepped pipelines in pneumatic conveying systems. Proc 15th Int Conf on Hydrotransport Incorporating the 11th Int Symp on Freight Pipelines. Banff, Canada. pp. 401–416. June 2002.

Chapter 12

Conveying capability

12.1 Introduction

In Chapter 11 a limited number of materials were considered in order to illustrate the global differences between dilute phase and dense phase conveying. For dense phase conveying only powdered materials having good air retention properties were considered. Within this framework the influence of air flow rate and conveying air velocity were considered, particularly in terms of power requirements and energy considerations.

Conveying with high pressure air was employed in most cases to show the influence on the conveying capability of the different materials being considered. Low pressure conveying data is therefore automatically included in all of the conveying characteristics presented in Chapter 11, but it does tend to get lost and overlooked in the overall scale. Similarly the low pressure, and hence dilute phase conveying, of the materials having good air retention, also tends to disappear into the bottom right hand corner of the overall conveying characteristics of these materials when conveyed with high pressure air.

In this chapter a much wider range of materials is considered and low pressure conveying data is specifically included so that the performance of all types of material can be examined at low values of solids loading ratio. Both sliding bed and plug flow modes of dense phase conveying are considered in the range of materials included.

12.2 The influence of materials

The conveying characteristics for different materials can vary significantly. This is particularly so for materials capable of being conveyed in dense phase. At low values of air flow rate the lines of constant conveying line pressure drop can have a wide variety of slopes. There is also the added complexity of different materials having different minimum conveying limits. Thus for a given air flow rate and conveying line pressure drop, material flow rates for different materials can vary considerably, and the air flow rate necessary to convey different materials can also vary considerably.

Some of these differences were illustrated in the previous chapter with the materials used to show how conveying characteristics are determined and to compare power and energy requirements. These differences, however, are not just a feature of conveying with high pressure air but will be found in low pressure systems also.

12.2.1 Low pressure conveying – Part I

If only low pressure air is available for conveying a material through a pipeline, such as that from a positive displacement blower or a vacuum system, and below about 1 bar gauge, a material will only be conveyed in dilute phase through a pipeline, unless the conveying distance is very short. Conveying data for four different materials are presented in Figure 12.1.

Each material was conveyed up to a limit of 0.5 bar in terms of conveying line pressure drop. All four materials were conveyed through the same pipeline, a sketch of which is given in Figure 12.2. A low pressure bottom discharge blow tank was used to

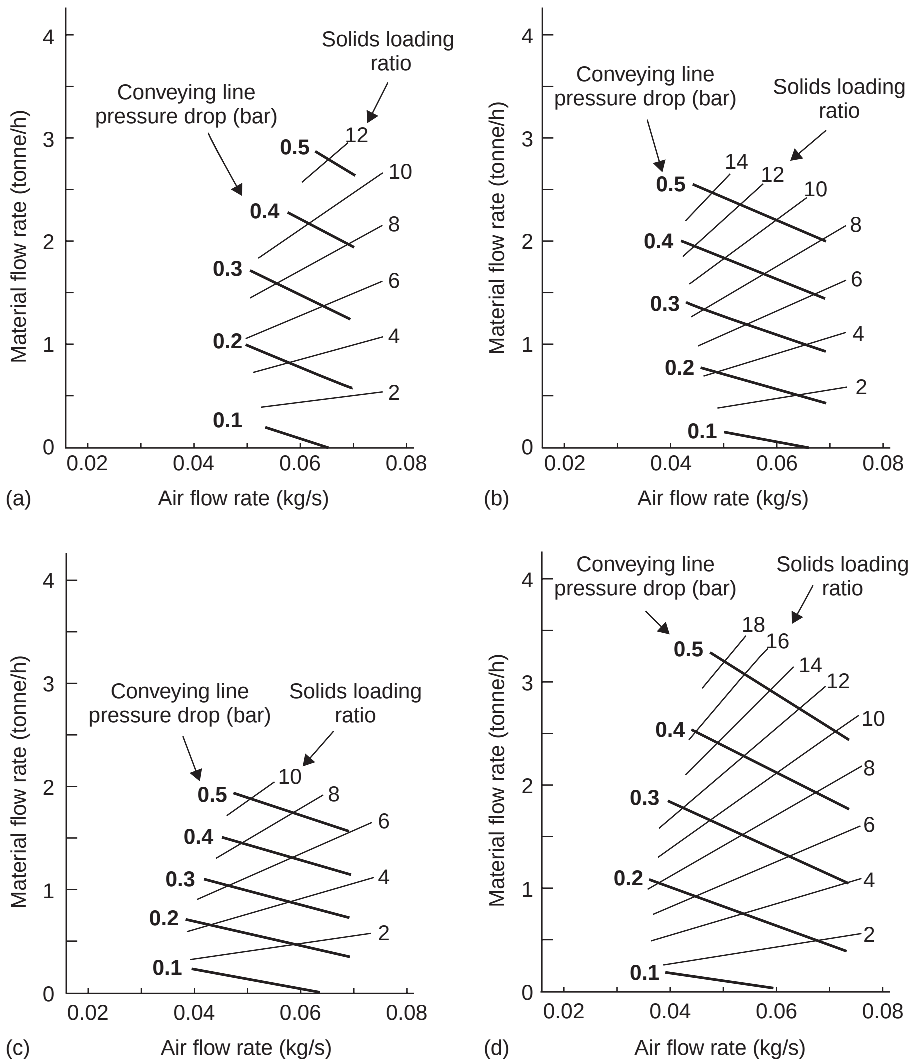


Figure 12.1 Conveying characteristics for materials conveyed through the pipeline shown in Figure 12.2 (pipeline no. 1): (a) coal (pearls), (b) sodium chloride (salt), (c) sodium carbonate (soda ash) and (d) pearlite.

feed each material into the pipeline. Although each material was conveyed in dilute phase, it will be seen that there are significant differences in their conveying capability.

The conveying characteristics for two further materials also conveyed through pipeline no 1 are presented in Figure 12.3.

The differences between the six materials presented are mainly in terms of the material flow rates achieved, varying from 4.3 tonne/h for the fly ash to 1.4 tonne/h for the iron powder, for a pressure drop of 0.5 bar. Since all the materials were conveyed in dilute phase, and they were all either powders or granular materials, such marked differences would not be expected in terms of minimum conveying air velocities. With a 0.2 bar pressure drop, these varied between 12 m/s for fly ash and 16 m/s for the coal.

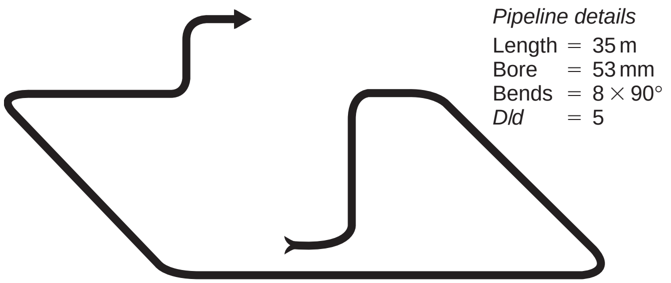


Figure 12.2 Sketch of pipeline no. 1.

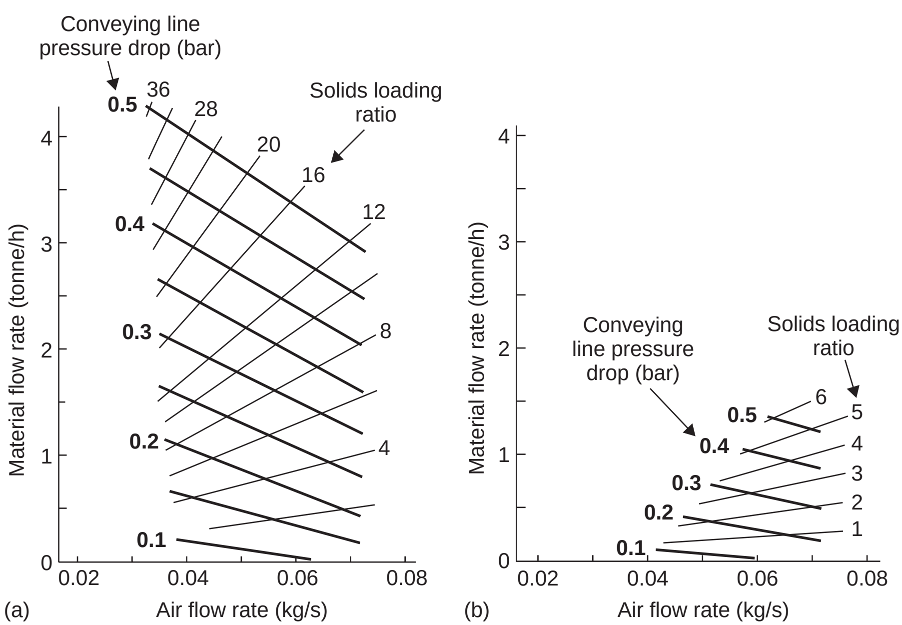


Figure 12.3 Conveying characteristics for materials conveyed through the pipeline shown in Figure 12.2 (pipeline no. 1): (a) fine grade of pulverized fuel ash and (b) iron powder.

Many different materials have been tested in the pipeline shown in Figure 12.2. To show how the conveying characteristics of different materials can vary in such a low pressure system, the 0.5 bar constant conveying line pressure drop curves from a number of such materials are compared in Figure 12.4.

Different conveying capabilities and air requirements mean that particular care must be taken if an existing system is to be used to convey another material, or if one system is required to convey a number of different materials. If the capability of a system is dictated by the pressure rating of the air mover, then different material flow rates must be expected, and the feeding device must be capable of meeting the needs of any other material. A different air flow rate may also be required, as shown by the different minimum values for the fly ash and coal in Figure 12.4.

12.2.1.1 Coal

The coal presented in Figure 12.1a is referred to as 'pearls'. It has a mean particle size of approximately 10 mm, with a top size of about 20 mm. There were no operating problems in conveying this material through the 53 mm bore pipeline, despite the relatively large particle size, although degradation of the coal was a problem [1]. Despite the large particle size, higher material flow rates were achieved than for some of the fine granular materials tested in this pipeline. As the coal had a very wide particle size distribution, and is very friable, there is no possibility of the material being conveyed in anything other than dilute phase in a conventional conveying system. The bulk density of the coal was about 690 kg/m^3 and the particle density 1320 kg/m^3.

12.2.1.2 Sodium chloride (salt)

The common salt conveyed very well, with a conveying performance similar to that of the coal. The mean particle size of the salt was about 390 μm. Like the coal, this material

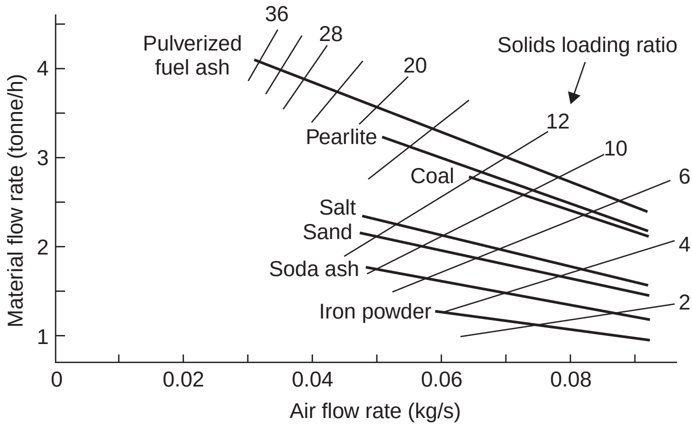


Figure 12.4 A comparison of materials conveyed through pipeline no. 1 with a conveying line pressure drop of 0.5 bar.

has no dense phase conveying capability and would not be conveyed in dense phase even if a very much higher air supply pressure was available. The bulk density of the salt was about 1220 kg/m^3 and the particle density 2630 kg/m^3.

12.2.1.3 Sodium carbonate (heavy soda ash)

Soda ash has something of a reputation of being a difficult material to convey. Further data on soda ash, albeit light soda ash, is presented in the next chapter. The fact that the material flow rate achieved was rather low may be part of the problem, and part of the reason for showing the performance characteristics of a wide range of materials is to illustrate the fact that a wide range of performance capabilities must be expected, even in dilute phase flow. There is no obvious correlation between any of the material properties and their performance 'ranking' in Figure 12.4. The mean particle size of the heavy soda ash tested was about 340 μm. This is yet another material with no natural dense phase conveying capability. The bulk density of the soda ash was about 1160 kg/m^3 and the particle density 2500 kg/m^3.

12.2.1.4 Pearlite

Pearlite is an exfoliated type material and had the lowest density of all the materials tested. The bulk density was about 100 kg/m^3 and the particle density 800 kg/m^3. The mean particle size was about 200 μm. With this combination of properties the material is capable of being conveyed in dense phase in a conventional conveying system and further conveying characteristics for this material will be found in the next section of this chapter on high pressure conveying.

12.2.1.5 Pulverized fuel ash (fly ash)

This material had the best performance of all those tested. The mean particle size was about 25 μm. Fly ash generally comes from the combustion of pulverized coal in the boiler of a thermal power plant and consists essentially of the non-combustible constituents in the coal. As a result of the high temperature and relatively low velocity suspension flow during combustion the particle shape is generally spherical. The material, therefore, has very good air retention properties and will readily convey in dense phase. Due to the very high material flow rates achieved, high values of solids loading ratio resulted, and as a consequence the fly ash was on the verge of being conveyed in dense phase with a pressure drop of only 0.5 bar. This explains why the minimum value of air flow rate required reduced with increase in pressure. The bulk density of the fly ash was about 700 kg/m^3 and the particle density 1700 kg/m^3.

12.2.1.6 Iron powder

The iron powder conveyed very well and no operating problems were experienced at all. The bulk density of this material was about 2380 kg/m^3 and the particle density 5710 kg/m^3. Whereas a solids loading ratio of 36 was achieved with the fly ash, a maximum of only six was obtained with the iron powder. The conveying characteristics are typical of those for a material conveyed in dilute phase. The conclusion, however, must not be that the material will only convey in dilute phase on the basis of this data. The mean particle size of the iron powder was about 64 μm and it had very good air retention properties. As a consequence the material will convey in dense phase, and to prove the point further, conveying characteristics for this material will be found in the next section of this chapter on high pressure conveying. Due to the very much lower material flow rate achieved with the iron powder, 0.5 bar is much too low a pressure drop for this length of pipeline to be at the point of transition to dense phase conveying, as was the case with the fly ash.

12.2.2 Low pressure conveying – Part II

A number of other materials were conveyed though a similar pipeline and this is presented in Figure 12.5 for reference. The materials were fed into the pipeline by the same low pressure bottom discharge blow tank. A blow tank was used because of this versatility in conveying such a very wide range of materials.

12.2.2.1 Alumina

The conveying characteristics for two grades of alumina are presented in Figure 12.6. The mean particle size for the calcined alumina was about 66 μm and that for the hydrate of alumina was about 60 μm. The mean particle size of the iron powder was between these two and was capable of dense phase conveying. Alumina generally needs to have a smaller mean particle size before it is capable of being conveyed in dense phase. The two grades shown in Figure 12.6 do not have sufficient air retention for them to be capable of being conveyed in dense phase in a conventional conveying system, even with a high air supply pressure.

The particle density for the calcined alumina was about 3920 kg/m^3 and that for the hydrate of alumina was about 2400 kg/m^3. There is, in fact, remarkably little difference in the conveying characteristics between these two materials. Only at the lowest air flow rates is there any significant difference and this is because the slope of the

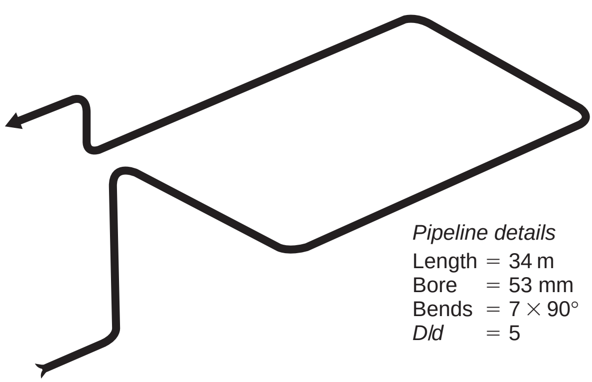


Figure 12.5 Sketch of pipeline no. 2.

constant pressure lines reduces with reduction in air flow rate. This is a feature of the conveying characteristics of a number of the materials presented here and will be considered further.

12.2.2.2 PVC powder

Conveying characteristics for PVC (polyvinylchloride) powder are presented in Figure 12.7a. This material had a mean particle size of about 90 μm, which is significantly higher than that of either of the alumina materials above, but as will be seen in the section on high pressure conveying data, has dense phase conveying capability. From Figure 12.7a it will be seen that at low values of air flow rate the slope of the constant pressure drop lines change in a similar manner to those for the hydrate of alumina in Figure 12.6b. Since the PVC powder can be conveyed with much lower air flow rate, when a higher pressure gradient is available, it will be seen how the lines of constant pressure drop develop.

12.2.2.3 Barytes

Conveying characteristics for barytes are presented in Figure 12.7b. Barytes is a material that is widely used as a drilling mud powder, mainly because it has a particle density of about 4250 kg/m^3. The material conveyed had a mean particle size of about 12 μm and its bulk density was 1590 kg/m^3. Almost any material having as low a mean particle size as this, regardless of its density, is generally capable of being conveyed in dense phase. This was demonstrated for barytes in the previous chapter with Figure

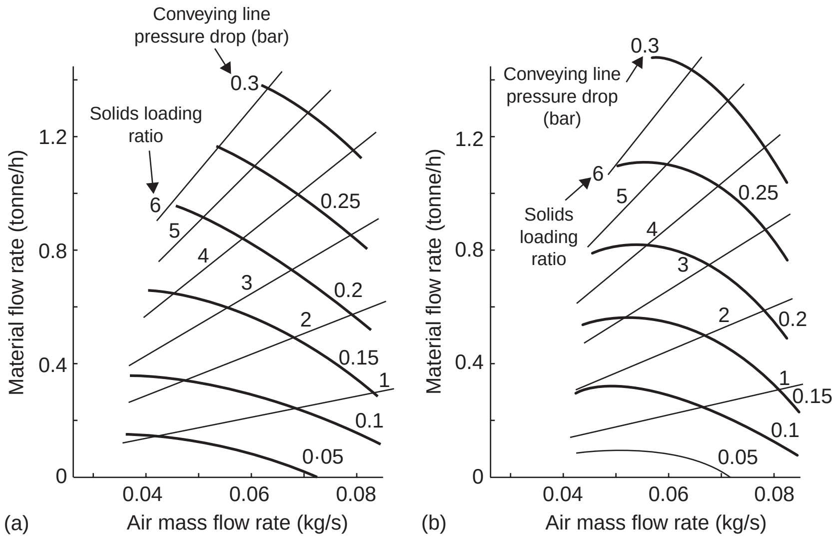


Figure 12.6 Conveying characteristics for alumina conveyed through the pipeline shown in Figure 12.5 (pipeline no. 2): (a) calcined alumina and (b) hydrate of alumina.

11.15 illustrating pressure gradient data for horizontal pipelines, and Figure 11.16 showing pressure drop data for 90° bends. With the low pressure gradient available for pipeline no. 2 the conveying of the barytes was limited to dilute phase.

12.2.2.4 Coal

Conveying characteristics for coal conveyed through the pipeline shown in Figure 12.5 are presented in Figure 12.8. A different grade of coal was conveyed through this pipeline. This had a top size of 25 mm, but still conveyed perfectly well through the 53 mm bore

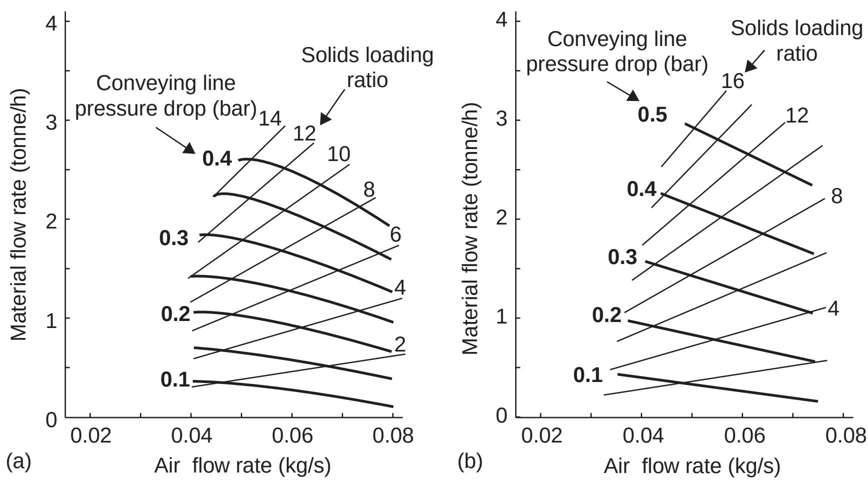


Figure 12.7 Conveying characteristics for materials conveyed through the pipeline shown in Figure 12.5 (pipeline no. 2): (a) PVC powder and (b) barytes.

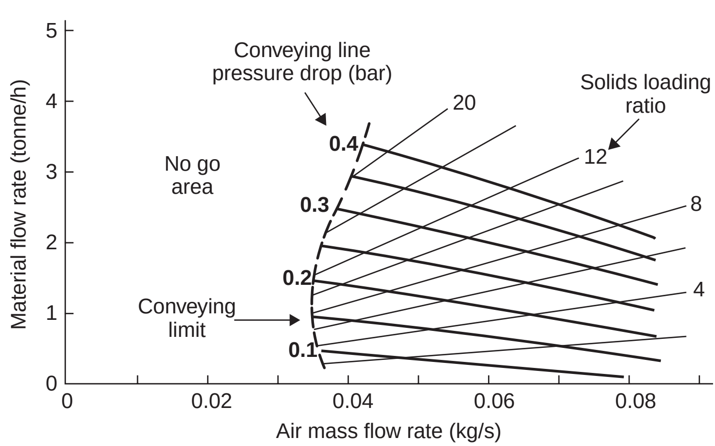


Figure 12.8 Conveying characteristics for coal in pipeline no. 2.

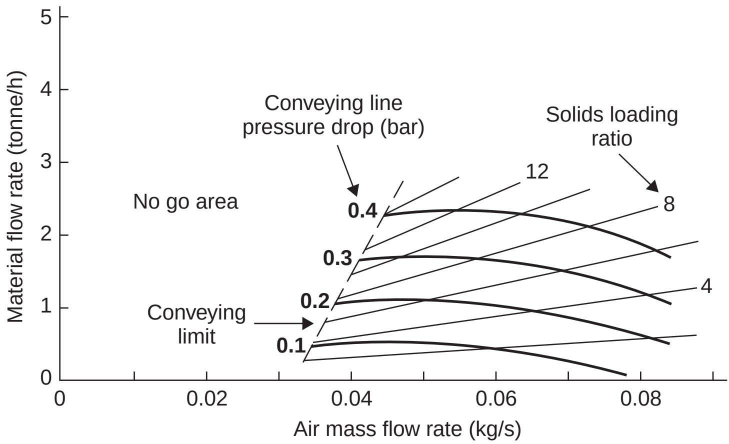


Figure 12.9 Conveying characteristics for 'bed ash' in pipeline no. 2.

pipeline with bends having a bend diameter, D, to pipe bore, d, ratio of 5:1. A conveying limit has been clearly identified on this set of conveying characteristics and corresponds to a conveying line inlet air velocity of about 12 m/s for this coal, with conveying line pressure drop values above about 0.2 bar, since the coal had a high proportion of fine material. A 'no go area' has also been clearly defined in which the pipeline will block if conveying is attempted in this area.

12.2.2.5 Fluidized bed combustor ash

Similar data for a fluidized bed combustor ash is presented in Figure 12.9. 'Bed ash' comes in a wide range of particle sizes and for this material it was about 1.2 mm. A particular feature of the material was that it was exceptionally abrasive.

The minimum conveying air velocity for the material was similar to that of the coal at about 12 m/s and, like the coal, contained a high proportion of 'fines'. This is another material for which the slope of the constant pressure lines reduces with lower air flow rates and consequently the conveying performance compared with coal is very much poorer.

12.2.2.6 Pulverized fuel ash

Conveying characteristics for another grade of fly ash conveyed through the pipeline shown in Figure 12.5 are presented in Figure 12.10. For dilute phase conveying the minimum conveying air velocity is about 11 m/s, but since the material conveys so well the transition to low velocity dense phase conveying is occurring and as a consequence the material is conveyed at a solids loading ratio of about 60 and with a corresponding conveying line inlet air velocity of about 6 m/s. Although these are all coal and ash products, Figures 12.8–12.10 do illustrate the wide range of conveying conditions that can be obtained with materials conveyed with low values of pressure gradient.

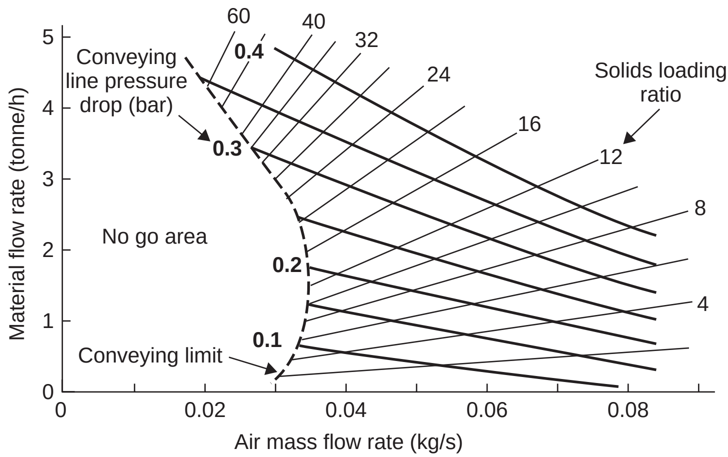


Figure 12.10 Conveying characteristics for a fine grade of fly ash in pipeline no. 2.

12.2.3 High pressure conveying – Part I

If high pressure air is available for conveying a material, and the pipeline is not too long, then the material could be conveyed in dense phase if the material is capable of being conveyed in dense phase. Conveying data for a group of four materials are presented in Figure 12.11. All four materials were conveyed through the same pipeline and this group of materials clearly illustrates the similarities and differences in conveying mode and capability when different materials are conveyed with high pressure air.

The compressor used for this high pressure work was capable of delivering 5.7 m^3/min of air at 7 bar gauge. A high pressure top discharge blow tank, also rated at 7 bar gauge, with a fluidizing membrane, was used to feed the materials into the pipeline. All four materials were conveyed through the same pipeline, a sketch of which is given in Figure 12.12. These four materials show three very different types of behaviour in pneumatic conveying pipelines. That dense phase conveying is possible is clearly demonstrated with the flour and the cement. Air pressures up to 3.4 bar were utilized and solids loading ratios well in excess of 100 were achieved. The minimum conveying air velocity for these two materials was about 3 m/s.

The conveying limit for these two materials has an interesting shape. At low pressures, and hence low solids loading ratios, it has a positive slope, characteristic of that for dilute phase conveying. As both pressure and solids loading ratio increase, the slope reverses. Although the compressibility effect of pressure tends to maintain the positive slope, the solids loading ratio influence on minimum conveying air velocity (see Figure 11.7b) has an over-riding effect. At higher values of solids loading ratio, compressibility takes over once again.

12.2.3.1 Wheat flour

Conveying characteristics for wheat flour are shown in Figure 12.11a and it will be seen that the material could be conveyed in dense phase. Although the mean particle

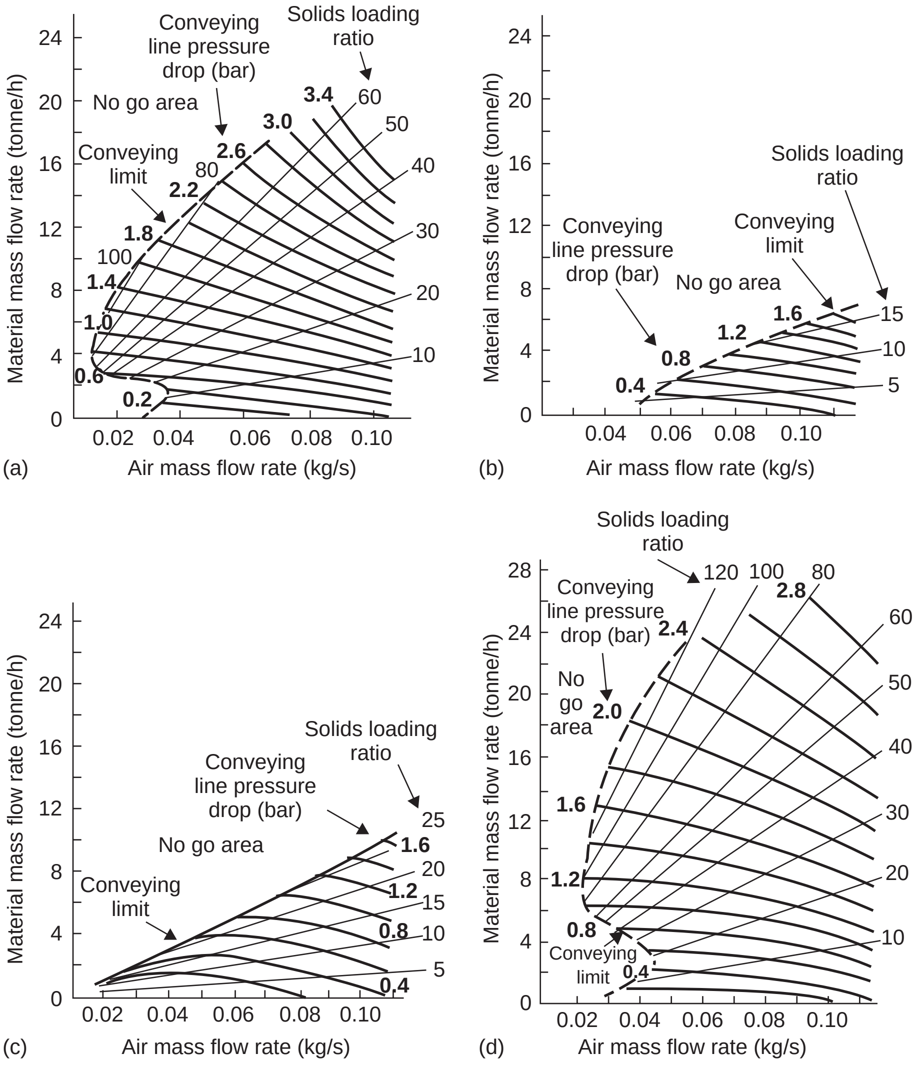


Figure 12.11 Conveying characteristics for materials conveyed through the pipeline shown in Figure 12.12 (pipeline no. 3): (a) wheat flour, (b) granulated sugar, (c) polyethylene pellets and (d) ordinary Portland cement.

size was about 90 μm it is the shape of the particles for this mean particle size that gives the material the necessary air retention that allows it to be conveyed in dense phase and at low velocity. The bulk density of the material was about 510 kg/m^3 and the particle density 1470 kg/m^3.

Although solids loading ratios of 100 were achieved, and conveying was possible with pick-up velocities below 3 m/s, this was only in the area of low material flow

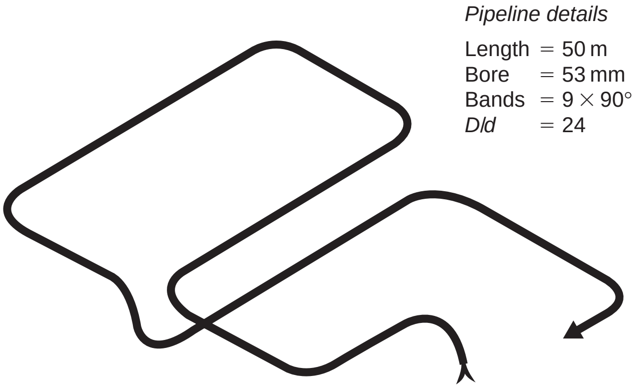


Figure 12.12 Sketch of pipeline no. 3.

rates. The data above this area is truncated as a consequence of the discharge characteristics of the blow tank employed with this particular material. Blow tank discharge characteristics for this wheat flour conveyed from this particular blow tank were presented in Figure 4.15a. It is fully expected that the material will convey successfully at much higher values of solids loading ratios and with much lower values of conveying line inlet air velocity with conveying line pressure drop values above 1.2 bar.

12.2.3.2 Granulated sugar

Conveying characteristics for granulated sugar are shown in Figure 12.11b and it will be seen that the material has no dense phase conveying capability at all. The maximum value of solids loading ratio achieved was only just above 15 and the minimum value of conveying line inlet air velocity was 16 m/s. The mean particle size of the sugar was about 460 μm and although it is manufactured to have as narrow a size distribution as possible, the material does not have the permeability necessary for it to be conveyed in the plug flow mode of dense phase conveying. The bulk density of the material was about 890 kg/m^3 and the particle density was 1580 kg/m^3.

The conveying characteristics for the granulated sugar are positioned alongside those for the flour since in food and confectionary plant there is often a need for these two materials to be conveyed in the same system. The conveying capabilities of the two materials, however, are very different and there is no obvious solution to the problem. A review of the possibilities is presented in Chapter 19 where multiple use systems are considered in general.

12.2.3.3 Polyethylene pellets

The polyethylene pellets tested had a mean particle size of about 4 mm and were essentially mono-sized. As a consequence the material could be conveyed very well in dense phase flow and at low velocity. Tests were carried out with conveying line inlet air velocities down to 3 m/s and it is quite possible that the velocity could have been reduced further without risk of blocking the pipeline. As can be seen from the conveying characteristics, however, material flow rates are so low that it is unlikely to be economical to convey the material at such a low velocity. The bulk density of the material was about 540 kg/m^3 and the particle density 912 kg/m^3.

Despite the fact that high pressure air was available the maximum value of solids loading ratio was little more than 25. This was due to the fact that the material was so permeable. When viewed through sight glasses in the pipeline short plugs of material separated by air gaps were clearly visible. These characteristics are considered further in the next chapter.

12.2.3.4 Ordinary Portland cement

Cement, with a mean particle size of about 14 μm is an obvious candidate for dense phase conveying in sliding bed flow. Very much better blow tank discharge characteristics were obtained and so solids loading ratios of over 100 were obtained at much higher values of conveying line pressure drop.

Conveying characteristics for another group of four materials conveyed through pipeline no. 3 with the top discharge high pressure blow tank are presented in Figure 12.13.

12.2.3.5 Iron powder

The conveying characteristics for iron powder, presented earlier in Figure 12.3b for low pressure dilute phase conveying, are shown again in Figure 12.13a for the high pressure conveying system. The difference between the two sets of data is quite remarkable and clearly illustrates the need for such test work to be undertaken. With the low pressure air a solids loading ratio of only six could be achieved, yet values of up to 120 are shown in Figure 12.13b. If the data is compared with that for the flour in Figure 12.11a it will be seen that for given conveying conditions, material flow rates achieved with the iron powder are higher than those achieved with the flour despite the differences in density values.

12.2.3.6 Barytes

Barytes was also presented earlier, in Figure 12.7b, and from the high pressure conveying characteristics it will be seen that the conveying performance is similar to that of the iron powder, although material flow rates are significantly better with the barytes. With solids loading ratios above about 80 with this material the conveying line inlet air velocity is down to 3 m/s. With the nature of these conveying characteristics, however, the highest material flow rates are achieved with the lowest conveying air velocities.

12.2.3.7 Pearlite

Pearlite was also considered in the low pressure conveying group of materials and, as will be seen from Figures 12.12 and 12.13c, it will convey in dense phase and at low velocity. Material flow rates and hence solids loading ratios are much lower than those

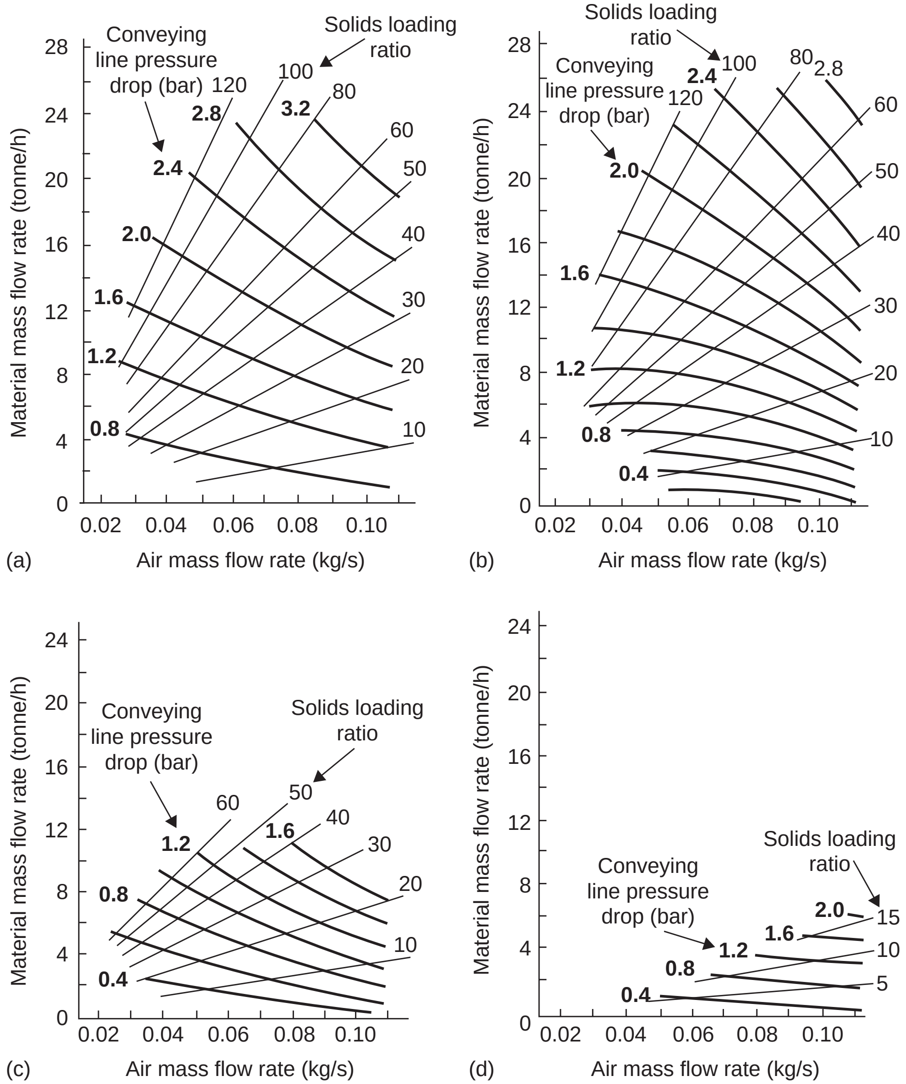


Figure 12.13 Conveying characteristics for materials conveyed through the pipeline shown in Figure 12.12 (pipeline no. 3): (a) iron powder, (b) barytes, (c) pearlite and (d) magnesium sulphate.

for the flour, cement, barites and iron powder, but conveying line pressure drop values are also much lower. It is believed that this limit is caused by the exceptionally low value of bulk density with this material and that it was probably a combination of blow tank discharge and pipeline conveying capabilities. For given values of conveying line pressure drop, material flow rates achieved with the pearlite are greater than those for the previous materials considered.

12.2.3.8 Magnesium sulphate

Conveying characteristics for magnesium sulphate are presented in Figures 12.12 and 12.13d and this is clearly the poorest performing material of all those considered so far. That high pressure is not synonymous with dense phase conveying is clearly shown with this material. It was a granular material and so had no natural dense phase conveying capability. Provided that the minimum conveying air velocity was kept above a value of about 14 m/s, however, the material would convey very well, but it must be recognized that the material does require a relatively high velocity and that the resulting flow rate of the material will be lower than that of most other materials. This does reinforce the point that is constantly being made that a very wide range of conveying capabilities exists and so materials must be tested for the purpose of system design.

Conveying characteristics for another two materials conveyed through pipeline no. 3 with the top discharge high pressure blow tank are presented in Figure 12.14.

12.2.3.9 Alumina

Low pressure conveying characteristics for alumina were presented in Figure 12.6. High pressure conveying characteristics for a calcined alumina are given in Figure 12.14. The minimum conveying air velocity was about 15 m/s and so as only 5.7 m^3/min (0.116 kg/s) of air was available the maximum conveying line pressure drop that could be utilized was only 1.4 bar. This data confirms the statement made at Section 12.2.2.1 that this material, although having a relatively small mean particle size, will not convey in dense phase even if a high pressure is available. The mean particle size for this particular material does need to be much smaller for dense phase to be possible with a conventional conveying system.

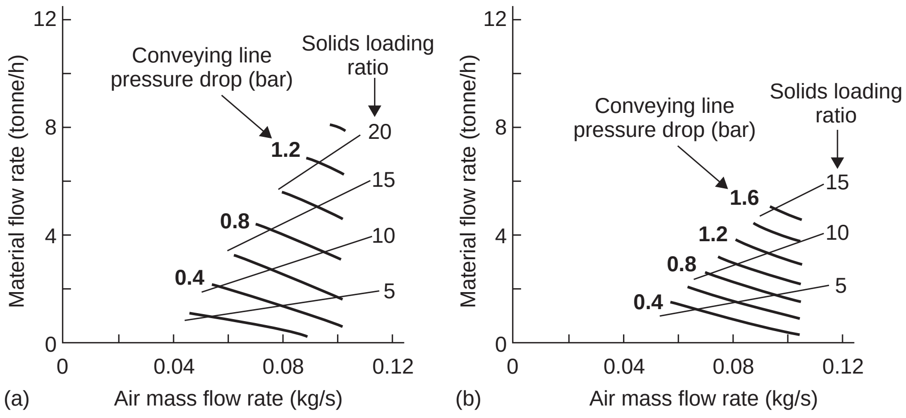


Figure 12.14 Conveying characteristics for further materials conveyed in pipeline no. 3: (a) alumina and (b) zircon sand.

12.2.3.10 Zircon sand

Conveying characteristics for zircon sand are presented in Figure 12.14b. Zircon sand has a mean particle size of about 120 μm with a fairly narrow particle size distribution and as a consequence has very poor air retention properties. It would only convey in dilute phase suspension flow and required a minimum conveying air velocity of about 14 m/s. The bulk density of the material was about 2600 kg/m^3 and the particle density was 4600 kg/m^3. This provides confirmation once again that high density materials present no problem with respect to pneumatic conveying and that at these particle sizes, density appears to have little influence on the minimum value of conveying air velocity.

12.2.3.11 Comparison of materials – flow rate

As a large number of different materials have been conveyed through pipeline no. 3, the 1.5 bar pressure drop lines have been taken from a representative number and plotted on a separate graph. This is presented in Figure 12.15 and illustrates the differences between the conveying capabilities of the different materials very well.

Every material presented is capable of being conveyed in dilute phase and Figure 12.15 illustrates the differences that can exist with this group of nine materials. With a conveying line inlet air velocity of 16 m/s granulated sugar only just gets on this plot but it does illustrate where the dilute phase conveying region is on the graph. At high velocity all the curves are now sloping down towards the horizontal axis, and hence zero material flow rate, and each one will probably reach the air flow rate axis at a value of about 0.45 kg/s (see Equation (10.21)). For dilute phase conveying, therefore, there is approximately a 2:1 spread in terms of material flow rate achieved for identical conveying conditions in this common pipeline.

At the low velocity end of this plot it will be seen that there is approximately a 20:1 spread in terms of material flow rate achieved for identical conveying conditions. The polyethylene pellets is the only material in this group capable of being conveyed in the

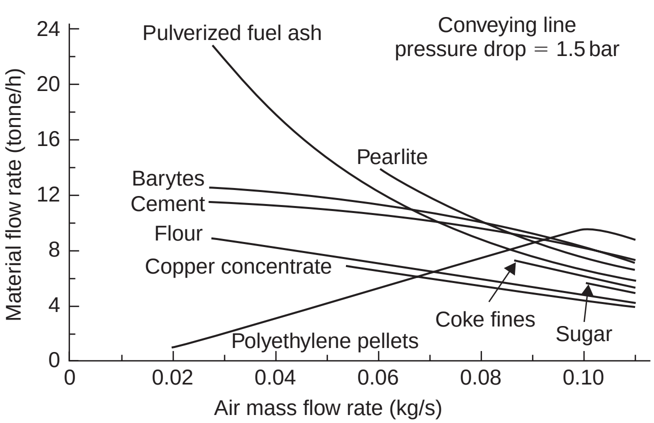


Figure 12.15 A comparison of the pneumatic conveying capability of different materials for identical conditions.

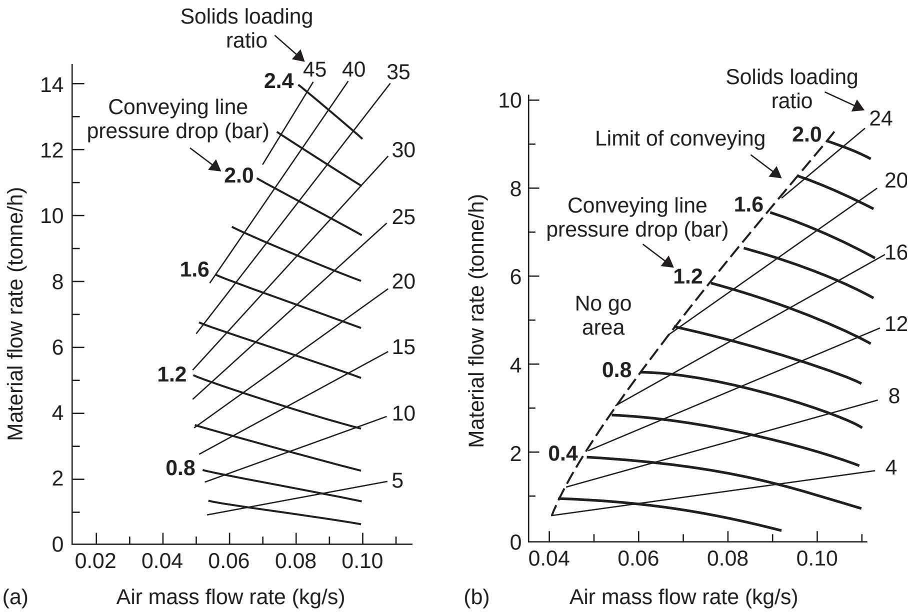


Figure 12.16 Conveying characteristics for further materials conveyed in pipeline no. 3: (a) copper concentrate and (b) coke fines.

plug flow mode of dense phase conveying but is typical of this group of materials. The PF ash (fly ash), barytes, cement and wheat flour are all in the sliding bed category of dense phase conveying capability and this plot illustrates the spread in capability that can exist with this group of materials at low values of conveying air velocity. It is suspected that the pearlite is limited because of its extremely low value of bulk density.

Conveying characteristics for the copper concentrate and the coke fines are presented in Figure 12.16.

12.2.3.12 Copper concentrate

The copper concentrate is one of those materials that is on the borderline of dense phase conveying but just does not have sufficient air retention capability. The mean particle size was about 55 μm and had a fairly narrow size distribution. With high pressure air it could be conveyed down to a minimum conveying air velocity of about 8 m/s but no lower. As a consequence the maximum value of solids loading ratio was about 45. The copper concentrate had a bulk density of about 1660 kg/m^3 and a particle density of 3950 kg/m^3.

12.2.3.13 Coke fines

The coke fines, presented in Figure 12.16b, are a petroleum coke derivative and had a mean particle size of about 800 μm with a fairly wide particle size distribution. The minimum conveying air velocity for the material was about 13 m/s. Compared with

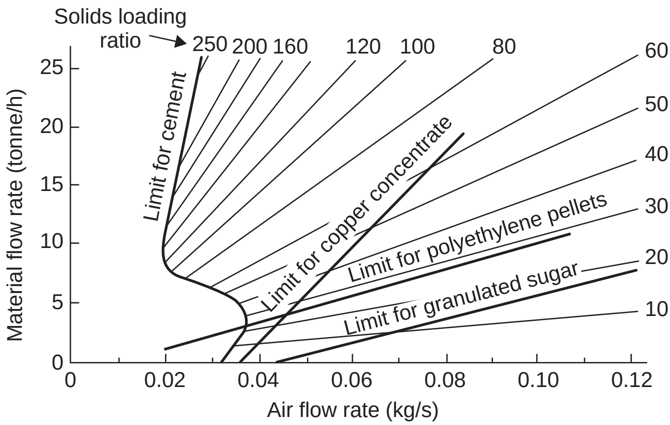


Figure 12.17 A comparison of material conveying limits for conveying under identical conditions.

the sugar the material flow rate for the coke is slightly higher and the minimum velocity slightly lower. As a consequence a solids loading ratio of about 25 was achieved, but this is still very much dilute phase conveying and is only high because of the very high pressure gradient available with a two bar pressure drop in the 50 m long pipeline.

12.2.3.14 Comparison of materials – conveying limits

Conveying limits in terms of minimum conveying air velocities and maximum solids loading ratios vary widely for different materials. This point is clearly illustrated in Figure 12.17 with the limits for four representative materials presented. Each material was conveyed through the 50 m long pipeline no. 3 of 53 mm bore in a full programme of tests.

12.2.3.15 Fly ash

In Figure 12.10 the low pressure conveying characteristics for a fine grade of pulverized fuel ash (fly ash) were showing very definite signs of the transition to dense phase conveying capability at high values of pressure drop. The conveying characteristics for this same material conveyed through pipeline no. 3 (Figure 12.12) are presented in Figure 12.18.

For dilute phase conveying the minimum conveying air velocity is about 11 m/s and in Figure 12.18 this is represented at the very bottom of the conveying characteristics. As explained above, this is in an insignificant area of these high pressure conveying characteristics. With a minimum conveying air velocity of about 3 m/s, once the solids loading ratio is above about 80, and constant pressure drop lines that always have a negative slope, very high values of solids loading ratio can be achieved without unduly high air supply pressures in such a short pipeline.

Certain grades of fly ash can be conveyed quite successfully at very much lower values of velocity than those reported here, but at these very low velocities there is a

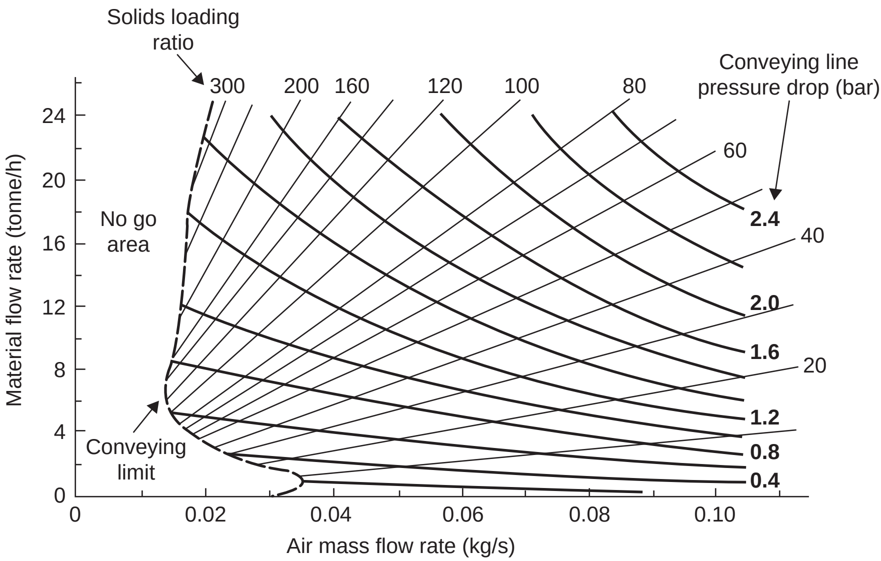


Figure 12.18 Conveying characteristics for a fine grade of fly ash in pipeline no. 3.

tendency for the slope of the constant pressure drop lines to change from negative to positive. Great care must be exercised with fly ash because there are an infinite number of grades and they all potentially have different conveying characteristics [2].

12.2.4 High pressure conveying – Part II

Two different materials that exhibit very distinct pressure minimum effects are illustrated in Figure 12.19. They were both conveyed through the pipeline as shown in Figure 12.20. This was another high pressure test facility and fed by a different high pressure top discharge blow tank, also having a fluidizing membrane. One of the materials was a PVC resin and is shown in Figure 12.19a. The other was terephthalic acid and this is shown in Figure 12.19b.

12.2.4.1 PVC resin

The PVC resin could be conveyed with air velocities below 2 m/s and still show no sign of imminent pipeline blockage. At low air velocity, however, the lines of constant pressure drop have a positive slope and point approximately towards the origin of the graph. This, perhaps, is what might be expected, with the material flow rate being zero at zero air flow rate. This is also the form of the conveying characteristics for the individual elements of straight pipeline presented in Figures 11.13–11.15.

At high velocities, in the dense phase conveying area of the conveying characteristics the constant pressure drop curves slope towards the horizontal axis in a similar manner to all the other materials presented. The transition of the slope of the constant pressure drop lines occurs at a value of conveying air velocity that is approximately

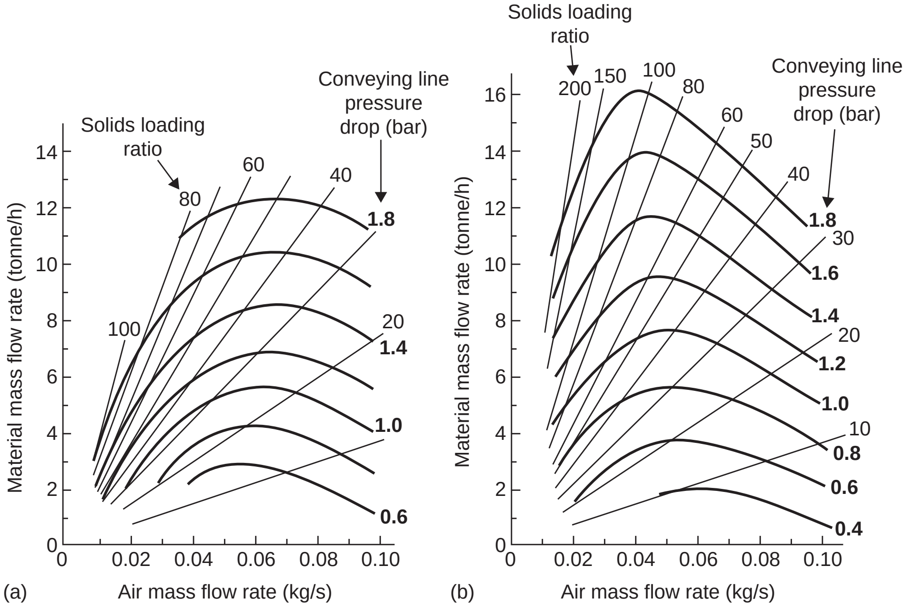


Figure 12.19 Conveying characteristics for materials conveyed through the pipeline shown in Figure 12.20 (pipeline no. 4): (a) PVC resin and (b) terephthalic acid.

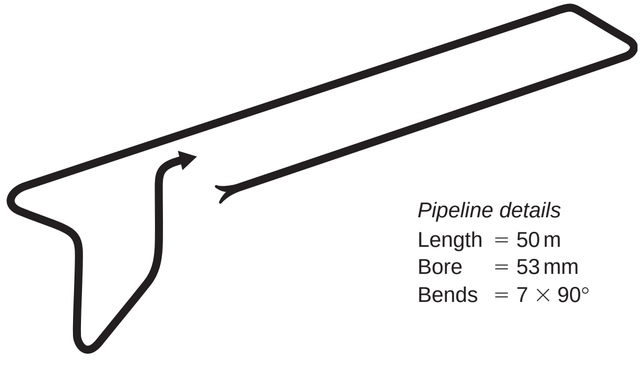


Figure 12.20 Sketch of pipeline no. 4.

equal to the minimum conveying air velocity for the dilute phase conveying of the material, being in the region of 9–12 m/s.

With the constant pressure drop curves changing slope there is clearly an optimum value of air flow rate at which the material flow rate is a maximum. If this data were to be plotted on a graph of pressure drop drawn against air flow rate, such as Figures 11.3 and 11.6a, there would be an optimum value of air flow rate at which a given material flow rate could be conveyed at a minimum value of pressure drop. This transition, therefore, is generally referred to as a ‘pressure minimum point’.

12.2.4.2 Terephthalic acid

The purified terephthalic acid (PTA) shown in Figure 12.19b was also conveyed through pipeline no. 4 (Figure 12.20). This shows very similar conveying characteristics to those of the PVC resin, but the slope reversal of the constant pressure drop curves occurs at much lower values of air flow rate, and hence conveying air velocity. As a result very much higher values of solids loading ratio are achieved with the PTA than with the PVC. Very much higher material flow rates are also achieved for given conveying conditions and so this has also contributed to the higher solids loading ratios.

The conveying characteristics for both of the Figure 12.19 materials are very different from those of the polyethylene pellets shown in Figure 12.11c. In Figure 12.11c the lines of constant pressure drop tend to merge together at low values of air flow rate and so conveying can be very unstable in this area. The pressure drop curves in Figure 12.19 materials are well separated and so there is no instability in the flow at low air flow rates.

12.2.5 High pressure conveying – Part III

Conveying characteristics for another group of four materials are presented in Figure 12.21. These were all conveyed from a high pressure top discharge blow tank and through a 70-m long pipeline of 53 mm bore that is shown in Figure 12.22.

12.2.5.1 Bentonite

The conveying characteristics for bentonite are shown in Figure 12.21a. Bentonite is another of the drilling mud powders. The material has a bulk density of about 760 kg/m^3 and a particle density of 2300 kg/m^3. The mean particle size of the bentonite was 24 μm and so was clearly capable of low velocity dense phase conveying. From Figure 12.21a it can be seen that it could be conveyed at solids loading ratios up to 140 in this 70 m long pipeline, and with conveying line inlet air velocities down to 3 m/s. It will also be seen that the form of the conveying characteristics are very similar to those for fine fly ash, with steeply sloping lines of constant pressure drop.

12.2.5.2 Fluorspar

Similar data for fluorspar is presented in Figure 12.21b. Material flow rates and solids loading ratios here are very much lower and this is partly due to the fact that the minimum conveying air velocity was about 7 m/s. The material, therefore is clearly conveyed in dense phase, but has limited capability. The mean particle size of the fluorspar was about 66 μm and so is in the transitional range of dense phase capability. With a lower particle size the material would probably have full dense phase conveying capability, like the bentonite, although the material flow rate would probably be much lower. The bulk density of the fluorspar was about 1580 kg/m^3 and the particle density 3700 kg/m^3.

12.2.5.3 Coal

The conveying characteristics for coal in Figure 12.21c are quite definitely dilute phase conveying. Although solids loading ratio values of up to 30 have been achieved this is

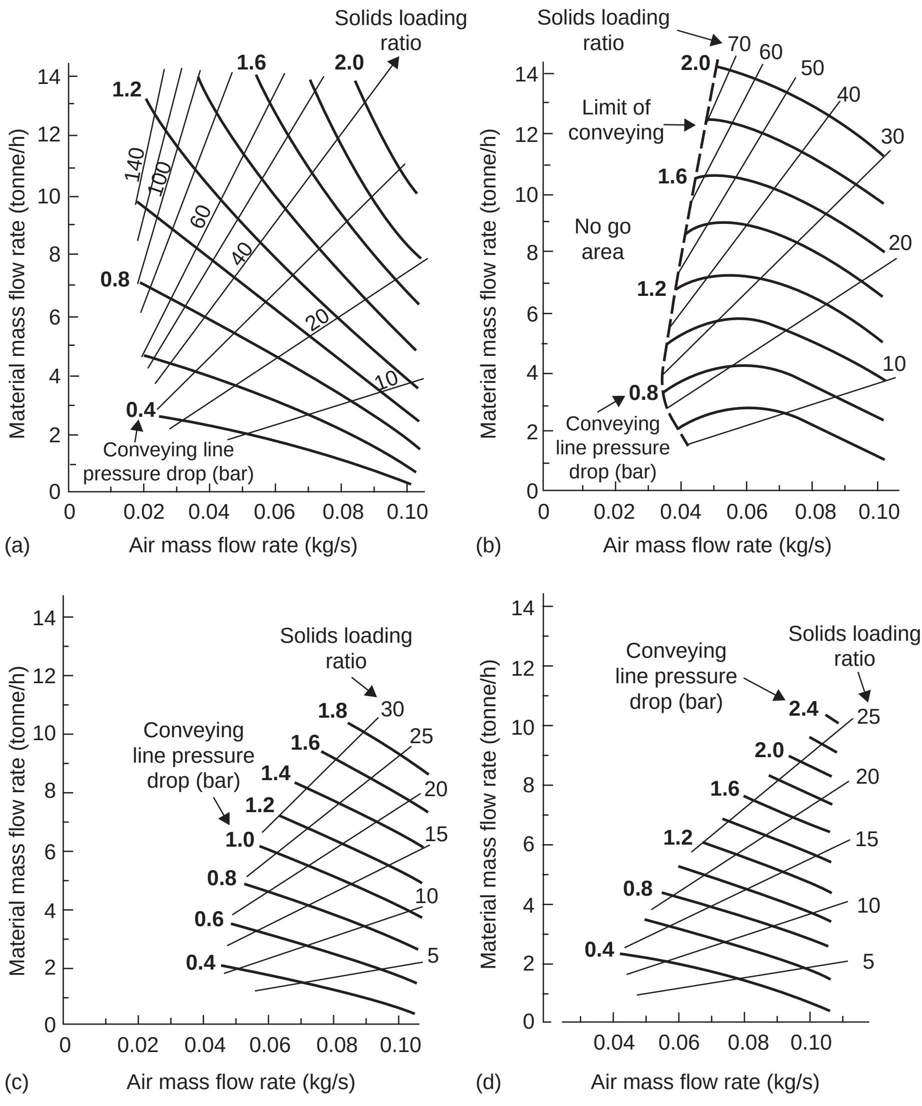


Figure 12.21 Conveying characteristics for materials conveyed through the pipeline shown in Figure 12.22 (pipeline no. 5): (a) bentonite, (b) fluorspar, (c) coal and (d) silica sand.

only because high pressure air has been used and the coal contained a high proportion of fine material. The fines have helped to lower the minimum conveying air velocity for the material to about 12 m/s, and as material flow rates for coal are quite high in relation to other materials, as will be seen from Figure 12.4, this has resulted in a high value of solids loading ratio for dilute phase conveying.

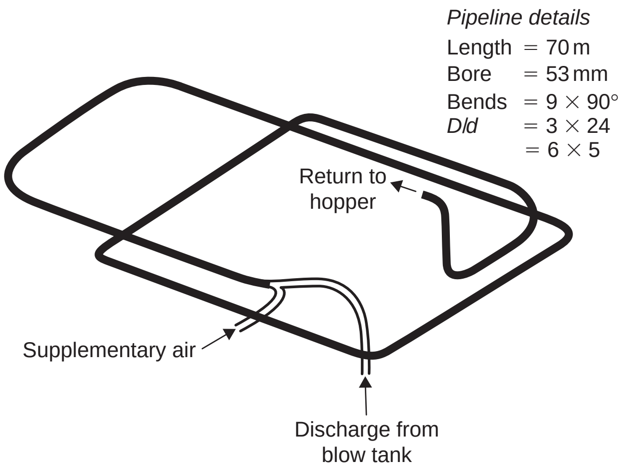


Figure 12.22 Sketch of pipeline no. 5.

12.2.5.4 Silica sand

Data for sand is presented in Figure 12.21d. The sand had a mean particle size of 70 μm, with a fairly narrow size distribution, and so there was no possibility of the material being conveyed in dense phase in a conventional conveying system, even with high pressure air available. The minimum conveying air velocity was similar to that for the coal and so this is quite clearly dilute phase suspension flow. The maximum value of solids loading ratio, however, was only 25, and this was only achieved with a conveying line pressure drop of 2.4 bar. The silica sand had a bulk density of about 1250 kg/m^3 and a particle density of 2630 kg/m^3.

12.2.6 High pressure conveying – Part IV

To complete the high pressure illustrations of material conveying characteristics four materials conveyed through a 95 m long pipeline of 81 mm bore are presented in Figure 12.23. With a longer pipeline the pressure gradient available for conveying is limited and with a larger bore line the air flow rate requirements are also very different.

12.2.6.1 Cement

The conveying characteristics for the cement were presented by way of illustration in the previous chapter with Figure 11.7a and are produced here in Figure 12.23a for comparison purposes. All four materials were conveyed through the pipeline shown earlier in Figure 11.2 and this is reproduced here in Figure 12.24 as pipeline no. 6 for reference.

The cement could be conveyed in dilute phase with a conveying line inlet air velocity of about 11 m/s but once again this is an insignificant part of the conveying characteristics since air supply pressures of 4 bar gauge were able to be used for conveying

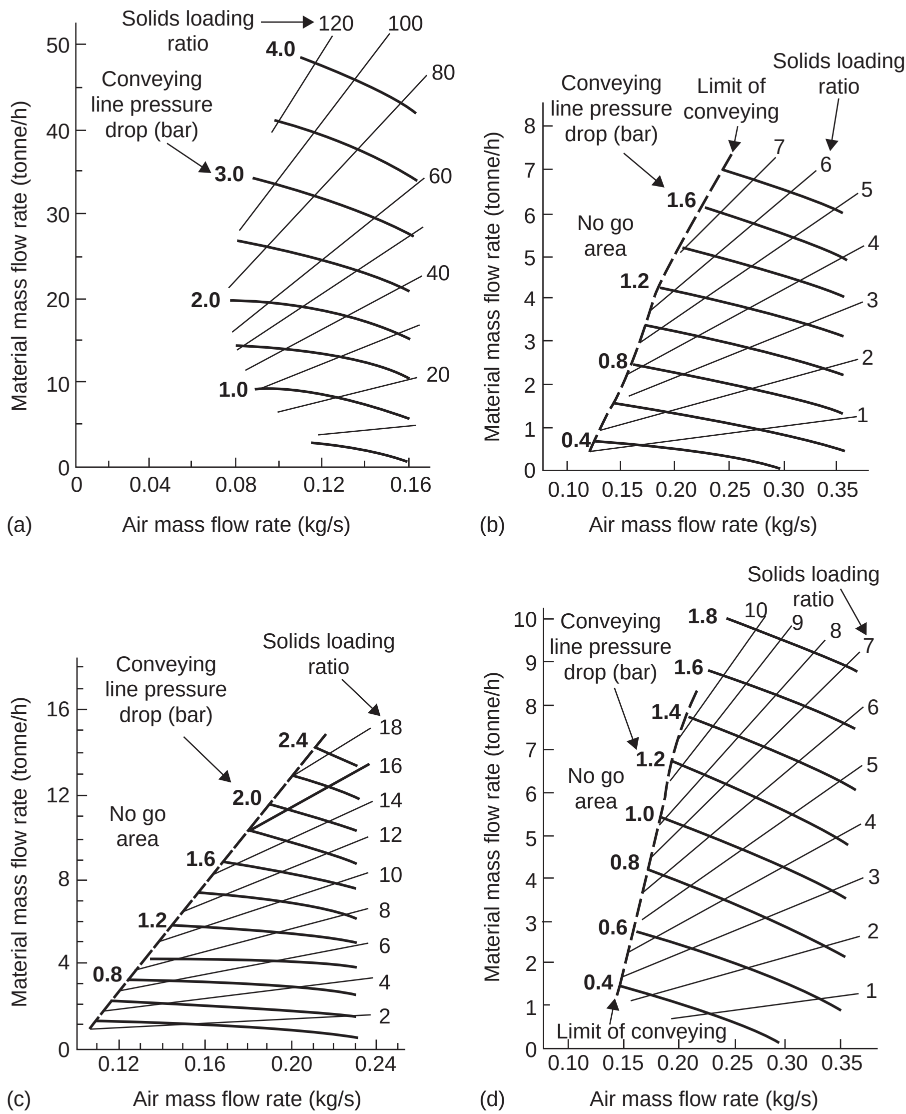


Figure 12.23 Conveying characteristics for materials conveyed through the pipeline shown in Figure 12.24 (pipeline no. 6): (a) cement, (b) potassium sulphate, (c) sodium sulphate and (d) magnesium sulphate.

the material. With high pressure air the cement could be conveyed quite reliably with conveying line inlet air velocities down to 3 m/s and so solids loading ratios of over 100 were achieved. Although the air supply pressure was high, the air flow rate required was relatively low since the air velocity required for conveying was low. As a consequence the air flow rate axis is only taken to 0.16 kg/s. The material flow rate

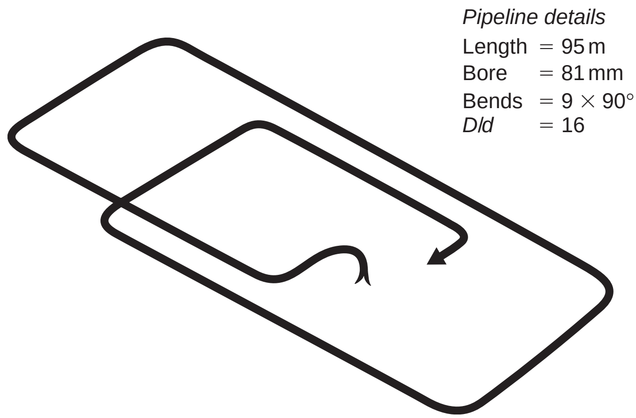


Figure 12.24 Sketch of pipeline no. 6.

axis is taken to 50 tonne/h and shows the potential capability of small bore pipelines for the conveying of this type of material.

12.2.6.2 Potassium sulphate

The conveying characteristics for the potassium sulphate are presented in Figure 12.23b. The minimum conveying air velocity was about 14 m/s and the material conveyed very well, but the conveying capability of the material, in terms of tonne/h, is probably the poorest of any presented here. With a conveying line pressure drop of 1.8 bar the solids loading ratio was only about seven, with just 7 tonne/h conveyed.

The conveying characteristics for potassium chloride, conveyed through this same pipeline, were presented in Figure 11.5b and 7 tonne/h was conveyed with a conveying line pressure drop of only 1.0 bar and the minimum conveying air velocity was 15 m/s.

12.2.6.3 Sodium sulphate

The conveying characteristics for sodium sulphate are presented in Figure 12.23c. This is a ground grade of the material. The material had a low minimum value of conveying air velocity at about 11 m/s, and this is why it was possible to convey the material with a conveying line pressure drop of 2.4 bar and achieve a solids loading ratio of 18, but there was no possibility of the material being conveyed in dense phase.

12.2.6.4 Magnesium sulphate

The conveying characteristics for magnesium sulphate are presented in Figure 12.23d. This material had a mean particle size of about 225 μm and the minimum conveying air velocity was about 14 m/s. The bulk density of the material was about 1020 kg/m^3 and the particle density 2350 kg/m^3. The conveying capability was similar to that of the sodium sulphate, but as the conveying line inlet air velocity was so much higher the maximum value of solids loading ratio achieved was only about 10.

12.3 System capability

For a given material a particular problem with pneumatic conveying systems is the evaluation of their conveying potential; and even for a first approximation value. The capability of a pneumatic conveying system, in terms of achieving a given material mass flow rate, depends primarily on the following three parameters:

1. the diameter of the pipeline
2. the distance to be conveyed, and
3. the conveying line pressure drop available.

Air flow rate is a secondary function, being primarily dependent upon the pipeline bore and air pressure. It is, however, important with respect to achieving optimum conveying conditions in a given pipeline. The properties of the material to be conveyed are also of paramount importance. Their main influence, however, in terms of material mass flow rate, is in placing an upper limit on the solids loading ratio at which the material can be conveyed under particular conditions, as shown in Figure 12.17.

12.3.1 Solids loading ratio – ϕ

The solids loading ratio of a conveyed material is the dimensionless ratio of the mass flow rate of the material being conveyed, $\dot{m}_p$, to the mass flow rate of the air used for conveying, $\dot{m}_a$:

$$\phi = \frac{\dot{m}_p}{3.6\ \dot{m}_a} \tag{12.1}$$

The constant of 3.6 is required to render the parameter dimensionless since material flow rate is in tonne/h and air flow rate is in kg/s.

Since air is a compressible fluid its density changes with pressure and so the volumetric flow rate of the conveying air can increase quite significantly along the length of a pipeline. Solids loading ratio, therefore, is a particularly useful parameter for describing the concentration of the material in the air in pneumatic conveying system pipelines, for it is a dimensionless quantity and its value remains essentially constant.

12.3.2 The influence of pipe bore

The mass flow rate of a material, $\dot{m}_p$, can be expressed in terms of the solids loading ratio, ϕ, at which the material is conveyed, by:

$$\dot{m}_p = \phi \dot{m}_a \text{ tonne/h} \tag{12.2}$$

where $\dot{m}_a$ is the air mass flow rate (kg/s).
Now

$$\dot{m}_a \propto \dot{V}_a \tag{12.3}$$

where $\dot{V}_a$ is the volumetric air flow rate, which is equal to $C \times A$, in which C is the conveying air velocity and A, the pipe section area, is equal to $\pi d^2/4$, where d is the pipe bore. Therefore,

$$\dot{m}_a \propto Cd^2 \tag{12.4}$$

As a first order approximation, for simplicity, C can be considered as being constant, so that:

$$\dot{m}_p \propto \phi d^2 \tag{12.5}$$

For a given system, therefore, throughput capability can be increased quite considerably by increasing the pipe bore and so enable high material flow rates to be achieved. The air requirements, of course, also have to be increased in the same proportion in order to maintain an equivalent air velocity.

In terms of achieving a given material flow rate over a specified distance, pipeline bore is probably the main variable. Pressure drop is also important, but an increase in air supply pressure is not always possible. Pipeline bore also has a significant effect on the air only pressure drop value, and this is particularly important if a low pressure air supply is to be used. A significant portion of the available pressure could be taken up in getting the air through the pipeline.

The situation is illustrated in Figure 12.25, which is a repeat of Figure 10.5. This is a plot of the air only pressure drop for pipelines, drawn against air flow rate, with lines of constant pipe bore superimposed. It is drawn for pipelines 300 m in length. The influence of pipe bore on the air only pressure drop value is clearly shown. In most systems, discharge is to atmospheric pressure, and so conveying line exit air velocity is directly proportional to air flow rate. As a result, conveying line exit air velocities

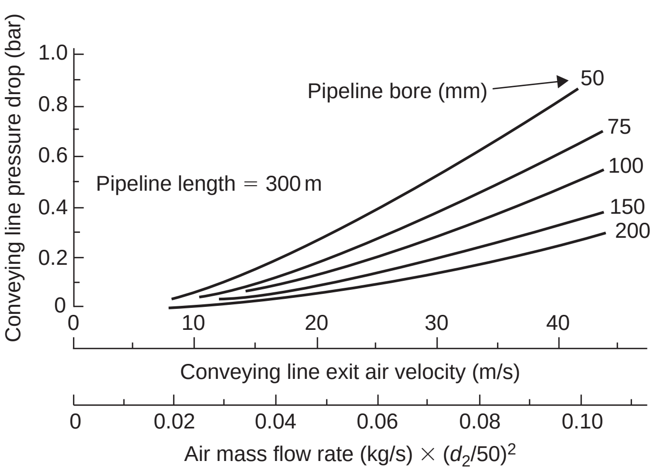


Figure 12.25 The influence of pipeline bore and air flow rate on the empty pipeline pressure drop.

have been included for reference, since air flow rate also has a significant effect on the air only pressure drop.

12.3.3 The influence of pressure drop

For a given system it is the pressure rating of the blower or compressor that is used to provide the air, which dictates how much and how far the material can be conveyed in a given bore of pipeline. The problem is summarized to a certain extent in the simplified diagram presented in Figure 12.26.

The inter-relating effects of conveying line pressure drop and conveying distance are further illustrated for high pressure systems in Figure 12.27, and for low pressure systems in Figure 12.28. It must be stressed that these figures are only approximations for the purpose of illustration and should not be used for design purposes. Pipe bore, conveying air velocity and material type all have an influence on the overall relationship.

Figure 12.27 shows that if very long conveying distances are required, the solids loading ratio will be relatively low, even with a high pressure system. With a low pressure

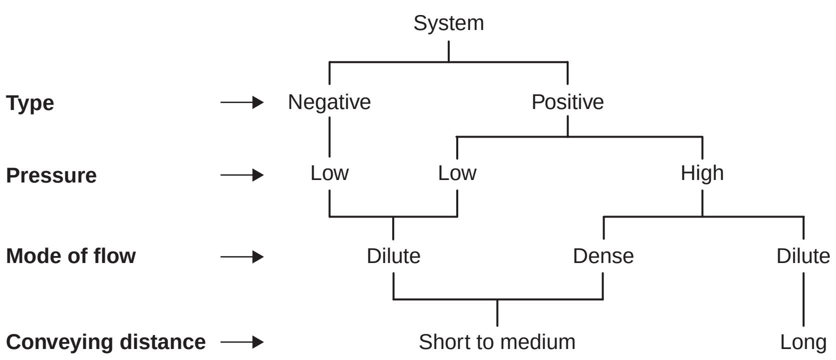


Figure 12.26 The influence of pressure drop on the inter-relationship between mode of flow and distance.

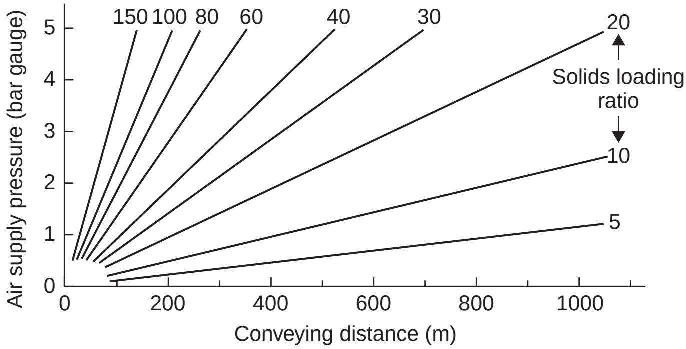


Figure 12.27 Influence of air supply pressure and conveying distance on maximum solids loading ratio for high pressure systems.

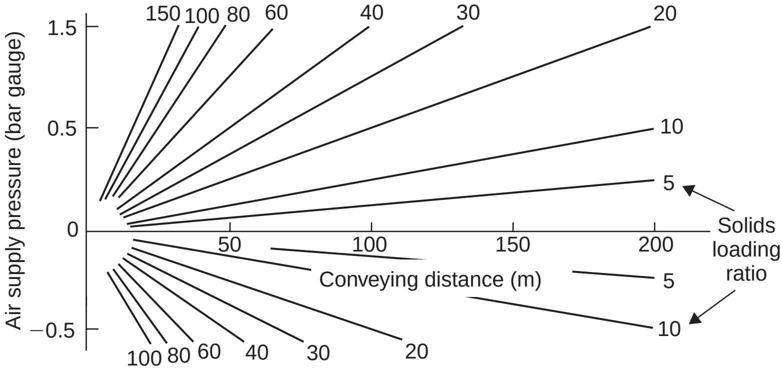


Figure 12.28 Influence of air supply pressure and conveying distance on maximum solids loading ratio for low pressure systems.

system the maximum solids loading ratio that can be achieved will be very low, and then only with a large bore pipeline.

For very short distances, however, it is quite possible to convey a material at high values of solids loading ratio, even with the limited pressure drop available with negative pressure systems, as will be seen in Figure 12.28, provided that the material is capable of being conveyed in this mode. Pressure gradient, therefore, is the parameter that will dictate the potential mode of conveying for a material that is capable of being conveyed in dense phase.

References

1. D Mills. The degradation of bulk solids by pneumatic conveying and its simulation by small scale rigs. Pub by BMHB. pp 195. February 1989.
2. D Mills and V K Agarwal. Pneumatic conveying systems – design, selection, operation and troubleshooting with particular reference to pulverized fuel ash. Trans Tech Publications. ISBN 0-87849-126-0. 2001.

Chapter 13

Material property influences

13.1 Introduction

In the previous chapter conveying characteristics were presented for a wide range of materials, both to illustrate the differences that can exist between materials and to provide reference data on materials. From the large number of materials considered certain material property influences were beginning to emerge with respect to identifying the potential of materials for low velocity dense phase conveying, but there were no clear guidelines.

In this chapter a review of possible material classifications and correlations are presented. These will show what has been done by way of trying to identify material properties that might provide a little more guidance on identifying the potential capability of a new and untried material for dense phase conveying, and the possible mode of flow that might be achieved with the material.

A particular problem in pneumatic conveying is that materials are often identified simply by means of a name, such as soda ash and fly ash. This is never sufficient for pneumatic conveying purposes. Many materials are available in a wide variety of forms and grades, such as sugar, with granulated, caster and icing, and the performance and capability of all three of these different 'grades' will be very different. This is apart from considering the range of brown sugars, such as Demerara, that tend to be very cohesive.

With friable materials pneumatic conveying of the material can also change the grade of the material and this can have totally unexpected consequences on the performance of the conveying system. These effects, therefore, are illustrated with a number of materials and these changes are also related to material performance correlations.

13.2 Conveying modes

To set the scene here a recap on the three main modes of conveying is presented. For this purpose three materials conveyed through pipeline no. 3 (Figure 12.12) are used as this will allow a direct visual comparison of performance. A sketch of the pipeline is given in Figure 13.1 for reference here.

13.2.1 Dilute phase non-suspension flow

Granulated sugar has been selected as being representative of materials conveyed in dilute phase and the conveying characteristics are presented in Figure 13.2. These

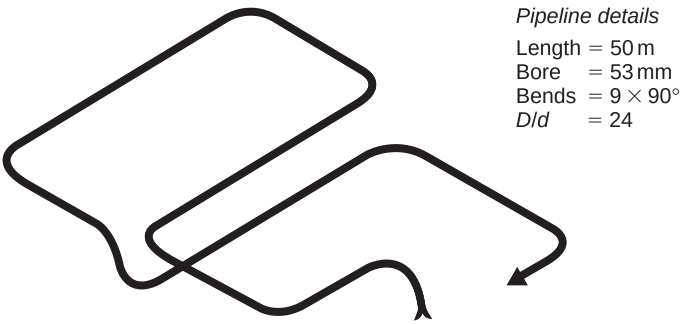


Figure 13.1 Sketch of pipeline no. 3.

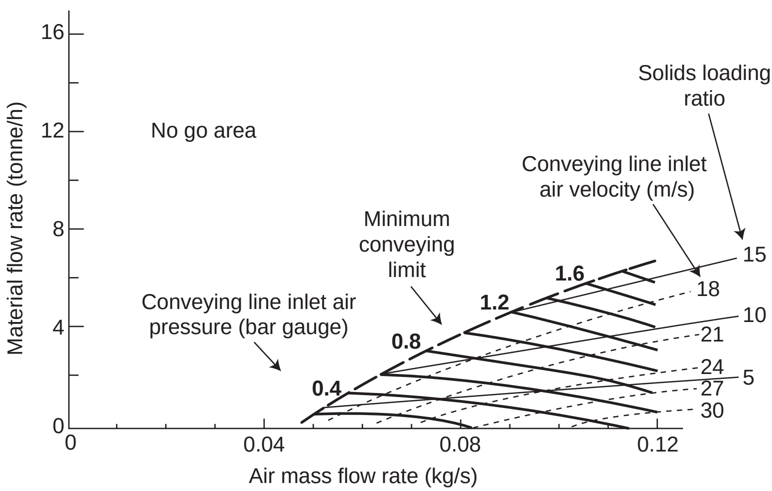


Figure 13.2 Conveying characteristics for granulated sugar in pipeline no. 3.

were presented earlier in Figure 12.11b. In Figure 13.2 they are shown with the inclusion of lines of constant conveying line inlet air velocity, since this is a critical parameter in distinguishing between dilute and dense phase flows.

Virtually any material, as has been mentioned before, can be conveyed in dilute phase. This also includes materials that are capable of being conveyed in dense phase. If the pressure gradient available for conveying a material is low either, because the pipeline is long or the air supply pressure is low, it will only be possible to convey materials that have dense phase conveying potential in dilute phase suspension flow. This point was illustrated in Figure 1.1.

The form of the conveying characteristics shown in Figure 13.2 is typical of all materials conveyed in dilute phase. The minimum value of conveying air velocity will be of the order of 10–12 m/s for fine powders, being closer to 10 m/s for ground materials such as flour and cement because of the particle shape. It will be in the region of 13–16 m/s for fine granular materials, being closer to 13 m/s if the material has a wide particle size distribution. That for granulated sugar was about 16 m/s. For materials that can only be conveyed in dilute phase suspension flow there is little change in the value of minimum conveying air velocity with the concentration of the material conveyed, or its solids loading ratio.

The conveying limit identified in Figure 13.2 has a positive slope as shown due to entirely the fact that air is compressible and the minimum value of conveying air velocity remains essentially constant. As the conveying line inlet air pressure, and hence the air supply pressure, increases more air is required to maintain the same velocity. It will be seen that the lines of constant conveying line inlet air velocity superimposed have a similar slope, since the minimum conveying limit is represented by a conveying line inlet air velocity of 16 m/s. The equation governing this comes from Chapter 9 and is a re-arrangement of Equation (9.20) which relates to air:

$$\dot{m}_a = \frac{2.74 p_1 d^2 C_1}{T_1} \text{ kg/s} \tag{13.1}$$

where $\dot{m}_a$ is the air mass flow rate (kg/s); p_1, conveying line inlet air pressure (kN/m^2 abs); d, the pipeline bore (m); C_1, the conveying line inlet air velocity (m/s) and T_1, the conveying line inlet air temperature (K).

Thus if the conveying line inlet air velocity remains constant, along with pipeline bore and temperature, the air flow rate must increase in proportion to the absolute pressure of the inlet air. On this plot lines of constant solids loading ratio are straight lines through the origin, as will be seen. As a consequence there is little scope for the material being conveyed at a higher value of solids loading ratio, even if a much higher air supply pressure was to be used, for the slope of the conveying limit curve (at 16 m/s) is only slightly steeper than that of the solids loading ratio line drawn at a value of 15.

Lines of constant conveying line inlet air velocity are also useful in terms of illustrating the adverse effect of velocity on conveying performance. Air flow rate on its own has no real meaning and is difficult to interpret, but conveying line inlet air velocity is a fundamental design parameter for pneumatic conveying systems. Conveying air velocity has a very significant influence on conveying performance and in dilute phase conveying there is only a narrow band of operating values. As will be seen from Figure 13.2 for the granulate sugar, if the conveying line inlet air velocity is below 16 m/s nothing will be conveyed because the pipeline will block, and if it is greater than about 30 m/s almost nothing will be conveyed because all of the available energy is lost to friction. This is the velocity squared term in the pressure drop equations presented in Equations (1.4) and (10.2).

13.2.2 Dense phase sliding bed flow

Ordinary Portland cement has been selected as being representative of materials conveyed in dense phase in a sliding bed mode of flow and the conveying characteristics

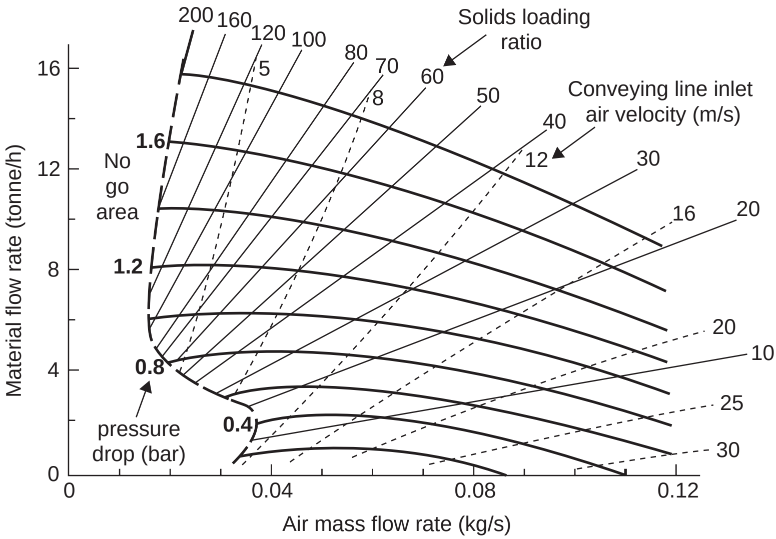


Figure 13.3 Conveying characteristics for cement in pipeline no. 3.

are presented in Figure 13.3. These were presented earlier in Figure 11.7a, where the air pressure was taken to 4 bar gauge. In Figure 13.3 they are shown with the inclusion of lines of constant conveying line inlet air velocity and are limited to a conveying line pressure drop of 1.8 bar for direct comparison with the other materials being considered here.

The first thing to emphasize here is that there is no abrupt transition between dilute and dense phase conveying. It is a little difficult to identify where the division might come, but if a conveying line inlet air velocity of about 10–12 m/s is taken it will provide an approximate location. Due to the lower velocity and the better conveying capability than the sugar the solids loading ratio for the cement is about 40–50 with a conveying line pressure drop of 1.8 bar, compared with about 15 for the sugar.

With the capability of conveying the cement with conveying line inlet air velocities down to 3 m/s much higher material flow rates are possible, because there is little change in the slope of the constant pressure drop curves with reduction in air flow rate. With lower air flow rates there is also a considerable reduction in power requirements. The only problematic area in conveying this type of material is in the transitional region between dilute and dense phase conveying at low values of pressure drop [1].

13.2.2.1 Transitional conveying limit

In Figure 13.3 the conveying limit is defined by a minimum conveying air velocity of about 11 m/s for the dilute phase conveying region and 3 m/s for the dense phase region. In between the two it is a function of solids loading ratio as defined by the relationship in Figure 11.7b. Due to its importance this is presented in more detail below. A very much longer pipeline is used for this purpose in order to magnify the extent of

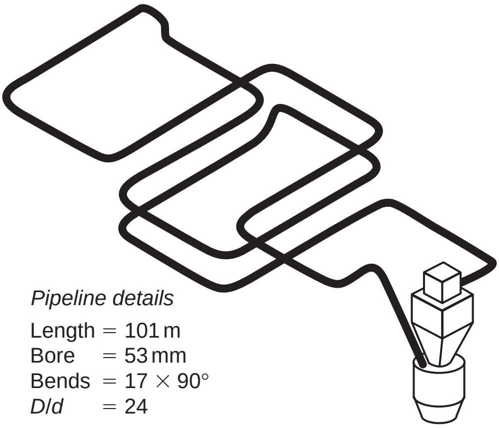


Figure 13.4 Sketch of pipeline no. 7.

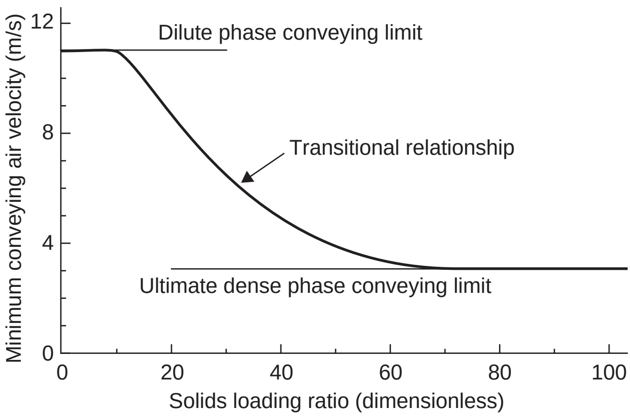


Figure 13.5 Typical conveying limits for ordinary Portland cement.

the transitional region. The pipeline was 101 m long, of 53 mm bore and incorporated 17 numbers of 90° bends. A sketch is given in Figure 13.4 for reference.

The relationship between solids loading ratio and minimum conveying air velocity that has been used is presented in Figure 13.5. This clearly identifies the transitional relationship between the dilute and dense phase conveying mode limits.

Plotting the locus of the conveying limit onto the conveying characteristics is a straightforward mathematical process. To illustrate the resulting curve only that part of the conveying characteristics in the area involved are presented so that the area could be magnified. This is presented in Figure 13.6 [1].

From Figure 3.6 it will be seen that the conveying limit can cut across constant pressure drop conveying lines of low value. The main point, however, is that most conveying systems generally operate with a constant value of air flow rate and so if a reduction in material flow rate should be required it is possible to block the pipeline by dropping

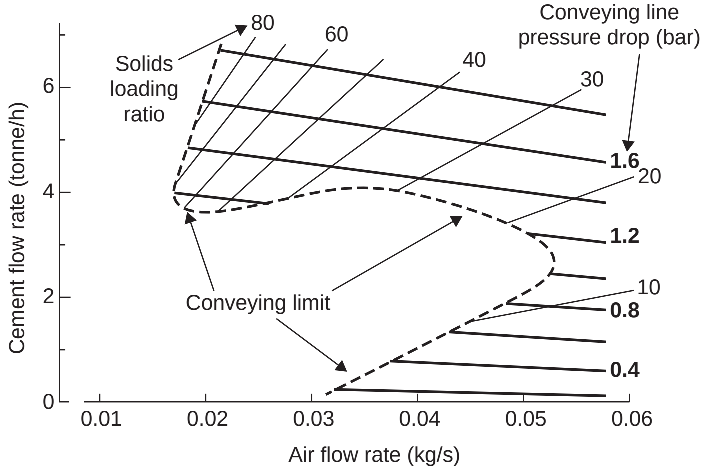


Figure 13.6 Expansion of conveying characteristics in transition region between dilute and dense phase conveying.

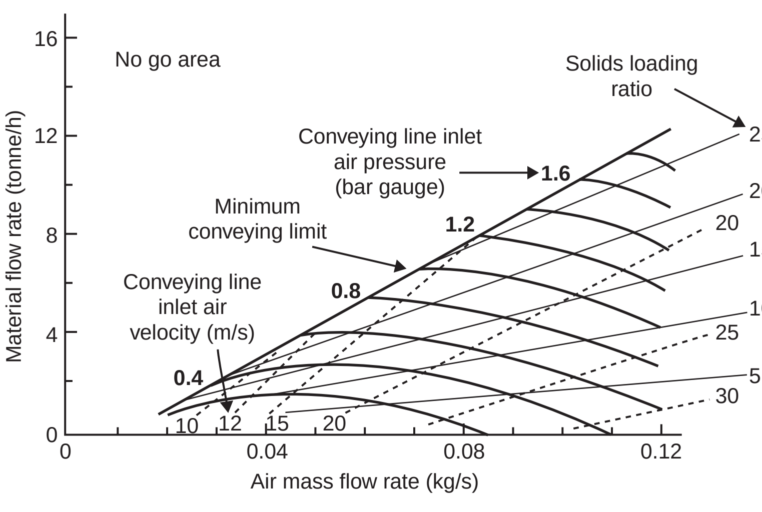


Figure 13.7 Conveying characteristics for polyethylene pellets in pipeline no. 3.

into the no go area. Due to the form of the dilute phase conveying characteristics, this is never a possibility in dilute phase conveying.

13.2.3 Dense phase plug flow

Polyethylene pellets have been selected as being representative of materials conveyed in dense phase in plug flow and the conveying characteristics are presented in Figure 13.7. These were presented earlier in Figure 12.11c. In Figure 13.7 they are shown with the

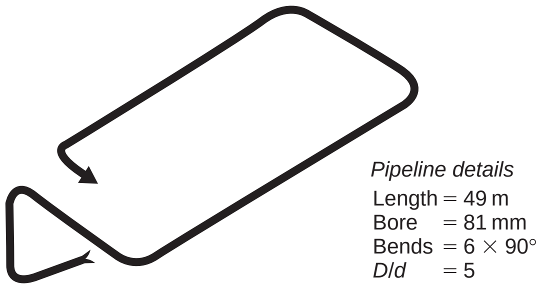


Figure 13.8 Sketch of pipeline no. 8.

inclusion of lines of constant conveying line inlet air velocity and are taken to a conveying line pressure drop of 1.8 bar for direct comparison with the other materials being considered here.

With this material there is a complete reversal in slope of the constant pressure drop curves at low values of air flow rate. In the high velocity dilute phase conveying region the performance and behaviour of the material is no different from that of any other material conveyed in dilute phase flow. The minimum conveying air velocity with respect to dilute phase conveying with this material is about 15 m/s. From Figure 13.7 it will be seen that the change in slope of the constant pressure drop curves occurs approximately at a velocity of about 15 m/s.

Due to the positive slope of the curves in the low velocity dense phase region of the conveying characteristics the area available for dense phase conveying is rather limited and material flow rates are significantly reduced. Figure 13.7 would also indicate that at velocities below about 15 m/s the constant pressure drop curves appear to merge. This means that the flow could be very unstable in this region. In order to determine how much of this is due to the small bore of the pipeline, tests were carried out with another material in a larger bore pipeline.

13.2.3.1 Tests with nylon pellets

Tests were undertaken with nylon pellets in a similar pipeline to that used above for the polyethylene pellets except that it was 81 mm bore and so required about twice the amount of air for conveying [2]. A sketch of the pipeline is presented in Figure 13.8 for reference. A high pressure bottom discharge blow tank was used for the conveying trials with this material. The nylon pellets, like the polyethylene pellets, had a mean particle size of about 4 mm and were essentially mono-sized.

Since the conveying characteristics for this type of material are so very different from those of materials conveyed in sliding bed flow, actual test data is presented to show the range of conveying conditions covered. The data is presented on two plots, as with the cement in Figure 11.6. One is a plot of the material flow rate test results and the other is of the conveying line pressure drop data.

It will be seen from these two figures that the lines drawn fit the data very well and that there was very little scatter in the results. Although the resulting material flow rate

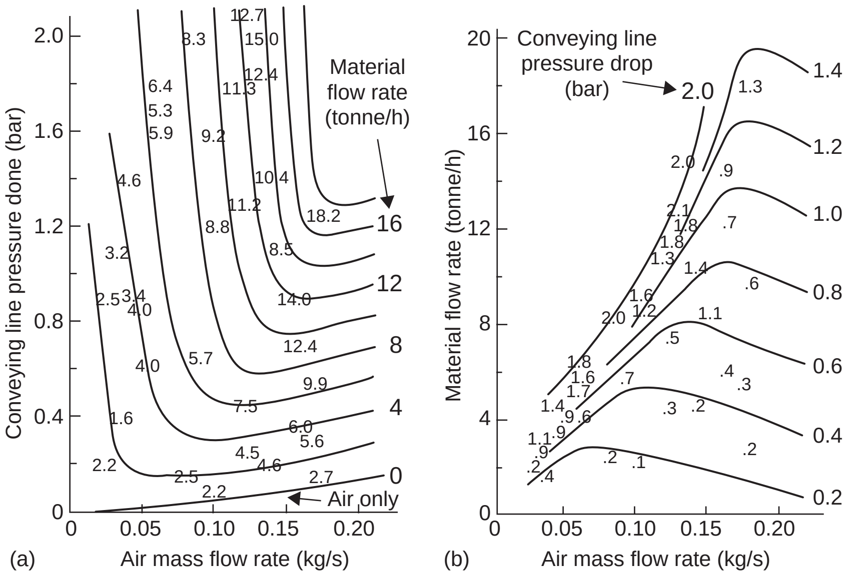


Figure 13.9 Presentation of conveying data for nylon pellets in pipeline no. 8: (a) material flow rate data and (b) pressure drop data.

curves shown in Figure 13.9a are remarkably steep, which would tend to indicate that material flow rate control would be a problem, it will be seen from the data points that this was not the case. In Figure 13.9b the lines of constant pressure drop are very closely spaced and this is why they were seen to merge with the smaller bore pipeline. Data in Figure 13.9b are presented without hindrance of the test results in Figure 13.10a and lines of constant solids loading ratio are added.

It will be seen that the maximum value of solids loading ratio is very similar to that achieved with the polyethylene pellets. In Figure 13.10b lines of constant conveying line inlet air velocity have been superimposed and the horizontal air mass flow rate axis has been replaced with one of conveying line exit air velocity. Once again the pressure minimum points on the conveying characteristics correspond with a conveying line inlet air velocity of about 12 m/s which will be close to minimum conveying air velocity with the material conveyed in dilute phase suspension flow.

13.3 Conveying capability correlations

Certain material characteristics can be used to predict the potential behaviour of a material when pneumatically conveyed. One is based on aeration and permeability properties, and another on basic property classifications, such as that by Geldart, presented in relation to fluidized motion conveying systems in Chapter 2.

The air retention capabilities of a bulk material are a good indicator of whether a material will convey in dense phase or not. Powdered materials such as fine fly ash, cement, bentonite and barytes have very good air retention properties and are capable

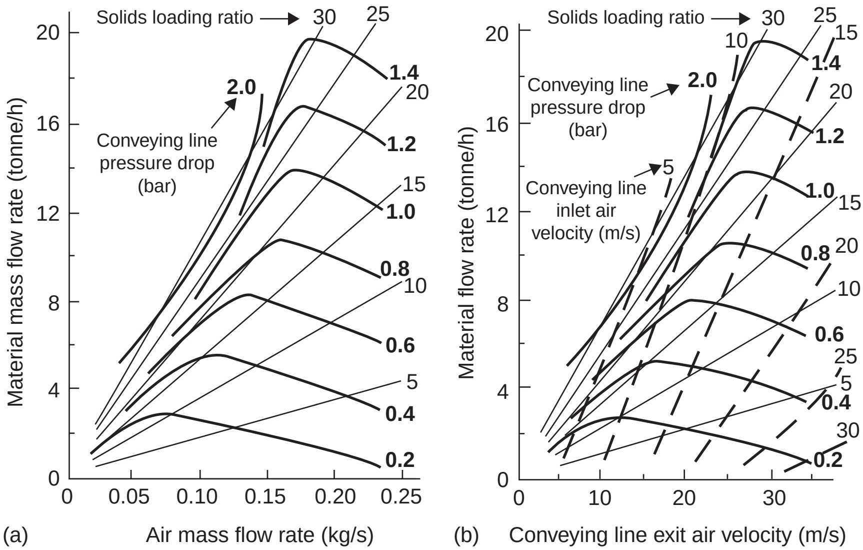


Figure 13.10 Conveying characteristics for nylon pellets in pipeline no. 8: (a) material conveying characteristics and (b) conveying air velocity data.

of being conveyed in dense phase and at low velocities. Coarse granular materials such as sand, salt and granular coal and ash have very poor air retention properties and cannot be conveyed in dense phase flow in conventional pneumatic conveying systems. If such materials have a very narrow particle size distribution and very good permeability, however, it is possible that they will convey in dense phase in plug flow.

13.3.1 Basic property classifications

A goal in pneumatic conveying is to make it possible to design a pneumatic conveying system without the need for carrying out full scale conveying tests with a material. In a conventional pneumatic conveying system not all materials can be conveyed in dense phase. A problem for users and manufacturers of pneumatic conveyors alike is identifying which materials have low velocity dense phase capability without performing full scale conveying trials [3].

Research is not yet at a point where a pneumatic conveying system can be reliably designed on the basis of measuring appropriate properties from a small representative sample of the material to be conveyed. It is important to realize that even different grades of the same material can exhibit very significant differences in terms of conveying capability. This issue is considered in detail later in this chapter.

As a result, it is still necessary to undertake conveying trials with a material in a reasonably large scale pneumatic conveying test facility in order to get reliable data for system design, particularly if it is a material for which no previous conveying experience is available, and if it is desired to convey the material at low velocity in a dense phase mode.

13.3.1.1 Modes of flow

The term 'dense phase' has become a little ambiguous since no universally accepted definition appears to exist. For reference purposes, therefore, some definitions need to be established in order to identify the modes of flow that can exist in pneumatic conveying. In the context of this work the term dense phase is used to cover all non-suspension flow regimes. It is evident from flow visualization that three major flow regimes exist for pneumatic conveying:

1. Suspension flow (dilute phase) – where all, or the majority, of the material is in suspension in the conveying gas.
2. Moving bed type flow (dense phase) – where the material is conveyed in dunes on the bottom of the pipeline or as a pulsatile moving bed.
3. Slug or plug type flow (dense phase) – where the material is conveyed as full bore plugs separated by air gaps.

There can be considerable overlap between the moving bed type flow and slug flow in term of velocity and solids loading ratio, depending on the material characteristics. Within each flow regime there are many sub-divisions and variations in flow characteristics that make the problem of behavioural prediction extremely difficult. In general, however, few materials are capable of being conveyed in both dense phase flow regimes.

The importance of material properties on pneumatic conveying performance has been appreciated by many workers in a qualitative manner. Two of the more common correlations that categorize in terms of particle density and mean particle size are considered for reference.

13.3.1.2 Geldart's classification

Geldart's classification, shown in Figure 13.11, provides limited guidance, but this was originally derived specifically for fluidization behaviour, with no reference at all to pneumatic conveying. The classification is essentially in terms of two material properties. One is the difference in densities between the particles and the fluidizing medium. For air this difference can simply be taken as the particle density. The other property is the mean particle size of the material. It includes four broad areas that identify the behaviour of bulk materials when aerated or fluidized. It has often been considered that this form of classification could be used to assess the suitability of materials for dense phase conveying.

The classification is based on the behaviour of a column of material when fluidized through a porous base. Group A materials retain aeration and the fluid bed collapses very slowly when the air is turned off. These materials are best candidates for dense phase conveying. Group B materials do not retain aeration and the fluid bed collapses almost instantaneously when the air supply is turned off. The division between the A (air retentive) and B materials is close to identifying dense phase conveying capability in a sliding bed mode. The important property that it lacks for this purpose, however, is particle size distribution. It is this that makes the A to B divide unreliable, and why it cannot identify plug flow capability with Group D materials.

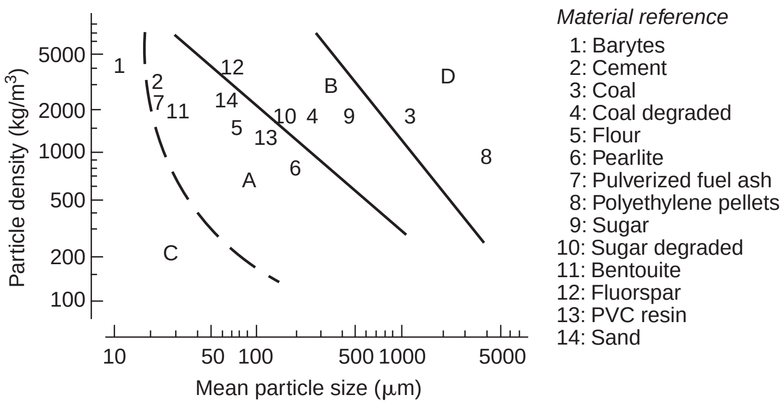


Figure 13.11 Geldart's classification of fluidization behaviour.

In Figure 13.11 data from a number of materials that have been tested and conveyed by the author and colleagues have been included. The conveying characteristics for many of the materials were presented in the previous chapter and the rest will be found later in this chapter. The dividing line between Groups A and B generally separates the materials quite well. Sand, however, which is in Group A, will not convey in dense phase and fluorspar, which is in Group B, will convey in dense phase. The Geldart's classification does not provide a sufficiently reliable indication for materials close to this divide. It is, of course, clearly not capable of identifying the pellets that will convey in dense phase.

An understanding of the role of particle properties such as size, and size distribution, shape or fractal properties and density will probably provide the ultimate solution to the problem. It is, however, very difficult to quantify properties such as particle shape and size distribution, and so measurable bulk properties associated with gas–particle interactions offer the best short-term means of using property values to predict pneumatic conveying performance. Air retention and permeability are probably the best bulk properties to consider for this purpose.

13.3.1.3 Dixon's slugging diagram

Dixon [4], among others, realized the importance of material type on the mode of conveying and devised a classification known as the Slugging Diagram, specifically for pneumatic conveying, which is shown in Figure 13.12. The axes are the same as those for the Geldart's classification: density difference, which can be taken as particle density when the conveying medium is air, and mean particle size.

The Dixon and Geldart diagrams are both divided into areas A, B, C, and D, and it is suggested that these group together materials with similar flow capability. Broadly speaking, Group A materials are considered to be powders that have good fluidizing capability and are identified with the moving bed type flow regime. Group B materials are coarser materials that are not likely to convey in dense phase in a conventional system.

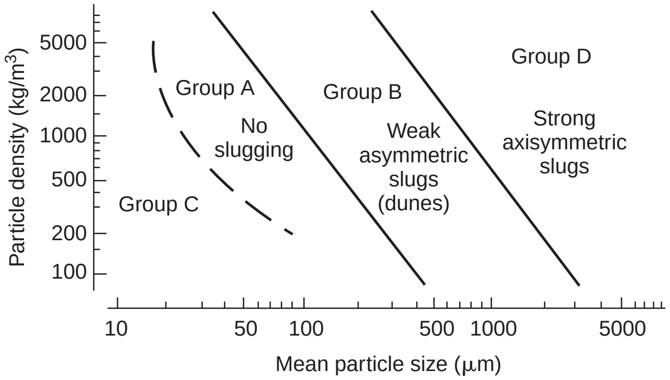


Figure 13.12 Dixon's slugging diagram.

Group C materials are cohesive, fine powders that can be difficult to fluidize, although they often have very good air retention characteristics once mixed with air. These materials can be conveyed in dense phase but can be troublesome, especially if they are allowed to de-aerate. Group D materials are large granular products that are possible candidates for plug or slug flow, provided that the particle size distribution is no too wide.

13.3.2 Aeration property classifications

The author and Mark Jones (now Professor and Director of the Centre for Bulk Solids & Particulate Technologies at The University of Newcastle, Australia) undertook a research study into possible correlations between material properties, obtained from small scale bench type tests, and material conveying characteristics obtained from full scale pneumatic conveying trials. Correlations were required both in terms of the mode of flow possible for a given material and for the flow rate of material that might be achieved. Material flow rate capability was included since this has been found to vary so widely for different materials, for both dilute and dense phase modes of flow.

In each case bulk properties of the material, using just a small sample, were to be measured that would relate as closely as possible to the air–material interactions that occur in the pneumatic conveying process. Correlations were sought that would allow reasonable predictions to be made as to whether a material will convey in dense phase or not, and what type of pressure drop/material flow rate characteristic is to be expected so that material flow rate capability might be predicted.

13.3.2.1 Conveying characteristics

The material conveying characteristics that have been presented in the various chapters here show a wide variety of capabilities. The pattern of curves that make up the conveying characteristics are influenced by two main factors; pipeline geometry and material type. Changes due to pipeline geometry, particularly conveying distance and bends, are reasonably predictable. It is the differences in conveying characteristics with respect to material type that present most difficulties, and so it is this issue that was addressed.

The conveying characteristics are built up from the lines of constant conveying line pressure drop and solids loading ratio, plotted as material flow rate against air flow rate, over the range of conveyability of interest for any given material. It is the lines of constant conveying line pressure drop that are important. For a given pipeline the shape, spacing and limits of the pressure drop lines can vary significantly from one material to another.

The differences and changes with respect to material type are not entirely predictable, and this is why it is necessary to carry out tests if there is no previous, or only limited, conveying experience with a material. Once data is available it can be scaled to the required pipeline geometry with a reasonable degree of accuracy. The scaling, however, must not extend beyond the limits for which the data is available and the conveying capability proven.

13.3.2.2 Material testing

A number of different materials were tested extensively for the benefit of the research. Two of the materials, granulated sugar and coal, degraded to such an extent during the conveying trials that their conveying characteristics changed. In each case it was possible to obtain conveying characteristics for these materials, in both the as received and degraded conditions, and property values were also determined.

With both conveying data and property values available for a wide range of materials, there was the possibility of deriving correlations between the two. Since pneumatic conveying is the transport of particulate solids in air, it was possible that the most likely correlations between conveying characteristics and material properties would be found from bench tests in which material–air interactions take place. For this reason a number of properties associated with aeration were determined. These included permeability factor, minimum fluidizing velocity, de-aeration rate and specific surface.

For similar reasons various density measurements were taken. Particle density and bulk density in both the 'as poured' and 'vibrated' conditions were measured. Voidage and degree of compaction were then derived from these values. Particle size is clearly important and so both the mean value and size distributions were determined. Particle shape and moisture content were also recorded, although these were included more for material reference purposes. Much of this data is logged in Appendix 1 for reference.

13.3.2.3 Conveying mode correlations

For a conveying mode correlation, air retention and permeability were the main bulk properties that were considered and it is these terms that have been used widely in terms of discussing material conveying capability and performance to this point in the Design Guide.

13.3.2.3.1 Permeability factor

To determine whether or not permeability factor can distinguish between materials that will convey in dense phase and those that will not, minimum conveying air velocity

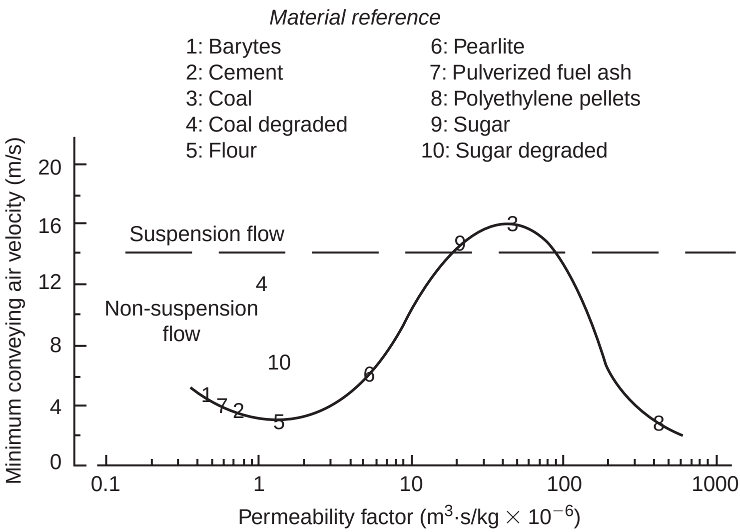


Figure 13.13 Influence of permeability factor on conveying mode.

was plotted against permeability factor for each of the materials. Minimum conveying air velocity was employed since this can be directly related to conveying capability. This plot is shown in Figure 13.13. If the degraded materials are ignored, the points indicate a general trend.

From Figure 13.13 it can be seen that materials that have values of permeability factor in a range from about 10×10^{-6} to 120×10^{-6} can only be conveyed in dilute phase. To the left of this region, where the permeability is poor, and consequently the air retention is good, there is a cluster of points where the minimum conveying air velocity is less than 5 m/s. To the right of the dilute phase region is a lone point representing polyethylene pellets. This area represents very good permeability. From the curve drawn it would appear that materials that have either good air retention properties or good permeability, are likely candidates for dense phase conveying. In the area where neither the air retention nor the permeability are particularly good, materials will only convey in dilute phase.

Through the sight glasses that were fitted into the pipelines it was possible to observe the various flows. Three major groups were identified according to the observed modes of flow. On the right hand side of Figure 13.13 are coarse materials which convey in slug type flow at low velocity. The middle group of materials represent those with no natural dense phase capability in a conventional system. On the left hand side are materials that have good dense phase capability in a moving bed type flow regime.

The two degraded materials, however, do not fit the pattern too well on this plot and it is suggested that the permeability of a material to air is not the primary factor influencing the ability or otherwise of a material to be conveyed in a moving bed type flow regime. It is further suggested, however, that the permeability is probably the dominant factor for the slug and plug type flow regime.

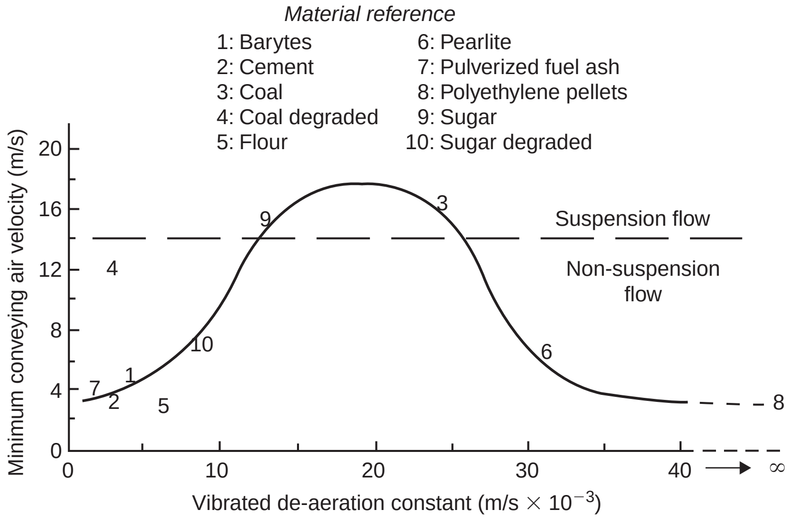


Figure 13.14 Influence of vibrated de-aeration constant on conveying mode.

13.3.2.3.2 Specific surface

The values of specific surface were derived from the same data from which the permeability factor was determined, which was permeametry with air. For this reason it could be expected that a correlation which appears to exist between permeability factor and conveying mode would be supported by any correlation that may exist between specific surface and conveying mode. These results, therefore, have not been included, but if specific surface is measured or derived by an entirely independent means it is suggested that it would be well worthwhile considering.

13.3.2.3.3 Vibrated de-aeration constant

The experimental data used to evaluate the vibrated de-aeration constant is completely independent of the data obtained from fluidization. Any correlation between the vibrated de-aeration constant and conveying mode, therefore, will provide independent support for the correlation achieved for permeability factor with respect to conveying mode. Details of the equipment used and method of analysis are given in Appendix 1.

This data is presented in Figure 13.14 and it can be seen that a similar pattern occurs once again when minimum conveying air velocity is plotted against vibrated de-aeration constant, on linear scale axes in this case. Once again, a definite region can be identified in which only dilute phase conveying can be achieved. On either side of this dilute phase region, materials will convey in dense phase.

The area on the left of Figure 13.14 groups materials that were observed to convey in a moving bed type flow regime. The centre section of the diagram represents materials that were observed to have no dense phase capability. The area to the right groups materials that were observed to convey in a slug type flow regime.

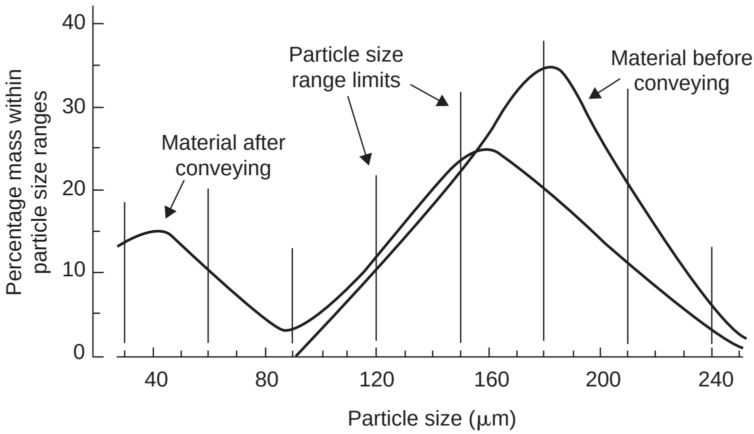


Figure 13.15 Potential influence of conveying on fractional size distribution of material.

On this plot only the degraded coal was out of place. This coal had the widest particle size distribution of any of the materials tested, other than the original coal. In addition, however, the size distribution was far from Gaussian, having two distinct peaks as a result of the particle degradation process with this friable material. The fines generated probably provided the material with a degree of air retention, while the coarse fraction retained a competing degree of permeability.

It may well be that materials that have size distributions that deviate widely from the Gaussian form should be viewed as possibly troublesome [3]. The above point concerning the particle size distribution is illustrated in Figure 13.15. This is a fractional size distribution and it shows the twin peak effect very clearly. A friable material, having an initial Gaussian type size distribution, can readily change as shown in Figure 13.15 as a result of particle degradation.

13.3.2.3.4 Empirical classification

By combining Figures 13.13 and 13.14 and plotting vibrated de-aeration constant against permeability factor, it has been possible to produce an empirical material classification for conventional pneumatic conveying systems. Such a plot, including the location of data points, is shown in Figure 13.16.

The points in Figure 13.16 each represent a single material and have been labelled with their material identity number. It can be seen that the materials form quite distinct groups. Using the boundaries identified, together with the broad groupings, a classification has been produced. The grouping in the bottom left hand corner represents materials that have dense phase capability in the moving bed type flow regime. The group in the top right hand corner represent materials with dense phase capability in plug type flow. The centre grouping represents materials that are generally restricted to dilute phase flow in a conventional conveying system. The material classification is presented again in Figure 13.17 without hindrance of data.

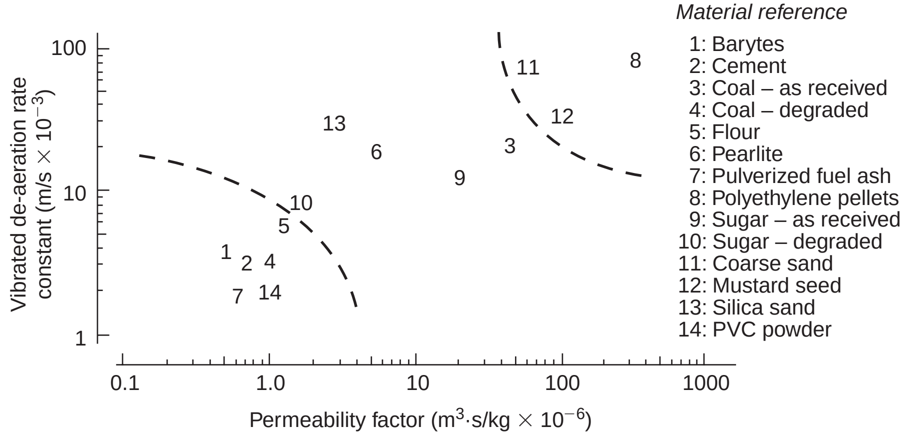


Figure 13.16 Classification for pneumatic conveying with location of materials tested.

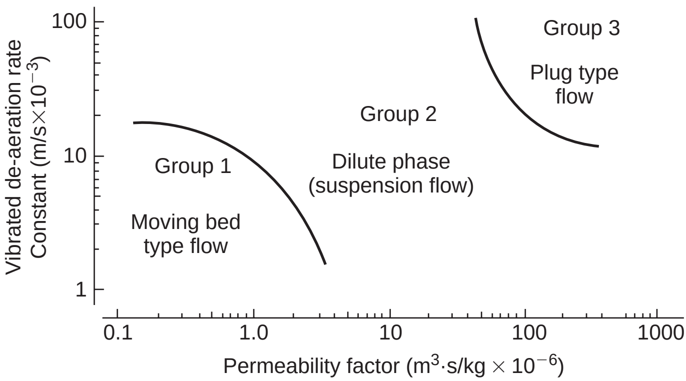


Figure 13.17 Material classification for pneumatic conveying.

13.3.2.4 Material flow rate correlations

The next correlation attempted was to provide an indication of the potential material flow rate that could be achieved through a pipeline, particularly in low velocity dense phase conveying. In Figure 12.15 it was shown that material flow rates could vary over an extremely wide range for identical conveying parameters. At very low velocity conveying the potential variation shown in Figure 12.15 is almost 20:1 and so this illustrates the importance of such a correlation.

13.3.2.4.1 Permeability factor

Permeability factor has already been shown to have considerable influence on the conveying characteristics in general. Figure 13.18 shows a plot of material flow rate against permeability factor for an air mass flow rate of 0.04 kg/s and two values of conveying

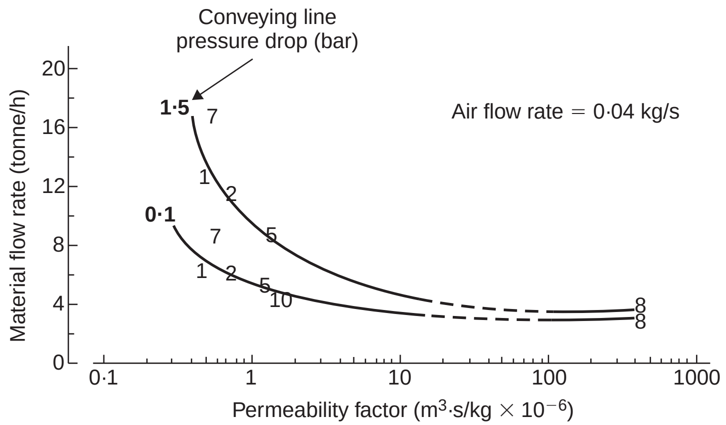


Figure 13.18 Influence of permeability factor on material flow rate.

line pressure drop (1.0 and 1.5 bar). This indicates that the lower the value of permeability factor, which effectively means the poorer the air permeability and the better the air retention, the greater the material flow rate.

A discontinuity in the curves in Figure 13.18 is shown by dotted lines. The correlation described earlier indicates that materials with a permeability factor in the range indicated by the dotted lines will probably not convey in dense phase. From the single point to the right of the graph (polyethylene pellets) it would appear that high conveying rates are not likely to be achieved with large granular materials, even if they will convey in a non-suspension mode.

13.3.2.4.2 Vibrated de-aeration constant

The values of vibrated de-aeration constant, as mentioned above, are obtained from data that is independent of permeametry, and so provide valuable support for correlations derived. Figure 13.19 is a plot of material flow rate values against vibrated de-aeration constant data. This shows that as the vibrated de-aeration constant decreases, which means that the air retention properties increase, the material flow rate increases. The two curves represent the two different conditions that were examined above. As with the other two aeration properties, the graph appears continuous, but there is a region, indicated by the dotted lines, where materials will not convey in non-suspension flow.

It should be noted that the above correlations are based on a rather limited number of materials and can, therefore, only indicate a trend. It is impossible with such a small number of materials to accurately identify boundaries or the ranges in which materials will convey in dilute and dense phase flows. However, it is possible to predict, with more confidence than would otherwise be possible, whether a material will convey in dense phase or not. This is clearly a very large task, particularly in deriving the conveying characteristics for such a large number of materials but it is hoped that such research will be continued so that correlations will become more generally available.

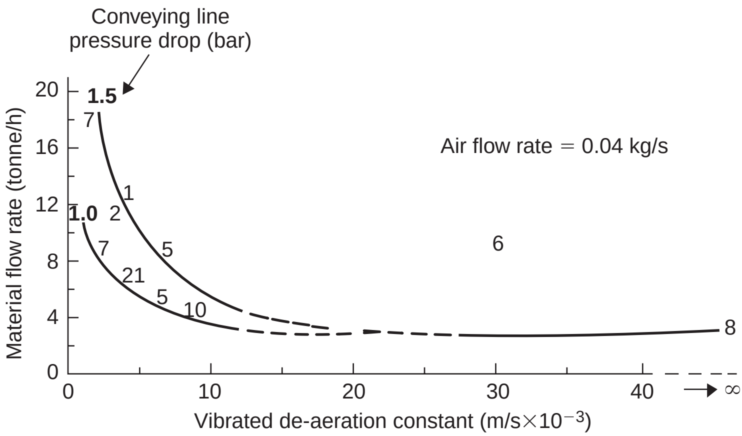


Figure 13.19 Influence of vibrated de-aeration constant on material flow rate.

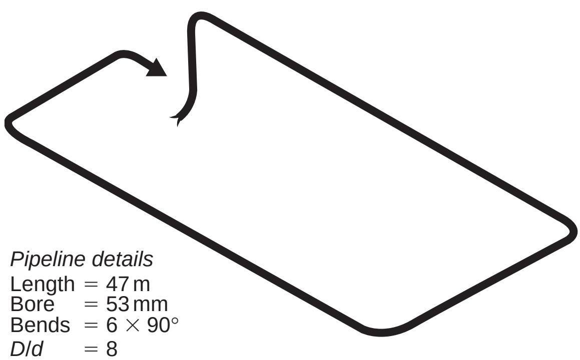


Figure 13.20 Sketch of pipeline no. 9.

13.4 Material grade influences

It has already been mentioned that many materials come in a variety of grades and that conveying capability and performance can vary widely with different grades of the same material. A number of cases are presented here to highlight this particular problem and to show the potential magnitude of the differences.

13.4.1 Alumina

Alumina comes in a variety of grades and these grades are often referred to as sandy and floury. The pipeline used for conveying such grades is shown in Figure 13.20 for reference.

The pipeline was 47 m long and of 53 mm bore. A high pressure bottom discharge blow tank was used to feed the materials into the pipeline. Tests were undertaken with

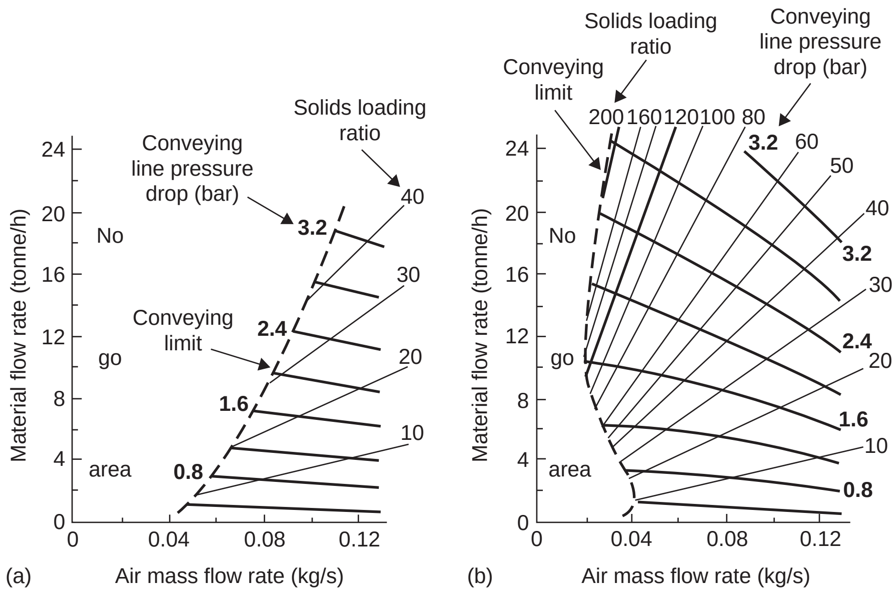


Figure 13.21 Conveying characteristics for alumina conveyed through pipeline no. 9: (a) a sandy grade of alumina and (b) a floury grade of alumina.

air supply pressures up to 3.2 bar gauge for each material. Conveying characteristics for the two grades of alumina tested are presented in Figure 13.21.

For the sandy alumina the minimum conveying air velocity was in the range of 10–12 m/s and this was dilute phase suspension flow. The high value of solids loading ratio achieved was due to the fact that the material could be conveyed at 10 m/s at high pressure, combined with the very high pressure gradient available. A pressure drop of 3.2 bar in a pipeline only 47 m long gives an exceptionally high pressure gradient, but despite this the material could only be conveyed in dilute phase. With the sandy alumina the minimum conveying air velocity was down to 3 m/s and solids loading ratios of 200 were achieved. This floury grade of alumina could be conveyed with a conveying line inlet air velocity of 11 m/s in dilute phase.

13.4.1.1 By-pass system performance

Probably the majority of the alumina that is manufactured is sandy grade and consequently by-pass systems are widely used for its conveying. The innovatory conveying systems were considered in Chapter 2 and a sketch given of various pipeline systems employed in Figure 2.14 is repeated here as Figure 13.22 for reference. The internal by-pass system is probably the most widely used, with flutes along its length as shown.

In a programme of work undertaken with a different grade of alumina in pipeline no. 9, a porous tube was used instead of a fluted pipe [5]. A porous pipe has the advantage of allowing the flow of air into and out of the by-pass pipe when and wherever it is required. The results of tests undertaken with the alumina in the pipeline without the

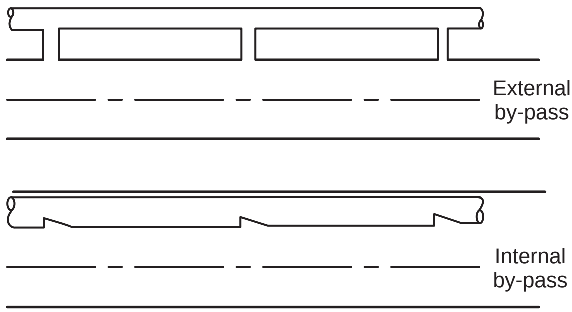


Figure 13.22 Sketch of various by-pass systems.

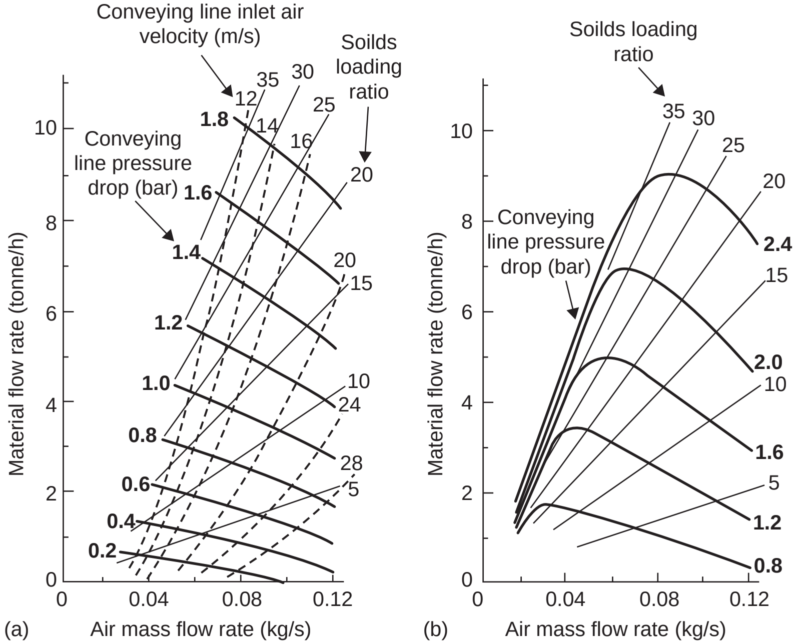


Figure 13.23 Further conveying characteristics for alumina conveyed through pipeline no. 9 for: (a) open pipeline and (b) porous by-pass pipe in pipeline.

by-pass pipe are presented in Figure 13.23a. Conveying characteristics for the alumina conveyed through the pipeline with a porous pipe inserted along its length are presented in Figure 13.23b.

The conveying characteristics for the alumina in Figure 13.23a compare directly with those for the alumina in Figure 13.21a. The material for Figure 13.23a is a different grade of sandy alumina and tests were only undertaken with material flow rates of up to about 10 tonne/h, but it will be seen that they are very similar. Lines of constant conveying line inlet air velocity have been superimposed on the conveying characteristics in Figure 13.23 for reference.

The conveying characteristics for the same material as presented in Figure 13.23a and conveyed through the same pipeline (pipeline no. 9), but with the insertion of the by-pass pipe, are presented in Figure 13.23b.The first point to note is that the material flow rate did not get to 10 tonne/h even with an increase in conveying line pressure drop to 2.4 bar. With the internal by-pass pipeline, at least 10 per cent of the available cross-sectional area for material flow is lost. This will also influence the air only pressure drop value for the pipeline. In addition there is an increase in wall surface area and so the wall friction loss will increase. As a consequence an approximate 40 per cent increase in pressure drop is required to achieve the same material flow rate.

Another major difference, of course, is the fact that the material will convey successfully in the pipeline with the porous by-pass pipe at a very low velocity. The resulting conveying characteristics are very similar in form to those of both the polyethylene pellets and the nylon pellets presented earlier in this chapter. It is recognized that the pelletized materials are naturally conveyed in plug flow, and as it is claimed that the object of the by-pass pipe is to split the flow up into plugs, it is perhaps not surprising that the conveying characteristics should be very similar. This does, however, mean that not only is the material flow rate reduced because of the loss in flow section area, it is also reduced as a consequence of the change in slope of the constant pressure drop lines at low air flow rates.

It will be noticed that there is no difference between the maximum values of solids loading ratio achieved between these two sets of conveying characteristics presented in Figure 13.23. That of 35 for the dilute phase conveying of a material that can only be conveyed in dilute phase suspension flow is typical of that achieved with other materials presented here when a high pressure gradient is available for conveying. That of 35 is also typical of the values reported for the dense phase conveying of pelletized materials in low velocity plug type flow.

13.4.2 Fly ash

Many hundreds of millions of tonnes of fly ash are produced around the world every year from the combustion of pulverized coal in thermal power stations and the majority of this is transported at some stage by pneumatic conveying systems. Although a considerable amount is transported by hydraulic conveying systems there is a gradual move away from the disposal of ash into lagoons on environmental grounds. Attempts are being made to find practical uses for the material, or to return it back to mines for underground stowing. For these purposes the ash is required in a dry form and so needs to be handled by pneumatic conveying systems.

13.4.2.1 Fly ash grades

As the flue gases pass through the boiler plant ducting, ash is collected at numerous locations along its route. The particle size of the fly ash will decrease as the distance of the collection point from the boiler combustion zone increases. Ash collected in the early economizer and air pre-heater hoppers tends to be granular while that collected

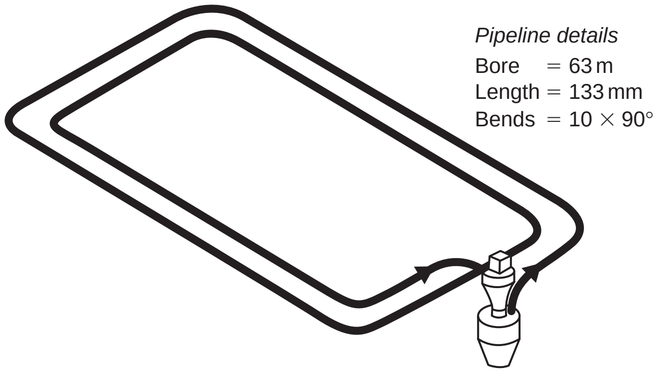


Figure 13.24 Sketch of pipeline no. 10.

in the electrostatic precipitator hoppers towards the end of the flow path tends to be a fine dust. There may be some 40 collection hoppers in a typical 200 MW boiler plant and they all have to be off-loaded. Although the material to be conveyed from every hopper will be essentially the same, the conveying capability can vary very significantly [6].

In a major programme of research work to investigate the conveying performance of power station fly ash, a high pressure pneumatic conveying test facility was used [7]. The pipeline used was 133 m long, of 63 mm bore and incorporated 10 numbers of 90° bends and a sketch of this is given in Figure 13.24. A top discharge high pressure blow tank was used to feed the fly ash into the pipeline.

Conveying characteristics for fly ash collected from an air pre-heater hopper are presented in Figure 13.25a and those for ash from the first field of an electrostatic precipitator hopper are shown in Figure 13.25b. The two sets of data are presented side by side for direct visual comparison because it is very often a system requirement that such different grades of ash should be conveyed by a common system. It is not unusual that the differences in conveying potential between these different grades of the same material are just not recognized and this is one of the major bulk solids produced in the world.

Lines of constant conveying line inlet air velocity have been superimposed on both sets of conveying characteristics and it will be seen that for the coarse ash the minimum value was about 13 m/s, and for the fine ash it was about 11 m/s for the low pressure dilute phase conveying and 3 m/s for high pressure dense phase conveying.

13.4.3 Dicalcium phosphate

Dicalcium phosphate is another material that is recognized by its name and in this case different grades are identified by percentage references. A 48 per cent grade was used in the previous chapter as an example of a typical material having natural dense phase conveying capability. The conveying characteristics for the material conveyed through pipeline no. 6 (Figures 11.2 and 12.24) were presented in Figure 11.8a. They are repeated here in Figure 13.26a for reference.

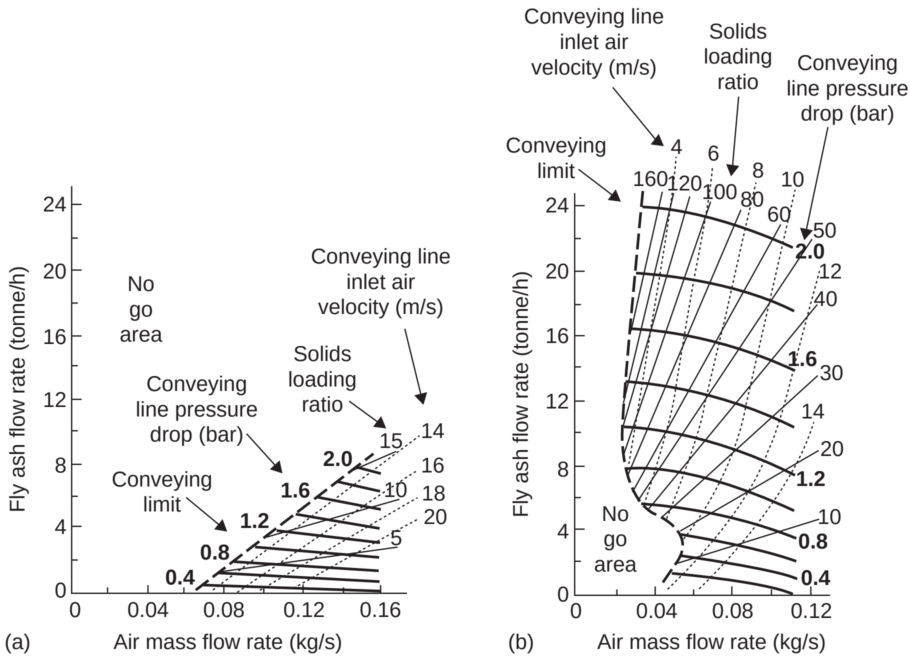


Figure 13.25 Conveying characteristics for fly ash in pipeline no. 10: (a) coarse fly ash and (b) fine fly ash.

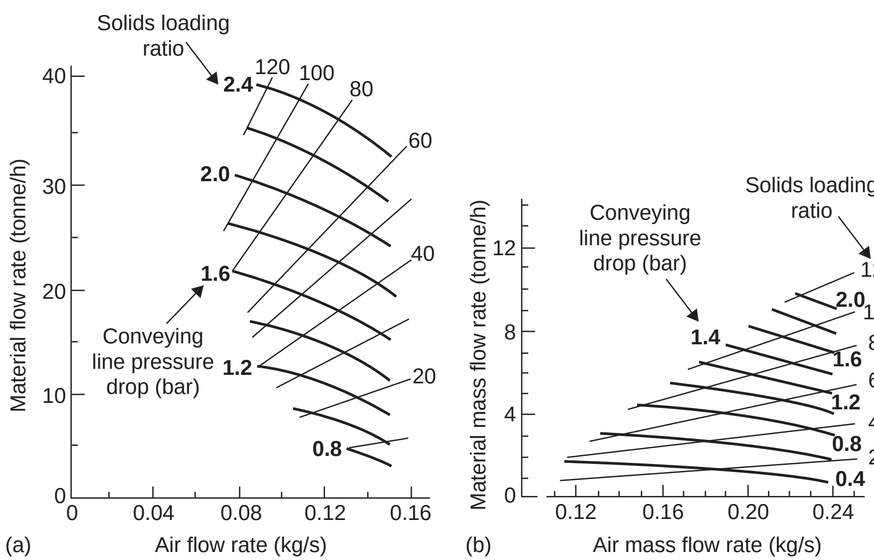


Figure 13.26 Conveying characteristics for dicalcium phosphate in pipeline no. 6: (a) 48% and (b) 52%.

Conveying characteristics for a 52 per cent grade of the same material are presented alongside in Figure 13.26b. Instead of using common axes for direct visual comparison, different axes have been used this time in order to magnify the data for the dilute phase conveying case. As will be seen there is a 10:1 difference between the materials in terms of solids loading ratios. The 52 per cent grade could only be conveyed in dilute phase and the minimum conveying air velocity was about 12 m/s. That for the 48 per cent grade was about 11 m/s for dilute phase conveying, but as will be seen from Figure 11.9b, with higher pressures this was able to be reduced to about 4 m/s for the dense phase conveying of the material.

13.5 Material degradation effects

Pneumatic conveying is potentially one of the most aggressive means of transporting materials. Only in low velocity conveying systems can the conveying of the material be described as being 'gentle' but even then the material is in constant contact with the pipeline walls and there is considerable particle to particle interaction. In dilute phase suspension flow there may be very little contact between the material and the pipeline walls, but in this case most of the damage occurs with the high velocity impact of the material against the pipeline bends. The subject of particle degradation in pneumatic conveying systems is dealt with specifically in Chapter 24.

If friable materials are conveyed, therefore, there is the potential for damage to the material. Degradation will cause a change in particle size and there is a tendency for 'fines' to be generated. This effect was illustrated earlier with Figure 13.15. Particle size distribution has the effect of reducing the permeability of a material and of increasing the air retention. This effect was mentioned in relation to many of the materials considered in the previous chapter. The minimum conveying air velocity of the granulated sugar, for example, having a very narrow size distribution, was about 16 m/s, and yet the minimum velocity for granular coal with a much larger mean particle size was only 13 m/s.

In the work reported above, to find a correlation between material properties and conveying performance, two materials were represented twice. These were coal and granulated sugar, in the 'as received' and 'degraded' conditions. Although each material was identical chemically, re-circulation in the conveying facility changed the material so much that in terms of their conveying characteristics, each was a completely different material. This made it possible to include the degraded materials as additional materials in the analysis.

13.5.1 Granulated sugar

The conveying characteristics for the granulated sugar in the 'as supplied' condition were shown in Figure 12.11b. The material was conveyed through pipeline no. 3 (Figure 12.12). The sugar had a mean particle size of about 460 μm and it had neither good permeability nor good air retention properties.

It was clearly a material that would not convey in dense phase in a conventional conveying system. This was confirmed during conveying trials, for as soon as conveying was attempted with a conveying line inlet air velocity below 16 m/s, the pipeline would block very rapidly. It will be seen from Figure 12.11b that the maximum solids

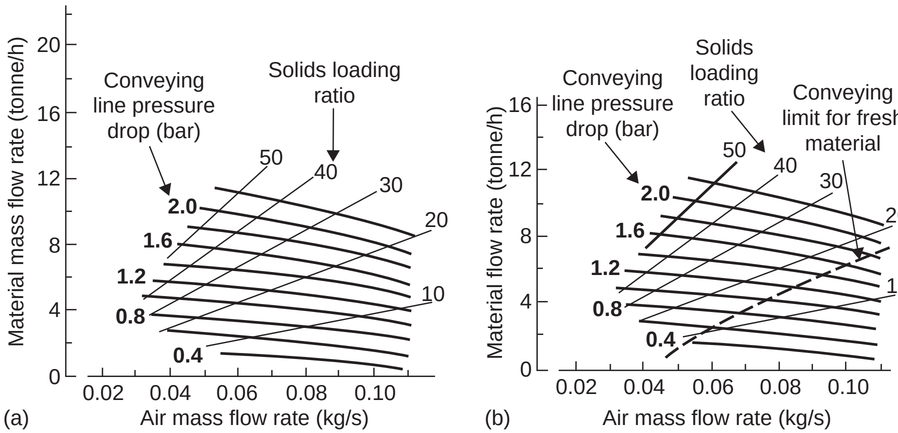


Figure 13.27 Conveying characteristics for granulated sugar in pipeline no. 3: (a) degraded material and (b) degraded and fresh material.

loading ratio that could be achieved was only 16, despite the fact that high pressure air was used for conveying.

13.5.1.1 Degraded material

The conveying characteristics for the degraded sugar conveyed through the same pipeline (no. 3) are shown in Figure 13.27a. With this material the minimum conveying air velocity was now down to 7 m/s and the maximum solids loading ratio that could be achieved was over 50.

If the material had been degraded further, it is possible that conveying with much lower velocities, and at much higher solids loading, would have been possible. In the 'as supplied' condition the sugar had a relatively narrow particle size distribution. Dilute phase pneumatic conveying of this friable material rapidly caused the generation of a considerable amount of fines in the material and so it very quickly obtained a degree of air retention.

With this material there was no significant change in the conveying capability with respect to material flow rate for a given pressure drop and air flow rate. As a consequence the conveying characteristics for the degraded material are simply an extension of the conveying characteristics for the fresh material. The two together are shown in Figure 13.27b and the influence of degradation in extending the range of conveying capability can be clearly seen. This situation is not common, however, for with the other materials included in this section on degradation, significant changes in both minimum velocity and material flow rates are reported.

13.5.2 Coal

Coal is a particularly friable material but it does convey very well. Degradation is generally not a problem since the conveyed material is often pulverized in the end for

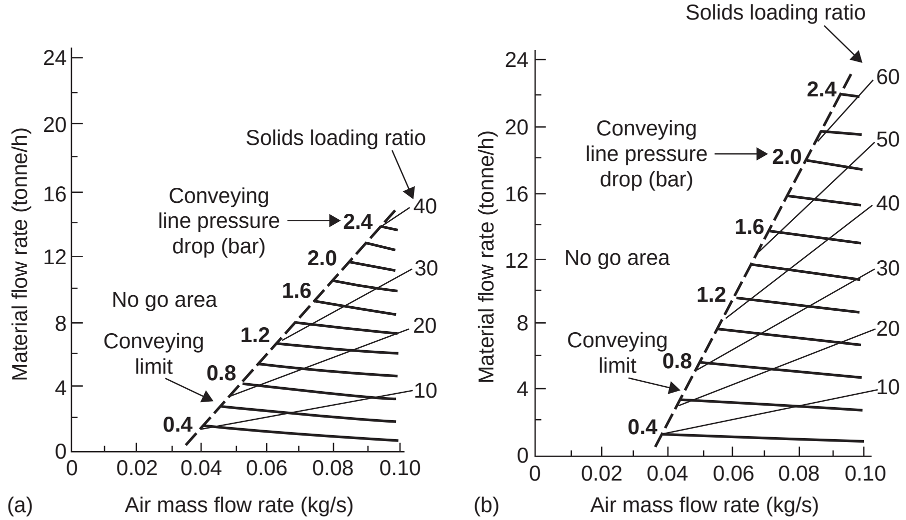


Figure 13.28 Conveying characteristics for granular coal in pipeline no. 3: (a) as supplied material and (b) degraded material.

combustion purposes. The changes that can occur with respect to conveying characteristics for the material, however, are worth reporting for they are very common effects that can occur with many materials. The coal, as supplied, had a mean particle size of about 778 μm. It was conveyed through pipeline no. 3 (Figure 12.12) and the conveying characteristics are shown in Figure 13.28a. The minimum conveying air velocity for the material was about 12 m/s.

When the coal had been degraded to the extent that the mean particle size had reduced to 146 μm it was tested again in the same pipeline, and the conveying characteristics are presented in Figure 13.28b. In this case they are presented alongside the data for the fresh material and with exactly the same set of axes for direct visual comparison. Whereas with the sugar there was no change with respect to the location of the pressure drop lines but there was a major shift in minimum conveying air velocity, the situation is completely reversed with the coal. There is very little change in the minimum conveying air velocity, but there is a significant increase in the material flow rate for a given pressure drop and air flow rate with the degraded coal.

13.5.3 Sodium sulphate

The conveying characteristics for a ground grade of sodium sulphate conveyed through pipeline no. 3 were presented in Figure 12.23c. A limited programme of tests was undertaken with an unground grade of the sodium sulphate in the same pipeline in order to check on the conveying capability. This data is presented in Figure 13.29a. If the two sets of conveying characteristics are compared it will be seen that there is very little difference between them. The minimum value of conveying air velocity in each case was about 12 m/s.

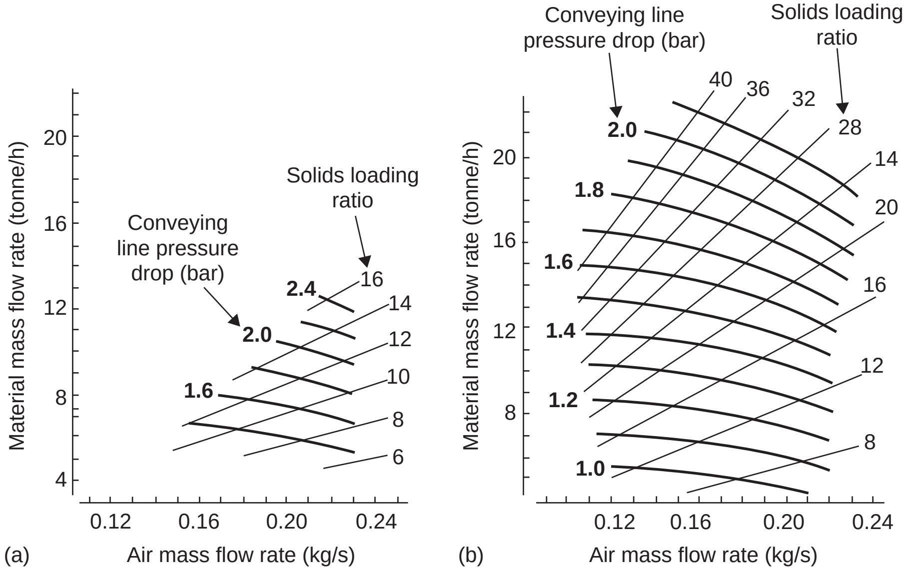


Figure 13.29 Conveying characteristics for unground sodium sulphate in pipeline no. 6: (a) as supplied material and (b) degraded material.

The sodium sulphate is very friable and after deliberately degrading the material, another set of conveying characteristic were obtained. These are presented in Figure 13.29b. The change in conveying characteristics for the degraded material are different yet again. In this case there was a change in both minimum conveying air velocity and material flow rates achieved. With a two bar pressure drop, for example, the material flow rate for the degraded material was 100 per cent greater, based on minimum conveying air conditions, and the conveying air velocity reduced from 12 to 8 m/s.

13.5.4 Soda ash

Light sodium carbonate (light soda ash) has a mean particle size of about 115 μm and has something of a reputation for being a difficult material to convey, as mentioned earlier with regard to heavy soda ash in Section 12.2.1.3. It is a friable material and is slightly hygroscopic. In order to learn something of its conveying capability a controlled programme of conveying trials was undertaken [8].

The programme of work, therefore, started with the knowledge that significant changes were likely to occur, and to occur quickly. As a consequence the conveying characteristics for the fresh, as supplied, material were undertaken with a fresh batch of material for every test point. A sketch of the pipeline used is presented in Figure 13.30.

The conveying characteristics obtained for the fresh material are presented in Figure 13.31a and those for the degraded material in Figure 13.31b. The two sets of conveying characteristics are presented together in Figure 13.31 and the same set of axes have been employed to allow direct visual comparison. Although there is no significant

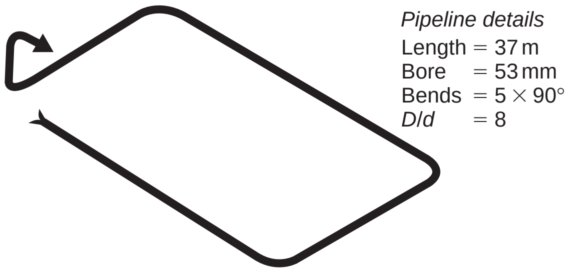


Figure 13.30 Sketch of pipeline no. 11.

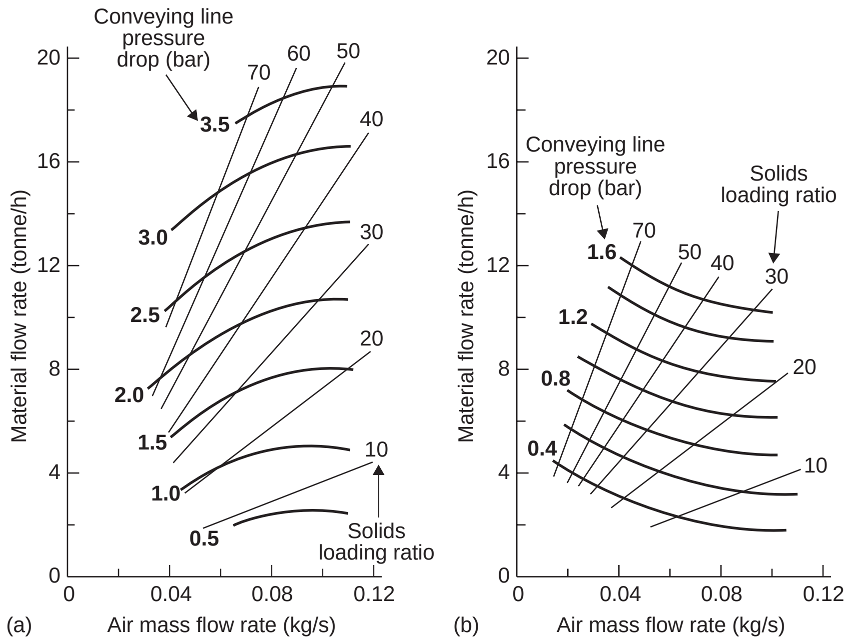


Figure 13.31 Conveying characteristics for light soda ash in pipeline no. 10: (a) fresh material and (b) degraded material.

or apparent change in solids loading ratio values and conveying air velocities, material flow rates achieved with the fresh material, for a given conveying line pressure drop, are considerably different. This difference increases with decrease in air flow rate, for the slope of the constant pressure drop lines is different for the two cases.

13.5.4.1 Particle size changes

For reference purposes a batch of material was re-circulated and samples were taken after every pass to show how the re-circulation influenced the mean particle size.

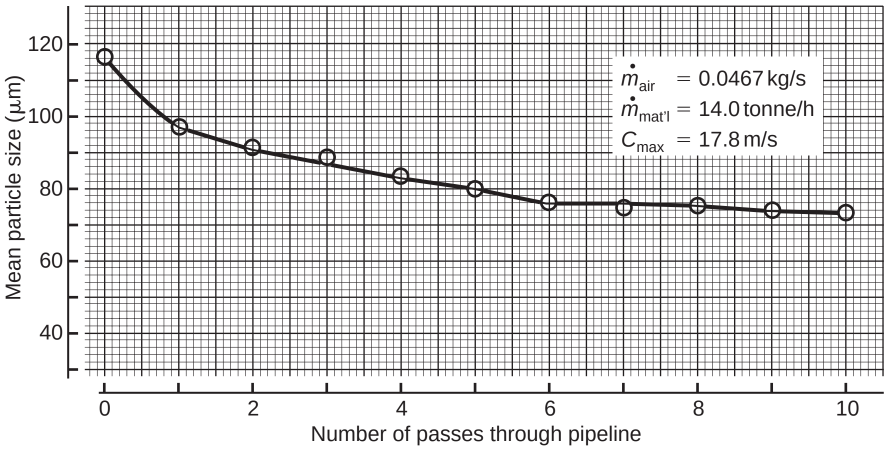


Figure 13.32 The influence of material conveying on mean particle size.

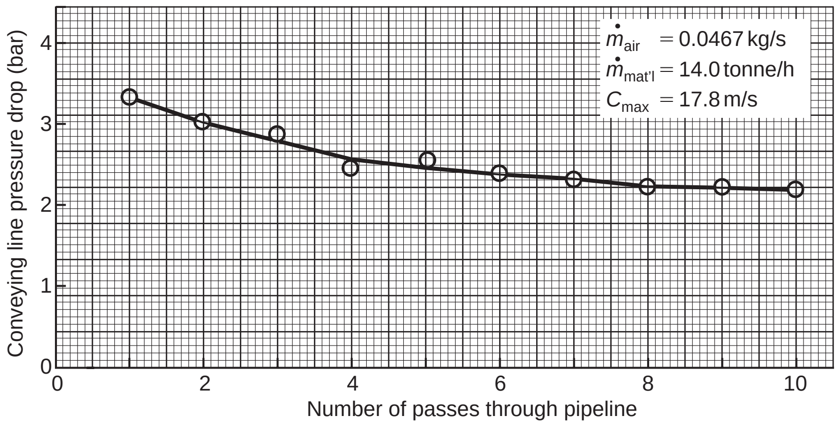


Figure 13.33 The influence of material degradation on conveying line pressure drop.

A typical set of results is shown in Figure 13.32. The pipeline was only 37 m long and in the case shown the material degraded from a mean particle size was about 97–117 μm in the first pass. After 10 passes, the mean particle size had reduced to about 73 μm. The maximum conveying air velocity was only 17.8 m/s in this programme.

13.5.4.2 Pressure drop changes

With such a dramatic change in conveying performance another controlled programme of tests was undertaken in order to monitor the gradual changes more closely. For this purpose the material was re-circulated with exactly the same air flow rate in each test, and the material flow rate was held constant each time. The influence on the conveying line pressure drop is shown in Figure 13.33. From this it will be seen that

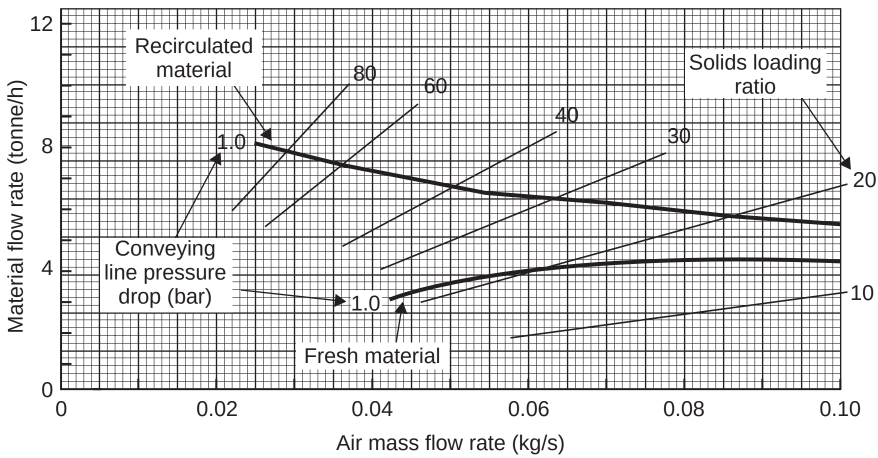


Figure 13.34 Comparison of pressure characteristics for fresh and re-circulated soda ash.

there is a gradual and significant reduction in pressure drop as the material is conveyed, particularly for the first few passes.

There are serious implications here for system design. If a material such as this is conveyed a couple of times to get a 'feel' for the material before undertaking a test to record conveying data, so that scaling can be carried out from the test pipeline to the plant pipeline, a significant change could occur, as shown with Figure 13.33. The scaling process would magnify the differences caused by re-circulation and the ultimate design could be in significant error. In nearly all cases re-circulation of the material results in an increase in conveying capability and so it follows that the material flow rate actually achieved with the plant would be well below that expected as a consequence. It must be emphasized, however, that this is an unusual situation.

From complete sets of conveying characteristics for the fresh and degraded materials the 1.0 bar pressure drop lines have been compared in Figure 13.34. The characteristics of the two soda ash materials are very different. For the conveying line pressure drop of 1.0 bar selected, the fresh material shows a pressure minimum point in its characteristics and a limit on solids loading ratio of about 20. The degraded material shows no intermediate pressure minimum point and the two lines diverge widely at low air flow rates, with the degraded material being conveyed at a solids loading ratio in excess of 80.

13.5.4.3 Conveying tests

Most reputable pneumatic conveying systems manufacturing companies have test facilities for carrying out conveying trials with materials in order to generate system design data for the given material. It is clearly important to establish whether the nature of the material is likely to change with conveying, and whether the conveying characteristics of the material will change as a result. This is particularly important if the batch size of material available for testing is limited, such that only a single batch is available.

References

1. D Mills. An investigation of the unstable region for dense phase conveying in sliding bed flow. Proc 4th Int Conf for Conveying and Handling of Particulate Solids. Budapest, Hungary. June 2003.
2. D Mills. The use of high pressure blow tanks for the pneumatic conveying of pelletised materials. Handbook of Conveying and Handling of Particulate Materials. Eds A Levy and H Kalman. Amsterdam: Elsevier. pp 387–303. 2001.
3. M G Jones and D Mills. Product classification for pneumatic conveying. Powder Handling and Processing. Vol 2, No 2. June 1990.
4. G Dixon. The impact of powder properties on dense phase flow. Proc Int Conf on Pneumatic Conveying. London. January 1979.
5. D J Mason and S Barton. The use of air-by-pass pipelines to enable low velocity gas–solids flow in pneumatic conveying systems. Proc 8th Int Freight Pipelines Symp. pp 109–116. The Univ of Pittsburgh. September 1995.
6. D Mills and V K Agarwal. Pneumatic Conveying Systems – design, selection, operation and troubleshooting with particular reference to pulverized fuel ash. Trans Tech Publications. ISBN 0-87849-126-0. 2001.
7. M D Bharathi. The pneumatic conveying of fly ash. PhD Thesis. Indian Institute of Technology, New Delhi. 2001.
8. M G Jones, D Mills and N Rolfe. The influence of product degradation on the pneumatic conveying capability of light sodium carbonate. Proc Pneumatech 4. pp 427–446. Glasgow. June 1990.

Chapter 14

Pipeline scaling parameters

14.1 Introduction

Although reliable models are now well established for single phase flow, no such relationships are available for gas–solid flows. The use of mathematical models is very limited, both in terms of the range of conveying conditions over which they can be applied and the range of materials for which they are applicable. Test data, therefore, is probably more widely used for system design and, if a system has to be designed for a material for which no previous experience exists, it is usual to carry out tests with the material in order to obtain the necessary data. Most companies in the business of manufacturing and selling pneumatic conveying systems have test facilities for this very purpose.

As it is rarely practicable to convey a material through a test pipeline of the exact geometry as the one to be built, it is usually necessary to scale the conveying characteristics obtained from a test pipeline to that required. If a number of design alternatives are to be considered, additional scaling will be necessary, for the conveying of a material through a range of pipelines of different bore will be very expensive and time consuming. Scaling in terms of pipeline geometry needs to be carried out with respect to conveying distance, pipeline bore, pipeline orientation, and the number of bends in the pipeline. Pipeline material, bend geometry, and stepped pipelines are other important parameters that also need to be considered.

The design of the pipeline is probably one of the first tasks to be undertaken in pneumatic conveying system design. The conveying distance and material flow rate for the plant are usually specified, and so it is necessary to determine the pipeline bore and the air supply pressure required. The starting point in this process is generally test data or some previous experience with the particular material to be conveyed. If the conveying characteristics are available for a material in a known pipeline they can be scaled, for the same material, to another pipeline, with a reasonable degree of accuracy.

14.2 Scaling requirements

The main requirements of scaling are that dynamic similarity should be maintained and that the scaling should remain within established flow regimes.

14.2.1 Conveying air velocity

If, for a given material, conveying data relating to one pipeline is to be scaled to that for another pipeline, it is essential that conveying conditions, in terms of air velocities, should be the same for the two situations. This means that scaling must be carried out for data points having the same conveying line pressure drop and air mass flow rate. If scaling is in terms of pipeline bore, the air mass flow rate must be in proportion to the pipe section area, or (diameter)^2 for a given conveying line pressure drop, to maintain similar air velocities.

14.2.2 Solids loading ratio

The data available from previous experience, or from conveying trials undertaken, should not be extended to higher values of solids loading ratio.

14.3 Conveying distance

To illustrate the scaling procedure with respect to conveying distance, the conveying characteristics for two materials with very different conveying capabilities are used. One is ordinary Portland cement, which is capable of being conveyed in dense phase and at low velocity, if the conveying line pressure gradient is high enough. The other is potassium sulphate, which can only be conveyed in dilute phase suspension flow, in a conventional conveying system, even if a high air supply pressure is used.

Both of these materials were conveyed through pipeline no. 6, which is 95 m long, of 81 mm bore and incorporates nine 90° bends having a D/d ratio of 16:1 (Figure 12.24). The conveying characteristics of the two materials were presented in Figure 12.23 and are reproduced here in Figure 14.1 for reference.

In each case conveying was carried out with line pressure drop values of up to about 3 bar. The cement was conveyed at solids loading ratios of up to 120, while the maximum

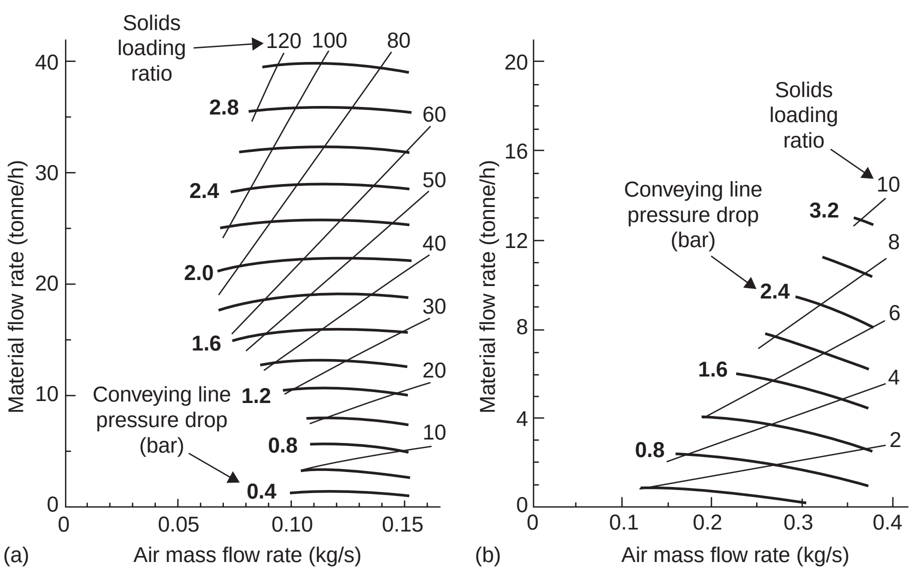


Figure 14.1 Conveying characteristics for materials conveyed through 95 m long 81 mm bore pipeline no. 6: (a) cement and (b) potassium sulphate.

for the potassium sulphate was only ten. This illustrates quite clearly the significant difference in conveying potential that can exist between different materials. With a conveying line pressure drop of 3 bar the cement could be conveyed at about 40 tonne/h and with only 0.085 kg/s of air, whereas the flow rate of the potassium sulphate was only 12 tonne/h and required 0.35 kg/s of air.

14.3.1 Minimum conveying air velocity

The relationship between the minimum conveying air velocity and the solids loading ratio at which the materials can be conveyed is presented in Figure 14.2. For the dilute phase conveying of the cement a minimum conveying air velocity of 11 m/s is required, but for the potassium sulphate it is about 14 m/s. At higher solids loading ratios the minimum conveying air velocity for the cement decreases until it is about 3 m/s, at a solids loading ratio of about 70. For the potassium sulphate the minimum conveying air velocity remains at 14 m/s. This is because conveying at a solids loading ratio greater than about 12 is not possible, even with much higher air supply pressures, in a conventional conveying system.

14.3.2 Scaling

To illustrate the influence of distance fully, the entire conveying characteristics for the two materials are first scaled to a conveying distance of 150 m and then to 200 m.

14.3.2.1 Empty line pressure drop

The pressure drop, Δp, for the flow of air through a pipeline of a given diameter, d, and length, L, can be determined from Darcy's Equation, presented in Equation (10.2). This is reproduced here for reference:

$$\Delta p = \frac{4fL}{d} \times \frac{\rho C^2}{2} \ \text{N/m}^2 \tag{14.1}$$

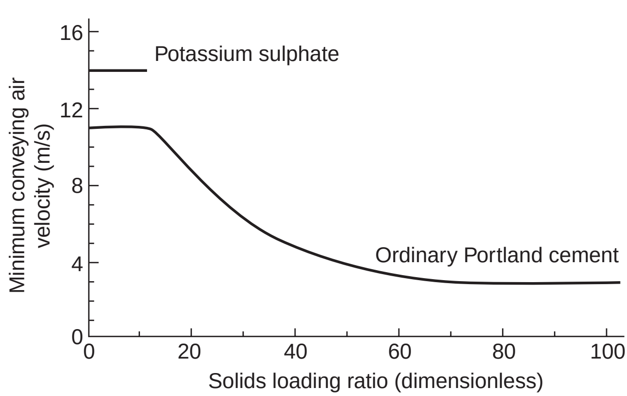


Figure 14.2 Conveying limits for materials considered.

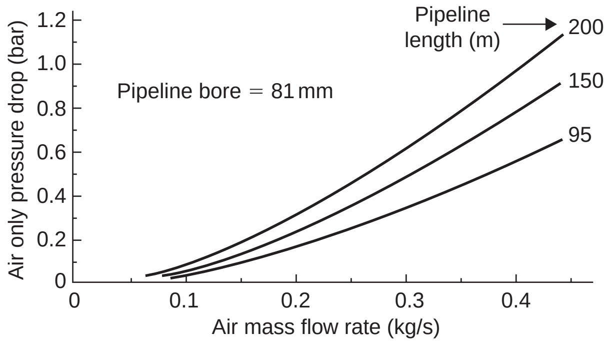


Figure 14.3 Influence of pipeline length and air flow rate on the empty pipeline pressure drop relationships.

With an increase in distance there will be a similar increase in pressure drop, both for the air in the empty line and for the conveying of the material. The increase in pressure drop for the empty line increases approximately in proportion to the increase in length, as will be seen from Equation (14.1). Data for the empty lines being considered is given in Figure 14.3.

Figure 14.3 shows the variation of pressure drop with air flow rate for the 95 m long pipeline of 81 mm bore, and for the 150 m and 200 m long pipelines of the same bore. For the scale up of the conveying characteristics in respect of distance, the change in datum for the empty line will have to be taken into account. If the air supply pressure remains the same, for an increase in conveying distance, an increase in the air only pressure drop value will mean a corresponding reduction in the pressure drop available for the conveying of the material.

14.3.2.2 Scaling model

Scale up of material flow rate with respect to conveying distance can be carried out with a reasonable degree of accuracy, if the extrapolation is not too great, on the basis of a reciprocal law:

$$\dot{m}_p \propto \frac{1}{L_e} \tag{14.2}$$

or alternatively:

$$\dot{m}_{p1} L_{e1} = \dot{m}_{p2} L_{e2} = Constant \tag{14.3}$$

For a constant conveying air flow rate and pressure drop due to the conveyed material. Where $\dot{m}_p$, material flow rate; L_e, equivalent length of pipeline; subscripts 1 and 2 relate to the test pipeline and the plant pipeline.

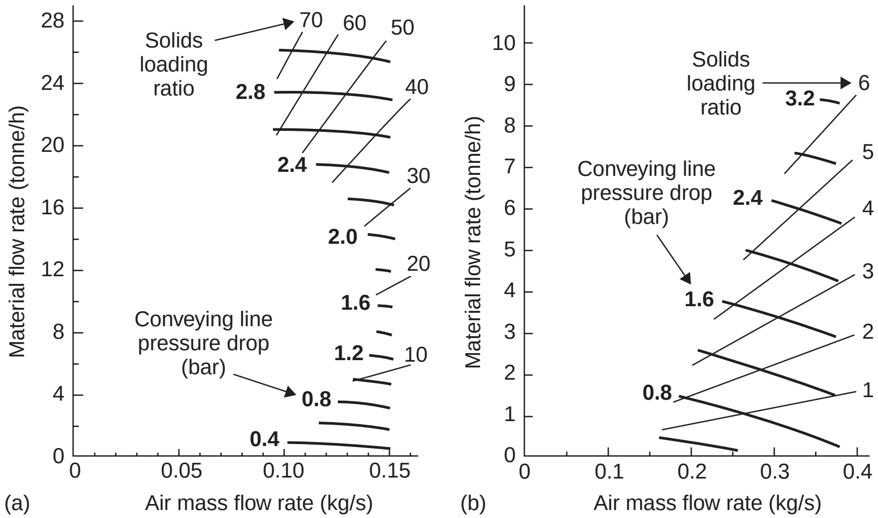


Figure 14.4 Conveying characteristics for materials conveyed through 150 m long pipeline of 81 mm bore: (a) cement and (b) potassium sulphate.

Conveying distance is expressed in terms of an equivalent length of the total pipeline. This comprises the three main elements of the pipeline routing or geometry. One is the length of the horizontal sections of pipeline, the second is the length of vertically up sections of the pipeline, and the third relates to the bends in the pipeline. Horizontal pipeline is taken as the reference. To this is added the equivalent length of straight horizontal pipeline represented by vertical sections of pipeline, and the equivalent length for all the bends in the pipeline.

For the purpose of illustrating the influence of conveying distance additional pipeline lengths of 150 and 200 m are used. The equivalent length of vertical pipeline and bends are considered in later sections of this chapter. For this exercise equivalent lengths have been taken as the length of horizontal pipeline, purely for simplicity in terms of illustration, in advance of considering vertical elements of pipeline and bends.

The working form of this scaling model is:

$$\dot{m}_{p2} = \dot{m}_{p1} \times \frac{L_{e1}}{L_{e2}} \tag{14.4}$$

14.3.2.3 Scaling procedure

For the scaling of the two sets of data presented in Figure 14.1, conveyed over a distance of 95 m, to a distance of 150 m, the datum pressure drop for the air only should first be changed throughout by the values given in Figure 14.3. Material flow rates, for given air mass flow rates and conveying line pressure drops, are then scaled in the ratio of L_{e1}/L_{e2}. The results of this are presented in Figure 14.4.

It can be seen from Figure 14.4a that the maximum value of cement flow rate has reduced from about 40 tonne/h over 95 m, to about 26 tonne/h over 150 m, for the same 3.0 bar pressure drop. This represents a 35 per cent reduction in cement flow rate, but this would be expected from Equation (14.4). A particularly important point to note is that the maximum value of solids loading ratio has dropped from just over 120 to about 70, which represents a 42 per cent reduction.

The reduction in solids loading ratio is clearly due to the decrease in cement flow rate. This increased reduction in solids loading ratio, however, is due to the fact that a higher value of conveying line inlet air velocity is required as a result of the lower value of solids loading ratio at which the cement is conveyed.

Solids loading ratio has a significant effect on the value of minimum conveying air velocity, as was shown in Figure 14.2. It is the need for a slightly higher conveying line inlet air velocity, and hence a higher air mass flow rate, that has caused the increased reduction in solids loading ratio.

14.3.2.3.1 Cement conveying limits

Conveying distance will have a significant effect on this particular relationship but so also does pressure since it is primarily a function of pressure gradient. This means that the limit of conveying, in terms of air mass flow rate, has to be changed for each pressure drop line according to the new conditions. The appropriate model for conveying line inlet air velocity was presented with Equation (9.20) and is reproduced here as Equation (14.5) for reference:

$$C_1 = 0.365 \frac{\dot{m}_a T_1}{d^2 p_1} \text{ m/s} \tag{14.5}$$

By using Equation (14.5), in conjunction with the relationship presented in Figure 14.2 for the cement, the locus of the conveying limit in Figure 14.4a can be established. It is a 'trial and error' solution, but with Equation (14.5) programmed into a calculator it should only take a matter of seconds to establish the value of minimum air mass flow rate for each conveying line pressure drop curve, and so determine the new boundary for the limit of conveying.

14.3.2.3.2 Potassium sulphate conveying limit

In the case of the potassium sulphate both the material flow rate and the solids loading ratio have reduced in proportion to the ratio of distances. This is because there is no change in value of the minimum velocity for the material, as will be seen from Figure 14.2, and hence the air flow rates required remain unchanged. The conveying characteristics for the potassium sulphate over 150 m are essentially geometrically similar to those for the material over 95 m. The only difference is due to the change in air only pressure drop values and not to a change in conveying limits.

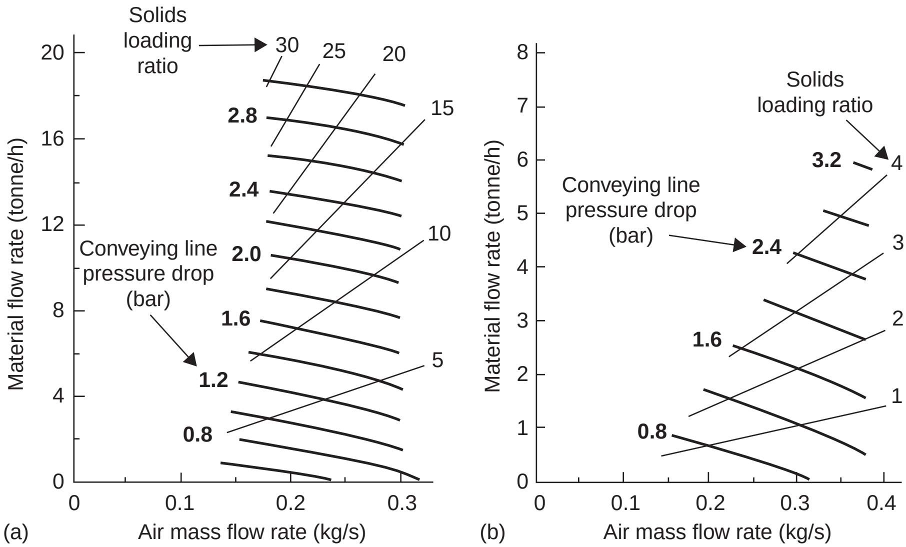


Figure 14.5 Conveying characteristics for materials conveyed through 200 m long pipeline of 81 mm bore: (a) cement and (b) potassium sulphate.

14.3.2.4 Scaling to longer distances

The results of the scaling of the conveying characteristics for the two materials to a distance of 200 m are presented in Figure 14.5.

For the cement in Figure 14.5a a very significant change has occurred, with an increase of the air flow rate axis required to accommodate the data. Compared with this same material conveyed over only about half the distance in Figure 14.1a, the maximum cement flow rate has been reduced from about 40 to 19 tonne/h. This, as explained above, is to be expected from Equation (14.4) and the increase in air only pressure drop. It is the reduction of the maximum value of solids loading ratio from 120 to 30 that has an over-riding effect on performance.

14.3.2.4.1 Dense phase conveying limit

It will be seen from Figure 14.5a that if the maximum flow rate capability of the compressor was limited to about 0.115 kg/s (200 ft^3/min), it would not be possible to use the compressor at all for conveying over a distance of 200 m, not even by restricting the pressure and using it for dilute phase conveying of the cement. From Equation (14.5) it will be seen that for a conveying line pressure drop of 0.8 bar and temperature of 20°C the conveying line inlet air velocity is only 10.6 m/s.

The relationship between inlet air velocity and solids loading ratio, as shown in Figure 14.2, is extremely important for materials capable of being conveyed in dense phase. Although the change in cement flow rate, with increase in distance, is as predicted by the model, the reduction in solids loading ratio is significantly more. A further increase in distance would result in this reducing to a point at which the cement could only be conveyed in dilute phase.

With a further increase in distance the boundary limit to conveying would be little different from those for the potassium sulphate, although the flow rate would remain at a slightly higher value. Dense phase conveying requires a high pressure gradient which is typically about 20 mbar/m for horizontal conveying at a solids loading ratio of about 100 (see Figure 1.1). Pressure gradient is simply the available pressure divided by conveying distance. Dense phase conveying, therefore, is possible, even with negative pressure systems, provided that the distance is short. For conveying over longer distances, higher pressures will be required, but there is a limit.

14.3.2.5 Iterative process

In scaling the conveying characteristics for the cement to longer distances, the upper part of the conveying characteristics become unavailable for scaling, since this is the area of maximum solids loading ratio and lowest velocity. A reduction in cement flow rate will automatically reduce the solids loading ratio by the same amount, for a given air flow rate and pressure drop, and this reduction in solids loading ratio will necessitate a correspondingly higher value of inlet air velocity. This means that a higher air flow rate will be required, which in turn means a further lowering of the solids loading ratio, as discussed above.

Over an even longer distance, therefore, it is clear that the cement will be restricted to dilute phase conveying, and if a conveying line pressure drop of 3.0 bar should need to be utilized, an air flow rate much higher than 0.115 kg/s would be required. In this case it is likely that the conveying line exit air velocity would be in excess of 50 m/s for a single bore pipeline. Great care must be taken, therefore, if a change in distance is needed for a material which is capable of being conveyed in dense phase. Air requirements for conveying a material must be based on the longest distance, and a reduction in air flow rate should ideally be made to achieve optimum conveying conditions over shorter distances.

For the potassium sulphate in Figure 14.5b the conveying characteristics have reduced almost geometrically, with a halving of both material flow rate and solids loading ratio, and no change in air requirements. In this case an iterative process of determining the minimum conveying limits is not necessary because there is no change in minimum conveying air velocity with respect to solids loading ratio for this material.

14.3.2.5.1 Note

It should be pointed out that the influence of bends in the pipeline has been taken into account in these examples. The number of bends has been scaled in proportion and so the conveying characteristics for the cement conveyed over 200 m includes approximately 19 bends. The number of bends in a pipeline can have a major influence on the conveying characteristics, as will be shown later, and the large number in this case has had a significant effect on the rapid transition from dense phase conveying, over 95 m, to almost dilute phase conveying, over 200 m, for the cement. The transition does not generally happen as quickly as this, since the example is a little artificial, but it is nevertheless illustrative of the process which is the main point of the exercise.

14.4 Pipeline bore

This rapid transition has also been accentuated by the small bore pipeline, since the increase in the air only pressure drop represents a significant proportion of the total pressure drop available for a long pipeline. This effect is illustrated with Figure 14.6. Stepping the pipeline to a larger bore part way along its length will also help in extending dense phase conveying capability to longer distances.

14.4.1 Empty line pressure drop

For the scale up of the conveying characteristics with respect to pipe bore, the change in datum for the empty line will also have to be taken into account. Data for empty lines, 95 m long, of different bore is given in Figure 14.6. In a similar manner to that for Figure 14.3, the data for Figure 14.6 was also obtained from the relationship presented in Equation (14.1). The variation of pressure drop with air flow rate for the 81 mm bore pipeline is included and so the change in datum can be obtained by taking the difference between the 81 mm and the required bore of pipeline. It will be seen from this that the air only pressure drop element reduces significantly with increase in pipeline bore.

14.4.2 Scaling model

Scale up of material flow rate with respect to pipeline bore can be carried out with a reasonable degree of accuracy, if the extrapolation is not too great, on the basis of pipe cross-sectional areas:

$$\dot{m}_p \propto A \propto d^2 \tag{14.6}$$

or alternatively:

$$\frac{\dot{m}_{p1}}{d_1^2} = \frac{\dot{m}_{p2}}{d_2^2} = \text{Constant} \tag{14.7}$$

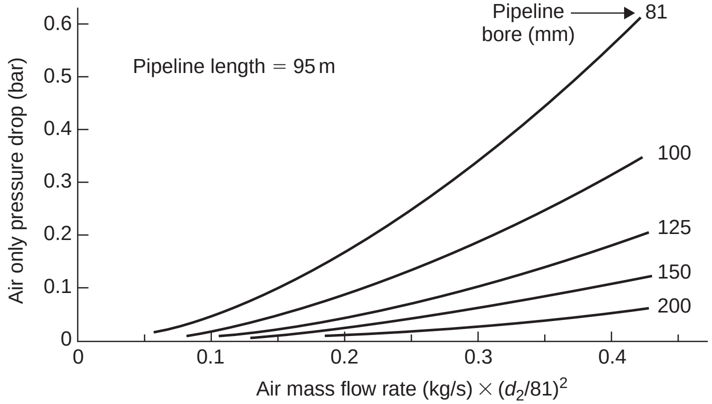


Figure 14.6 Influence of pipeline bore and air flow rate on the empty pipeline pressure drop relationships.

14.4.2.1 Working model

The working form of this scaling model is:

$$\dot{m}_{p2} = \dot{m}_{p1} \times \left(\frac{d_2}{d_1}\right)^2 \tag{14.8}$$

where subscripts 1 and 2 relate to the appropriate pipe bores of the two pipelines. It is for this reason that the air mass flow rate axis in Figure 14.6 is in terms of the air required for the 81 mm bore pipeline $\times (d_2/81)^2$. Conveying air velocities scale up exactly and so a common axis can be used. For the scaling up of the conveying characteristics in Figure 14.1, with the materials conveyed over 95 m through an 81 mm bore pipeline, to a pipeline of larger bore, the datum pressure drop should first be changed throughout by the appropriate values obtained from Figure 14.6. Material mass flow rates for a given air mass flow rate and conveying line pressure drop are then scaled in the ratio of $(d_2/81)^2$.

14.4.3 Scaling procedure

The scale up of the conveying characteristics for the two materials conveyed over 95 m through the 81 mm bore line to a 100 mm bore line is presented in Figure 14.7.

The influence of minimum conveying conditions, for the cement, has not had the radical effect that was obtained with the scale up in terms of conveying distance. This is because the air flow rate is scaled up by essentially the same model as the material flow rate. The scale up in terms of pipe bore produces a set of curves that are basically geometrically similar for both materials, apart from the slight change due to the shift

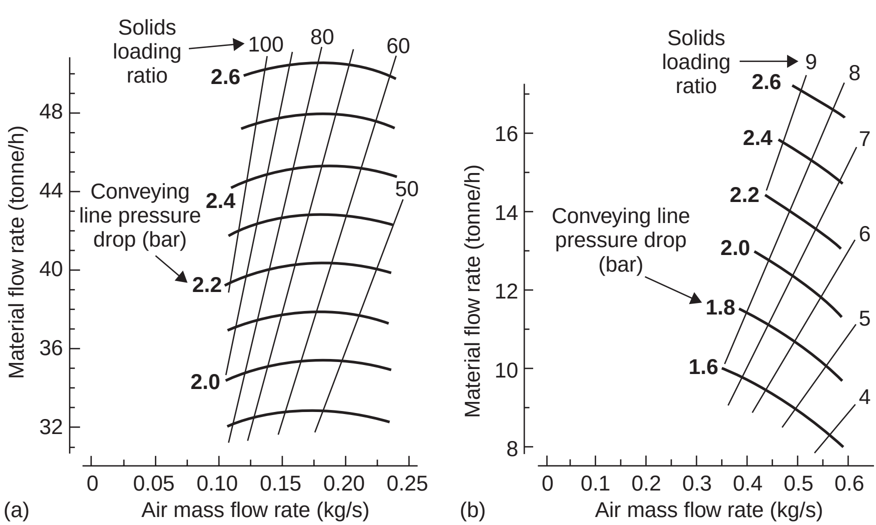


Figure 14.7 Conveying characteristics for materials conveyed through 95 m long pipeline of 100 mm bore: (a) cement and (b) potassium sulphate.

in datum for the empty line pressure drop relationship. There is, therefore, little difference in minimum conveying conditions for different pipeline bores, since similar solids loading ratios result at the same values of conveying line pressure drop. Air mass flow rates are totally different, of course, as these have been scaled up in proportion to the cross-sectional area of the pipeline.

14.4.3.1 Scaling to larger bores

The results of scaling the conveying characteristics over a distance of 95 m to larger bore pipelines are presented in Figures 14.8–10. These are for pipeline bores of 125, 150 and 200 mm. In each case only that part of the conveying characteristics between material flow rates of approximately 30 and 50 tonne/h, for the cement, and 8 and 16 tonne/h, for the potassium sulphate, have been included.

In the vast majority of cases a system has to be designed to achieve a given flow rate of material and this is why the scaling of the conveying characteristics has been limited to narrow bands of material flow rate, rather than complete sets of data as with conveying distance. With a range of pipeline bores considered it will be possible to illustrate the inter-relating effects of pipeline bore and conveying line pressure drop on material flow rate for a given system specification. It should be noted that since the same length of the air flow rate axis has been used in each case, this has distorted the shapes of the curves and has produced very steep lines of constant solids loading ratio as a consequence.

If 40 tonne/h of cement and 12 tonne/h of potassium sulphate are considered, by way of example, the influence of pipeline bore on the type of conveying system can be illustrated with these two sets of conveying characteristics. With the 81 mm bore

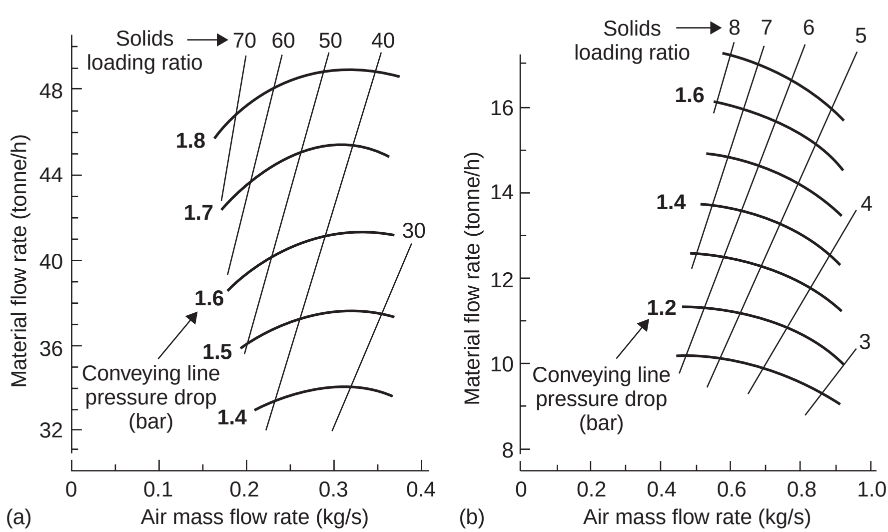


Figure 14.8 Conveying characteristics for materials conveyed through 95 m long pipeline of 125 mm bore: (a) cement and (b) potassium sulphate.

pipelines, in Figure 14.1, both materials could be conveyed at these flow rates, but high pressure blow tank systems would be required. With the 100 mm bore pipelines, in Figure 14.7, air supply pressures are down to about two bar gauge and so there is now a possible choice between high pressure rotary valves (for the non-abrasive potassium sulphate), screw pumps (for the air retentive cement) and blow tanks for feeding the materials.

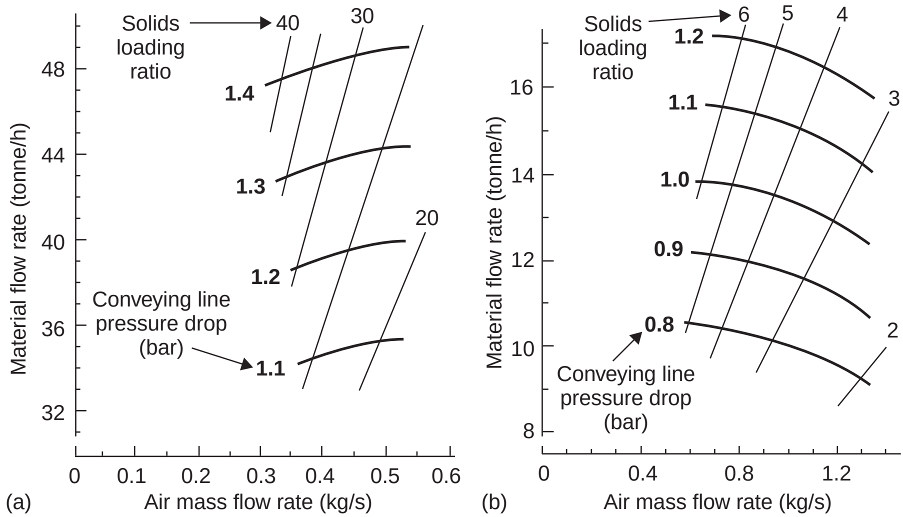


Figure 14.9 Conveying characteristics for materials conveyed through 95 m long pipeline of 150 mm bore: (a) cement and (b) potassium sulphate.

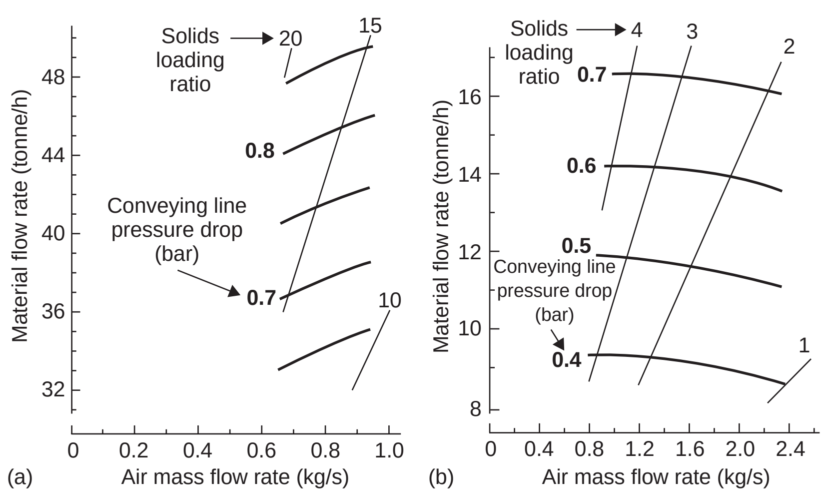


Figure 14.10 Conveying characteristics for materials conveyed through 95 m long pipeline of 200 mm bore: (a) cement and (b) potassium sulphate.

There is a further reduction in air supply pressure with the increase to 125 mm, in Figure 14.8. With an abrasive material such as cement this would be a better choice for use in conjunction with a screw pump than the higher pressure required for the 100 mm bore line. With the 200 mm bore pipeline (Figure 14.10) pressure requirements are in the range where low pressure rotary valves could be considered, and in the case of potassium sulphate the pressure drop is such that a vacuum conveying system could be considered for the duty.

14.4.3.2 Influence on conveying parameters

A comparison of these sets of conveying characteristics will show that as the pipeline bore increases, the air flow rate required increases, and the solids loading ratio and conveying line pressure drop decrease for a given material flow rate. This is shown in Tables 14.1 and 14.2 where a comparison is made of these parameters for the conveying of the cement at 40 tonne/h and the potassium sulphate at 12 tonne/h. In each case the data is based on an air flow rate 20 per cent greater than the minimum value corresponding to the given material flow rate. In both cases this represents a satisfactory margin for design purposes.

Table 14.1 Influence of pipeline bore on air requirements and conveying parameters for the pneumatic conveying of cement at 40 tonne/h over a distance of 95 m

Pipe bore (mm)	Air required		Solids loading ratio (–)	Conveying air velocity (m/s)		Power required (kW)
	Pressure (bar gauge)	Flow rate (kg/s)		Inlet	Exit	
81	3.00	0.102	109	4.2	16.8	23
100	2.20	0.128	87	4.3	13.5	24
125	1.61	0.207	54	5.4	14.0	32
150	1.22	0.405	27	8.6	19.0	53
200	0.73	0.785	14	12.0	20.7	70

Table 14.2 Influence of pipeline bore on air requirements and conveying parameters for the pneumatic conveying of potassium sulphate at 12 tonne/h over a distance of 95 m

Pipe bore (mm)	Air required		Solids loading ratio (–)	Conveying air velocity (m/s)		Power required (kW)
	Pressure bar gauge	Flow rate (kg/s)		Inlet	Exit	
81	3.20	0.41	8.2	16.3	67.7	96
100	1.93	0.47	7.1	17.1	49.6	83
125	1.26	0.57	5.8	17.2	38.5	76
150	0.90	0.71	4.7	17.6	33.3	74
200	0.51	1.03	3.2	18.0	27.2	69

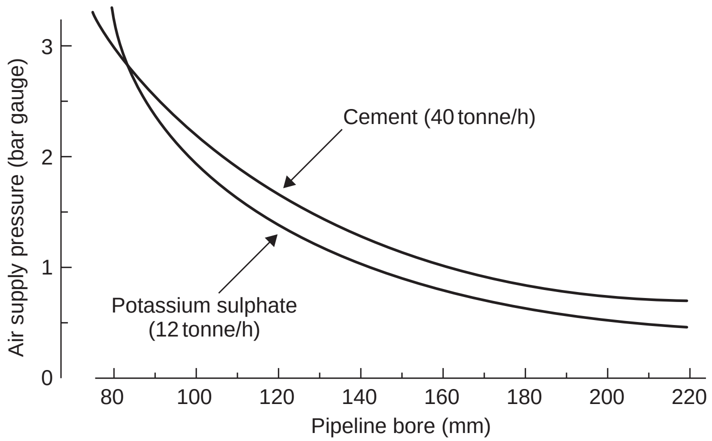


Figure 14.11 Influence of pipeline bore on air supply pressure for given parameters.

These tables show that there is a wide range of air supply and pipeline bore combinations that are capable of meeting any given duty for a material. For the cement there is an almost eightfold increase in air flow rate required, with a corresponding reduction in solids loading ratio; and for the potassium sulphate there is a sixfold reduction in air supply pressure, over the range of pipe bores considered.

14.4.3.2.1 Air supply pressure

To illustrate the point with regard to the influence of pipeline bore on air supply pressure, the data from Tables 14.1 and 14.2 is presented graphically in Figure 14.11.

With a wide range of pipeline bore and air supply pressure combinations being capable of achieving a given material flow rate, the obvious question is which pipeline bore or air supply pressure results in the most economical design? Plant capital costs could vary considerably, for with different pipeline bore and air supply pressures there are corresponding differences in feeder types, filtration requirements and air mover types, apart from widely different pipeline costs, and so a major case study would need to be carried out. Power requirements, and hence operating costs, however, are largely dependent upon the air mover specification and so these can be determined quite easily by using Equation (6.6).

14.4.3.2.2 Power requirements

The approximate power requirements for the cases considered are given in Tables 14.1 and 14.2, and they are presented graphically in Figure 14.12. In most cases the power required for the air mover represents the major part of the total system power requirement, although for screw pumps a major allowance must also be made for the screw drive. Figure 14.12 presents an interesting trend for both of the materials considered. For the cement the smallest bore pipeline is clearly the best, but for the potassium sulphate it is the largest bore pipeline.

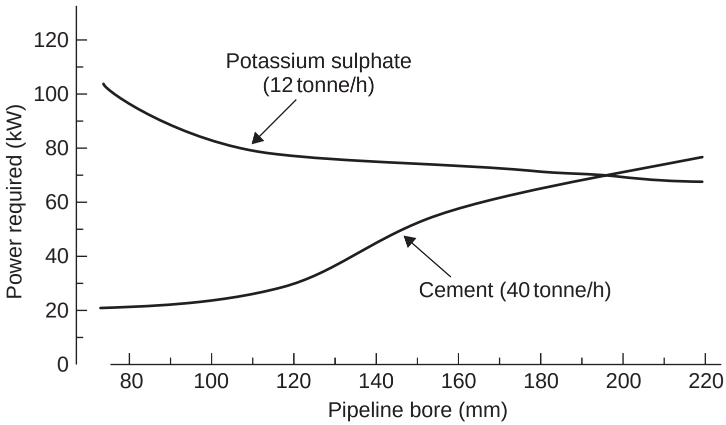


Figure 14.12 Influence of pipeline bore on power requirements for given parameters.

For the potassium sulphate the decrease in power requirements with increase in pipeline bore can be explained in terms of the decrease in velocity through the pipeline. With a conveying line inlet air pressure of 3.2 bar gauge the conveying line exit air velocity will be about 68 m/s, and this reduces to 27 m/s with the much lower air supply pressure required for the 200 mm bore pipeline. Pressure drop increases significantly with increase in conveying air velocity and so the pipeline with the lowest velocity profile will generally give the lowest power requirement for a material such as potassium sulphate.

For the cement the increase in power with increase in pipeline bore can also be explained in terms of velocity profiles, but in this case it is values of conveying line inlet air velocity that are relevant. Since cement is capable of being conveyed in dense phase, the relationship between minimum velocity and solids loading ratio dictates. In an 81 mm bore pipeline the inlet velocity is only 4.2 m/s, since the solids loading ratio is 109. In the 200 mm bore pipeline the solids loading ratio is reduced to 14 and so the inlet air velocity is 12.0 m/s.

14.5 Pipeline bends

The influence of pipeline bends has long been an issue of some considerable doubt. This is mainly due to the problems of obtaining the necessary data, as discussed in Section 5.2.4.3. In the notes on pipeline bends in Section 11.6.4, actual pressure drop values were presented, in the form of conveying characteristics in Figure 11.16 and this showed a range of values from 50 to 170 m bar per bend. Ideally an equivalent length, in terms of horizontal pipeline, is required for pipeline bends.

14.5.1 Equivalent length

Such an analysis was carried out specifically for the Pneumatic Conveying Design Guide. Two pipelines and two different materials were used in a major programme of

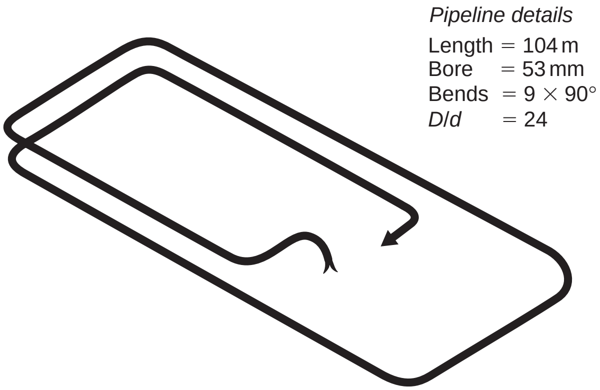


Figure 14.13 Sketch of pipeline no. 11.

tests. The two pipelines used were of approximately the same length but contained a different number of bends. By this means the sets of conveying characteristics produced could be compared and the differences between them could reasonably be attributed to the difference in the number of bends.

One of the pipelines used was that presented in Figure 13.4 (pipeline no. 7). This was 101 m long, of 53 mm bore and contained seventeen 90° bends. The other pipeline used was 104 m long, also of 53 mm bore but contained only nine 90° bends and is shown here as pipeline no. 11 in Figure 14.13 for reference. All of the bends in the two pipelines were of the same geometry, having a bend diameter, D, to pipe bore, d, ratio of 24:1, and all the bends were preceded by a sufficient length of straight horizontal pipeline to ensure that the particles had been accelerated to their terminal velocity before impact with the bend.

Complete sets of conveying characteristics were obtained for both barytes and cement through pipeline no. 7 (101 m long with 17 bends) and through pipeline no. 12 (104 m long with 9 bends). The two sets of conveying characteristics obtained with the barytes are presented in Figure 14.4. Very similar sets of conveying characteristics were obtained with the cement.

The same axes have been used for the two sets of data and it will be seen that very much higher values of conveying line pressure drop had to be used for the pipeline with 17 bends to achieve the material flow rates obtained with the pipeline having only nine bends. For identical conveying conditions the flow rate through the line with nine bends was between 18 and 58 per cent greater than that through the line with 17 bends.

14.5.1.1 Method of analysis

To show the difference between the two sets of data in Figure 14.4 the ratio of the mass flow rates is presented in Figure 14.15a. A grid was constructed on Figure 14.14a of constant pressure drop, spaced at 0.4 bar, and constant air flow rate, spaced at 0.01 kg/s. The values plotted represent the ratio of the mass flow rate of barytes in the pipeline

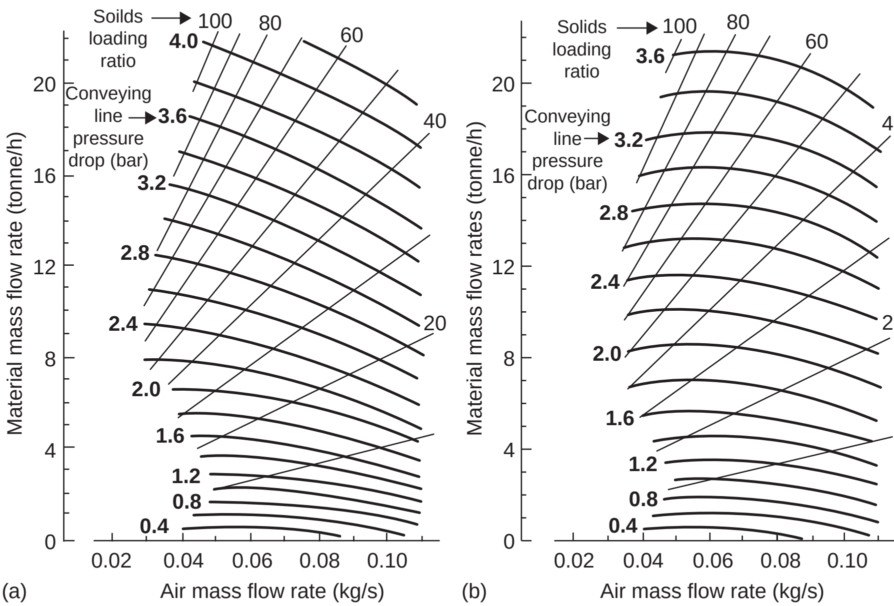


Figure 14.14 Conveying characteristics for barytes:through (a) pipeline no. 7 and (b) pipeline no. 11.

with 17 bends to that of the mass flow rate of barytes in the pipeline with nine bends. The slope of the lines drawn, of constant value of the ratio through the data, is very similar to those of constant conveying air velocity. With the ratio decreasing from about 0.85 at low velocity to 0.65 at high velocity the influence of the bends, and also that of velocity, clearly have a very significant influence on the conveying capability of pipelines [3].

In order to assign a value of equivalent length to the bends Equation (14.3) can be used for this purpose:

$$\dot{m}_{p1}\, L_{e1} = \dot{m}_{p2} L_{e2} = \mathit{Constant} \tag{14.3*}$$

The equivalent length of pipeline no. 7 (Figure 13.4) will be:

$$L_{e1} = (101 + 17b)$$

where b is the equivalent length of straight horizontal pipeline per bend (m).
The equivalent length of pipeline no. 11 (Figure 14.13) will be

$$L_{e2} = (104 + 9b)$$

Thus:

$$\dot{m}_{p1}(101 + 9b) = \dot{m}_{p2}(104 + 17b) \tag{14.9}$$

*Reintroduced here.

With the mass flow rate ratios plotted on Figure 14.15a, Equation (14.9) can be solved for every grid point. This was done and a number of correlations were tried but the only one that produced a consistent relationship was in terms of conveying line inlet air velocity. This is presented in Figure 14.15b. A very similar relationship was derived for the cement and a mean of the two sets of data is presented in Figure 14.16. This shows that for low velocity, dense phase conveying, the equivalent length of bends is very low, being only about 2 m per bend at 4 m/s, but rises considerably for dilute phase suspension flow, being about 16 m per bend at 15 m/s [3].

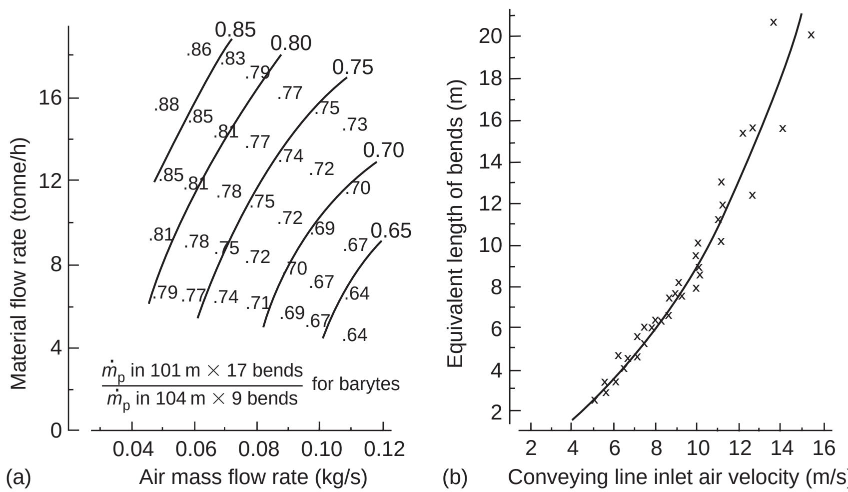


Figure 14.15 Analysis of conveying data for barytes: (a) ratio of material mass flow rates and (b) equivalent length of bends.

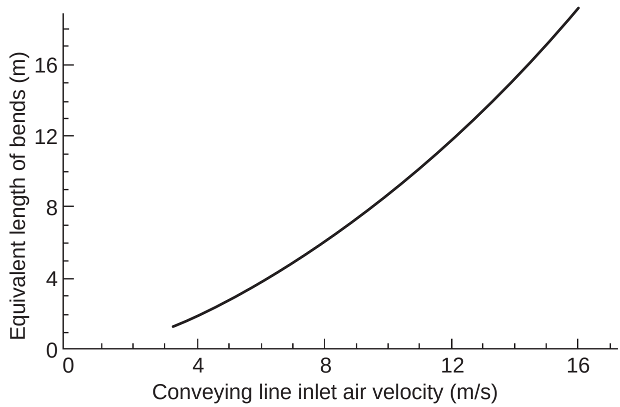


Figure 14.16 Equivalent horizontal length of bends for 90° bends of 53 mm bore with a *D*/*d* of 24.

14.5.1.1.1 Bend location

This method of analysis is very straightforward and can be undertaken with little in the way of instrumentation. One problem that it cannot solve, however, is that of whether the location of the bend in the pipeline is important. The correlation presented in Figure 14.14b is in terms of the conveying line inlet air velocity and it was not possible to detect any influence of position along the length of the pipeline.

The test work was undertaken with single bore pipelines and so the velocity will increase from one bend to the next. Conveying line pressure drops of up to 4 bar were employed and so in some tests there will have been a fivefold increase in velocity from the start to the end of the pipeline. It might be expected that the pressure drop across a bend would depend to a large extent on the velocity at the bend itself. Pressure drop, however, is due to re-acceleration of the particles, as discussed in Section 5.2.4.3 and so it is the difference in velocity across the bend that is probably more important.

14.5.1.2 Pressure drop data

An alternative form of this data for the barytes, but derived in the form of actual values of pressure drop was presented in Figure 11.16 and this is reproduced here in Figure 14.17 for comparison. This data does not identify bend location either and assumes that the pressure drop for each bend in the pipeline is the same. A similar wide range of values, from 50 mbar/bend for dense phase to 170 mbar/bend for dilute phase conveying were obtained. The significance of this is that if there are six bends in a pipeline and the pressure loss is 170 mbar/bend, then a pressure drop of one bar is attributed simply to the convenience of pipeline routing. The necessity of each bend in a pipeline, therefore, should be given serious consideration.

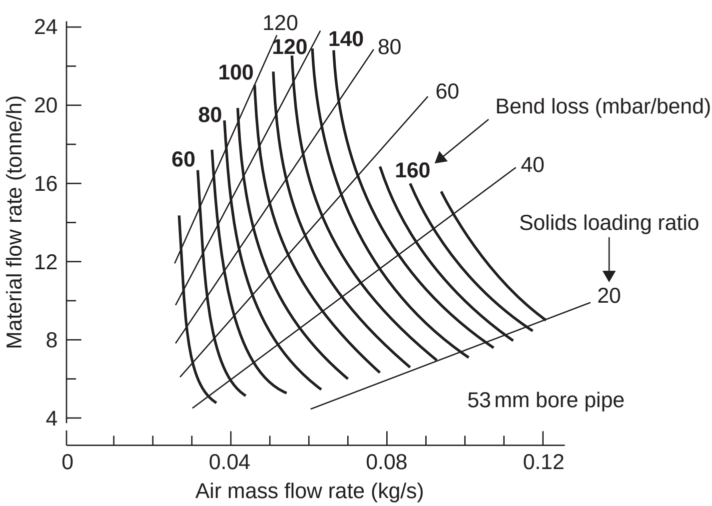


Figure 14.17 Influence of conveying conditions on bend losses for barytes.

14.5.1.2.1 Classical analysis

The classical method of determining the pressure drop across a bend in a pipeline is to use pressure transducers along the length of the pipeline as discussed in Section 5.2.4.3.

Typical of the method employed, analysis and data obtained are the results presented in Figure 14.18 [1]. The material conveyed here was a wheat flour, conveyed at a solids loading ratio of about thirty in a 53 mm bore pipeline. The bend had a *D*/*d* ratio of about 5:1. The pressure profile indicated by the data points clearly shows the pressure drop due to the re-acceleration of the particles that occurs in the straight length of pipeline following the bend. The pressure drop attributed to the bend is determined as indicated in Figure 14.18.

With pressure transducers in the straight length of pipeline approaching the bend it is possible to determine the pressure gradient in this section of pipeline. With this recorded at about 5.6 mbar/bend, and the pressure drop across the bend assessed at about 130 mbar, the equivalent length of the bend comes to approximately 23 m. The conveying line inlet air velocity to the pipeline was about 16 m/s and so although the data point appears to fit well on Figure 14.17, the equivalent length is very much greater than that predicted in Figure 14.16.

It is believed that the increase in equivalent length, and hence pressure drop, is due to the material. It has already been shown that the conveying characteristics for different materials can vary significantly. This has been for the total pipeline and so a major element of this difference may well be due to the bends. From Figure 14.18 it will be seen that much of the energy loss is due to re-accelerating the particles after leaving the bend. The coefficient of restitution between the particles and the bend walls must play a part. Cement and barytes are relatively hard materials, while flour is very much softer. The flour, therefore, will probably have a lower coefficient of restitution and hence have a lower exit velocity from bends, which will result in a higher pressure drop. This aspect of pipeline performance is considered further when pipeline material is considered later in this chapter.

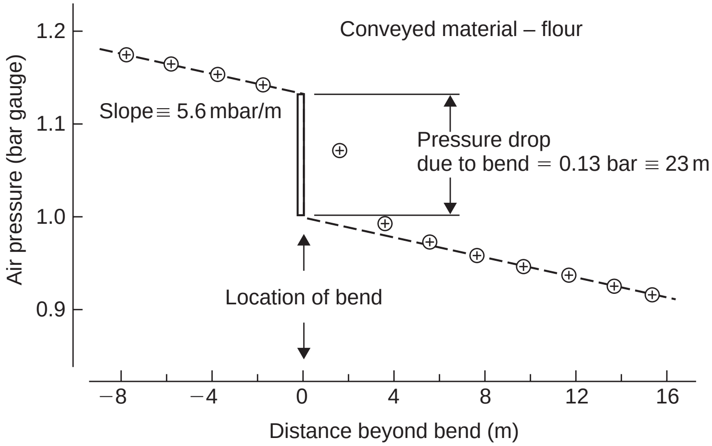


Figure 14.18 Pressure profile in straight pipeline either side of a bend.

14.5.2 Bend geometry

The bends for which the data was presented in Figures 14.16 and 14.17 had a bend diameter to pipe bore ratio of 24:1. Bends having a wide range of geometries, however, are employed in conveying system pipelines, as illustrated earlier in Figure 5.1. Short radius bends and elbows are cheaper to install than long radius bends, take up less space and are easier to support. To combat erosive wear, however, long radius bends are often employed.

Figure 14.16 shows that the equivalent resistance for each bend varies from about 2 m in low velocity, dense phase conveying, to more than 20 m in high velocity, dilute phase flow. In the scaling procedure for conveying distance the model presented in Equation (14.4) has been found to work well for pipeline combinations of both distance and bends, if the total equivalent length of the pipeline is used.

14.5.2.1 Air only relationships

The influence of bend geometry on pressure drop with air only has been well documented. Representative data was presented in Figure 10.6 and is reproduced for reference in Figure 14.19a. This would tend to indicate that for radiused bends there is little influence of bend geometry on pressure loss for a very wide range of *D*/*d* ratios. It is only with very short radius bends, below a *D*/*d* ratio of about 3:1, that there is any significant change. Below this value pressure prop would appear to increase considerably. Modelling procedures for single phase flow for bends was considered with Equation (10.8), and in terms of an equivalent length with Equation (10.9).

14.5.2.2 Conveying data

In order to assess the relative effects of bend geometry on pressure drop, a pipeline was specially built with a double loop in which the bends at the corners could be easily

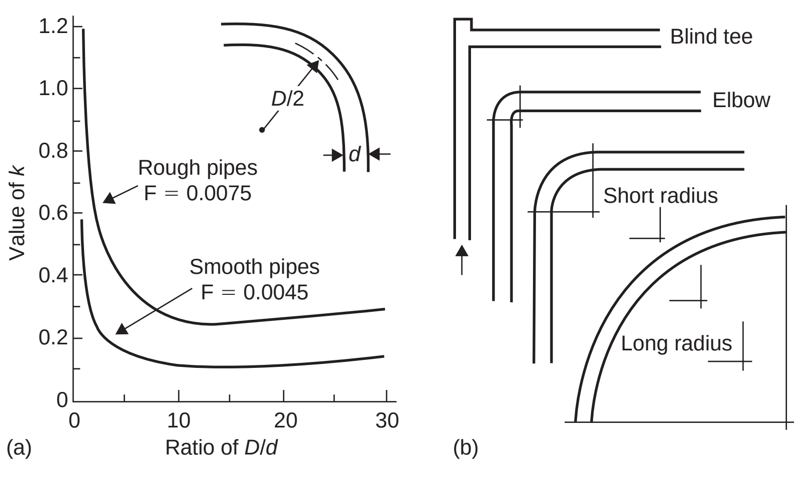


Figure 14.19 Data on 90° bends: (a) head loss for radiused bends and (b) sketch of bends tested.

replaced [2]. The pipeline was about 50 m long, of 53 mm bore and contained a total of eleven 90° bends.

Seven of the bends were changed at a time and tests were carried out with sets of long radius bends, ($D/d = 24$), short radius bends ($D/d = 6$), elbows ($D/d = 2$) and blind tees ($D/d = 0$). A proportioned sketch of the bends is given in Figure 14.19b and a sketch of the pipeline employed is given in Figure 14.20. Fine fly ash was used as the conveyed material so that a very wide range of conveying conditions could be examined.

A full set of conveying characteristics was obtained for each of the four sets of bends tested in this common pipeline. Two of the sets of conveying characteristics obtained are shown in Figure 14.21. They are for the pipeline with seven long radius bends, which are presented in Figure 14.21a, and for the pipeline with seven blind tees, which are shown in Figure 14.21b.

It will be seen from these conveying characteristics that the tests were carried out over a very wide range of conveying conditions, with solids loading ratios up to 120 and conveying line inlet air velocities down to about 4 m/s. The fly ash was conveyed over a similar wide range of conveying conditions with each of the other two sets of bends tested. With four sets of conveying characteristics, for the same material conveyed through the same pipeline, it was possible to analyse the relative influence of the different bend sets tested [4].

A characteristic of fine fly ash, from previous conveying data, has been the very steep slope of the constant pressure drop lines, and this will be observed in both sets of data included in Figure 14.21. Although the only difference between the two sets of conveying data in Figure 14.21 is the change in geometry of seven of the bends, the difference in conveying performance is quite dramatic.

14.5.2.3 Comparison of performance

To illustrate the difference: if a pressure drop of 1.8 bar and an air flow rate of 0.05 kg/s are considered it will be seen that 10 tonne/h of fly ash will be conveyed through the pipeline with the seven blind tees, and 20 tonne/h will be achieved through the same pipeline with seven long radius bends. This is a 100 per cent improvement in

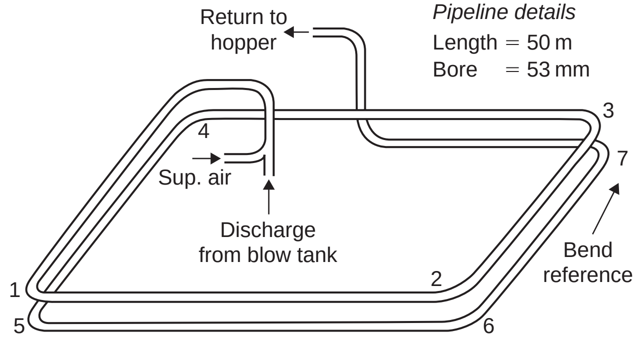


Figure 14.20 Sketch of pipeline no. 12.

performance for no change in power input, no change in conveying distance, and only seven of the eleven bends in the pipeline changed.

To provide a global comparison between the sets of data, rectangular grids were drawn on the sets of conveying characteristics and the pressure drop noted for every grid point. The comparison was based on the pressure drop required to achieve a specified material flow rate for a given air flow rate. This comparison was undertaken over the entire range of conveying conditions.

A comparison of the blind tees and long radius bends is given in Figure 14.22a. It will be seen from this that the pressure drop in the line with the blind tees was about 40 per cent greater than that for the line with the long radius bends. This increase in pressure drop is due entirely to the additional resistance created by changing seven long radius bends for blind tees, since everything else associated with the two pipelines is common. In terms of energy considerations, therefore, blind tees could not be recommended for conveying system lines [4].

A similar comparison for the elbows ($D/d = 2$) and long radius bends showed that when the conveying line pressure drop was below about 1.2 bar the elbows were slightly better than the long radius bends, with a maximum improvement of about 10 per cent. Above 1.2 bar the situation was revered and the conveying line pressure drop for the elbows was up to about 20 per cent greater.

A comparison of the short radius ($D/d = 6$) and long radius bends is given in Figure 14.22b. This shows that the short radius bends are clearly the best of those tested in terms of minimum pressure drop. Only at the very highest material flow rates are the long radius bends slightly better.

It must be realized that the pressure drop ratios given in the data presented in Figure 14.22 are for the total pipeline system and not just the set of seven bends.

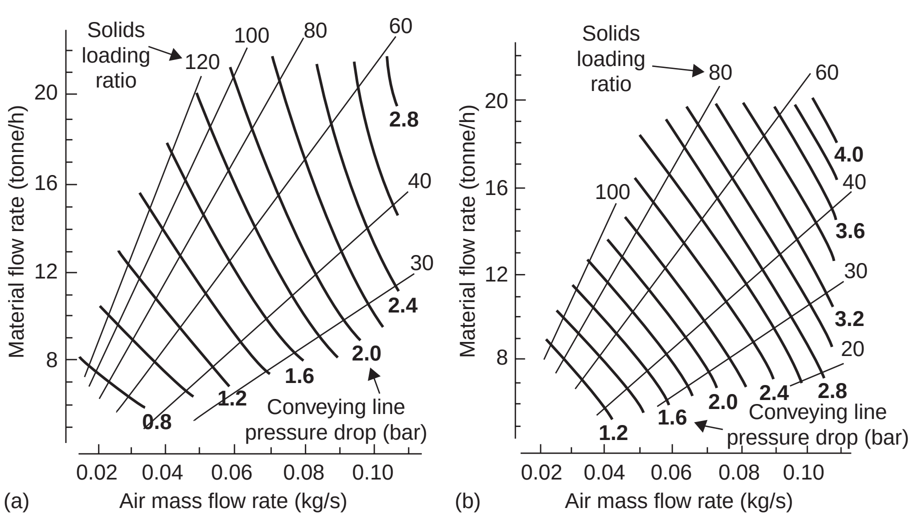


Figure 14.21 Conveying characteristics for fly ash in pipeline no. 12. with: (a) seven long radius bends and (b) seven blind tees.

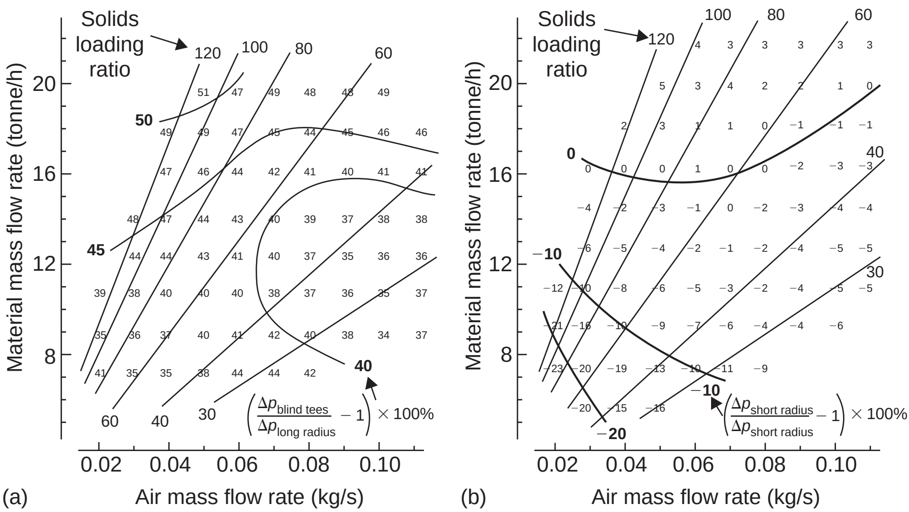


Figure 14.22 Comparison of conveying performance for different bend geometries: (a) blind tees with long radius bends and (b) short radius with long radius bends.

The pressure drop for the horizontal pipeline and the connecting bends will be approximately constant, and so the pressure drop ratios for the seven bends alone will be significantly higher. In terms of bends alone, therefore, the data presented for air alone in Figure 14.19a appears to hold reasonably well for the conveying of material also.

14.6 Vertical pipelines

At least one section of vertically up pipeline will feature in the majority of pipeline systems, if only to elevate the material into a reception vessel at the end of the pipeline. In some cases the length of the vertically up section of pipeline can be 500 m or more, as in mining and shaft sinking operations. Vertically down sections may also occur if the pipeline is routed around some obstacle in its path. In the mining industry, materials such as fly ash and cement are often conveyed vertically down mine shafts to underground workings. In order to determine the influence of vertical sections in a pipeline it is generally necessary to use pressure tappings along the length of the section to be considered, as discussed in Section 10.6. By this means, data can be obtained for the vertical sections in isolation from any bends and the rest of the pipeline [5–7].

14.6.1 Conveying vertically up

In the majority of pneumatic conveying system pipelines the proportion of horizontal conveying is very much greater than that of vertical conveying. A scaling parameter, therefore, is required in terms of an equivalent length of straight horizontal pipeline.

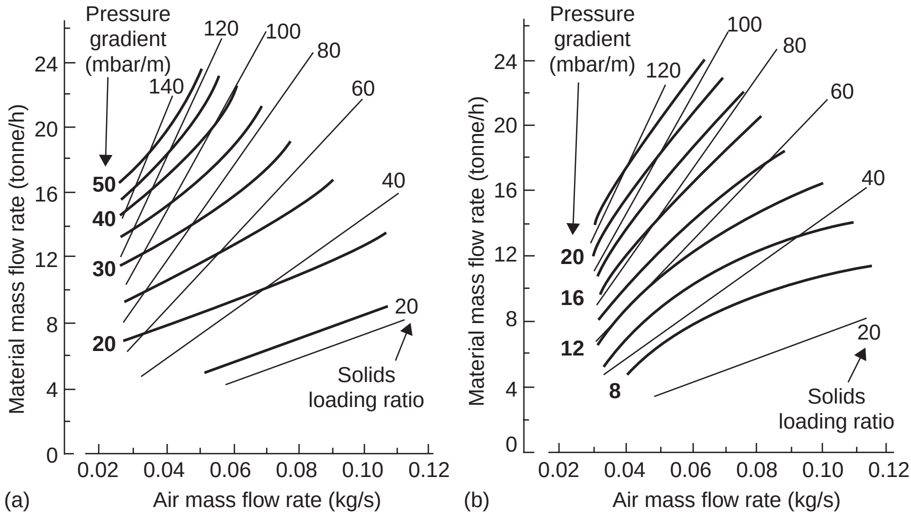


Figure 14.23 Pressure gradient data for barytes conveyed through 53 mm bore pipelines for: (a) vertical flow and (b) horizontal flow.

14.6.1.1 Scaling parameter

Data for the vertically upward conveying of barytes in a 53 mm bore pipeline is presented in Figure 14.23a. Similar data for both fly ash and cement, conveyed vertically upwards, was presented earlier in Figures 11.13 and 11.14. These are all conveying characteristics for the material in terms of pressure gradient. Similar data for the barytes conveyed in a horizontal pipeline of 53 mm bore was presented in Figure 11.15. This is now reproduced in Figure 14.23b to be alongside the vertical data for bartyes so that a direct visual comparison of the two can be made.

With these two sets of data in Figure 14.23, a scaling parameter can be determined simply by evaluating the ratio between the two sets of data. In order to provide the necessary comparison of the vertical and horizontal 53 mm bore pipeline conveying characteristics, a rectangular grid was placed on both sets of curves and pressure gradient values were noted at every grid point.

In Figure 14.24a the value of the ratios of the vertical line pressure gradient divided by the horizontal line pressure gradient, determined for every grid point, are presented.

They are also plotted on a graph of material flow rate against air mass flow rate and, from the various lines of constant solids loading ratio superimposed, it can be seen that the relationship obtained covers a very wide range of conveying conditions. A similar analysis was carried out with a fine grade of fly ash, which is presented in Figure 14.24b, and this produced almost identical results.

It will be noticed that there is little variation in this ratio from minimum to maximum values of conveying air velocity, and from minimum to maximum values of solids loading ratio. The only deviation from a mean value of about 2.0 would appear to be at the two extreme limits of the pressure gradient curves, where the data is least reliable.

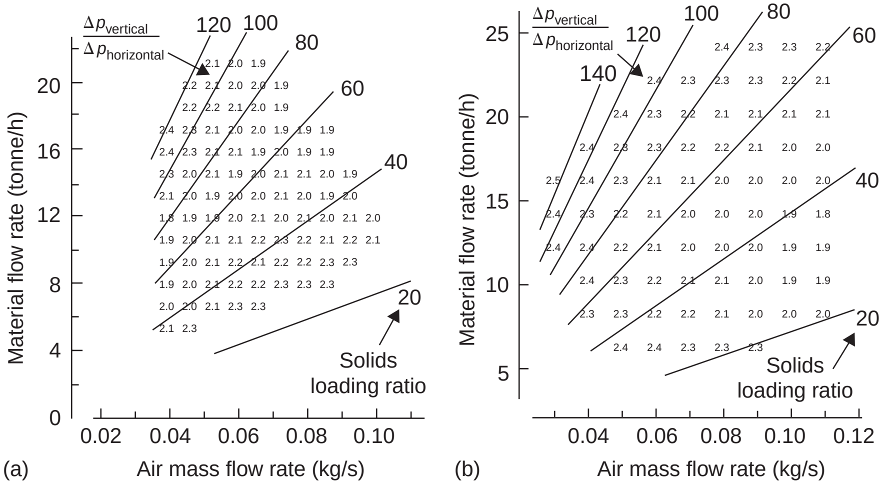


Figure 14.24 Ratio of vertically up to horizontal conveying line pressure gradient data for (a) barytes (for consistency) and (b) fine grade of fly ash.

This, therefore, shows that the pressure drop in vertically up conveying is approximately double that in horizontal conveying, for given conveying conditions, over the entire range of conveying conditions. The scaling parameter, therefore, for vertically upward conveying is simply two, so that the length of vertically upward sections of pipeline should be doubled to give the equivalent length of straight horizontal pipeline.

14.6.2 Conveying vertically down

Similar data for the conveying of barytes vertically down in a 53 mm bore pipeline is presented in Figure 14.25. Similar data for a fine grade of fly ash was shown earlier in Figure 11.13a. These both show a very much more complex pattern, with a pressure drop occurring for dilute phase flows and a pressure recovery for dense phase flows.

For short vertically down sections of pipe, in an otherwise long pipeline, it would be suggested that the length of such sections could be disregarded, if they are no more than a few metres, although connecting bends must always be included. If the vertically down section of pipeline is of any significant length, it must be taken into account. If the material is conveyed in dilute phase there will be a pressure drop, although of a lower value than for horizontal flow. If the material is conveyed in dense phase flow there could be a significant pressure recovery and it would be essential to take this into account in the pipeline design.

14.6.3 Inclined pipelines

The recommendation with regard to pipeline orientation is generally that pipelines should run either vertically up or horizontal, and that inclined sections of pipeline should

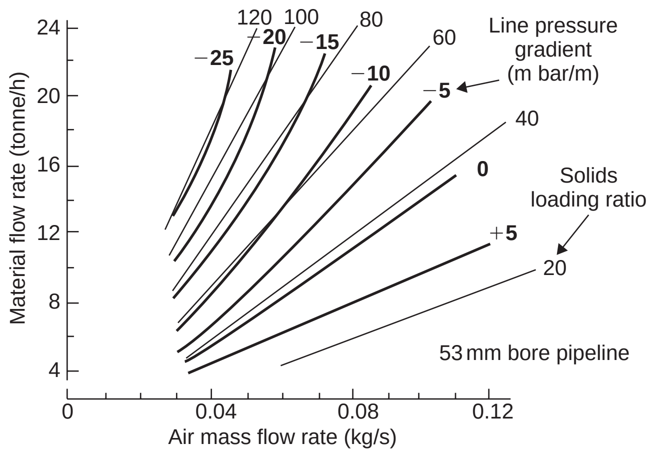


Figure 14.25 Pressure gradient data for the vertically downward flow of barytes in a 53-mm bore pipeline.

be avoided, even if their use means that the pipeline length is reduced. Two separate factors have to be taken into account in the use of inclined sections of pipeline. One is the influence on the minimum value of conveying air velocity and the other is the effect on conveying line pressure drop.

14.6.3.1 Minimum conveying air velocity

The vast majority of data presented here has been for horizontal pipeline, with particular concern for dilute phase suspension flow. For a material with a minimum conveying air velocity of 15 m/s for horizontal flow, the corresponding minimum value for flow in a vertically up pipeline will be lower. In the vast majority of pipelines it is just not practically possible to benefit from this, since material is generally fed into horizontal sections of pipeline. In addition, vertical sections of pipeline are short in comparison to horizontal pipeline, and the velocity of the air automatically increases along the length of the pipeline as the pressure reduces.

In horizontal pipeline, as the conveying air velocity is reduced, particles begin to settle on the bottom of the pipeline and form a layer. This settled layer will reduce the effective cross sectional area of the pipeline and so increase the conveying air velocity, which can lead to a degree of stability. There will, however, with a further reduction in velocity, be a tendency to duning of the layer and if this is swept up to fill the pipe bore then the pipeline is likely to block, particularly at a bend.

In vertical pipelines, particles will tend to drop out of suspension in the boundary layer near to the wall first, where the conveying air velocity is lowest. These particles, however, will initially be re-entrained in the upward flow since there is no surface on which they can settle.

In pipeline inclined upwards, saltating particles will drop to the bottom of the pipeline. Due to the incline they will tend to be more mobile and so form dunes more readily. As a consequence the minimum conveying air velocity for pipeline inclined

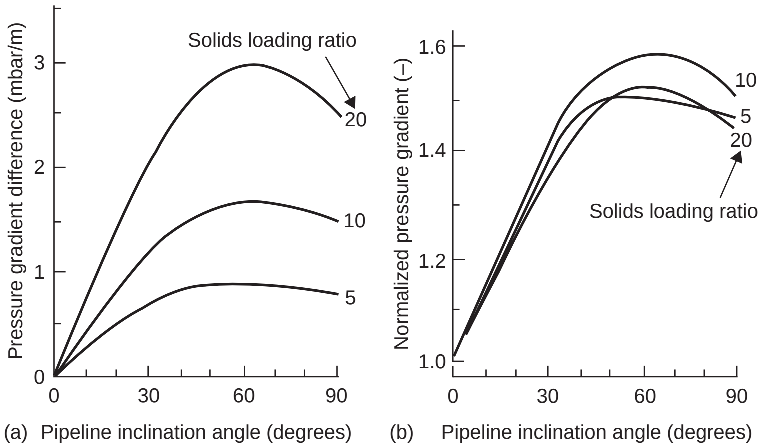


Figure 14.26 Pressure gradient data for pipeline inclined upwards: (a) normalized pressure gradient and (b) pressure gradient difference.

upwards tends to be higher than that for horizontal pipeline. Such an inclined section well along the length of a pipeline is not likely to be a problem in this respect since the conveying air velocity will have increased to a much higher velocity. This is not so much of a problem in pipelines that slope downwards.

14.6.3.2 Pipeline pressure gradient

The pressure gradient in vertically upward flow is significantly greater than that for horizontal pipeline, as was illustrated in Figures 14.23 and 14.24. A colleague of the author undertook research into the influence of pipeline inclination and some of his data on this issue is presented in Figure 14.26 [8].

The work was undertaken with a 100 m long pipeline of 81 mm bore, having a central section 8 m long that could be conveniently adjusted to provide inclinations ranging from −20° to +90°. The test work reported was undertaken with 3 mm polymer pellets. In Figure 14.26a the results are presented in terms of the difference between the total pressure gradient for an inclined pipe and that for a horizontal pipe, while in Figure 14.26b the results are in terms of a normalized pressure gradient, which is the ratio of the pressure gradient for a particular angle of inclination divided by that for the horizontal. Solids loading ratios of 5, 10 and 20 were considered. This shows quite clearly that pipelines inclined upwards should be avoided if at all possible.

14.7 Pipeline material

In nearly all the work presented so far only steel pipelines have been used and considered. Other pipeline materials are sometimes used, and in particular rubber hose. Conveying data on alternative pipeline materials, however, is very limited. The use of rubber hose and some pressure drop data for the material was presented in Section 5.4.

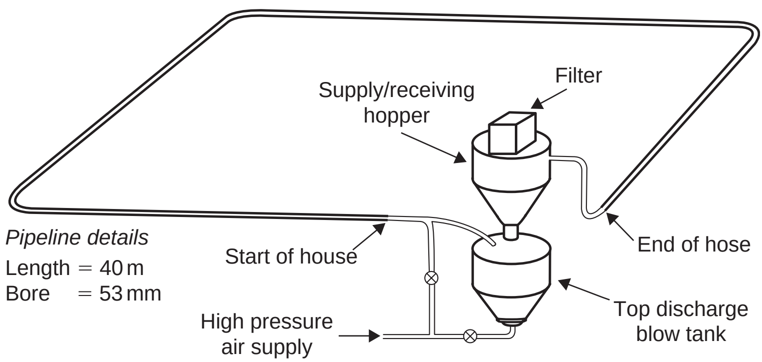


Figure 14.27 Sketch of pipeline no. 14.

14.7.1 Rubber hose

In many applications rubber hoses are used in pneumatic conveying lines. They find wide use in transport situations where a rigid line is not practicable. This is particularly the case in the loading and off-loading of ships. In order to determine the influence of rubber hose in pneumatic conveying, a number of programmes of tests were carried out with several fine materials conveyed over a distance of 40 m through a 53 mm bore pipeline [9, 10]. A sketch of the pipeline and high pressure blow tank test facility used is given in Figure 14.27.

In one programme barytes was conveyed and in another an oil well grade of cement was tested. They were first conveyed through pipeline no. 14, comprising 40 m of steel pipe and five 90° bends. For the second part of the programme 35 m of the steel pipeline was replaced by rubber hose, with the hose strapped to the steel pipeline to replicate the routing and the bend geometries over this length, in order to produce an identical pipeline. The location of the 35 m of rubber hose in the 40 m long pipeline is indicated in Figure 14.27.

The results for the barytes conveyed through the two pipelines are given in Figure 14.28. These are complete conveying characteristics for the material conveyed over as wide a range of conveying conditions as could be achieved. High pressure air was employed and as the pipeline was relatively short, solids loading ratios of up to 150 were obtained with the material.

With the two sets of data presented together, and with the same set of axes, direct visual comparison is possible. Despite the fact that the two pipelines are identical with respect to both conveying distance and the number and geometry of bends, significant differences between the two sets of conveying characteristics will be seen. Identical data for the oil well cement conveyed through these two pipelines is presented in Figure 14.29.

A comparison of the conveying performance for the two materials in the two pipelines, with respect to pipeline material, is given in Figure 14.30. The comparison is based on the ratio of the conveying line pressure drop for the hose divided by that for the steel pipeline, to achieve the same material flow rate. A rectangular grid was placed on each of the sets of conveying characteristics for the purpose.

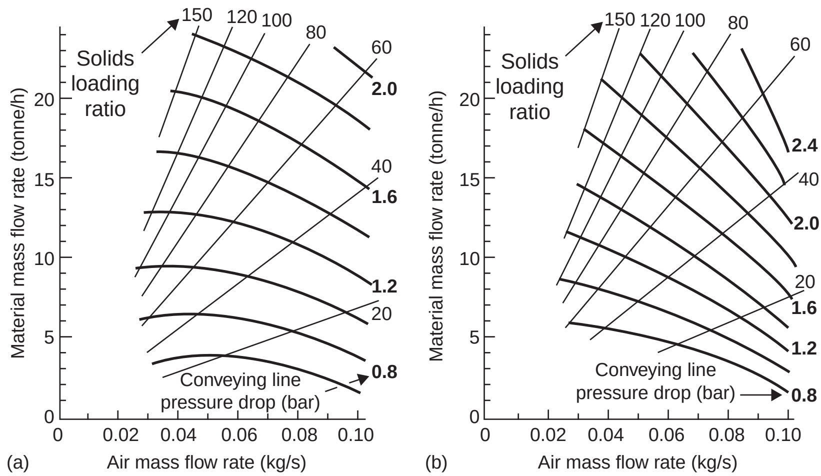


Figure 14.28 Conveying characteristics for barytes conveyed through pipeline no. 14 for: (a) steel pipeline and (b) rubber hose line.

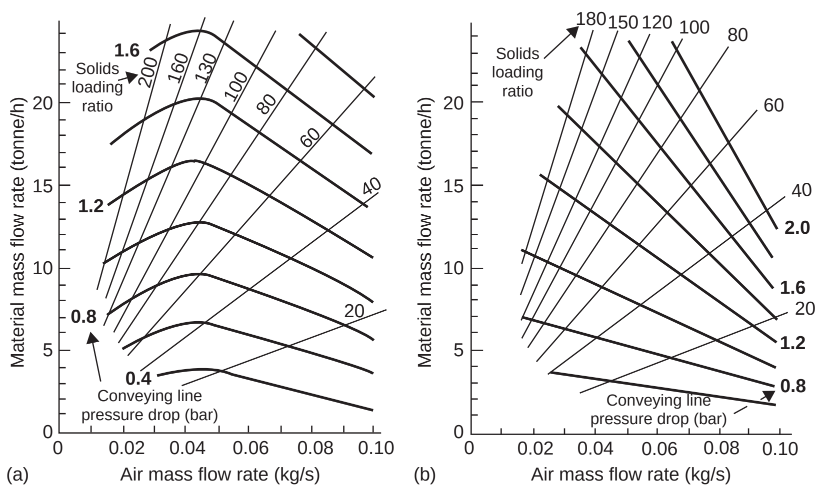


Figure 14.29 Conveying characteristics for oil well cement conveyed through pipeline no. 14 for: (a) steel pipeline and (b) rubber hose line.

14.7.2 Comparison with steel

From Figure 14.29 it can be seen that in very low velocity dense phase flow the resistance of the rubber hose is slightly lower than that of the steel pipeline. With high velocity, dilute phase conveying, however, the resistance of the rubber hose can be as much as 50 per cent greater than that of the steel pipeline. It is believed that the increase in pressure drop is due to the difference in coefficient of restitution between

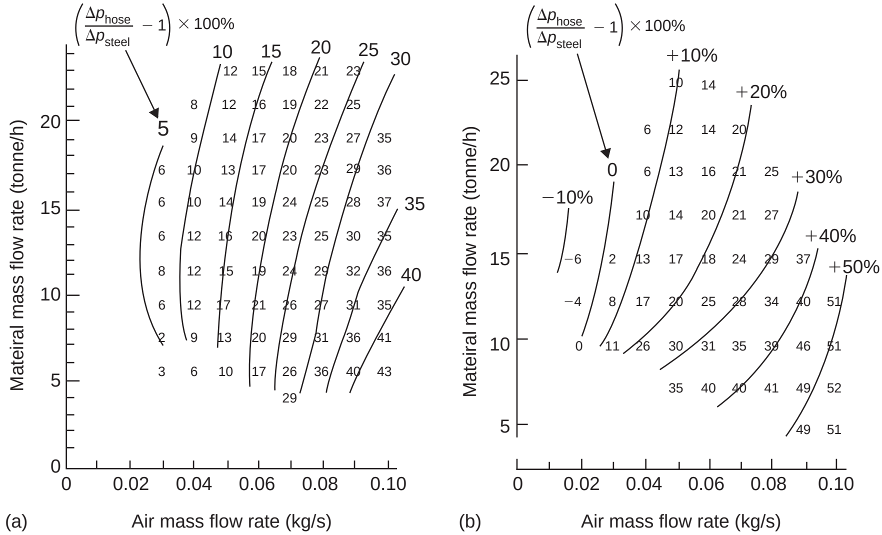


Figure 14.30 Comparison of conveying performance of steel pipeline and rubber hose for (a) barytes and (b) oil well cement.

steel and rubber. The rubber will absorb the energy of particles impacting and so the particles will rebound after impact at a much lower velocity. These particles will then have to be re-accelerated back to their terminal velocity, and it is this process that absorbs more energy with increase in velocity.

The results obtained with both the barytes and oil well and cement are very similar. The recommendation from this, therefore, is that, when and wherever possible, flexible rubber hoses should be used as close as possible to the start of a conveying line in order to reduce the overall pipeline resistance by ensuring that the hose is used at the low velocity end of the line.

14.8 Stepped pipelines

The design and performance of stepped pipeline systems is another area where little information is available. If a high pressure air supply is used for a pneumatic conveying system a high exit velocity will result if a single bore pipeline is used. Apart from adding significantly to problems of erosive wear if the material is abrasive, and to particle degradation if the material is friable, the unnecessarily high velocity towards the end of the pipeline will magnify the flow resistance and thereby restrict the throughput.

If the pipeline is stepped to a larger diameter part way along its length, the velocity in the next section will be reduced. It is clearly necessary to ensure that the new diameter and position of the step are such that the conveying air velocity does not fall below the minimum value for the material otherwise the pipeline is liable to block. Several such steps may be necessary if a very high air supply pressure is to be used. These points, and others such as pipeline purging, were considered earlier with Figures 9.11–9.16, in relation to both positive pressure and vacuum conveying systems. In this chapter the potential influence of stepping a pipeline on system performance is considered.

14.8.1 Conveying performance data

In order to provide some information on the possible benefits of stepped pipeline systems, in terms of increased material flow rate, a major programme of tests was carried out. A 115 m long pipeline of 53 mm bore and incorporating ten 90° bends was built and a sketch of this is given in Figure 14.31 for reference [11].

It was proposed that tests should be carried out in the single bore pipeline, then with the pipeline stepped about half way to 69 mm bore, and finally with the last quarter of the pipeline stepped to 81 mm bore. The stepping of the pipeline was done by simply sleeving one pipeline inside the other and welding to make it pressure tight as shown in Figure 14.32. This was just for convenience as the diameters, with relatively small bore lines, were fairly close. With larger bore pipelines it would be recommended that expansion sections should be fitted to join pipelines, as a degree of energy recovery will be obtained with these at the expansion point (see Figure 10.9).

The material used for testing purposes was a fine grade of fly ash, since it is capable of being conveyed over a very wide range of flow conditions. The conveying characteristics for the fly ash in the above single bore pipeline are presented in Figure 14.33a.

From this it will be seen that the material was conveyed at solids loading ratios of up to 180, with conveying line pressure drop values of up to 3.2 bar, and over a very wide range of air flow rates. These conveying characteristics provide the reference data against which alternative stepped pipeline arrangements can be compared.

For the first comparison with the single bore pipeline, the second half of the pipeline was changed from 53 mm to 69 mm bore pipe. The resulting conveying characteristics are presented in Figure 14.33b and it will be seen that there is a very significant improvement in performance over the entire range of conveying conditions considered. Much higher values of fly ash flow rate were achieved, and with lower values of

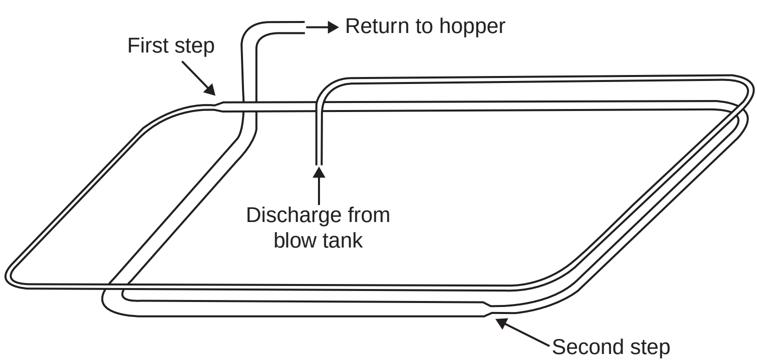


Figure 14.31 Sketch of pipeline no. 15.

conveying line pressure drop, and solids loading ratios of over 200 were achieved in this 115 m long pipeline [11].

To illustrate the magnitude of the improvement a comparison of the single step and single bore pipelines is given in Figure 14.34. The data points given in Figure 14.34 represent the ratio of fly ash flow rates, and this shows that the material flow rate achieved through the pipeline with a single step was about 1.9 times or 90 per cent greater than that for the single bore pipeline for exactly the same air flow and power requirements. There is little change in the value of this ratio over the entire range of conveying conditions examined. The improvement applies equally to low velocity dense phase conveying, and high velocity dilute phase conveying.

Since the diameter of the first section of the pipeline remains the same, the air mass flow rate remains the same. This has direct application to existing systems, for if a single bore pipeline is used with a high pressure system, the only change may be in terms of

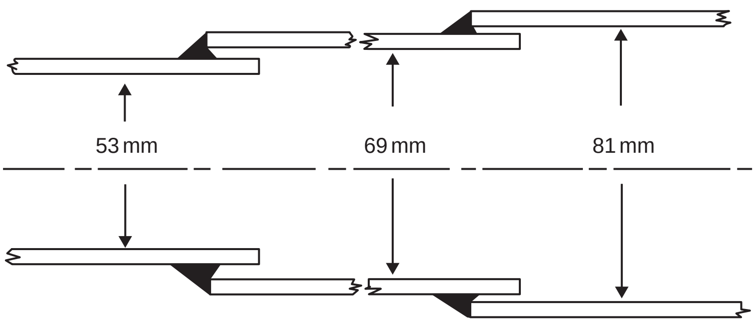


Figure 14.32 Sketch showing welded transition sections in stepped pipeline.

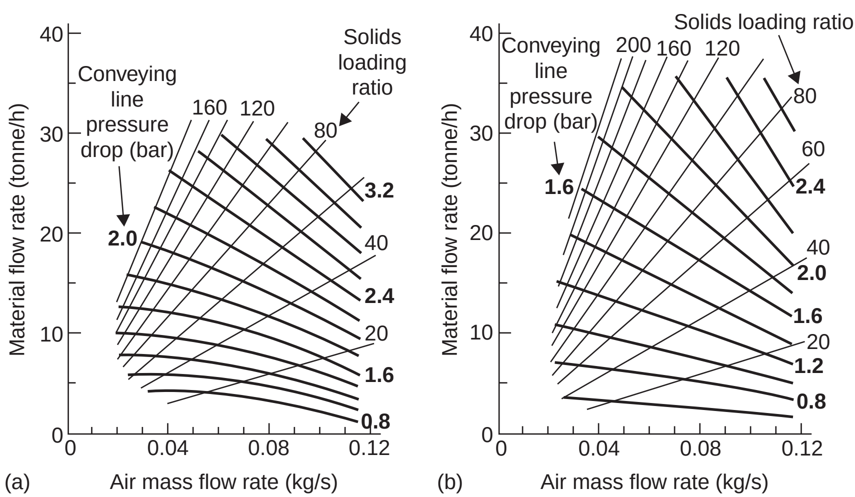


Figure 14.33 Conveying characteristics for fly ash in pipeline no. 15: (a) single bore pipeline and (b) single step pipeline.

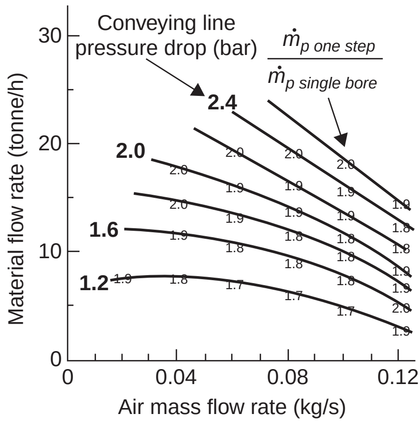


Figure 14.34 Comparison of flow rate data for single bore and single step lines.

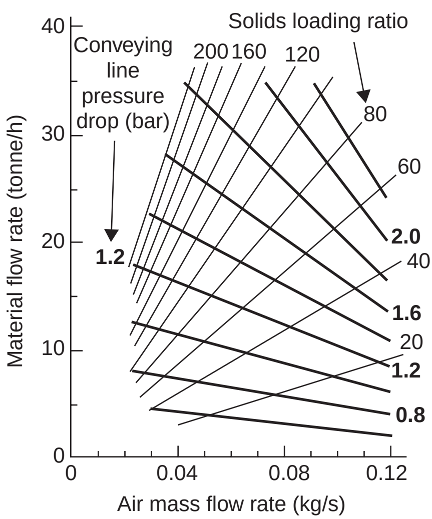


Figure 14.35 Conveying characteristics for fine fly ash in pipeline with two steps.

stepping the pipeline. No change need be made to the compressor or to the filtration plant either.

For the second comparison the last quarter of the pipeline was changed from 69 to 81 mm bore. Thus the first 58 m was of 53 mm, the next 29 m was 69 mm and the last 28 m was of 81 mm bore pipe. It should be noted that these are by no means the ideal proportions. They were selected to illustrate the potential improvement that might be achieved over a very wide range of conveying conditions. The optimum position of the pipeline steps will depend very much upon the air supply pressure and pipeline bores available. The resulting conveying characteristics for this pipeline with two steps to larger bore pipe are presented in Figure 14.35. It will be seen from this that a further

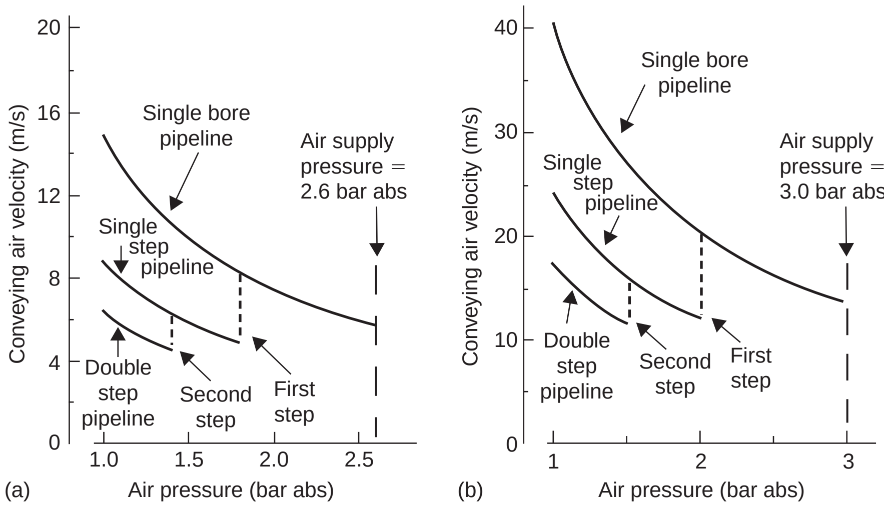


Figure 14.36 Comparison of velocity profiles: (a) for 0.04 kg/s of air and (b) with 0.11 kg/s of air.

improvement over the single step pipeline has been obtained. A similar analysis to that presented in Figure 14.34 showed that the ratio of material flow rates between the double step and single bore pipelines was about 2.2:1.

14.8.2 Velocity profiles

To illustrate the influence that the stepping of the pipeline has had on the conveying air velocity profiles, two representative test runs are presented in Figure 14.36.

In these figures it will be seen that the stepping of the pipeline has had a very significant effect in providing a uniform velocity profile. In the low air flow rate case the maximum velocity of 14.8 m/s was reduced to 8.8 m/s with a single step and to 6.4 m/s with a double step. In the high air flow rate case the maximum velocity of 40.8 m/s was limited to 24.1 m/s with a single step and to about 20.4 with a double step. In both cases the average velocity values have been significantly lowered with each pipeline.

It is this, to a large extent that has so dramatically increased the conveying performance over the entire range of conveying conditions considered.

References

1. M S A Bradley and D Mills. Approaches to dealing with the problem of energy losses due to bends. Proc 13th Powder and Bulk Solids Conf. pp 705–715. Chicago. May 1988.
2. D Mills and J S Mason. The influence of bend geometry on pressure drop in pneumatic conveying system pipelines. Proc 10th Powder and Bulk Solids Conf. pp 203–214. Chicago. May 1985.

3. P Marjanović and D Mills. The influence of bends on the performance of a pneumatic conveying system. Proc 15th Powder and Bulk Solids Conf. pp 391–399. Chicago. June 1990.
4. D Mills and J S Mason. The influence of bend geometry on pressure drop in pneumatic conveying system pipelines. Proc 10th Powder and Bulk Solids Conf. pp 203–214. Chicago. May 1985.
5. D Mills, J S Mason and P Marjanović. A comparison of pressure drops in horizontal and vertical dense phase pneumatic conveying. Proc 3rd Conf on Pneumatic Conveying. Pecs, Hungary. March 1985.
6. D Mills, J S Mason and P Marjanović. An analysis of the dense phase pneumatic conveying of cement in vertical pipelines. Proc 9th Powder and Bulk Solids Conf. pp 125–147. Chicago. May 1984.
7. D Mills, J S Mason and P Marjanović. Pneumatic conveying – vertically down. Proc 8th Powder and Bulk Solids Conf. pp 546–557. Atlanta. May 1983.
8. D Mills. A review of the research work of Professor Predrag Marjanoviać. Proc 4th Int Conf for Conveying and Handling of Particulate Solids. Budapest, Hungary. June 2003.
9. P Marjanović, D Mills and J S Mason. The influence of pipeline material on the performance of pneumatic conveying systems. Proc Pneumatech 4. pp 453–464 Glasgow. June 1990.
10. D Mills. Using rubber hose to enhance your pneumatic conveying process. Powder and Bulk Engineering. pp 79–87. March 2000.
11. D Mills and J S Mason. An analysis of stepped pipelines for pneumatic conveying systems. Proc 12th Powder and Bulk Solids Conf. pp 696–704. Chicago. May 1987.

Chapter 15

Design procedures

15.1 Introduction

A pneumatic conveying system may be designed using mathematical models, available test data or a combination of the two. If mathematical models are to be used, some degree of confidence needs to be established as to their suitability for a particular application, such as conveying a particular material under closely defined conditions, before they are employed. Test data is used extensively in system design. This data may have been obtained from a test facility or from conveying experience on an actual plant.

It is essential however that the available data relates to the same grade of material for which the new plant design is required. It is also essential that the data is available to slightly higher values of solids loading ratio and to slightly lower values of conveying line inlet air velocity, than are contemplated for the new design. Existing data should never be scaled beyond known conveying boundaries. In cases where no previous experience of the material or the range of conveying conditions required is available, then conveying trials are usually carried out in order to obtain the necessary test data for system design purposes.

A set of logic diagrams are presented and these can be used for the purpose of both designing a new conveying system and for checking the capability of an existing system, using both mathematical models and test data.

15.2 The use of equations in system design

The design of pneumatic conveying systems using mathematical models is generally the preferred method. There are, however, a limited number of reliable equations available at present.

15.2.1 Logic diagram for system design

A logic diagram for the design of a pneumatic conveying system based on the use of mathematical models is presented in Figure 15.1. The procedure starts with the specification of the fixed parameters, goes through the necessary selection and calculation of conveying and system parameters to the final specification of the most suitable pipeline bore and air requirements. The numbers of the boxes in Figure 15.1 corresponds to the number of the sections in which the relevant calculation is discussed.

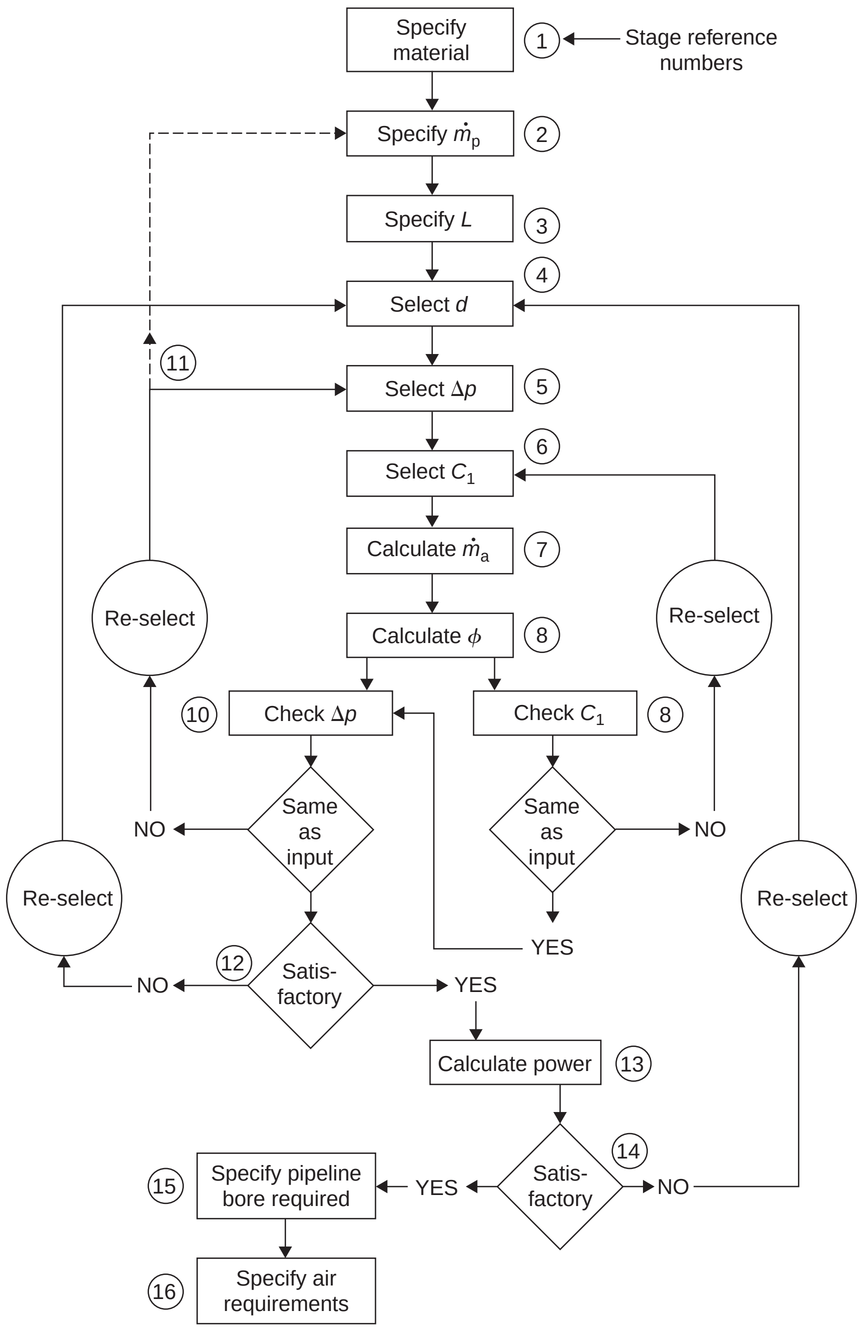


Figure 15.1 Logic diagram for the design of a pneumatic conveying system based on the use of mathematical models.

15.2.1.1 Specify material

A bulk particulate material will be specified through a knowledge of some of all of the following parameters:

- Material name
- Bulk properties:
  1. density,
  2. particle size distribution,
  3. free moisture,
  4. permeability,
  5. air retention.
- Particle properties:
  1. density,
  2. shape,
  3. hardness,
  4. friability.

Bulk densities, for example, are needed for the sizing of system components, such as rotary valves and blow tanks. Properties associated with drag, friction and shearing forces are desirable as these have an influence on the conveying potential for specified conveying conditions. Information on air retention and permeability would be useful as this relates to the potential mode of conveying and to the minimum conveying air velocity that can be employed. Particle hardness is important in terms of potential wear problems, and these are considered in detail in Chapter 23. Particle friability is similarly important in terms of material degradation and this is considered in Chapter 24.

For contractual reasons it would always be recommended that all parties involved should make a note of as many of the material properties as possible, for reference and identification purposes. These, of course, are the properties of the material upon which the design is based. Material property influences on conveying performance were considered at length in Chapter 13, where it was shown that a slight change in grade of a material can, with some materials, have a significant effect on the conveying capability of the material.

15.2.1.2 Specify mass flow rate of material required

This will generally be specified as a steady hourly rate, or a time averaged mean value. For continuously operating systems this value is the flow rate that needs to be specified. For batch operating systems the system will have to be designed to a higher value than this to take account of the fact that continuous conveying cannot be achieved, as discussed in relation to Figure 2.7. The ratio between the value to be specified for design purposes and the time averaged mean will depend upon the type of batch system to be used.

If the type of system required is known from the outset, then the appropriate value of material flow rate can be specified. If the investigation or survey is to cover a wide variety of pipeline bores, then a wide range of conveying line pressure drop values will result. The value of conveying line pressure drop may, to a certain extent, dictate the choice of system. The provisional feed-back loop to material flow rate specification, therefore, is to take account of a change from continuous to batch operating systems which could occur within such an investigation.

The system design procedure outlined here relates essentially to the pipeline and specification of the air requirements to ensure that the material is conveyed at the specified flow rate. Due consideration will have to be given to the device used to feed the material into the conveying line, for this must also be capable of meeting the flow rate requirements. Feeder design and specification, however, can generally be considered in isolation from that of the pipeline system, and so is not included here. The same situation applies with regard to the design of systems for discharging the conveying line.

15.2.1.3 Specify conveying distance required

It will be required to specify the conveying distance, together with the routing and details of the pipeline. It is the actual distance that is of primary importance, but the orientation of the pipeline and the number of bends and their geometry are also important. Pipeline length has to be considered in terms of the individual lengths of horizontal, vertically up and vertically down sections. Bend geometry is considered in terms of the bend angle and the ratio of the bend diameter, D, to the pipe bore, d. The influence of pipeline length, orientation and bends were considered in detail in Chapter 14. Pipeline bore is an entirely separate variable and is not considered at this stage.

15.2.1.4 Select pipeline bore

The diameter of the pipeline is one of the primary variables in terms of achieving a specified material flow rate through a pipeline. In combination with the conveying line pressure drop a wide range of pipeline bores will often meet the conveying requirements, as illustrated with Figure 14.11. It is, therefore, necessary to select a value of pipeline bore, and in the first instance this may well be and estimated value or guess. If this proves to be unacceptable for some reason it will be necessary to re-select. This will be requested automatically by means of the various loops incorporated into the logic diagram. Subsequent values of pipeline bore, however, will be selected with the benefit of the initial estimate.

At this stage no provision is made for stepped pipelines. Should an increase in pipeline bore be required part way along its length, however, it could be designed in isolation. Such a design could be based on the required single pipeline bore, and steps could be evaluated as indicated in Section 9.4. A comparison of single and stepped bore pipelines was presented in Section 14.8 and it would be suggested that the mathematical model being employed could be tested against that data, for the benefits achieved by stepping the pipeline are very material dependent.

15.2.1.5 Select conveying line pressure drop

In a similar manner to pipeline bore, it will be necessary to select a value of conveying line pressure drop. This may also be an estimated value or guess. If the selection is to be restricted to negative pressure or low pressure systems, however, the range will be limited automatically. Once again, if the value chosen proves to be unacceptable for some reason it will be necessary to re-select, and the necessary loop is incorporated for this purpose.

15.2.1.6 Select conveying line inlet air velocity

At the end of the design process two parameters will emerge. One is pipeline bore and the other is the air requirements, in terms of volumetric flow rate and pressure capability. There is, therefore, a necessity for a conveying air velocity to be evaluated. Although the air velocity at free air conditions is the most convenient for this purpose, a major design parameter is that of the conveying air velocity at the material feed point into the pipeline. This is the conveying line inlet air velocity, C_1.

The conveying line inlet air velocity is not a parameter whose value is estimated, and certainly not guessed. It must be selected and specified precisely. This is why, in Chapter 12, a multitude of values were given for the various materials considered so that a 'feel' for this critical design parameter would be obtained in terms of the different properties of the materials. That the value is dependent upon the type of material was illustrated with the compilation plots in Figures 12.4 and 12.15.

For dilute phase conveying the value of the minimum conveying air velocity, C_{min}, will almost certainly be above 10 m/s. For cement it is about 10–11 m/s, fine fly ash 11–12 m/s, granular alumina 13–14 m/s and about 16 m/s for granulated sugar, the value depending mainly upon mean particle size, particle shape and particle size distribution. For dense phase conveying the minimum conveying air velocity can be as low as 3 m/s with many materials, such as cement, fly ash, barytes and bentonite. For design purposes a value of conveying line inlet air velocity, C_1, would be taken as the minimum conveying air velocity plus a 20 per cent margin:

$$C_1 = 1.2 \times C_{min} \text{ m/s} \tag{15.1}$$

It is clearly not advisable to use the minimum value of conveying air velocity for design purposes. The margin is to allow for surges in material flow rate and a safety factor. A surge in material flow rate will cause an increase in pressure, and this will result in a slight reduction in conveying air velocity from two separate sources. One is due to the problems of compressibility of air (see Equation (9.11) and Figure 9.9) and the other is due to the operating characteristics of the compressor (see Figures 6.3 and 6.5).

An additional problem with dense phase conveying, in sliding bed flow for powdered materials, is that the minimum value of conveying air velocity is dependent upon the solid loading ratio and so in this case an initial estimate will have to be made. This relationship has already been illustrated three times, because of its importance, and so it is not reproduced again here for reference. In Figure 8.1 the relationship for all three modes of conveying was included for comparison purposes, in Figure 13.5 the transitional relationship between dilute and dense phase conveying was highlighted for cement, and then in Figure 14.2 specific data for cement and potassium sulphate was presented. The maximum value of solids loading ratio that can be achieved with a material, conveyed in dense phase sliding bed flow, is dependent upon the pressure gradient available and this was illustrated in Figure 1.1.

For most materials the value of conveying line inlet air velocity that is used is that given by Equation (15.1). An unnecessarily high margin is not recommended because of the adverse effect of velocity on conveying performance, as has been adequately illustrated with the multitude of conveying characteristics presented. For a few materials, however, this is not necessarily the case. These are materials that can be conveyed at low velocity and show pressure minimum points in their conveying characteristics. These include polyethylene pellets in Figure 12.11c, PVC and PTA in Figure 12.19, and nylon pellets in Figure 13.10. With these materials the optimum point may be chosen, or a lower velocity, particularly if there is a concern about degradation of the material.

To cater for the variation of minimum conveying air velocity with solids loading ratio, for materials capable of being conveyed in dense phase in sliding bed flow, a check and feedback loop are incorporated into the logic diagram. It is unlikely that a correct estimate of the value to be taken for conveying line inlet air velocity would be made in the first instance. Also, if a review of alternative conveying parameters is being undertaken, different air supply pressures will result, and these will give different pressure gradients. Solids loading ratio, in turn, is dependent upon pressure gradient, and minimum conveying air velocity is dependent upon solids loading ratio.

15.2.1.7 Calculate air mass flow rate

The determination of the air mass flow rate is the first stage in evaluating the solids loading ratio and providing a check on the value of the conveying line inlet air velocity. Air mass flow rate can be evaluated from the Ideal Gas Law and this was presented in Equation (9.4). This was developed into an expression in terms of the conveying line inlet air velocity with Equation (9.19) and this is reproduced here as Equation (15.2):

$$C_1 = \frac{4\dot{m}_a R T_1}{\pi d^2 p_1} \text{ m/s} \tag{15.2}$$

where C_1 is the conveying line inlet air velocity (m/s); $\dot{m}_a$, air mass flow rate (kg/s); R, characteristic gas constant (kJ/kg·K); T_1, conveying line inlet temperature (K); d, pipeline bore (m) and p_1, conveying line inlet air pressure (kN/m^2).

Re-arranging this equation in terms of the air mass flow rate and substituting $R = 0.287$ kJ/kg·K for air gives:

$$\dot{m}_a = \frac{2.74 p_1 C_1 d^2}{T_1} \text{ kg/s} \tag{15.3}$$

where d is the the pipeline bore selected at stage 4; C_1, the conveying line inlet air velocity selected at stage 6; p_1, for a negative pressure system will be equal to the atmospheric pressure, p_{atm}, of 101.3 kN/m^2 abs or the appropriate local value if at elevation and for a positive pressure system will be equal to $p_{atm} + 100\,\Delta p$, where Δp is the conveying line pressure drop (in bar) selected at stage 5.

15.2.1.8 Calculate solids loading ratio

Solids loading ratio, ϕ, is the ratio of the material flow rate, $\dot{m}_p$, specified at stage 2 to the air mass flow rate, $\dot{m}_a$, calculated at stage 7. For consistency in units:

$$\phi = \frac{\dot{m}_p}{3.6\,\dot{m}_a} \text{(dimensionless)} \tag{15.4}$$

15.2.1.9 Check conveying line inlet air velocity

This is the first of the loops in this logic diagram used to provide a check on the input data for which an initial estimate was necessary. This particular check is for conveying line inlet air velocity and so only applies to materials that are capable of being conveyed in dense phase, as discussed at stage 6. For such materials the value of minimum conveying air velocity, and hence conveying line inlet air velocity, is dependent upon the value of solids loading ratio.

Having evaluated solids loading ratio at stage 8, the value obtained can be used to determine the corresponding value of conveying line inlet air velocity. This can either be by means of a relationship such as that shown in Figure 13.5 for the material, or some equation of the form:

$$C_1 = \text{constant} \times \phi^{-n} \text{ m/s} \tag{15.5}$$

An approximate model that would fit the transitional relationship for the cement in Figure 13.5, for example, and so allow the checking process to be undertaken mathematically would be:

$$C_1 = 36\phi^{-0.3} - 7 \text{ m/s} \tag{15.6}$$

where C_1 is the conveying line inlet air velocity and ϕ, the solids loading ratio.

If the value of conveying line inlet air velocity, corresponding to the solids loading ratio for the material, differs from that of the initial estimate, it will be necessary to return to stage 6. The new value can be used as a guide for the next value to be selected, and then the process from stage 6 can be repeated. This is an iterative process that does not converge quickly, and so the next value of conveying line inlet air velocity to be selected must be judged on the basis of previous results, and not simply be a transfer of the result obtained from the check carried out.

If the material has no dense phase conveying potential, or the pressure gradient is such that the material can only be conveyed in dilute phase suspension flow, this particular operation is not necessary. The value chosen will not change to any significant degree over the range of solids loading ratio values that will be possible with the material.

15.2.1.10 Check conveying line pressure drop

At this point a value for all the main parameters will be available and so a check can be made of the value of conveying line pressure drop selected. Mathematical models for system design are generally in terms of evaluating the conveying line pressure drop for a given set of conditions. The model used, therefore, can be applied to the system and the resulting value of conveying line pressure drop can be checked against that selected at stage 5.

If the value determined by means of the model used differs from that selected it will be necessary to return to stage 5. This is the second of the loops in the logic diagram used to provide a check on the input data from which an initial estimate was necessary. The process is similar to that described above for conveying line inlet air velocity.

15.2.1.11 Re-specify material mass flow rate

If the check on conveying line pressure drop is close to the original estimate, it will only be necessary to return to stage 5 and select a new value. If the check shows a considerable discrepancy, however, it may be necessary to think in terms of a totally different system, for which a change in material flow rate may be required, in addition to a change in conveying line pressure drop, for the current bore of pipeline.

If, for example, an original estimate for conveying line pressure drop was 0.8 bar, and the check revealed that for the specified conditions it would actually be two or three times greater than this, then a change in system could be considered. At 0.8 bar a continuously operating system with a low pressure rotary valve and positive displacement blower would be appropriate. With a very much higher operating pressure, a system based on blow tanks, or a high pressure screw or rotary valve would need to be considered, along with a screw compressor. In the case of a high pressure blow tank the material mass flow rate would need to be modified, as discussed earlier at stage 2.

15.2.1.12 Re-select pipeline bore

If the value of conveying line pressure drop that results from the analysis at stage 10 is not satisfactory, then it will be necessary to select another pipeline bore if the alternatives at stage 11 are not acceptable. If, for example, the design is to be restricted to a low pressure continuously operating system, then a larger pipeline bore will have to be selected at stage 4 and the analysis from there will have to be repeated.

15.2.1.13 Calculate power required

Having evaluated all the parameters necessary for the system, it is now possible to determine the power required, and hence the approximate cost associated with operating the system. For an accurate assessment of the power it will be necessary to consult manufacturers' literature. By this means different machines capable of meeting the duty could be compared. For a quick, approximate assessment, to allow a comparison to be made of different variables in the design, a simple model based on isothermal compression could be used. Such a model was presented in Equation (6.6) and is reproduced here for reference:

$$\text{Power} = 165\dot{m}_\text{a}\ln\left(\frac{p_4}{p_3}\right)\text{kW} \tag{15.7}$$

where $\dot{m}_\text{a}$ is the air mass flow rate (kg/s); p_3, compressor inlet pressure (kN/m^2 abs) and p_4, compressor delivery pressure (kN/m^2 abs).

The air mass flow rate in kg/s was evaluated at stage 7, but an allowance should be made for any air leakage across rotary valves, etc. The pressure difference across the compressor, $p_4 - p_3$, equates to the conveying line pressure drop at stage 5, but an allowance should be made for any pressure drop across the feeder, filter and any air supply and extraction lines. One of these values is usually atmospheric pressure.

15.2.1.14 System re-assessment

It was shown with Figure 14.11 that a wide range of combinations of pipeline bore and conveying line pressure drop values could be obtained that would meet a required duty. It was further shown with Figure 14.12 that the power required would probably vary from one set of design parameters to another, and that material type has a very significant influence on the relationship. This loop is added here to allow a full survey to be made, so that the most suitable combination of parameters will ultimately be selected.

The starting point in carrying out a further analysis is to select a different pipeline bore. This will result in a different conveying line pressure drop and so allow a full picture to emerge for the system. It should be noted that pipeline bore is positioned before conveying line pressure drop in this logic diagram since pipes are only available in incremental sizes, whereas conveying line pressure drop is infinitely variable.

15.2.1.15 Specify pipeline bore required

The final requirement in the design process is to specify the pipeline bore required and the necessary rating of the air mover. If the full analysis has been carried out, as specified in this logic diagram, then the most suitable pipeline size should result. If the pipeline is required to handle more than one material, however, a compromise may well have to be made on both pipeline bore and air requirements, Problems associated with multiple material handling are considered in Chapter 19.

15.2.1.16 Specify air requirements

Air requirements are specified in terms of volumetric flow rate and delivery or exhaust pressure. The air mass flow rate was evaluated at stage 7 and the relationship between mass and volumetric flow rates is given by:

$$\dot{m}_a = \rho \times \dot{V} \text{ kg/s} \tag{15.8}$$

where $\dot{m}_a$ is the air mass flow rate (kg/s); ρ, density of air (kg/m^3) and $\dot{V}$, volumetric flow rate of air (m^3/s).

It is the volumetric flow rate at free air conditions, $\dot{V}_0$, that is required and so the corresponding density of air at free air conditions is needed. This was evaluated at Section 10.2.1.2 as 1.225 kg/m^3. Note that the reciprocal of this is referred to as specific volume and is 0.818 m^3/kg at free air conditions.

In systems where there is likely to be an air leakage, at the material feed point in the case of positive pressure systems, and at the material discharge point in vacuum systems, an allowance for this must be made in the specification of the volumetric air flow rate required. The delivery or exhaust pressure required is equal to the conveying line pressure drop, plus an allowance for air filtration, the feeding device, air supply and exhaust lines and safety margin. Having determined the necessary air requirements the most appropriate choice of air mover can be made. The capabilities and performance of a number of different types of air mover were considered in Chapter 6.

15.2.2 Logic diagram for system capability

A logic diagram, based on the use of mathematical models, for determining the capability of an existing pneumatic conveying system is presented in Figure 15.2. This type of analysis is generally required in situations where a change in use or layout of a pneumatic conveying system is involved. If a given system is required to convey a different material, or if a shortening or extension of the conveying line is made, it would be well worthwhile carrying out such an analysis in order to provide a check on the air requirements, in addition to determining the new flow rate of the material.

15.2.2.1 Specify material to be conveyed

This specification is the same as that for stage 1 in the previous logic diagram.

15.2.2.2 Specify conveying distance

This specification is the same as that for stage 3 in the previous logic diagram.

15.2.2.3 Specify pipeline bore

For an existing system the pipeline bore will not be a variable. If the resulting flow rate with the new material in the existing system is insufficient, however, it may be necessary to consider installing a pipeline with a larger bore. In this case the design procedure outlines previously in Figure 15.1 for basic system design will be more appropriate, although reference to Chapter 21 on the 'Optimising and Up-Rating of Existing Systems' would probably be the best starting point since a change of pipeline bore would also influence the air mover specification, as well as that of the filtration plant.

15.2.2.4 Specify maximum value of conveying line pressure drop

For an existing system an air mover will be available. It is suggested that, as a starting point in the analysis, the maximum pressure rating of the air mover should be used. The corresponding maximum value of conveying line pressure drop can be obtained by subtracting appropriate pressure drop allowances for pipeline feeding, air separation, transmission losses and operating safety margin, as discussed in relation to power requirements at stage 13 in connection with system design for the previous logic diagram. As this represents the upper limit available any necessary changes will be to a lower value.

15.2.2.5 Select conveying line inlet air velocity

Once again the same basic philosophy of matching conveying line inlet air velocity with solids loading ratio, as expounded at stage 6 in the previous logic diagram applies. This, of course, is only the case for materials that have dense phase conveying potential.

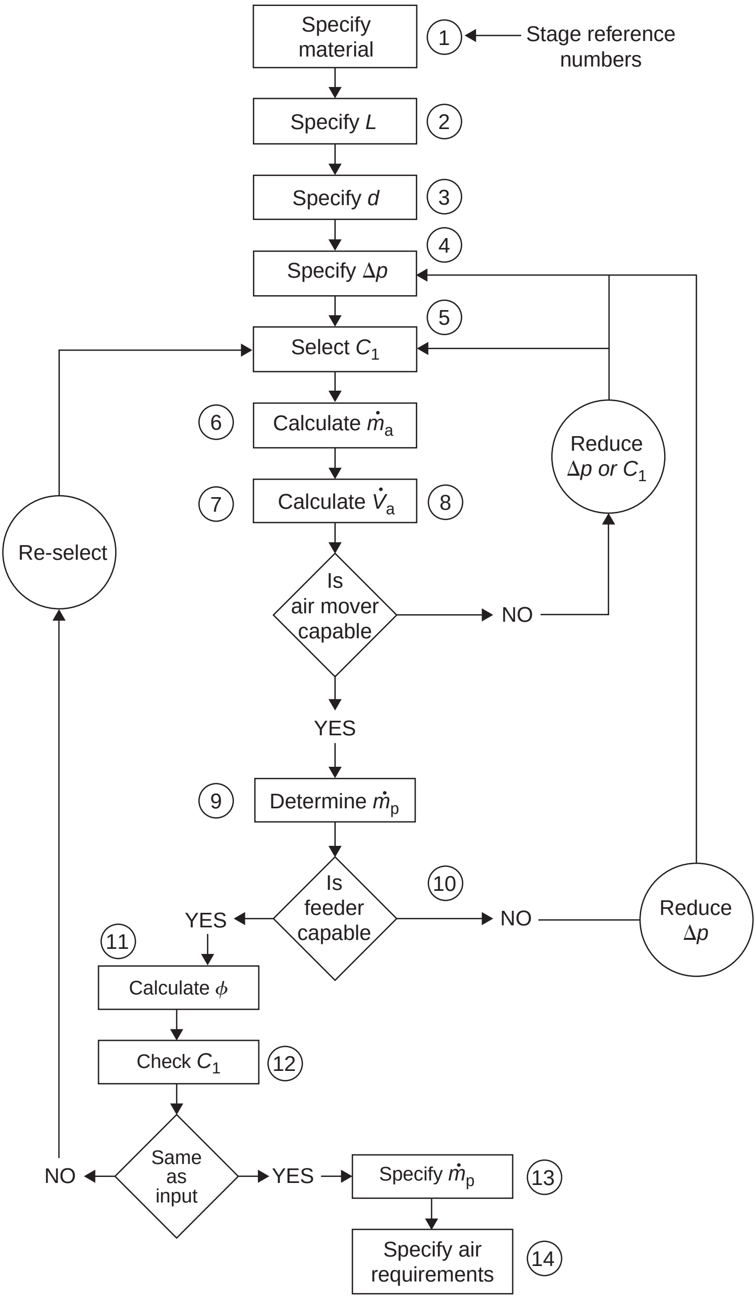


Figure 15.2 Logic diagram for determining the capability of an existing system based on the use of mathematical models.

With an existing system the capabilities of the air mover have to be considered. As a starting point in the analysis, therefore, it is suggested that the maximum velocity available should be used, or the maximum velocity necessary for the material if this is lower. As this represents the highest value available, or necessary, any subsequent changes will only be to lower values.

15.2.2.6 Calculate air mass flow rate

The air mass flow rate, $\dot{m}_a$, can be evaluated using Equation (15.3) presented above.

15.2.2.7 Calculate volumetric air flow rate

The volumetric flow rate of the air, $\dot{V}_a$, at free air conditions, $\dot{V}_0$, can be determined from the air mass flow rate evaluated in the previous stage, using a re-arrangement of Equation (15.8):

$$\dot{V}_0 = 0.816\dot{m}_a \ \mathrm{m^3/s} \tag{15.9}$$

The constant of 0.816 is the value of the specific volume of the air at free air conditions and has the units of $\mathrm{m^3/kg}$.

15.2.2.8 Is the air mover capable?

At stage 4 the conveying line pressure drop was specified, and hence the supply or exhaust pressure can be obtained, and the volumetric flow rate was determined at stage 7. With an existing system it is necessary to check that the requirements are within the capabilities of the air mover, and the above parameters are those necessary for such a check to be made.

In the first instance the conveying line pressure drop and conveying line inlet air velocity are chosen to ensure that this is the case. If at a subsequent stage, the relationship between conveying line inlet air velocity and solids loading ratio is not satisfied and it is necessary to make changes, then a further check is advisable. If it is found that the air mover is not capable, a reduction will have to be made in either the conveying line pressure drop or the conveying line inlet air velocity.

The possibility of a reduction in conveying line inlet air velocity will depend upon the value of the solids loading ratio to be evaluated at stage 11. If a reduction in conveying line inlet air velocity cannot be made, then a reduction in conveying line pressure drop will have to be made. In addition to satisfying the conveying requirements, the characteristics of the air mover will also have to be consulted in order to check on the possibility of making such changes.

15.2.2.9 Determine material flow rate

At this point a value of all the main parameters is available, with the exception of the solids loading ratio, but since $\dot{m}_p = \phi \times \dot{m}_a$ by definition, a simple relationship exists that should present no difficulty in incorporating. It should be possible, therefore, with the appropriate model, to evaluate the material flow rate for the given set of conditions.

15.2.2.10 Is the material feeding device capable?

If an existing system is required to handle another material, it is quite possible that the material flow rate with the new material could be significantly different from that of the original material. If the new flow rate is lower, or higher, the possibility of using the feeding device satisfactorily must be investigated. If it is established that the feeding device has a maximum capability that is less than that of the pipeline system with the new material, then a reduction in conveying line pressure drop should be made in order to reduce the capability of the pipeline to match that of the feeder. If this is done it should result in a saving in operating power. In the case of positive displacement feeders the bulk density of the new material must also be taken into account.

15.2.2.11 Calculate solids loading ratio

This is evaluated in the same way as described at stage 8 in the previous logic diagram with Equation (15.4).

15.2.2.12 Check conveying line inlet air velocity

Having determined the material flow rate at stage 9, and then the solids loading ratio at stage 11, it is now possible to check the value of conveying line inlet air velocity at stage 5. This process is the same as that outlined at stage 9 for the previous logic diagram.

15.2.2.13 Specify material flow rate

When a check at stage 12 is obtained between solids loading ratio and conveying line inlet air velocity, the process will be complete. The final value of material flow rate determined at stage 9 can be specified as the actual rating of the system with the given material.

15.2.2.14 Specify air requirements

A loop is built into the logic diagram to ensure that the air mover is capable of meeting the required demand. It is quite possible, however, that some changes may have to be made, such as restricting delivery pressure, restricting flow rate, changing drive speed, etc, and so this will need to be clearly specified.

15.3 The use of test data in system design

The application and use of test data is probably the most common method of designing a pneumatic conveying system. This is used extensively in cases where test data or previous experience with a material is available. Where no previous experience with a particular material is available, it is usual to obtain test data specifically for the purpose of system design, since the use of mathematical models is particularly unreliable in these situations. As for the section on the use of equations in system design, two logic diagrams are also presented here, one for the original design of a system, and another for evaluating the capability of an existing system.

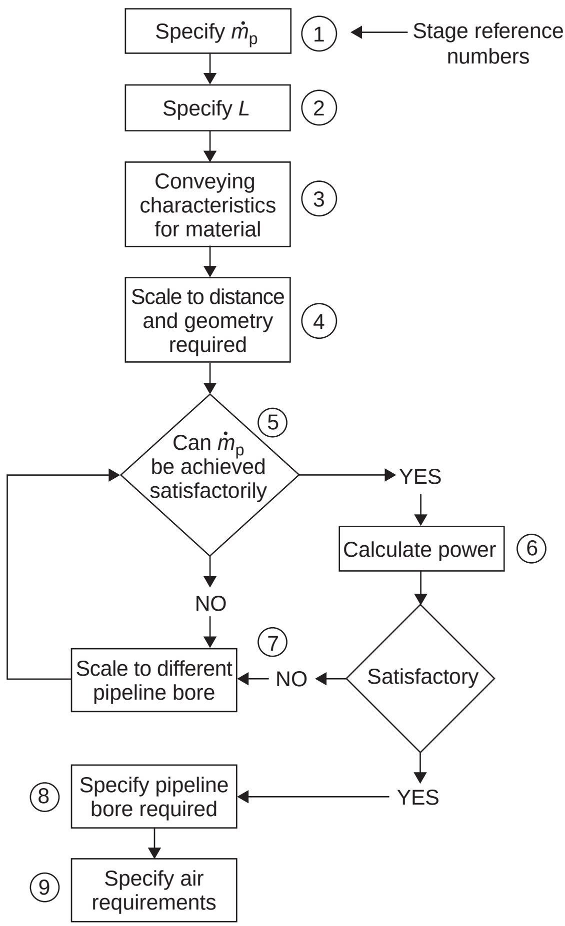


Figure 15.3 Logic diagram for the design of a pneumatic conveying system based on the use of available conveying data.

15.3.1 Logic diagram for system design

A logic diagram for the design of a pneumatic conveying system based on the use of test data is presented in Figure 15.3. The process is traced from the specification of the fixed parameters, through the necessary scaling procedures, to the final specification of the most suitable pipeline bore and air requirements. Full details are given of all the individual stages, as indicated in Figure 15.3, together with an explanation of the various loops incorporated.

15.3.1.1 Specify mass flow rate of material required

This specification is essentially the same as that at stage 2 for the corresponding logic diagram in Figure 15.1, based on the use of equations. Account must be made of whether the system is to be continuous or batch operating, and the conveying line feeding device must be capable of meeting the flow rate requirements.

Although not specifically added as a stage to this logic diagram, it would always be recommended that comprehensive details of every material to be conveyed should always be kept on file for reference, as detailed in Section 15.2.1.1.

15.3.1.2 Specify conveying distance required

This specification is also the same as that for conveying distance at stage 3 in Figure 15.1. Pipeline bore is again an entirely separate variable and is not considered at this stage.

15.3.1.3 Conveying characteristics for material

The conveying data points or set of conveying characteristics for a material obtained from conveying trials form the starting point in a design based on experimental data. Conveying characteristics for a number of materials were presented in the previous four Chapters. These were included to illustrate the potential differences that can exist between materials with respect to minimum conveying air velocities, mode of conveying, material flow rates for given conveying conditions, and the slope of the constant conveying line pressure drop curves. All this information is embodied in the conveying characteristics, and so system design is simply based on the scaling of the conveying characteristics for a specified material from the test situation to the plant requirements. The scaling is in terms of the pipeline geometry.

Scaling is clearly critical in this process, and the closer the test line is to the plant situation the more accurate will be the analysis. However, scaling can be carried out with a reasonable degree of accuracy over a fairly wide range of pipeline bores and distances.

Scaling parameters for various aspects of pipeline geometry are presented in Chapter 14. Conveying characteristics are presented at numerous points throughout this Design Guide and in each case details of the pipeline through which the material was conveyed are also given. These conveying characteristics could, therefore, be used as the starting point for a system design for the pneumatic conveying of any of the materials presented.

15.3.1.4 Scale to conveying distance

Scaling the conveying characteristics for a material is best carried out in two stages. The first stage involves scaling to the required conveying distance, with allowances for vertical sections and bends. In the second stage the resulting data or conveying characteristics are scaled in terms of pipeline bore.

Scaling with respect to conveying distance is a fairly complex process and can result in marked differences in conveying parameters, as was illustrated between Figure 14.1 and 14.4. Significant changes can result in material flow rate, solid loading ratio, and air flow rate (in the case of materials capable of being conveyed in dense phase). In order to illustrate the order of magnitude of these changes, and to provide additional guidance at this point, the influence of conveying distance, pipeline bore and material type is specifically considered later in Section 4 of this chapter.

Once again it is recommended that when actual design data is extracted from the results of the scaling process a margin of 20 per cent is allowed with regard to air flow rate for the design point taken in relation to the minimum conveying conditions. This is summarized with Equation (15.1).

15.3.1.5 Can material flow rate be achieved?

This stage is essentially one of checking whether, for the given pipeline bore the material flow rate can be achieved. If the conveying characteristics for the material were determined for a wide range of conveying line pressure drop values, it is probable that the required material flow rate would be achieved if a wide range of pipeline bores are considered. The decision here is essentially the same as that outlined at stage 14 for Figure 15.1. If a preference exists for a low pressure system or a particular pipeline bore, then the choice will be automatically restricted. If there are no restraints then a full survey could be carried out in order to determine the most economic combination of parameters.

15.3.1.6 Calculate power required

If, for a specified pipeline bore, the material flow rate can be achieved, then the power required can be determined. A model that can conveniently be used to determine the approximate power required was presented with Equation (15.7). The air mass flow rate is required for this model but it can be obtained directly from the conveying characteristics for the material.

15.3.1.7 Scale to different pipeline bore

If the required material flow rate cannot be achieved with a given pipeline bore, or if the power requirement for a certain pipeline bore is not satisfactory, the conveying characteristics should be scaled to another size of pipeline and the process repeated. The influence of pipeline bore on conveying parameters is also considered in Section 4 of this chapter.

15.3.1.8 Specify pipeline bore required

This specification is the same as that for pipeline bore at stage 15 in connection with Figure 15.1.

15.3.1.9 Specify air requirements

This specification is the same as that for air requirements at stage 16 in Figure 15.1, where an appropriate model for volumetric air flow rate was presented (see also Equation (15.9)). Allowances will also have to be made for air leakage and other component pressure drops as discussed at stage 16 for the corresponding logic diagram based on the use of equations.

15.3.2 Logic diagram for system capability

A logic diagram, based on the use of test data, for determining the capability of an existing pneumatic conveying system is presented in Figure 15.4.

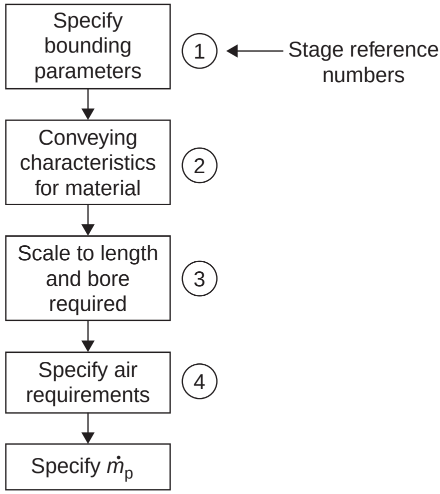


Figure 15.4 Logic diagram for determining the capability of an existing system based on the use of available conveying data.

15.3.2.1 Specify bounding conditions

With an existing system, the pipeline will form part of the established system, and so length, geometry and bore will all be fixed. An air supply will also be available, but it may be possible to alter the balance of flow rate and pressure should this be necessary.

15.3.2.2 Material conveying characteristics

Conveying characteristics for the material form the starting point in this process, as they did for the original system design considered earlier.

15.3.2.3 Scale conveying characteristics

With a clearly defined pipeline length, bore and geometry, the available conveying data for the material can be scaled directly to that of the plant pipeline.

15.3.2.4 Specify air requirements

All the information relating to the conveying of the material will be found within the scaled conveying characteristics. Air requirements will need to be established first as these have a direct influence on the material flow rate. With an existing system the pressure capability will be known and so if allowances are made for pressure drops associated with material feeding, air separation, etc, as discussed in relation to other design procedures, a value for the conveying line pressure drop can be obtained. With a 20 per cent allowance on minimum conveying air velocity, the value of air flow rate necessary can be obtained from the conveying characteristics. If the corresponding air flow rate does not match the capability of the air mover, the characteristics of the air mover will have to be consulted in order to check on the possibility of making any necessary changes.

15.3.2.5 *Specify material flow rate*

Once the air requirements have been specified satisfactorily, so that both the pressure and flow rate requirements are within the capabilities of the air mover, the corresponding material flow rate can be obtained directly from the conveying characteristics.

15.4 Typical pipeline and material influences

The scaling of the data, from the pipeline and the conditions from which the data was obtained, to the pipeline and conditions required, is a major feature of the design process when using test data. It was recommended in the logic diagrams that scaling should be carried out first with respect to conveying distance, and then with respect to pipeline bore. The determination of power requirements was also included in the logic diagrams.

In Chapter 8 several series of graphs were included to illustrate the relative influences of the main parameters, and to show the potential of pneumatic conveying systems for the transport of bulk particulate materials. Two different materials were considered, covering the extremes of material conveyability, and the influence on power requirements was introduced.

In Chapter 14 complete sets of conveying characteristics were presented for a number of different materials, to illustrate the influence of material type. They were also used to show how conveying conditions could influence power requirements and specific energy, and they were used to show the potential influences of conveying distance on material flow rate. To illustrate these influences further and to provide some guidance on the effect of the different parameters at the various stages in the logic diagram, a further series of graphs are included. These also extend the analysis presented in Chapter 8 and so provide a little more detailed reasoning for the nature of the relationships.

15.4.1 The influence of conveying distance

In Chapter 8 conveying distance was shown to have a very significant effect on both material flow rate and the solids loading ratio at which the material could be conveyed. The scaling of the sets of conveying characteristics in Chapter 14 also showed that there could be a significant change in air flow rate required for materials capable of dense phase conveying. In order to present a more complete picture and to show the influence of distance on material flow rate, solids loading ratio and air requirements, as well as conveying line pressure drop and power required complete sets of conveying characteristics are presented in Figures 15.5–15.12. The influence of material type is also included, with one set of data for dilute phase conveying and the other for materials with dense phase capability.

Actual details of the scaling procedures necessary to obtain these different sets of conveying characteristics are given in Chapter 14.

For each material the conveying characteristics are included for conveying distances of 50, 100, 200 and 500 m. They all relate to materials conveyed through a 75 mm bore pipeline.

These conveying characteristics provide the necessary design data on air mass flow rate, and also show the effect of air flow rate on material flow rate and power

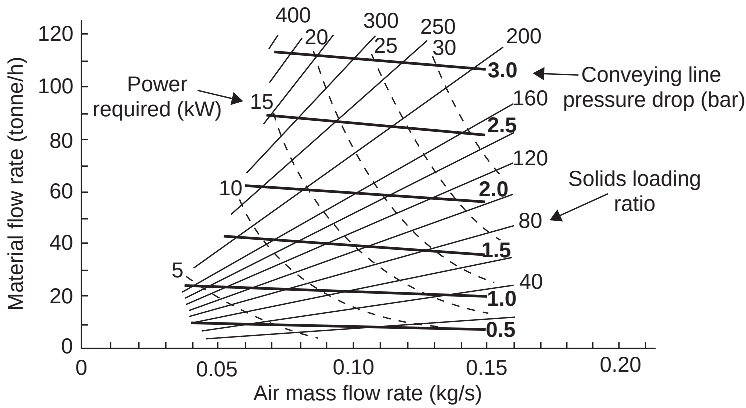


Figure 15.5 Conveying characteristics for material conveyed over 50 m through a 75 mm bore pipeline for a material having very good air retention.

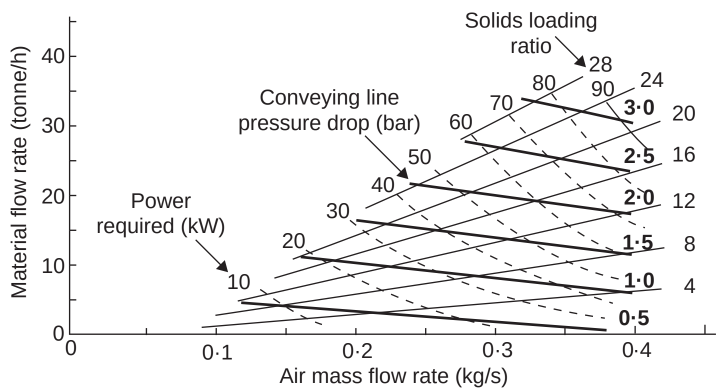


Figure 15.6 Conveying characteristics for material conveyed over 50 m through a 75 mm bore pipeline for a material having very poor air retention properties.

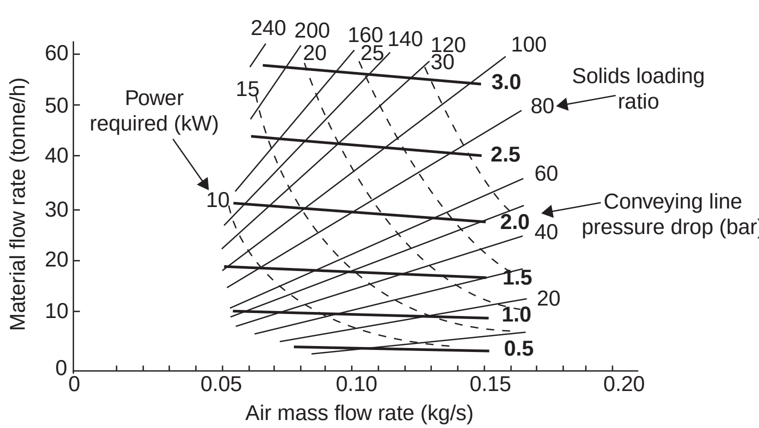


Figure 15.7 Conveying characteristics for material conveyed over 100 m through a 75 mm bore pipeline for a material having very good air retention.

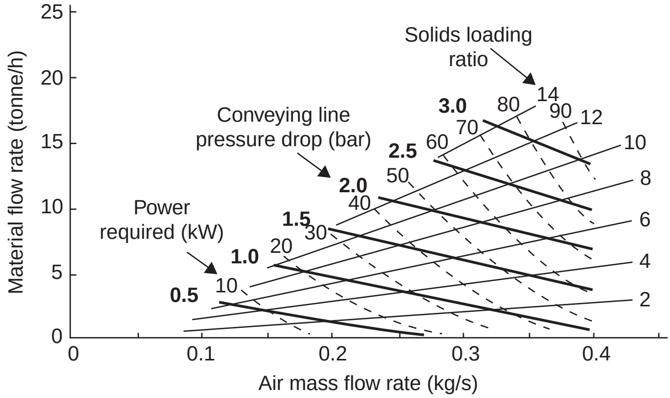


Figure 15.8 Conveying characteristics for material conveyed over 100 m through a 75 mm bore pipeline for a material having very poor air retention properties.

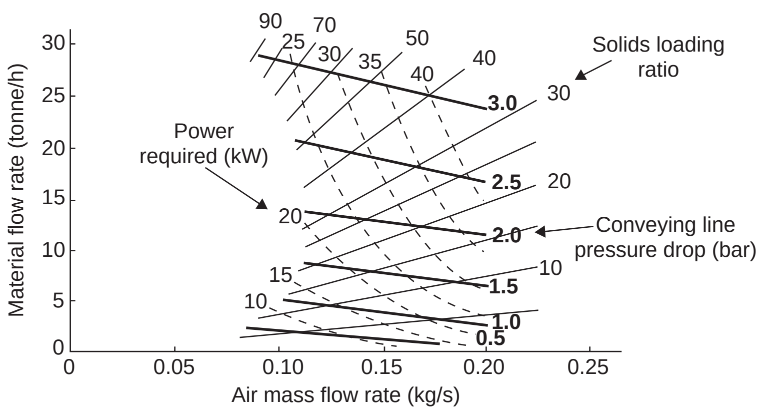


Figure 15.9 Conveying characteristics for material conveyed over 200 m through a 75 mm bore pipeline for a material having very good air retention.

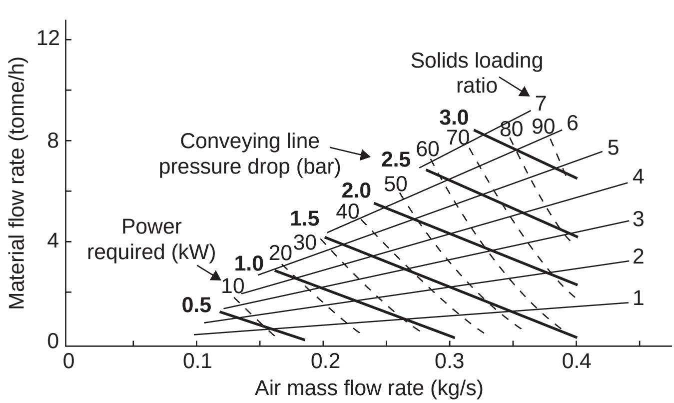


Figure 15.10 Conveying characteristics for material conveyed over 200 m through a 75 mm bore pipeline for a material having very poor air retention properties.

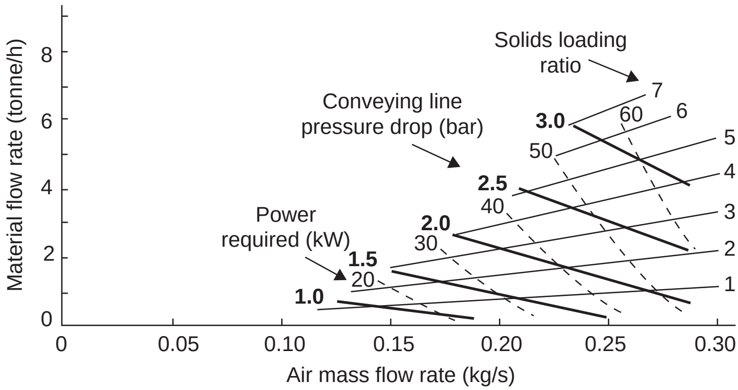


Figure 15.11 Conveying characteristics for material conveyed over 500 m through a 75 mm bore pipeline for a material having very good air retention.

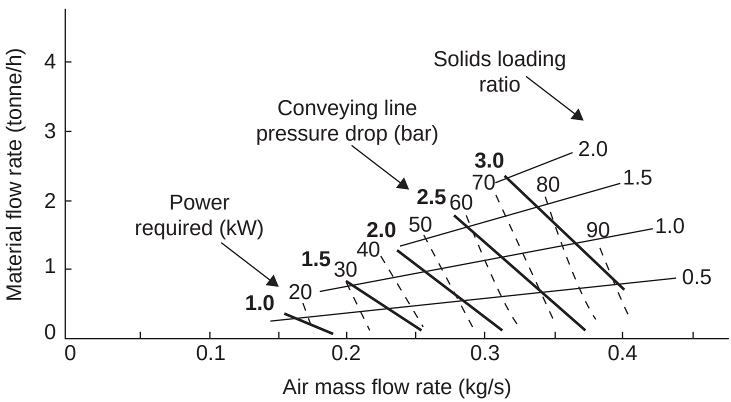


Figure 15.12 Conveying characteristics for material conveyed over 500 m through a 75 mm bore pipeline for a material having very poor air retention properties.

requirements. In the case of both materials considered here an increase in air flow rate results in a decrease in material flow rate and an increase in power required.

This adverse effect of an increase in air flow rate is not the same for all materials, however. The relationships for materials such as PVC and PTA, shown in Figure 12.19, and nylon pellets shown in Figure 13.10, are very different, but this is only the case for the low velocity dense phase conveying of these materials. This is another reason why it is essential that reliable test data should be obtained for system design, particularly if it is a material for which no previous experience exists.

As these conveying characteristics provide design data on air flow rate it will be seen that the air requirements for a given conveying distance differ quite considerably for the two materials. For the material with very good air retention properties they also differ significantly with respect to conveying distance. The problem of matching air requirements in situations where different materials need to be conveyed with a common system is considered in Chapter 19.

15.4.2 The influence of pipeline bore

For a given conveying distance and conveying conditions, pipeline bore can have a very significant effect of material flow rate. If a specified material flow rate has to be achieved, however, there is usually a wide range of pipeline bores and conveying line pressure drop combinations that will meet the demand. The power requirements are likely to be different for each, and so the loops were incorporated into the logic diagrams for system design Figures 15.1 and 15.3, in order to ensure the selection of the most satisfactory combination.

The influence of pipeline bore was shown briefly in Chapter 8, but in order to present a more complete picture and to show the inter-relating effect of conveying line pressure drop, complete sets of conveying characteristics are presented in Figures 15.13–15.20. The common point with regard to this group is that the pipeline length is 200 m in each case.

These figures show the influence of solids loading ratio and air requirements, as well as the effect of material type. The conveying characteristics presented are in two sets once again, one for a material with very good air retention properties and one for a material with very poor air retention properties.

For each material the conveying characteristics are included for pipelines of 50, 100, 125 and 150 mm bore. They all relate to the materials conveyed through a pipeline having an equivalent length of 200 m. The corresponding conveying characteristics for the missing 75 mm bore pipeline in this group were included earlier in Figures 15.9 and 15.10.

Conveying line pressure drop values up to 3 bar have been considered in each case. These two materials are the same as those considered in Chapter 8. It will be noted from this set of curves that for a specified material and conveying line pressure drop,

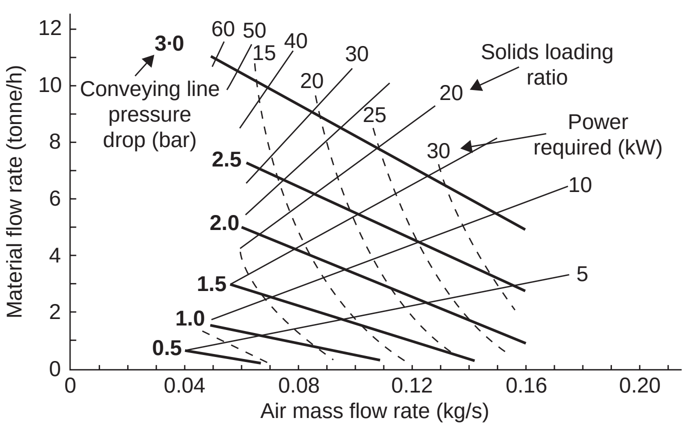


Figure 15.13 Conveying characteristics for material conveyed over 200 m through a 50 mm bore pipeline for a material having very good air retention.

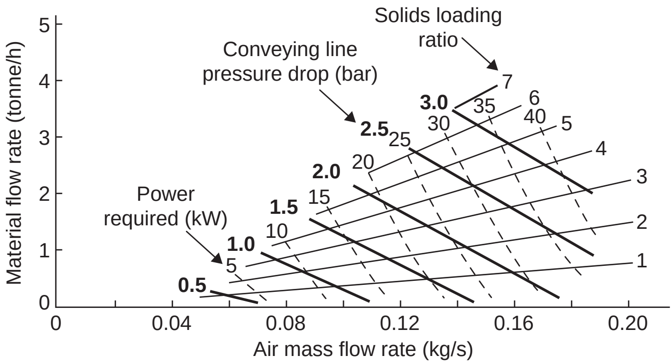


Figure 15.14 Conveying characteristics for material conveyed over 200 m through a 50 mm bore pipeline for a material having very poor air retention properties.

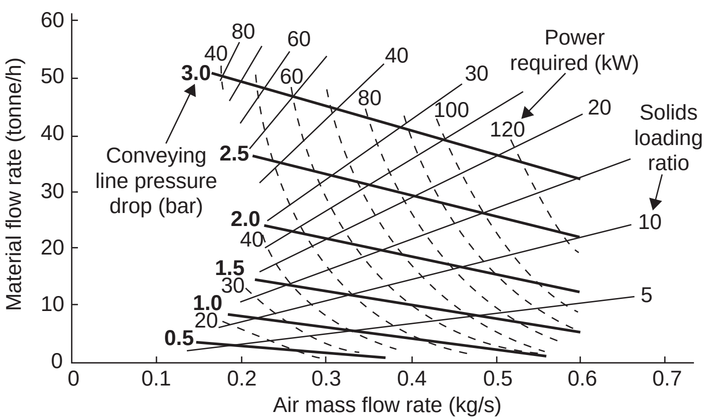


Figure 15.15 Conveying characteristics for material conveyed over 200 m through a 100 mm bore pipeline for a material having very good air retention.

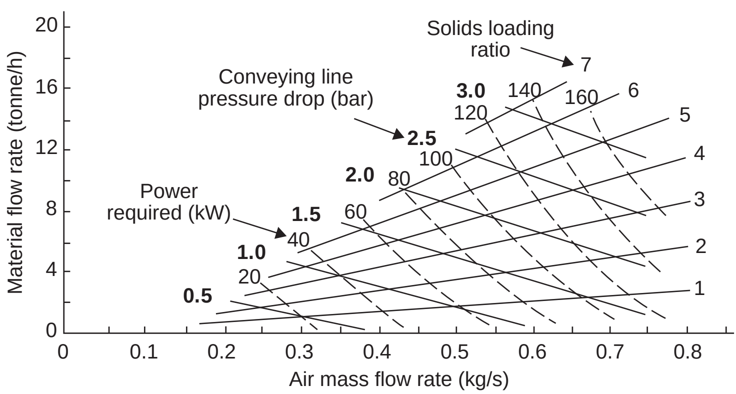


Figure 15.16 Conveying characteristics for material conveyed over 200 m through a 100 mm bore pipeline for a material having very poor air retention properties.

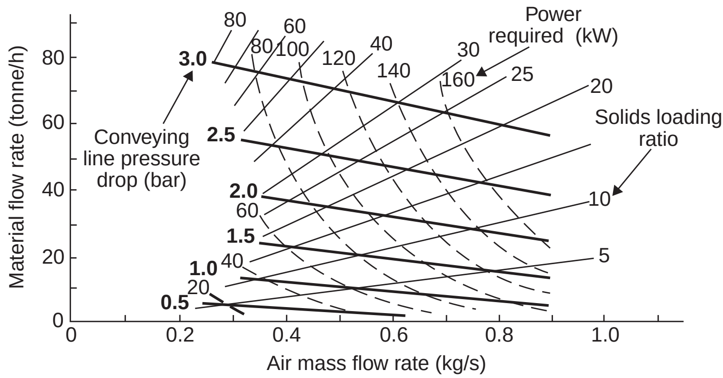


Figure 15.17 Conveying characteristics for material conveyed over 200 m through a 125 mm bore pipeline for a material having very good air retention.

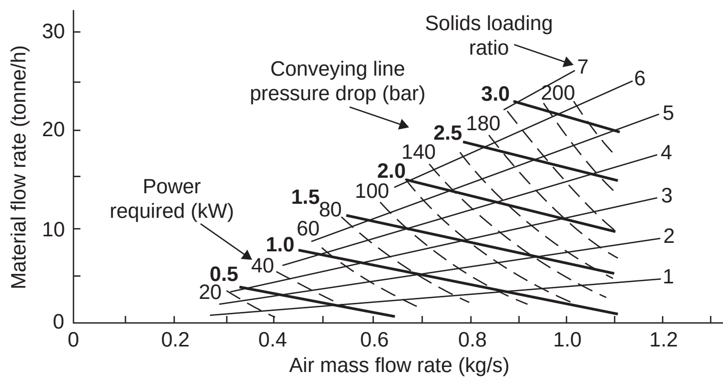


Figure 15.18 Conveying characteristics for material conveyed over 200 m through a 125 mm bore pipeline for a material having very poor air retention properties.

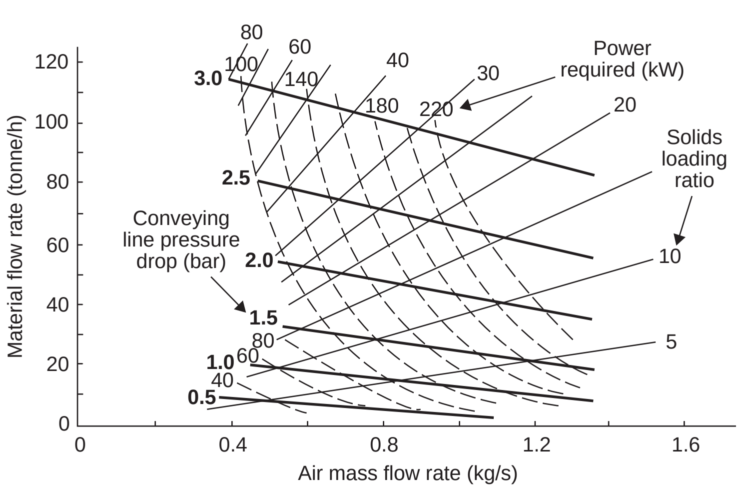


Figure 15.19 Conveying characteristics for material conveyed over 200 m through a 150 mm bore pipeline for a material having very good air retention.

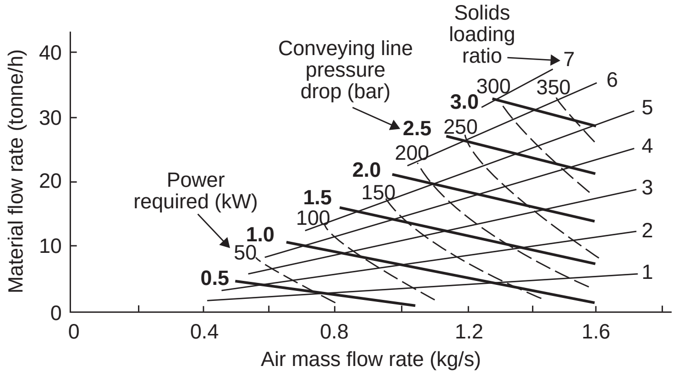


Figure 15.20 Conveying characteristics for material conveyed over 200 m through a 150 mm bore pipeline for a material having very poor air retention properties.

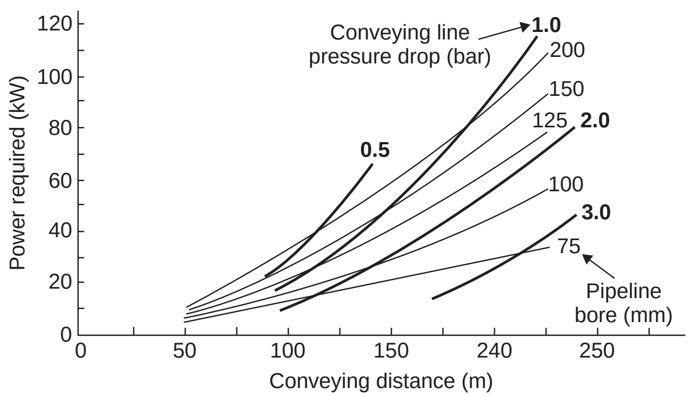


Figure 15.21 Parameters relating to the conveying of a material having very good air retention properties at a flow rate of 30 tonne/h.

pipeline bore has little influence on the solids loading ratio at which the material is conveyed. The conveying potential, air flow rate, and power required, all increase considerably with increase in pipeline bore.

Once again, with complete sets of conveying characteristics, the influence of air flow rate on both material flow rate and power required can be clearly seen.

15.4.3 Design curves

In order to provide a little more guidance on the potential relationships between material flow rate and power requirements, and the choice between conveying line pressure drop and pipeline bore, some design curves are presented. These are based on the data presented in Figures 15.5–15.20 on the effects of conveying distance and pipeline bore, and are for the two materials considered. Figures 15.21 and 15.22 are plots for power required.

Power required is plotted against conveying distance, with lines of both constant conveying line pressure drop and pipeline bore superimposed. Figure 15.21 is drawn for a material having very good air retention properties and Figure 15.22 is for a material having very poor air retention properties.

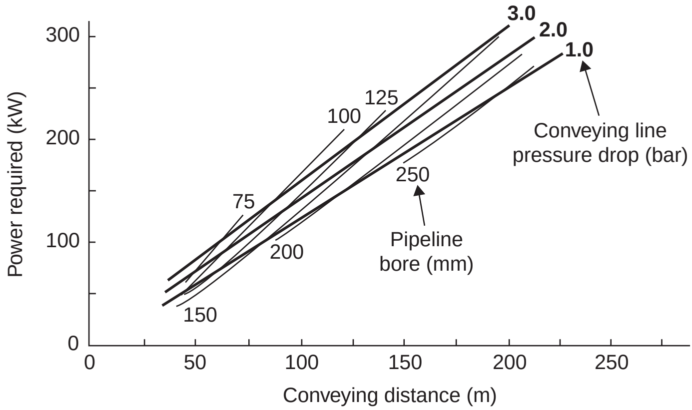


Figure 15.22 Parameters relating to the conveying of a material having very poor air retention properties at a flow rate of 30 tonne/h.

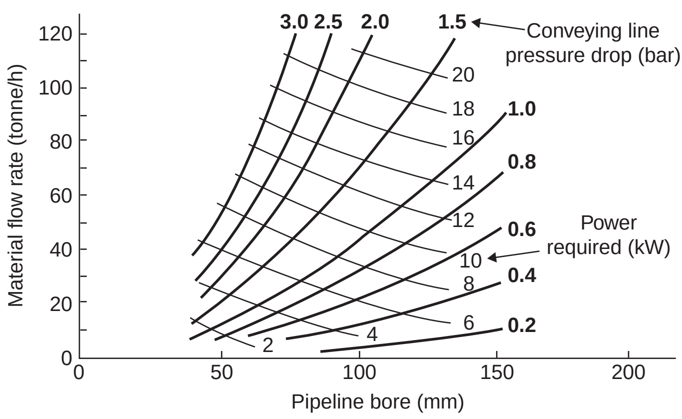


Figure 15.23 Power requirements and conveying potential of 50 m long pipelines for conveying a material with very good air retention properties.

Both pipeline bore and conveying line pressure drop are presented together on Figures 15.21 and 15.22, but this particular plot does not show the inter-relating effects very well, particularly for the material having very poor air retention properties, and so only the one representative plot is given for each material.

In Figures 15.23–15.30 material flow rate is plotted against pipeline bore and the families of curves drawn are of conveying line pressure drop and power required. Plots are presented for the two materials conveyed over distances of 50, 100, 200 and 500 m. These are similar to the graphs included in Chapter 8 to illustrate the potential of systems.

Lines of constant power have been added to provide additional information to assist with the selection of design parameters. All the data presented in Figures 15.21–15.30 is based on conveying line inlet air velocities 20 per cent greater than the minimum conveying air velocity values.

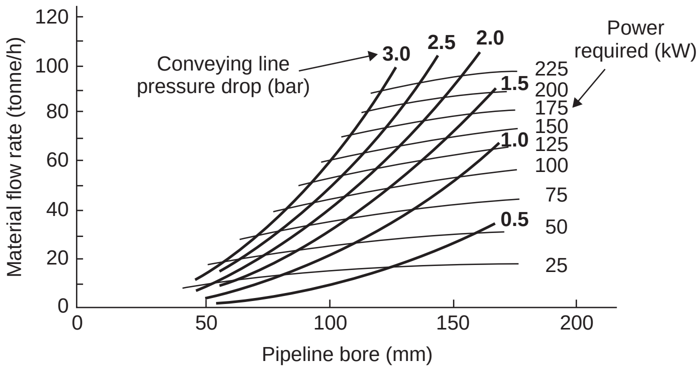


Figure 15.24 Power requirements and conveying potential of 50 m long pipelines for conveying a material with very poor air retention properties.

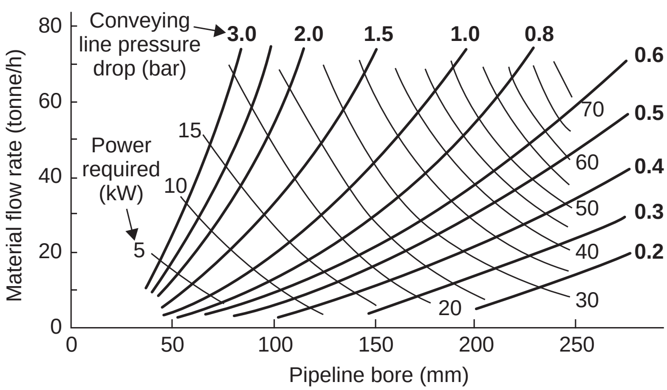


Figure 15.25 Power requirements and conveying potential of 100 m long pipelines for conveying a material with very good air retention properties.

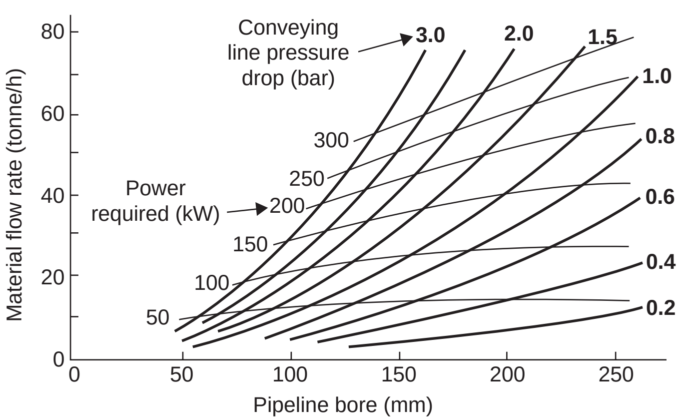


Figure 15.26 Power requirements and conveying potential of 100 m long pipelines for conveying a material with very poor air retention properties.

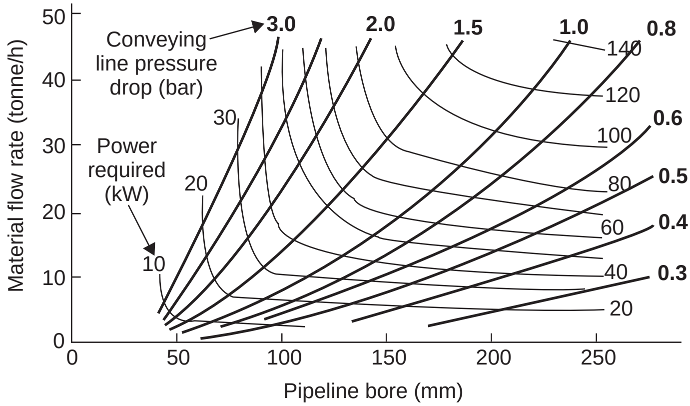


Figure 15.27 Power requirements and conveying potential of 200 m long pipelines for conveying a material with very good air retention properties.

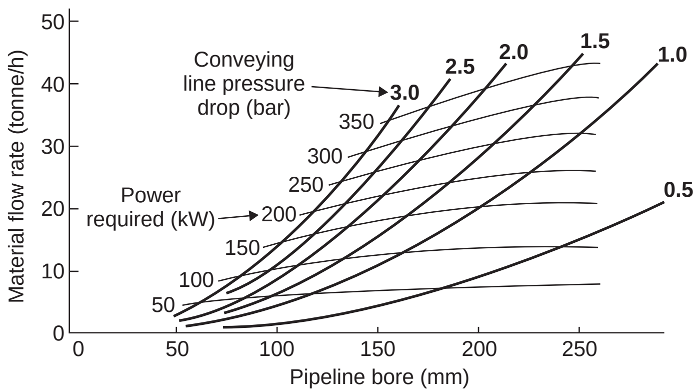


Figure 15.28 Power requirements and conveying potential of 200 m long pipelines for conveying a material with very poor air retention properties.

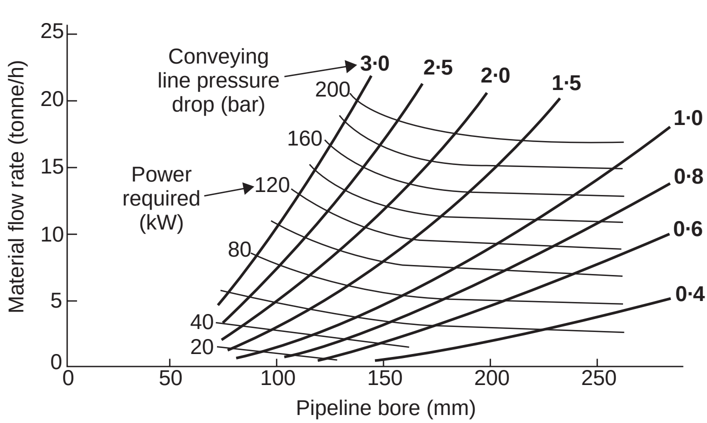


Figure 15.29 Power requirements and conveying potential of 500 m long pipelines for conveying a material with very good air retention properties.

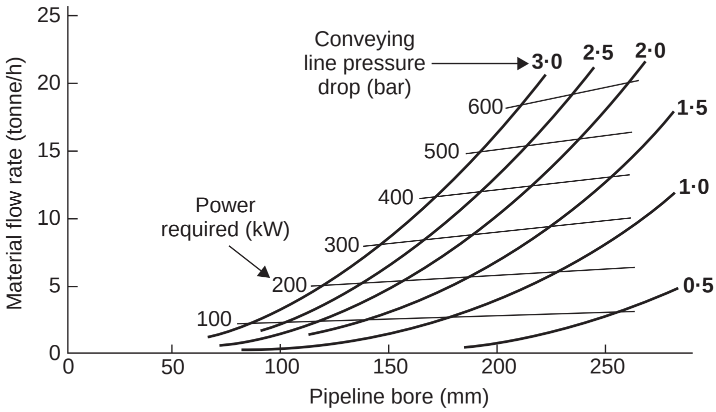


Figure 15.30 Power requirements and conveying potential of 500 m long pipelines for conveying a material with very poor air retention properties.

Since several loops are involved in the logic diagram for system design, and as some of these do not converge very quickly, these figures will provide some guidance on the initial selection of variables. This should help to reduce the work involved, particularly in the case of system design based on the use of mathematical models.

Chapter 16

Case studies

Part 1: Fine material

16.1 Introduction

Pneumatic conveying systems are usually designed on the basis of scaling available data. This may come from an existing plant pipeline in which the identical material has been conveyed, and conveying data has been obtained. Alternatively the data will be obtained from a test facility in which the required material will have been conveyed, specifically to obtain test data.

From an existing plant pipeline it is quite likely that just a single data point will be obtained, for there is generally little scope for varying either air or material flow rates. With a test facility air and material flow rates can generally be varied widely, as well as conveying line pressure drop, and instrumentation would be available for the measurement of all of these parameters.

It is most unlikely, however, that sufficient data would be taken so that full sets of conveying characteristics could be drawn. For most systems manufacturing companies this would be an unnecessary and expensive luxury. Relatively few tests would be carried out under chosen conditions that would scale to the required material flow rate for the type of system that the company would want to supply to a customer. If this is a dense phase design they would clearly establish that the material had the necessary conveying capability as part of the test procedure.

16.1.1 Dense phase conveying of cement

To illustrate the scaling process for system design with regard to dense phase conveying, ordinary Portland cement has been selected. This is a material that, by virtue of its mean particle size and particle shape, conveys very well in dense phase at low velocity. It is a major bulk commodity on a worldwide scale and because of its size it is generally conveyed by pneumatic conveying systems. A considerable number of countries manufacture cement and several produce more than 100 million tonne/year. The UK manufactures about 20 million tonne/year and is about twentieth in the 'league'. It is not just in manufacturing plants that it requires conveying. It is distributed to depots by road, rail and sea.

To illustrate the system design process just a single point on the conveying characteristics is taken. If it should be required to scale the whole or part of the conveying characteristics, as was illustrated in Chapter 14 on 'Pipeline scaling parameters', it is simply a matter of repeating the process. For this purpose a grid could be drawn on the

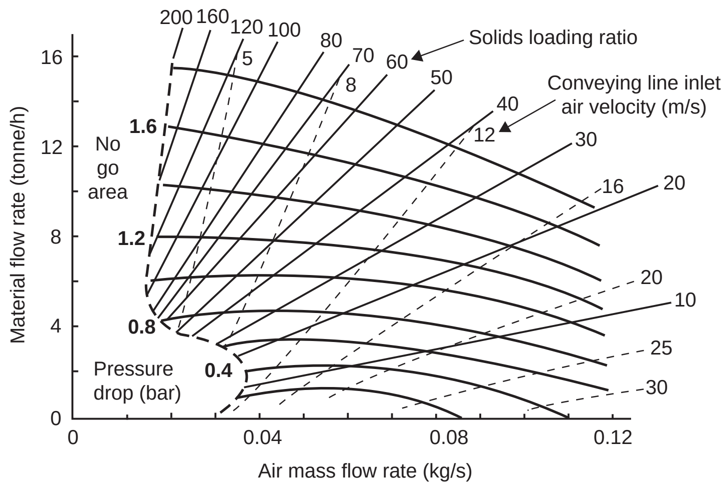


Figure 16.1 Conveying characteristics for cement in pipeline no. 3.

conveying characteristics to be scaled and the value for each grid point evaluated so that a set of conveying characteristics can be constructed for the required pipeline.

16.2 Conveying data

Conveying data for cement conveyed in a conventional pneumatic conveying system was presented in Figure 13.3. It is this data that is to be used in the scaling process and so is reproduced in Figure 16.1 for reference. The conveying system used to generate the data employed a high pressure blow tank for feeding material into the pipeline. This type of feeder is ideal for abrasive materials such as cement since it has no moving parts and is capable of achieving the wide range of conveying conditions required.

The test pipeline used was about 50 m long, 53 mm bore and incorporated nine 90° bends. It was almost entirely in the horizontal plane. This is pipeline no. 3 from Figure 12.12 and is reproduced here in Figure 16.2 for reference.

16.2.1 Conveying duty

It is suggested that a design should be considered for the conveying of the cement over a distance of about 155 m at a rate of 70 tonne/h and that a screw compressor with a 2 bar gauge rating should be used. A sketch of the proposed pipeline is given in Figure 16.3.

The pipeline routing includes a total of 120 m of horizontal pipeline and a total of 35 m of pipeline in which the material is conveyed vertically up. Six 90° bends are incorporated in the pipeline. A steel pipeline is proposed.

16.2.2 Conveying capability

The equivalent length of bends was considered in Section 14.5 and data for 90° bends having a *D*/*d* ratio of 24:1 was presented in Figure 14.16. It was also shown in Section

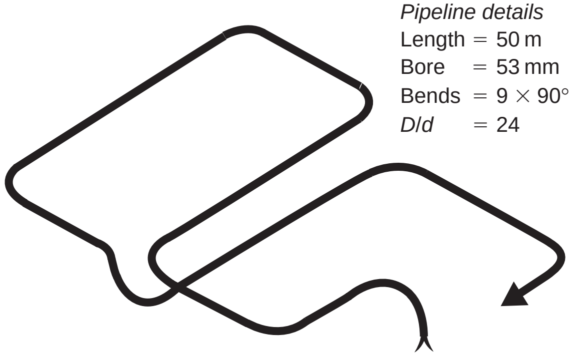


Figure 16.2 Sketch of pipeline no. 3.

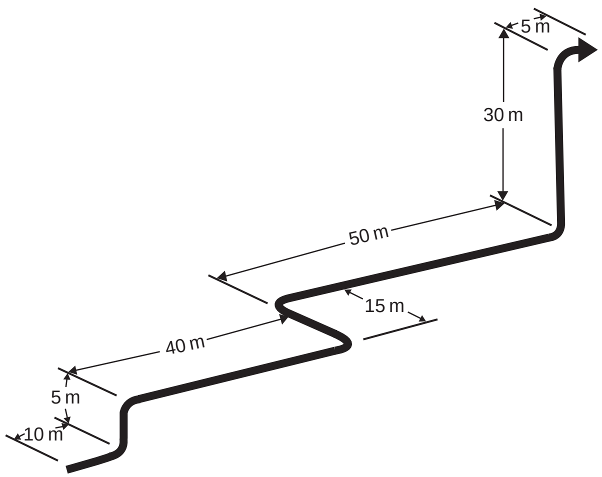


Figure 16.3 Sketch of proposed plant pipeline.

14.5 that the *D*/*d* ratio had little effect on equivalent length for *D*/*d* ratios between about four and forty. It is suggested that radiused bends would be used and Figure 14.16 is reproduced here in Figure 16.4 for reference. It is believed that this relationship is influenced by material type but that this data provides a reasonable average. For materials having a high coefficient of restitution the equivalent length will be lower, but it will be higher for materials such as wheat flour, as considered in Section 14.5.

Cement, as will be seen from Figure 16.1, is capable of being conveyed in dense phase and at low velocity. The potential influence of solids loading ratio on the minimum conveying air velocity was first presented in Chapter 11 with Figure 11.7b. The influence of this relationship on the scaling of the conveying characteristics was considered in Chapter 13. Data specifically for ordinary Portland cement was presented in Figure 13.5 and so this is reproduced here in Figure 16.5 for reference. A similar relationship between minimum conveying air velocity and solids loading ratio holds for all materials capable of being conveyed in dense phase in sliding bed flow. There will, of course, be

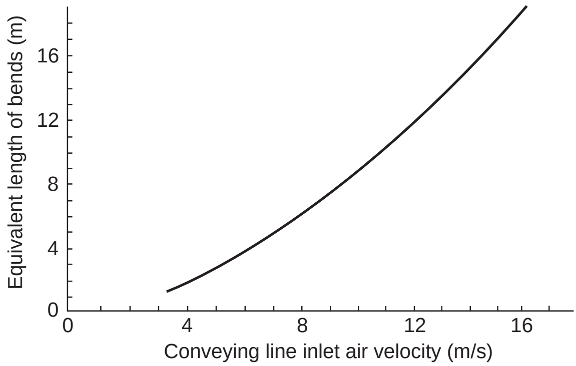


Figure 16.4 Equivalent length of bends.

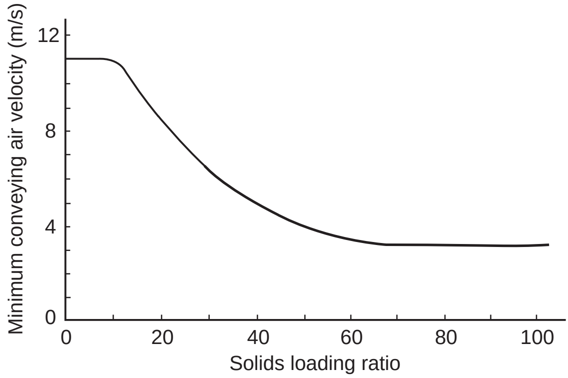


Figure 16.5 Influence of solids loading ratio on the minimum conveying air velocity.

slight variations in the dilute phase conveying limit and the transition to full dense phase conveying capability, as illustrated on Figure 13.5, for other materials.

The design is based on the use of a conveying line inlet air velocity 20 per cent greater than the minimum value as recommended. It is suggested that the design be based upon achieving the 70 tonne/h with a conveying line pressure drop of 1.6 bar. The diameter of pipeline needed to achieve the given duty has to be established first. The volumetric flow rate of air required then needs to be determined for specification of the compressor, together with the power required for the drive motor.

16.2.3 Summary

Design duty

Material		Ordinary Portland Cement
Mean particle size		14 μm
Bulk density	ρ_b	1070 kg/m^3
Particle density	ρ_p	3060 kg/m^3

Pipeline		Figure 16.3
Horizontal	h	120 m
Vertical	v	35 m
Bends	b	$6 \times 90°$
Capability		
Material flow rate	$\dot{m}_p$	70 tonne/h
Air supply		Screw compressor
Delivery pressure	p	2.0 bar gauge
Pipeline inlet pressure	p_1	1.6 bar gauge
Pipeline pressure drop	Δp	1.6 bar
Pipeline inlet velocity	C_1	$1.2 \times C_{min}$
Determine		
Pipeline bore	d	
Free air delivered	$\dot{V}_0$	
Power required	P	

16.3 Procedure

The location of the equivalent operating point on the conveying characteristics for the test pipeline needs to be established first, taking account of the pressure and air flow rate requirements. Scaling is conveniently carried out in two stages. In the first stage scaling is with respect to conveying distance, and this includes both pipeline orientation and bends. In the second stage the scaling is with respect to pipeline bore.

Air only pressure drop values need to be established and so this procedure is also included. In this case, as the pipeline is longer and will be of a larger bore the two effects are likely to cancel each other. If there is likely to be a noticeable difference between the two it would always be recommended that this should be taken into account. Appropriate equations, derived earlier in the Design Guide, are reproduced where required for convenient reference.

16.3.1 Operating point

The operating point on the conveying characteristics for the test pipeline on Figure 16.1 must first be identified. At 1.6 bar the minimum air flow rate is about 0.021 kg/s and so the operating point will correspond with an air flow rate 20 per cent higher at 0.025 kg/s. The corresponding material flow rate is approximately 12.8 tonne/h. This is shown on Figure 16.6 and is identified as point (a) as a first estimate.

16.3.1.1 Conveying line inlet air velocity

The minimum conveying air velocity, C_{min}, corresponding to the conveying limit for a pressure drop of 1.6 bar can be determined by using Equation (9.20), reproduced here as Equation (16.1).

$$C_1 = 0.365 \frac{\dot{m}_a T_1}{d^2 p_1} \text{ m/s} \tag{16.1}$$

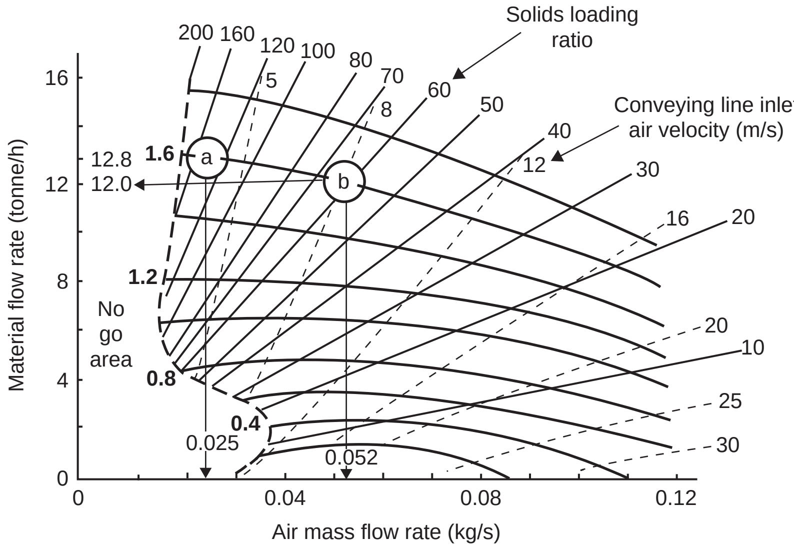


Figure 16.6 Repeat of Figure 16.1 with appropriate operating point identified.

For a pipeline bore, d of 0.053 m, a conveying line inlet air temperature of 15°C ($T_1 = 288$ K), a conveying line inlet air pressure, p_1 of 261.3 kN/m^2 abs, and the above air mass flow rate of 0.021 kg/s, gives:

$$C_{\min} = 0.365 \frac{0.021 \times 288}{0.053^2 \times 261.3} \text{ m/s} = 3.0 \text{ m/s}$$

This corresponds with the conveying limit on Figure 16.5 for a solids loading ratio in excess of seventy. The conveying line inlet air velocity, C_1, will be 20 per cent higher and so:

$$C_1 = 1.2 \times 3.0 = 3.6 \text{ m/s}$$

16.3.1.2 Air only pressure drop for operating point

The air only pressure drop for a pipeline, Δp, can be determined using Equation (10.6), reproduced here as Equation (16.2).

$$\Delta p_a = \left(p_2^2 + \frac{64 f L \dot{m}_a^2 RT}{\pi^2 d^5} \right)^{0.5} - p_2 \quad \text{N/m}^2 \tag{16.2}$$

Taking the conveying line exit air pressure, p_2, to be standard atmospheric pressure of 101 300 N/m^2, the pipeline friction factor, f, to be 0.0045, the length of the test pipeline,

L, as 50 m, the air flow rate as determined above at 0.025 kg/s, R for air $= 287\ \text{J/kg}\cdot\text{K}$, the air temperature $T = 288$ K and the test pipeline bore, d of 0.053 m, gives:

$$\Delta p_a = \left(101\,300^2 + \frac{64 \times 0.0045 \times 50 \times 0.025^2 \times 287 \times 288}{\pi^2 \times 0.053^5}\right)^{0.5} - 101\,300$$

$$= 886\text{N/m}^2 = 0.89\text{kN/m}^2 = 0.009\text{bar}$$

As will be seen this is negligible and not really worthwhile taking into account. This is because it is for very low velocity conveying in a relatively short pipeline. For high velocity dilute phase conveying in a long pipeline it would be essential that this should be taken into account.

Note

For greater accuracy with this air only pressure drop value, if it is be required, an allowance for the bends in the pipeline should also be included. If Equation (10.9) is used for the purpose and a value for k for the bends of 0.2 is taken from Figure 10.6 it will be seen that the equivalent length for all nine bends will come to about 5.4 m. This value should be added to the actual pipeline length of 50 m and used in Equation (16.2).

16.3.2 Equivalent lengths

The equivalent length of a pipeline for the conveying of material takes the length of horizontal pipeline as the reference value. To this is added an equivalent length of straight horizontal pipeline, both for the vertically up sections of pipeline and for the bends in the pipeline. These two elements were considered in Chapter 14 on 'Pipeline scaling parameters'.

For vertically up elements of pipeline in Section 14.6 it was shown that the scaling parameter was two, so that the length of the vertically up sections of pipeline is simply doubled. No significant influence of conveying conditions were found and so it is applied universally to dilute and dense phase conveying. For pipeline bends in Section 14.5 it was shown that the equivalent length of the bends could be related to the conveying line inlet air velocity and the analysis reported provides the basis of the relationship presented in Figure 16.4. It was found that the equivalent length of pipe bends varied little with bend geometry, being reasonably consistent over a D/d range from about four to forty. For very short radius bends, and blind tee bends in particular, however, the equivalent length would be very much greater.

The equivalent length of a pipeline, L_e, therefore, can be expressed as:

$$L_e = h + 2v + Nb \ \text{m} \tag{16.3}$$

where h is the total length of horizontal sections of pipeline; v, the total length of vertically up sections of pipeline; N, the total number of bends in pipeline and b, the equivalent length of each bend.

16.3.2.1 Test pipeline

A sketch of the test pipeline is given in Figure 16.2 and from this it will be seen that the equivalent length of the test pipeline, L_{e1}, is:

$$L_{e1} = 50 + (2 \times 0) + (9 \times 1\tfrac{1}{2}) = 64 \text{ m}$$

There is no significant vertical lift and there are nine bends in the test pipeline. With a conveying line inlet air velocity of 3.6 m/s the equivalent length of the bends, from Figure 16.4, is about 1½ m each.

16.3.2.2 Plant pipeline

A sketch of the plant pipeline is given in Figure 16.3 and from this it will be seen that the equivalent length of the plant pipeline, L_{e2}, is:

$$L_{e2} = 120 + (2 \times 35) + (6 \times 1\tfrac{1}{2}) = 199 \text{ m}$$

The actual length of the plant pipeline is 155 m and it is this length that needs to be used to evaluate the air only pressure drop for the plant pipeline having the same bore as the test pipeline. Neglecting the effect of the bends once again and substituting the length of 155 m in place of 50 m into Equation (16.2) (this is the only parameter to change in this equation), gives:

$$\Delta p_a = 2721 \text{ N/m}^2 = 2.72 \text{ kN/m}^2 = 0.027 \text{ bar}$$

Although this is three times greater than that for the test pipeline, as would be expected, it is still insignificant in terms of the 1.6 bar conveying line pressure drop value. The increase in the air only pressure drop from 0.009 bar to 0.027 bar means that 0.018 bar less pressure is available for conveying material.

This loss in pressure of 0.018 bar should be deducted from the 1.6 bar, which gives 1.582 bar, and it is this value that should be used on Figure 16.6 in order to determine the material flow rate to be used for scaling purposes. Once again, for low velocity high pressure conveying, these pressure drop terms are insignificant, but for long distance, high velocity, low pressure conveying these terms will be significant and will have to be taken into account. This will be illustrated in the next case study in the next chapter.

16.3.3 Scaling for length

The scaling model for pipeline length is given in Equation (14.4) and is reproduced here in Equation (16.4):

$$\dot{m}_{p2} = \dot{m}_{p1} \frac{L_{e1}}{L_{e2}} = 12.8 \times \frac{64}{199} = 4.12 \text{ tonne/h} \tag{16.4}$$

The two equivalent lengths were determined immediately above, and the material flow rate for the test pipeline was obtained from Figure 16.6; 4.12 tonne/h is the material flow rate that would be expected, for the same conveying line pressure drop and air flow rate, if the pipeline had the same bore as the test pipeline, neglecting the effect of the air only pressure drop.

Before considering the options from this result the conveying parameters need to be checked.

16.3.3.1 Conveying conditions – check

A check needs to be made at this point to evaluate the new value of solids loading ratio. This needs to be done in order to determine whether the material can still be conveyed in dense phase, since the operating point for scaling is based on a conveying line inlet air velocity of 3.6 m/s and an air mass flow rate of 0.025 kg/s. The new solids loading ratio, from Equation (1.3), will be:

$$\phi = \frac{4.12}{3.6 \times 0.025} = 45$$

From Figure 16.5 it will be seen that at a solids loading ratio of 45 the minimum value of conveying air velocity is about 4.5 m/s and not 3.0 and so the initial operating point identified on Figure 16.6 is not valid for scaling. As a consequence an operating point on Figure 16.6 having a conveying line inlet air velocity much higher than $1.2 \times 4.5 = 5.4$ m/s will be required to compensate.

16.3.3.2 Conveying conditions – re-calculate

As the check failed at this point it is necessary to return to the operating point on Figure 16.6 and locate a new operating point. From the benefit of the first calculation it would be suggested that a value of conveying line inlet air velocity of about 8 m/s should be tried. This is identified on Figure 16.6 as point (b). The new operating point needs to be a large increase on the first, for in the solids loading ratio term the material flow rate will remain approximately the same, while the air mass flow increases significantly.

From Figure 16.6 the new material flow rate for the test pipeline is now 12.0 tonne/h and the new air flow rate is 0.052 kg/s. Although the air flow rate is very much higher the air only pressure drop values will still be very small, in comparison with the conveying line pressure drop, and so can be neglected once again. The equivalent length of the bends, from Figure 16.4, however, is very much greater. These have increased from 1.6 m/bend for a conveying line inlet air velocity of 3.6 m/s, to 6.1 m/bend for the conveying line inlet air velocity of 8 m/s.

The revised equivalent length for the test pipeline has increased from 50 m to 105 m, and that for the plant pipeline of 53 mm bore has increased from 199 m to 227 m. With these new values in Equation (16.4) the revised material flow rate of

12.0 tonne/h becomes 5.55 tonne/h for the plant pipeline of 53 mm bore. The revised solids loading ratio will be:

$$\phi = \frac{5.55}{3.6 \times 0.052} = 30$$

From Figure 16.5 it will be seen that the minimum conveying air velocity corresponding to a solids loading ratio of 30 is about 6.3 m/s. With a 20 per cent safety margin this gives a conveying line inlet air velocity of about 7.6 m/s. Since the revised calculation was based on a conveying line inlet air velocity of 8.0 m/s this is higher than necessary but reasonably close for the calculation to proceed.

16.3.4 Scaling for bore

A scaling model for pipeline bore is given in Equation (14.8). This is in terms of the material flow rate that will be achieved if the diameter of the pipeline is increased to a given value. In this case the material flow rate has been specified and so the appropriate diameter of pipeline is required. The appropriate equation can be obtained by re-arranging Equation (14.8) and this is presented in Equation (16.5).

$$d_2 = d_1 \left[\frac{\dot{m}_{p2}}{\dot{m}_{p1}} \right]^{0.5} \quad \text{m} \tag{16.5}$$

Substituting data into this equation gives:

$$= 53 \left(\frac{70}{5.55} \right)^{0.5} = 188 \text{ mm}$$

188 mm bore pipeline is not an option, of course, and so the possible options need to be considered:

1. If 70 tonne/h is not critical a 150 mm bore pipeline could be considered. Using Equation (14.8) gives a material flow rate of 44 tonne/h.
2. If a 200 mm bore pipeline is chosen the material flow rate that could be achieved would be about 79 tonne/h.
3. The flow rate of 70 tonne/h could be achieved in a 150 mm bore pipeline if a higher conveying line pressure drop was to be used. With a higher pressure drop the cement could be conveyed at a higher solids loading ratio and this would mean that a lower conveying line inlet air velocity could be used.
4. The flow rate of 70 tonne/h could be achieved in the 200 mm bore pipeline with a lower conveying line pressure drop. With a lower material flow rate, however, the solids loading ratio will be lower and there could be a risk of blocking the pipeline. This situation was considered with Figure 13.6.
5. It is possible that 70 tonne/h could be achieved with a 1.6 bar pressure drop in a 150 mm bore pipeline if it were to be stepped to 200 mm part way along its length.

In assessing tender proposals for such a system, where a design might come on the border-line of pipeline bores, or pressure rating for different components, it is essential that the design options be interrogated in order to determine what margins have been incorporated.

16.3.5 Air requirements

An air supply pressure of 2 bar gauge was selected at the outset, along with a conveying line pressure drop of 1.6 bar, and so the free air flow and an approximate value for the power supply are now required.

16.3.5.1 Air flow rate

The air flow rate will be evaluated for the 200 mm bore pipeline, assuming that the air supply pressure will be about 1.6 bar gauge. The equations for evaluating air flow rate were developed in Chapter 9. The design here is based on a conveying line inlet air velocity of 8.0 m/s and Equation (9.10), reproduced here as Equation (16.6) is appropriate:

$$\dot{V}_0 = 2.23 \frac{d^2 p_1 C_1}{T_1} \text{ m}^3/\text{s} = 2.23 \times \frac{0.200^2 \times 261.3 \times 8.0}{288} = 0.647 \text{ m}^3/\text{s} \qquad (16.6)$$

This is the volumetric flow rate of the air at free air conditions, which are the reference conditions required for the specification of a compressor.

16.3.5.2 Power required

An approximate value for the compressor drive power required was presented in Equation (6.5) and this is reproduced here as Equation (16.7):

$$\text{P} = 203 \dot{V}_0 \ln\left[\frac{p_4}{p_3}\right] \text{kW} = 203 \times 0.647 \ln\left[\frac{261 \times 3}{101 \times 3}\right] = 125 \text{ kW} \qquad (16.7)$$

Chapter 17

Case studies

Part II: Coarse material

17.1 Introduction

For this case study a material has been chosen that has no natural dense phase conveying capability and so can only be conveyed in dilute phase suspension flow in a conventional pneumatic conveying system. The magnesium sulphate had a mean particle size of about 225 μm and so de-aerated very rapidly. The bulk density of the material was about 1010 kg/m^3 and the particle density 2350 kg/m^3. As with dense phase conveying, the minimum conveying air velocity for a material is a critical design parameter, but unlike dense phase conveying there is no significant change in its value with solids loading ratio.

Data on the pneumatic conveying of magnesium sulphate was presented in Chapter 12. The material was conveyed through pipeline no. 6 (Figure 12.24) and the conveying characteristics were presented in Figure 12.23d. It was reported (Section 12.2.6.4) that the minimum conveying air velocity for the material was about 14 m/s. Tests were carried out with conveying line pressure drop values up to 1.8 bar and the maximum value of solids loading ratio that could be achieved was about 10.

17.1.1 Dilute phase conveying of magnesium sulphate

To illustrate the scaling process for system design with regard to dilute phase conveying, the magnesium sulphate is used. Once again just a single point is selected for scaling but the entire conveying characteristics can be scaled if required.

17.2 Conveying data

A sketch of the test pipeline used for this case study is given in Figure 17.1. It is almost identical to pipeline no. 6 reported above but the bore of the pipeline was 105 mm instead of 81 mm.

The pipeline was 95 m long and almost entirely in the horizontal plane. The pipeline incorporated nine 90° bends and they all had a *D*/*d* ratio of 12:1. The pipeline was fed by a high pressure top discharge blow tank. Conveying characteristics for the magnesium sulphate conveyed through this pipeline are presented in Figure 17.2.

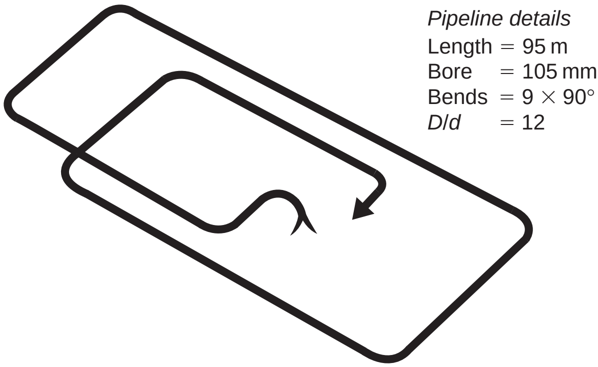


Figure 17.1 Sketch of pipeline no. 15.

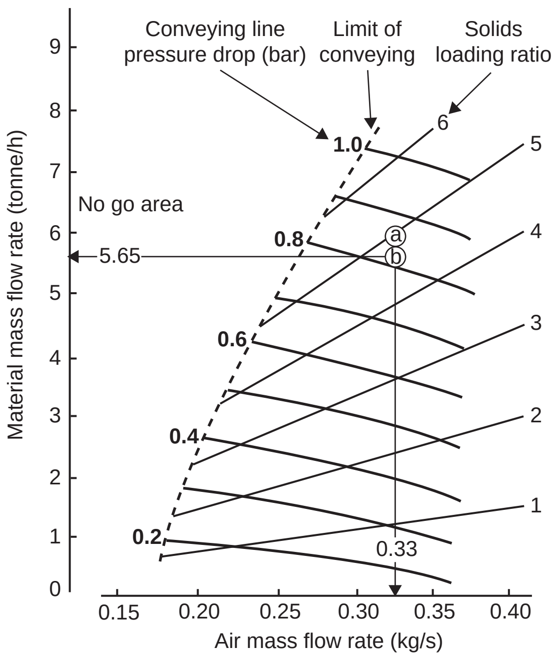


Figure 17.2 Conveying characteristics for magnesium sulphate in pipeline no. 15.

17.2.1 Conveying duty

It is suggested that a design should be considered for the conveying of the magnesium sulphate over a horizontal distance of 300 m at a rate of 15 tonne/h and that a positive displacement blower having a 1 bar gauge delivery pressure capability should be used. It is proposed that the design should be based on a conveying line pressure drop of 0.85 bar. The pipeline routing has a total vertical lift of 25 m and incorporates seven 90° bends.

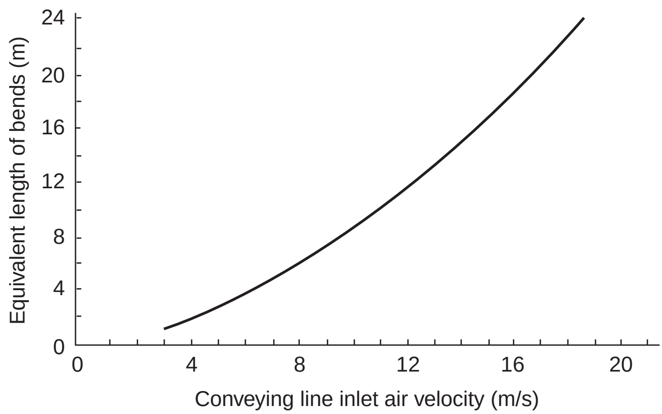


Figure 17.3 Equivalent length of bends.

17.2.2 Conveying capability

In dilute phase conveying the pipeline bends can play a very significant role and so data on the equivalent length of bends from Figure 14.16, and used in the previous case study, is also required here. It is reproduced in Figure 17.3 for reference. The minimum conveying air velocity for the magnesium sulphate in pipeline no. 15 was also 14 m/s. The conveying line inlet air velocity will be based on a velocity approximately 20 per cent higher than this as generally recommended.

17.2.3 Summary

Design duty		
Material		Magnesium sulphate
Mean particle size		225 μm
Bulk density	ρ_b	1010 kg/m^3
Particle density	ρ_p	2350 kg/m^3
Pipeline		
Horizontal	h	300 m
Vertical	v	25 m
Bends	b	$7 \times 90°$
Capability		
Material flow rate	$\dot{m}_p$	40 tonne/h
Minimum air velocity	C_{min}	14 m/s
Air supply		Blower
Delivery pressure	p	1.0 bar gauge
Pipeline inlet pressure	p_1	0.85 bar gauge
Pipeline pressure drop	Δp	0.85 bar
Pipeline inlet velocity	C_1	$1.2 \times C_{min} = 17$ m/s

Determine

Pipeline bore	d
Free air delivered	$\dot{V}_0$
Power required	P

17.3 Procedure

The location of the equivalent operating point on the conveying characteristics for the test pipeline needs to be established first, taking account of the pressure and air flow rate requirements. Scaling is conveniently carried out in two stages. In the first stage scaling is with respect to conveying distance, and this includes both pipeline orientation and bends. In the second stage the scaling is with respect to pipeline bore. Air only pressure drop values need to be established and so this procedure is also included.

17.3.1 Operating point

The operating point on the conveying characteristics for the test pipeline on Figure 17.2 must first be identified. Since the pressure drop line has been chosen as 0.85 bar and the conveying line inlet air velocity has been determined as 17 m/s, the appropriate air mass flow rate can be calculated. This can be determined from Equation (13.1), reproduced here as Equation (17.1) for reference and use:

$$\dot{m}_a = \frac{2.74 p_1 d^2 C_1}{T_1} \text{ kg/s} \tag{17.1}$$

where $\dot{m}_a$ is the air mass flow rate (kg/s); p_1, the conveying line inlet air pressure (185 kN/m^2 abs); d, the pipeline bore (0.105 m); C_1, the conveying line inlet air velocity (17 m/s) and T_1, the conveying line inlet air temperature (288 K (15°C)).

Substituting these values in Equation (17.1) gives

$$\dot{m}_a = 0.330 \text{ kg/s}$$

This operating point is located on Figure 17.2 as point (a) and it will be seen that it is approximately 20 per cent in-board from the conveying limit.

17.3.2 Air only pressure drop values

The air only pressure drop for a pipeline, Δp_a, can be determined using Equation (10.14), reproduced here as Equation (17.2).

$$\Delta p_a = \left[\left(1.0 + \frac{1.34 \psi \dot{m}_a^2}{d^4 \times 10^5} \right)^{0.5} - 1.0 \right] \text{bar} \tag{17.2}$$

where $\psi = (4fL)/d + \sum k$ from Equation (10.11).

17.3.2.1 Test pipeline

Taking the pipeline friction factor, f, to be 0.0045, the length of the test pipeline, L, as 95 m, the pipeline bore, d, as 0.105 m, and the bend loss coefficient as 0.2 (Figure 10.6) for each of nine bends, gives:

$$\psi = \frac{4 \times 0.0045 \times 95}{0.105} + (9 \times 0.2) = 18.1$$

Substituting this value, the air flow rate of 0.330 kg/s and the pipeline bore of 0.105 m into Equation (17.2) gives:

$$\Delta p_a = 0.103 \text{ bar}$$

From this it will be seen that the air only pressure drop is quite significant for dilute phase flow. This value of pressure drop is automatically included in the conveying characteristics in Figure 17.2. A constant pressure drop line of 0.103 bar, if included on the plot, would strike the horizontal axis at an air flow rate of 0.330 kg/s. It also means that at the operating point only $0.850 - 0.103 = 0.747$ bar is used for conveying material. This value will decrease with increase in pipeline length.

17.3.2.2 Plant pipeline of 105 mm bore

The actual length of the plant pipeline is 325 m and it is this length that needs to be used to evaluate the air only pressure drop for the plant pipeline having the same bore as the test pipeline. Taking the pipeline friction factor, f, to be 0.0045, the length of the plant pipeline, L, as 325 m, the pipeline bore, d, as 0.105 m and the bend loss coefficient as 0.2 (Figure 10.6) for each of seven bends, gives:

$$\psi = \frac{4 \times 0.0045 \times 325}{0.105} + (7 \times 0.2) = 57.1$$

Substituting this value, the air flow rate of 0.330 kg/s and the pipeline bore of 0.105 m into Equation (17.2) gives:

$$\Delta p_a = 0.298 \text{ bar}$$

This represents an increase in air only pressure drop of $0.298 - 0.103 = 0.195$ bar. This means that instead of having 0.747 bar for conveying material, it is now reduced to $0.747 - 0.195 = 0.552$ bar. This represents a 26 per cent reduction in available pressure drop and so this will have a very significant effect on the material flow rate that can be achieved. This is in addition to the reduction as a consequence of scaling to a longer pipeline.

To achieve the 15 tonne/h in the plant pipeline, however, a much larger bore pipeline will be required and this will improve the situation considerably. When the conveying characteristics are scaled in total these features can be seen, as with Figures 14.1, 14.4

and 14.5. When only a single point is used the intermediate stage of the data scaled to the plant pipeline, of the test pipeline bore, is not available. This means that a value for the plant pipeline bore needs to be selected at this point. If the value chosen does not meet the required duty the calculation will have to return to this point with an updated value. For 15 tonne/h a bore of 250 mm will be selected.

17.3.2.3 Plant pipeline of 250 mm bore

Taking the pipeline friction factor, f, to be 0.0045, the length of the plant pipeline, L, as 325 m, the pipeline bore, d, as 0.250 m and the bend loss coefficient as 0.2 (Figure 10.6) for each of seven bends, gives:

$$\psi = \frac{4 \times 0.0045 \times 325}{0.25} + (7 \times 0.2) = 24.8$$

For the larger bore of pipeline a new air flow rate will be required. This can either be determined by using Equation (17.1), as for the test pipeline, or scaling the 0.330 kg/s for the test pipeline in proportion to the larger pipe section area. Either way the new air flow rate will come to 1.87 kg/s.

Substituting the new value for ψ, the new air flow rate of 1.87 kg/s and the pipeline bore of 0.250 m into Equation (17.2) gives:

$$\Delta p_{\mathrm{a}} = 0.139 \text{ bar}$$

The original operating point on the material conveying characteristics on Figure 17.2 was set at a pressure drop of 0.85 bar (point a). For the plant pipeline the air only pressure drop is 0.139 bar whereas for the test pipeline it is 0.103 bar, which represents an increase of 0.036 bar. The operating point on Figure 17.2 therefore needs to be reduced by this amount for scaling purposes, to take account of the difference in air only pressure drop values. The new operating point (b) is therefore at a pressure drop of 0.814 bar.

17.3.3 Equivalent lengths

The equivalent length of a pipeline for the conveying of material takes the length of horizontal pipeline as the reference value. To this is added an equivalent length of straight horizontal pipeline, both for the vertically up sections of pipeline and for the bends in the pipeline. These two elements were considered in Chapter 14 on 'Pipeline scaling parameters'. This procedure was considered at this point in the previous case study and an expression for the equivalent length, L_{e}, of a pipeline was given with Equation (16.3). This is reproduced here as Equation (17.3) for use in this case study:

$$L_{\mathrm{e}} = h + 2v + Nb \quad \text{m} \tag{17.3}$$

where h is the total length of horizontal sections of pipeline; v, the total length of vertically up sections of pipeline; N, the total number of bends in pipeline and b, the equivalent length of each bend.

17.3.3.1 Test pipeline

A sketch of the test pipeline is given in Figure 17.1 and from this it will be seen that the equivalent length of the test pipeline, L_{e1}, is:

$$L_{e1} = 95 + (2 \times 0) + (9 \times 20) = 275\,\text{m}$$

There is no significant vertical lift and there are nine bends in the test pipeline. With a conveying line inlet air velocity of 17 m/s the equivalent length of the bends, from Figure 17.3, is about 20 m each. It will be seen from this that the bends can have a dominating effect in dilute phase conveying systems.

17.3.3.2 Plant pipeline

The equivalent length of the plant pipeline, L_{e2}, with 300 m of horizontal pipeline, 25 m of vertical pipeline and seven 90° bends is:

$$L_{e2} = 300 + (2 \times 25) + (7 \times 20) = 490\text{ m}$$

17.3.4 Scaling

The data for the test pipeline can now be scaled to that for the plant pipeline. The first stage is in terms of equivalent length and the second in terms of pipeline bore.

17.3.4.1 Scaling for length

The scaling model for pipeline length is given in Equation (14.4) and is reproduced here in Equation (17.4):

$$\dot{m}_{p2} = \dot{m}_{p1} \frac{L_{e1}}{L_{e2}} = 5.65 \times \frac{275}{490} = 3.17\text{ tonne/h} \tag{17.4}$$

The two equivalent lengths were determined immediately above, and the material flow rate for the test pipeline of 5.65 tonne/h was obtained from the revised operating point on Figure 17.2; 3.17 tonne/h is the material flow rate that would be expected, for the same conveying line pressure drop and air flow rate, if the pipeline had the same bore as the test pipeline.

17.3.4.2 Scaling for bore

A scaling model for pipeline bore is given in Equation (14.8). This is reproduced here as Equation (17.5) for application in this case:

$$\dot{m}_{p2} = \dot{m}_{p1} \times \left[\frac{d_2}{d_1}\right]^2 \tag{17.5}$$

It is the 3.17 tonne/h that needs to be scaled here and substituting data into this equation gives:

$$= 3.17 \times \left(\frac{250}{105}\right)^2 = 18.0 \text{ tonne/h}$$

This is greater than the 15 tonne/h required, but significantly less than 15 tonne/h would be achieved with a smaller 200 mm bore pipeline. A pressure greater than 1.0 bar would be needed if it was required to use a 200 mm bore pipeline, but then it would not be possible to use a positive displacement blower.

With a conveying line inlet air pressure of 0.85 bar gauge the case for stepping the pipeline to a larger bore is marginal. Little improvement in conveying performance would be achieved, but it would certainly help if there was a need to reduce erosive wear of particle degradation.

17.3.5 Air requirements

An air supply pressure of 0.85 bar gauge was selected at the outset and so the free air flow rate and an approximate value for the power supply are now required.

17.3.5.1 Air flow rate

The air flow rate will be evaluated for the 250 mm bore pipeline, assuming that the air supply pressure will be about 0.85 bar gauge. The equations for evaluating air flow rate were developed in Chapter 9. The design here is based on a conveying line inlet air velocity of 17 m/s and Equation (9.10), reproduced here as Equation (17.6) is appropriate:

$$\dot{V}_0 = 2.23\frac{d^2 p_1 C_1}{T_1}\,\text{m}^3/\text{s} = 2.23 \times \frac{0.250^2 \times 185 \times 17}{288} = 1.522\,\text{m}^3/\text{s} \tag{17.6}$$

This is the volumetric flow rate of the air at free air conditions, which are the reference conditions required for the specification of a compressor.

17.3.5.2 Power required

An approximate value for the compressor drive power required was presented in Equation (6.5) and this is reproduced here as Equation (17.7):

$$\text{P} = 203\dot{V}_0 \ln\left[\frac{p_4}{p_3}\right]\text{kW} = 203 \times 1.522 \ln\left[\frac{185}{100}\right] = 190\,\text{kW} \tag{17.7}$$

17.3.5.3 Specific cost

Pneumatic conveying, and particularly dilute phase conveying, does require high energy levels. The cost of transporting material, therefore, is often taken into account when selecting a conveying system. With an estimated value for power required it is possible to evaluate conveying costs.

If the unit cost of electricity is taken as €0.10/kW · h the specific cost can be evaluated as follows:

$$\text{Specific cost} = 190\ \text{kW} \times \frac{\text{h}}{18\,\text{tonne}} \times \frac{10\text{c}}{\text{kW}\cdot\text{h}} = €1.06 \text{ per tonne conveyed}$$

17.3.5.4 Solids loading ratio

The solids loading ratio, ϕ, does not feature at all in these calculations. It is often quoted for reference and so its value will be:

$$\phi = \frac{18}{3.6 \times 1.87} = 2.7$$

As can be seen this is very dilute phase conveying, as expected, but is typical of low pressure long distance conveying systems handling this type of material.

Chapter 18

First approximation design methods

18.1 Introduction

Pneumatic conveying system design is generally carried out either by using published mathematical models, or by using reliable conveying data that may be available. Mathematical models are often used when some confidence has been established in their suitability for a particular application, such as the conveying of a specified material over a given range of conveying conditions. They are, however, generally restricted to dilute phase suspension flow.

Conveying data is used extensively in situations where previous experience is available, or from the results of tests specifically carried out for the purpose of system design. In cases where no previous experience of the material, or the range of conveying conditions required is available, then conveying trials are usually carried out in order to obtain the necessary data for system design. This is particularly so if dense phase conveying is required.

In many cases a quick approximate answer is all that is required initially, rather than a full design study, particularly if it is a feasibility study that is being carried out. A quick check on the expected throughput of a given system is often wanted, or the diameter of pipeline necessary for a given material flow rate may be needed. Very often the air requirements, in terms of supply pressure and volumetric flow rate, are wanted so that the approximate power required, and hence operating cost of the system can be evaluated, as illustrated at the end of the last chapter.

Two first approximation methods for pneumatic conveying system design are presented that will provide a quick solution. One is applicable to both the dilute and dense phase conveying of materials while the other is only for dilute phase suspension flow. It must be emphasized that these are only first approximation solutions, as the title states, and that they should not be used for design purposes. They will, however, provide a reasonable guide to system parameters and can be applied very easily. A particular advantage of one method is that it can be applied to dense phase conveying as well as dilute phase.

18.1.1 Methods presented

One method is based on the value of the air only pressure drop for the pipeline, which is a relatively straightforward parameter to evaluate. All the models and data likely to be required for such an evaluation are presented in Chapter 10, and several applications of the equations are included in the case studies presented in the previous two chapters. It would be recommended that the use of this method should be restricted to dilute phase suspension flow since the accuracy reduces at velocities below about 10 m/s and at solids loading ratios above 20.

The second method is based on the use of a universal set of conveying characteristics, comprising two sets of data. One relates to straight pipeline and the other to the bends in the pipeline. The data covers both dilute and dense phase conveying, but the dense phase conveying is only applicable to sliding bed flow and hence fine powdered materials. It must be emphasized once again that these are strictly quick check methods and will provide only a first approximation solution. This is primarily because there is no reference anywhere in these procedures to the conveyed material.

18.2 Air only pressure drop method

Many of the basic models that are used in pneumatic conveying are mathematically correct, or very closely so. This is the case in evaluating conveying air velocities, for in most pneumatic conveying situations the volume occupied by the conveyed material will be negligible in comparison with that of the air.

18.2.1 Basic equations

The Ideal Gas Law relates the volumetric flow rate of the air to the pressure and temperature of the air. The volumetric flow rate of the air can also be expressed in terms of the conveying air velocity and the pipeline bore. These models, therefore, can be used quite reliably in gas–solid flow situations. Material mass flow rate can be introduced in terms of the solids loading ratio of the conveyed material. The solids loading ratio is a parameter that is often known approximately, and in these cases quite simple equations can be derived equating the variables.

18.2.1.1 Solids loading ratio

Solids loading ratio, ϕ, is defined as the ratio of the mass flow rate of the material conveyed, to the mass flow rate of the air used to convey the material and was presented in the introductory chapter with Equation (1.3). This is a dimensionless ratio and is a particularly useful parameter since its value remains constant along the length of a pipeline, regardless of the air pressure and temperature, and conveying air velocity. It is presented here as Equation (18.1):

$$\phi = \frac{\dot{m}_p}{3.6\dot{m}_a} \qquad (18.1)$$

where ϕ is the solids loading ratio (dimensionless), $\dot{m}_p$, the mass flow rate of material (tonne/h) and $\dot{m}_a$, the mass flow rate of air (kg/s).

18.2.1.2 The Ideal Gas Law

Air mass flow rate is not always a convenient parameter in this work and air flow rate is often better expressed in volumetric terms. The Ideal Gas Law, for a steady flow situation, however, presented in Equation (9.4), can be expressed in terms of air flow rate:

$$\dot{m}_a = \frac{p\dot{V}}{RT} \text{ kg/s} \tag{18.2}$$

18.2.1.3 Volumetric flow rate

An alternative, and more direct, expression for volumetric flow rate is derived from the flow situation:

$$\dot{V} = \text{Velocity} \times \text{Flow Area}$$

and for a circular pipe:

$$\dot{V} = C \times \frac{\pi d^2}{4} \text{ m}^3\text{/s} \tag{18.3}$$

This is the actual volumetric flow rate. Since air and other gases are compressible, volumetric flow rate will change with both pressure and temperature. It also means that the conveying air velocity will vary along the length of a pipeline. A full explanation and analysis of this was included in Chapter 9.

18.2.2 Derived relationships

The three equations presented above can be considered as being exact equations, and so any combination of these equations will similarly produce precise relationships. Although these equations include all the basic parameters in pneumatic conveying, they will not produce design relationships. This is because they do not include the necessary fundamental relationships between material flow rate, pressure drop and conveying air velocity. Combinations of these three equations, however, produce equations that can be usefully used to check system designs. They will also provide a good basis for the inclusion of design relationships.

18.2.2.1 Material flow rate

By substituting Equation (18.3) into (18.2) and then into Equation (18.1) and re-arranging gives:

$$\dot{m}_p = 3.6\phi \times \frac{\pi d^2}{4} \times \frac{pC}{RT} \text{ tonne/h}$$

By putting $R = 0.287\,\text{kJ/kg} \cdot \text{K}$ for air gives:

$$\dot{m}_p = 9.85\phi \frac{pCd^2}{T} \text{ tonne/h} \tag{18.4}$$

18.2.2.2 Pipeline bore

For a given material flow rate and conveying conditions, the diameter of the pipeline is generally required. An alternative arrangement of Equation (18.4) gives:

$$d = 0.319\left[\frac{\dot{m}_p T}{pC\phi}\right]^{0.5} \text{ m} \tag{18.5}$$

18.2.2.3 Conveying line pressure drop

An alternative arrangement, in terms of the pressure required to convey the material gives:

$$p = 0.1015\frac{\dot{m}_p T}{Cd^2\phi} \text{ kN/m}^2 \text{ abs} \tag{18.6}$$

18.2.2.4 Reference conditions

The variables in these equations can be taken at any point along the pipeline. In the case of air pressure and velocity, however, these are generally only known, with any degree of accuracy, at the very start and end of a pipeline. Since the conveying line inlet air velocity is probably the most critical parameter in system design it is generally conditions at the material feed point, at the start of the pipeline, that are used for this purpose.

18.2.3 Empirical relationships

It will be seen from Equations (18.4) to (18.6) that, for a given material and pipeline, there are only a limited number of variables relating the main conveying parameters. Of these the conveying air temperature will be known and either the material flow rate required, pipeline bore to be used, or conveying line pressure drop available will be specified. This means that there are only four variables in these equations.

It will be possible to provide solutions to Equations (18.4)–(18.6), therefore, if two further relationships can be provided. These will, by necessity, be empirical, and so the accuracy of any expressions developed will depend upon the accuracy of the empirical relationships used.

18.2.3.1 Conveying line inlet air velocity

The conveying line inlet air velocity, C_1, to be employed is a value that should be known with a high degree of certainty. The value depends very much upon the material to be conveyed, although for dilute phase conveying it will be in a fairly narrow range of values, and is generally expressed in terms of the minimum value of conveying air velocity for the material.

For dilute phase conveying the minimum value of conveying air velocity, C_{min}, will almost certainly be above 10 m/s. For cement and similar materials it is about 10–11 m/s, and for fine fly ash and similar materials it is about 11–12 m/s. For granular alumina it

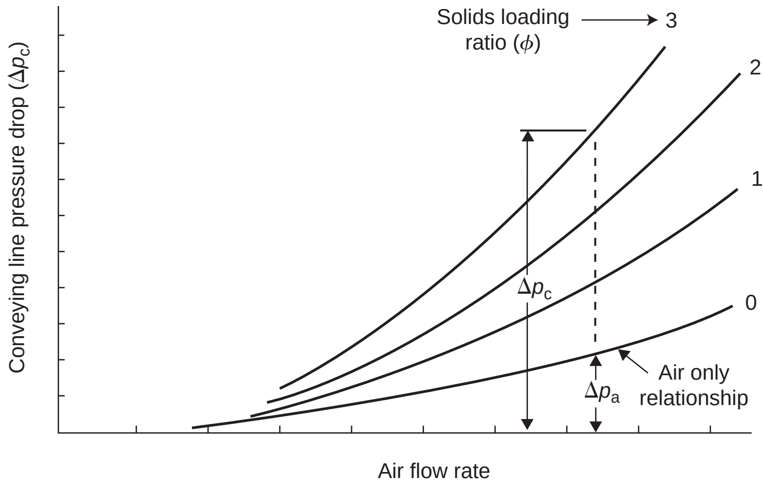


Figure 18.1 Influence of solids loading ratio and air flow rate on conveying line pressure drop for dilute phase suspension flow.

is about 13–14 m/s and for granulated sugar approximately 16 m/s, the value depending mainly upon mean particle size, particle shape and particle size distribution.

Design would generally be based on a conveying line inlet air velocity, C_1, 20 per cent greater than the minimum conveying air velocity:

$$C_1 = 1.2C_{\text{min}} \text{ m/s} \tag{18.7}$$

18.2.3.2 Solids loading ratio

An approximate relationship between pressure drop and solids loading ratio, for dilute phase conveying, is presented in Figure 18.1. This is an alternative way of plotting test data for a material, such as that presented in Figure 11.6, but is rarely done because it is of limited use. The relationship is based upon the assumption that the curves on Figure 18.1 are equi-spaced with respect to conveying line pressure drop. When conveying test data is plotted in this manner it is surprising how many materials approximate to this relationship in dilute phase flow. A mathematical expression for this is:

$$\phi = \frac{\Delta p_c}{\Delta p_a} - 1 \tag{18.8}$$

where Δp_c is the conveying line pressure drop (kN/m^2) and Δp_a, the air only pressure drop (kN/m^2).

18.2.4 Working relationships

With the set of three derived relationships that can be considered to be reasonably precise, and two empirical relationships, some straightforward relationships can be obtained that can be used for providing a quick check on a system design or on the operation of an existing system.

18.2.4.1 Material flow rate

By directly equating Equations (18.1) and (18.8) and re-arranging, an expression for material flow rate is derived:

$$\dot{m}_p = 3.6\dot{m}_a\left[\frac{\Delta p_c}{\Delta p_a} - 1\right] \text{tonne/h} \tag{18.9}$$

If air mass flow rate, $\dot{m}_a$, is not a convenient parameter, it can be expressed in terms of conveying air velocity by substituting Equation (15.3) to give:

$$\dot{m}_p = 9.85\,\frac{pCd^2}{T} \times \left[\frac{\Delta p_c}{\Delta p_a} - 1\right] \text{tonne/h} \tag{18.10}$$

Pipeline inlet conditions are the most convenient to use here.

18.2.4.1.1 Negative pressure systems

For vacuum systems the pressure, p, will be atmospheric.

18.2.4.1.2 Positive pressure systems

For positive pressure systems the pressure, p, in Equation (18.10) will be equal to the conveying line pressure drop, Δp_c, plus atmospheric pressure. This is:

$$p = \Delta p_c + p_{atm}$$

where Δp_c is the conveying line pressure drop (kN/m^2) and p_{atm}, atmospheric pressure (kN/m^2)

18.2.4.2 Pipeline bore

By substituting the solids loading ratio, ϕ, from Equation (18.8) into (18.5), the expression can be in terms of the pipeline bore required:

$$d = 0.319\left[\frac{\dot{m}_p T \Delta p_a}{pC(\Delta p_c - \Delta p_a)}\right] \text{m} \tag{18.11}$$

The situation for both positive and negative pressure systems is the same as above.

18.2.4.3 Air supply pressure

Alternatively, the expression can be in terms of the pressure required to convey the material. Substituting the solids loading ratio, ϕ, from Equation (18.8) into (18.6) gives:

$$p = 0.1015 \times \frac{\dot{m}_p T}{Cd^2} \times \frac{\Delta p_a}{(\Delta p_c - \Delta p_a)} \quad \text{kN/m}^2 \text{ abs} \tag{18.12}$$

Pipeline inlet conditions are again the most convenient to use.

18.2.4.3.1 Negative pressure systems

For negative pressure systems the pressure, p, will be atmospheric and hence Δp_c can be determined, which is the value required in this case. Re-arranging Equation (18.12) and expressing in terms of pipeline inlet conditions gives:

$$\Delta p_c = \Delta p_a \left[0.1015 \frac{\dot{m}_p T_1}{C_1 d^2 p_{atm}} + 1 \right] \text{kN/m}^2 \tag{18.13}$$

18.2.4.3.2 Positive pressure systems

For a positive pressure system:

$$\Delta p_c = p - p_{atm}$$

Substituting this into Equation (18.12) and expressing in terms of pipeline inlet conditions gives:

$$p_1(p_1 - p_{atm} - \Delta p_a) = 0.1015 \times \frac{\dot{m}_p T_1 \Delta p_a}{C_1 d^2}$$

This is a quadratic equation, the solution to which is:

$$p = \frac{1}{2} \left\{ p_{atm} + \Delta p_a + \left[(p_{atm} + \Delta p_a)^2 + \frac{\dot{m}_p T_1 \Delta p_a}{2.46\, C_1 d^2} \right]^{1/2} \right\} \tag{18.14}$$

Note: This will give the correct root.

18.2.4.4 Air only pressure drop

Since the air only pressure drop, Δp_a, features prominently in these models, a convenient expression for this pressure drop is required. An expression that will give the air only pressure drop in terms of conveying line inlet, or exit, air velocity is needed.

18.2.4.4.1 Negative pressure systems

For negative pressure systems the expression also needs to be in terms of the inlet air pressure, p_1, since this is generally known (usually atmospheric). Such an equation was developed in Chapter 10 (Equation (10.20)) and is:

$$\Delta p_a = p_1\left[1 - \left(1 - \frac{\psi C_1^2}{RT_1}\right)^{0.5}\right] \tag{18.15}$$

Note: The value of R for air will have to be 287 J/kg · K to make the group in the brackets dimensionless, and then the units of Δp_a will be same as those used for p_1.

18.2.4.4.2 Positive pressure systems

For positive pressure systems the expression needs to be in terms of the exit pressure, p_2, since this is generally known (usually atmospheric). Such an equation, also developed in Chapter 10 (Equation (10.17)) is:

$$\Delta p_a = p_2\left[\left(1 + \frac{\psi C_2^2}{RT_2}\right)^{0.5} - 1\right] \tag{18.16}$$

Note that R must have units of J/kg · K as in Equation (18.15) above.

18.2.4.5 Vertical conveying

The models presented so far relate essentially to horizontal pipelines. Most pneumatic conveying systems, however, will include a vertical lift and so this needs to be taken into account. The pressure drop in vertical conveying over a very wide range of solids loading ratio values, is approximately double that for horizontal conveying, as considered in Chapter 14. Sections of vertical conveying in a pipeline, therefore, can most conveniently be accounted for by working in terms of an equivalent length and allowing double for vertical lifts. This equivalent length replaces the actual pipeline length in Equation (10.2) and subsequent equations.

18.2.5 Procedure

To illustrate the process it is proposed to investigate the possibility of conveying a coarse material at a flow rate, $\dot{m}_{p1}$, of 30 tonne/h using a positive displacement blower and a positive pressure conveying system. The pipeline is 135 m long, with 110 m horizontal and 25 m vertical lift, giving an equivalent length, L_e, of 160 m, plus five 90° bends. It is assumed that the temperature of the air and material at the conveying line inlet, T_1, are 300 K (27°C).

In the first instance the possibility of conveying the material in a 200 mm bore pipeline, d_1, is to be investigated. Since the material can only be conveyed in dilute phase suspension flow a conveying line inlet air velocity, C_1, of 17 m/s is taken.

18.2.5.1 Air only pressure drop

The starting point in the process is to evaluate the air only pressure drop, Δp_a, for the pipeline and potential conveying parameters. Details of the pipeline are specified but those for the conveying parameters will not be known until the calculation is completed, and so assumptions will need to be made in order to get the process started. If, at the end of the calculation the assumptions made are too far removed from the values calculated, the process will have to be repeated, and hence it is an iterative solution.

Possibly the best equation for the air only pressure drop for the given situation is Equation (18.16) presented above. The conveying line outlet air velocity, C_2, is the only unknown here and so a value has to be estimated. If it is estimated that the conveying line pressure drop will be about 0.75 bar, then C_2 will approximately equal $1.75 \times C_1$, and as C_1 is 17 m/s, as specified earlier, then C_2 will be approximately 30 m/s.

The pipeline friction loss coefficient was presented in Chapter 10:

$$\psi = \frac{4fL}{d} + \Sigma k \qquad (18.17)$$

This was Equation (10.11). Taking a bend loss coefficient of 0.2 (Figure 10.6) for each of the five bends, and a pipeline exit loss coefficient of 1.0 (Figure 10.10), gives a value of $\Sigma k = 2$. Substituting a pipeline friction coefficient $f = 0.0045$, the equivalent length of 160 m and the pipeline bore of 0.2 m gives:

$$\psi = 16.4$$

Substituting these values for C_2 and ψ into Equation (18.16), along with the known parameters, gives:

$$\Delta p_a = 101.3\left[\left(1 + \frac{16.4 \times 30^2}{287 \times 300}\right)^{0.5} - 1\right] = 8.34\ \text{kN/m}^2$$

18.2.5.2 Air supply pressure

Since the pipeline bore and material flow rate have been specified, it is the conveying line pressure drop that needs to be determined. Equation (18.14), developed and presented above, is appropriate for the given situation and the substitution of the parameters into this equation gives:

$$p = \frac{1}{2}\left\{101.3 + 8.34 + \left[(101.3 + 8.34)^2 + \frac{30 \times 300 \times 8.34}{2.46 \times 17 \times 0.2^2}\right]^{1/2}\right\}$$

$$= 174.1\ \text{kN/m}^2\ \text{abs}$$

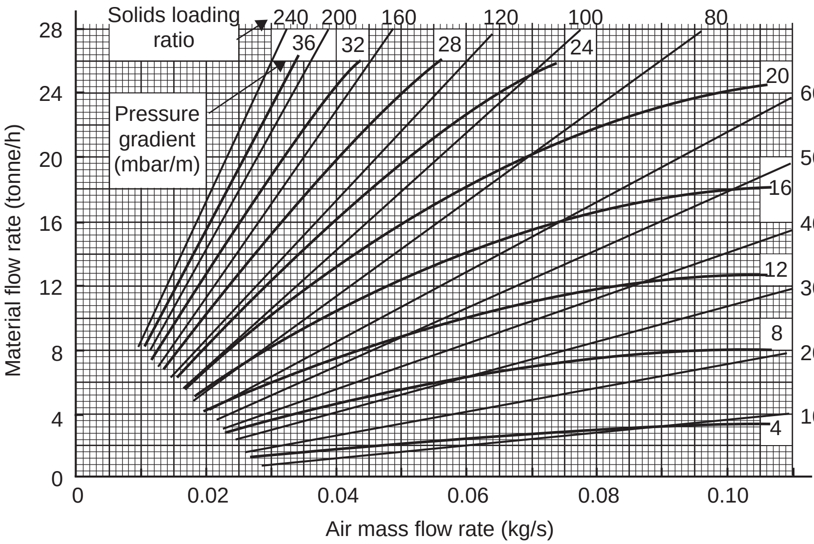


Figure 18.2 Reference pressure gradient data for horizontal conveying in 53 mm bore pipeline.

and this equates to a conveying line pressure drop

$$\Delta p_c = 73 \text{ kN/m}^2 \quad \text{or} \quad 0.73 \text{ bar}$$

Since this value is lower and very close to that of the original estimate then a 200 mm bore pipeline would appear to be appropriate for the duty.

18.3 Universal conveying characteristics method

The pressure required to convey a material through a pipeline can be divided into a number of component parts. The most important are the straight pipeline sections and the bends. For each of these elements there are a multitude of sub variables that can have and influence, but their incorporation necessarily adds to the complication of the process. A compromise is clearly needed in order to provide a quick first approximation method.

18.3.1 Straight pipeline

A considerable amount of published data exists on the pneumatic conveying of materials through pipelines. Much of it was generated by the author when commissioned by the Department of Trade and Industry in the UK to write the original Design Guide for Pneumatic Conveying, and even more has been generated subsequently. Typical data for the horizontal conveying of material through straight pipeline is presented in Figure 18.2.

Figure 18.2 is a graph of material flow rate plotted against air mass flow rate, which is the usual form for presenting the conveying characteristics for materials. Lines of constant solids loading ratio can be drawn quite easily on this plot as they are simply straight lines through the origin. Lines of constant pressure gradient, in mbar/m, are also superimposed. The data was initially derived from conveying trials with cement and barytes, but has since been found to be reasonably close to that for many other materials.

The data in Figure 18.2 represents the pressure gradient, in mbar/m, for conveying material through straight horizontal pipeline of 53 mm bore. As will be seen, it covers both dilute and dense phase, with a smooth transition between the two. This first approximation method is based on the use of this data and so it will be seen that there is no specific reference to material type, and hence this is one of the main reasons for this being an approximate method, as the title states.

To the pressure drop for conveying the material must be added the pressure drop for the air alone in the pipeline. Vertical elements of pipeline and bends also need to be considered. Pipeline bore and hence air flow rates need to be taken into account and decisions need to be taken on conveying air velocity, particularly with dense phase conveying capability.

18.3.1.1 Vertical pipelines

For flow vertically up it was shown in Chapter 14 that the pressure gradient is approximately double that for horizontal conveying and that this applies over an extremely wide range of solids loading ratios. To take account of vertically up sections of pipeline, therefore, the pressure gradient values on Figure 18.2 simply need to be doubled for any operating point on the chart.

For flows in vertically down sections of pipeline the situation is very different. In dense phase flows there is a pressure recovery, such that the pressure gradient has a negative value. For dilute phase flows, however, there is a pressure loss. The transition between the two occurs at a solids loading ratio of about 35 and at this value materials can be conveyed vertically down with no pressure drop at all. Figure 18.2, therefore, cannot be used in this case.

If, in a long pipeline, there is only a very short length of vertically down pipeline, it is suggested that it can be ignored, in terms of the overall accuracy of this method, for both and dense phase flows. If a conveying system does have a significant proportion of pipeline which is vertically down, the user if referred to the more detailed conveying characteristics presented in Figures 11.13 and 14.25.

18.3.1.2 Pipeline bore

Material flow rate varies approximately in proportion to pipe section area, and hence in terms of (diameter)^2. Air flow rate, to maintain the same velocity in a pipeline of different bore, varies in exactly the same way. To determine the pressure gradient for flow in a pipeline having a bore different from that of the reference data in Figure 18.2, both the material and air flow rates should be adjusted in proportion to $(d_2/53)^2$, where d_2 is the diameter of the plant pipeline in mm. It will be noted that there will, therefore, be no change in the value of the solids loading ratio.

It must be appreciated that along the length of a pipeline, as the pressure drops and the conveying air velocity increases, the pressure gradient is likely to increase. In Figure 18.2 a single value is given for the entire pipeline. This value can be taken to be

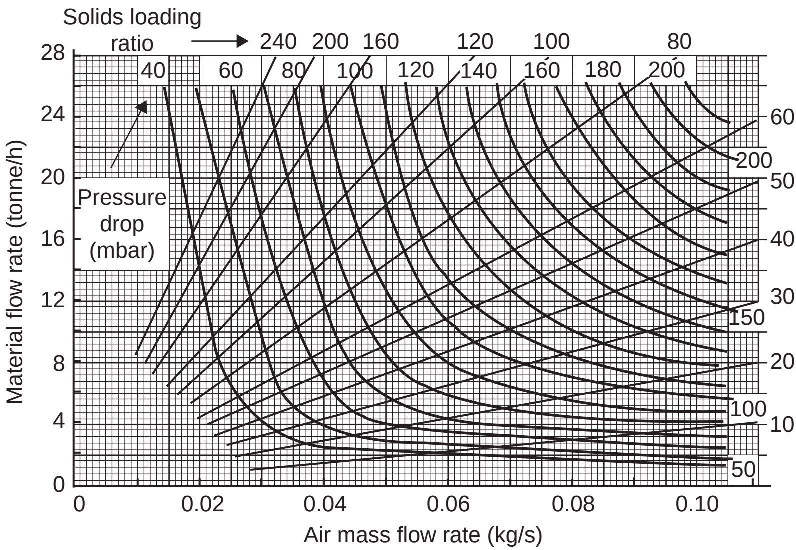


Figure 18.3 Pressure drop data for 90° radiused bends in a 53 mm bore pipeline.

an average for the pipeline, but it is another feature that reinforces the point that this is only an approximate method.

18.3.1.3 Stepped pipelines

When high pressure air is employed it is usual to increase the bore of the pipeline to a larger diameter along the length of the pipeline. By this means the very high velocities that will result in a single bore pipeline, from the expansion of the air, can be prevented. By this means it is often possible to gain a significant increase in performance of the pipeline.

The pressure drop in a stepped bore pipeline can be evaluated in exactly the same way as outlined above. A critical point in stepped bore pipelines is the location of the steps along the length of the pipeline. At each step in the pipeline the conveying air velocity must not be allowed to fall below a given minimum value, otherwise the pipeline is liable to block at that point. The solution, therefore, is likely to be an iterative one since the velocity of the air at the step depends upon the pressure at the step.

18.3.2 Pipeline bends

Pressure drop data for bends in pipelines is presented in Figure 18.3. This is an identical plot to that in Figure 18.2 and covers exactly the same range of conveying conditions, in terms of both air and material flow rates and hence solids loading ratios. The pressure drop in this case is for an individual bend in the pipeline and hence is in mbar per bend.

The data presented in Figure 18.3 relates to 90° radiused bends in a 53 mm bore pipeline. This is also data that was initially derived from conveying trials with cement and barytes, but has since been found to be reasonably close to that for many other materials. From an extensive programme of conveying trials with bends of different bend diameter, D, to pipe bore, d, ratios, and reported in section 14.5.2, it was found that pressure drop varied little over a very wide range of D/d ratios.

It has been found that the pressure drop in blind tee bends, however, is significantly higher. An appropriate allowance, therefore, should be made if very short radius bends, blind tees or similar pocketed bends are to be fitted into a pipeline.

Little data exists for bends other than those having an angle of 90° and so it is suggested that the data in Figure 18.3 is used for all bends, since 90° bends are likely to be in the majority in any pipeline. In the absence of any reliable data on the influence of pipeline bore it is suggested that the data in Figure 18.3 is used for all bends, regardless of pipeline bore. For larger bore pipelines the material and air flow rates will have to be scaled in the same way as outlined for the straight pipeline in Figure 18.2.

18.3.3 Minimum conveying air velocity

The conveying line inlet air velocity to be used is the starting point in the design process and a value is based on the minimum conveying air velocity. Once a value is established, together with a conveying line inlet air pressure, the air mass flow rate can be determined so that the operating point on Figures 18.2 and 18.3 can be located.

For dilute phase conveying a relatively high conveying air velocity must be maintained to ensure that the material does not drop out of suspension and block the pipeline. This is typically in the region of 10–12 m/s for a very fine powder, to 14–16 m/s for a fine granular material, and beyond for larger particles and higher density materials. For dense phase conveying, air velocities can be down to 3 m/s, and lower in certain circumstances.

18.3.3.1 Conveying line inlet air velocity

It is generally recommended that, for design purposes, the pick-up, or conveying line inlet air velocity at the material feed point, should be about 20 per cent greater than the minimum conveying air velocity, as discussed above with Equation (18.7). This should provide sufficient margin to allow for surges in material flow, air mover characteristics, and other contingencies. An unnecessarily high conveying air velocity should not be employed as this will have an adverse effect on system performance, in terms of air pressure needed, and hence power requirements.

For guidance purposes an approximate value of the pick-up or conveying line inlet air velocity to be employed for pneumatic conveying is given in Figure 18.4 and so this incorporates the 20 per cent margin. For convenience, materials here are classified as being either ‘floury’ or ‘sandy’. Floury materials are those that are very fine and have good air retention properties and will convey in dense phase in a moving bed type of flow. Sandy materials are typically fine granular materials that have neither air retention nor permeability and so will only convey in dilute phase suspension flow in a conventional pneumatic conveying system. These curves simply represent ‘average’ materials for which Figures 18.2 and 18.3 also apply.

18.3.4 Operating point

Knowing the conveying line inlet air velocity, C_1, the air mass flow rate can be evaluated so that the operating point on Figures 18.2 and 18.3 can be established. The appropriate

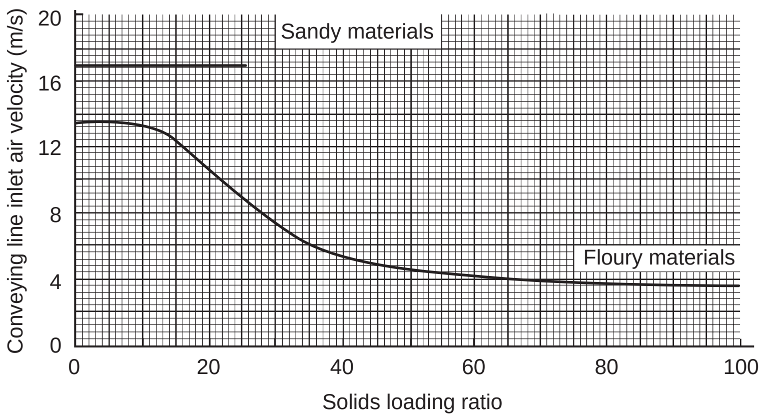


Figure 18.4 The influence of solids loading ratio on conveying line inlet air velocity for sandy and floury materials.

model for this was presented with Equation (17.1), reproduced here as Equation (18.18) for reference:

$$\dot{m}_a = \frac{2.74\, p_1 d^2 C_1}{T_1} \text{ kg/s} \tag{18.18}$$

where $\dot{m}_a$ is the air mass flow rate (kg/s); p_1, the conveying line inlet air pressure (kN/m^2 abs); d, the pipeline bore $= 0.053$ m; C_1, the conveying line inlet air velocity (m/s) and T_1, the conveying line inlet air temperature (K).

A value of conveying line inlet air pressure, p_1, will have to be specified, if not known, but this is part of the 'loop' in this iterative method of analysis.

18.3.4.1 Solids loading ratios

The solids loading ratio, ϕ, is included on Figures 18.2 and 18.3 and can be used in helping to identify the location of the operating point on these two figures, in addition to air and material flow rates. Any two of these three parameters can be used.

For dilute phase conveying, maximum values that can be achieved are generally of the order of 15, although this can be higher if the conveying distance is short or the available pressure high. Typical conveying characteristics for materials having only dilute phase conveying capability, with a high pressure air supply were shown earlier in Chapters 11 and 12.

For moving bed flows, solids loading ratios of well over 100 can be achieved if materials are conveyed with pressure gradients of the order of 20 mbar/m. Typical conveying data for a number of materials having such conveying capability was also shown earlier in Chapters 11 and 12.

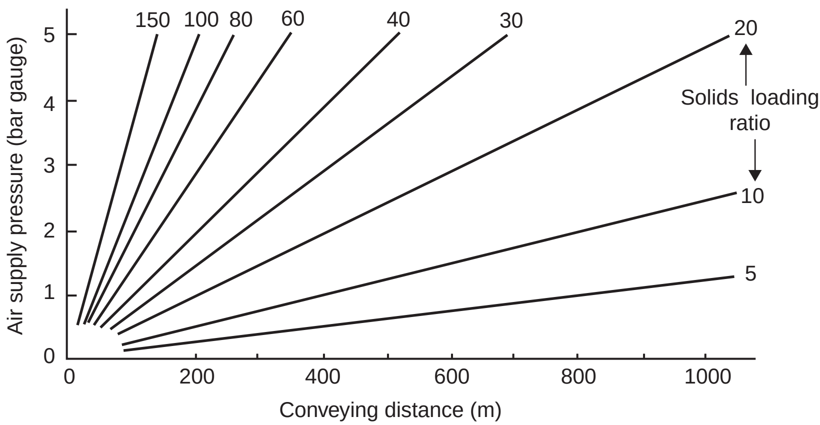


Figure 18.5 Influence of air supply pressure and conveying distance on solids loading ratio for high pressure systems.

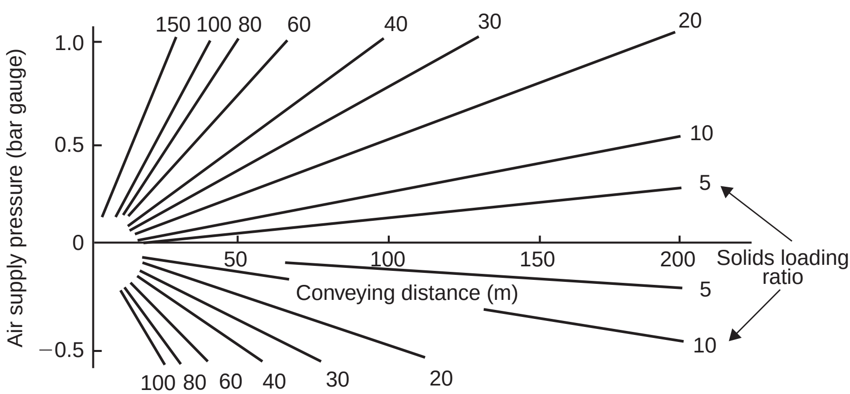


Figure 18.6 Influence of air supply pressure and conveying distance on solids loading ratio for low pressure systems.

18.3.4.2 Influence of distance and pressure

The design method presented here is an iterative process, and particularly so for dense phase conveying where the conveying line inlet air velocity is a function of the solids loading ratio. To provide some guidance in this process, for dense phase conveying, the potential influence of conveying distance and air supply pressure on the solids loading ratio is presented in Figures 18.5 and 18.6. These were presented earlier in Figures 12.27 and 12.28. Once again it must be stressed that these figures are only approximations for the purpose of illustration and should not be used on their own for design purposes.

Figure 18.5 is drawn for high pressure, long distance conveying systems, with air supply pressures up to 5 bar gauge and pipeline lengths up to 1 km. It will be noticed from this that the capability of dense phase conveying gradually reduces with increase in conveying distance and this is due to the pressure gradient requirement mentioned above.

Figure 18.6 is drawn for shorter distance, low pressure systems, up to 1 bar gauge, and with vacuum conveying included. It should be noted that dense phase conveying is possible with low pressure vacuum conveying systems, as will be seen on Figure 18.6. This is because dense phase conveying is a function of pressure gradient, as mentioned above, and not on distance or pressure drop alone.

Figures 18.5 and 18.6 are included in order to provide guidance in the design process presented. Pipeline bore, conveying air velocity and material type will all have an influence on the overall relationship and so they cannot be used for design purposes, as mentioned above.

18.3.5 Air only pressure drop

As mentioned earlier, the data in Figure 18.2 relates to the conveying of the material through the pipeline, and so the pressure drop required for the air alone must be added. The potential influence of pipeline length on the value of the air only pressure drop was presented in Figure 10.4, and the influence of pipeline bore was illustrated in Figure 10.5. All the equations and data necessary for evaluating this quantity were presented in Chapter 10. A number of the equations included in Chapter 10 were used in the case studies in Chapters 16 and 17. They were used there to evaluate the air only pressure drop for specific operating points and this is what is required here also.

18.3.6 Procedure

To illustrate the process two cases are considered, one for dilute phase and another for dense phase conveying. The same pipeline and duty that were taken in the example used for the previous air only pressure drop method are also used. This was to convey the material at 30 tonne/h. The pipeline was 135 m long, with 110 m horizontal and 25 m vertical lift, giving an equivalent length, L_e, of 160 m, plus five 90° bends. It was assumed that the temperature of the air and material at the conveying line inlet, T_1, are 300 K (27°C). Local atmospheric pressure is taken to be 101.3 kN/m^2.

18.3.6.1 Dilute phase conveying

For the dilute phase conveying case a low pressure conveying system is considered having a positive displacement blower operating with a conveying line pressure drop of about 0.75 bar. A sandy material is chosen, and from Figure 18.4a conveying line inlet air velocity of 17 m/s is taken, which is the same as in the case at Section 18.2.5.

From Equation (18.18), taking a conveying line inlet air pressure of 0.75 bar gauge, the air mass flow rate in a 53 mm bore pipeline will be:

$$\dot{m}_a = \frac{2.74 \times 176.3 \times 0.053^2 \times 17}{300} = 0.077 \text{ kg/s}$$

As an initial estimate it is assumed that a 200 mm bore pipeline will be required. Since the data in Figures 18.2 and 18.3 relates to a 53 mm bore pipeline the 30 tonne/h needs to be scaled down, for which Equation (14.8) can be used:

$$\dot{m}_{p53} = \dot{m}_{p200} \times \left[\frac{d_{53}}{d_{200}}\right]^2 \text{ tonne/h} \tag{18.19}$$

so that

$$\dot{m}_{p53} = 30 \times \left[\frac{53}{200}\right]^2 = 2.1 \text{ tonne/h}$$

With this material flow rate and the above air flow rate, the operating point can be located on both Figures 18.2 and 18.3. This will now allow an evaluation of the three elements of pressure drop that need to be taken into account: (1) the pressure drop for conveying material through the pipeline, (2) the pressure drop due to the bends and (3) the air only pressure drop for the total pipeline.

1. From Figure 18.2 the pressure gradient is about 2.8 mbar/m and so as the equivalent length of the pipeline (straight sections only in this case) is 160 m, this element of pressure drop is 160 m $\times$ 2.8 mbar/m $=$ 0.448 bar.
2. From Figure 18.3 the pressure drop for the bends is 43 mbar/bend and so for a total of five bends this element of pressure drop is 5 bends $\times$ 43 mbar/bend $=$ 0.215 bar.
3. The air only pressure drop for the given conveying conditions can be obtained by applying Equation (18.16). The value of ψ comes to 16.4. The conveying line exit air velocity, C_2, as determined in the procedure for the previous method is about 30 m/s, and substituting these values into Equation (18.16) gives a value for the air only pressure drop of 0.083 bar.

The total pressure drop, therefore, to convey 30 tonne/h comes to 0.448 + 0.215 + 0.083 = 0.746 bar. As the original estimate was 0.75 bar, a repeat of the calculations with a second loop is clearly not necessary. This type of breakdown of the different elements of the pressure drop shows that about 11 per cent of the total is due to the air alone and 29 per cent is due to the five bends in the pipeline. An evaluation of power requirements gives about 100 kW.

18.3.6.2 Dense phase conveying

For the dense phase conveying case a high pressure conveying system is considered having a screw compressor operating with a conveying line pressure drop of about 2.5 bar. A floury material is chosen and so the selection of a value for the conveying line inlet air velocity is more complicated, depending upon the value of solids loading ratio, and hence involving an additional loop in the calculation procedure.

By reference to Figure 18.5, an approximate value of solids loading ratio can be obtained to start the process. The pipeline has a horizontal length of 110 m, a vertical lift of 25 m, and five bends. Doubling the vertical length and making an estimate of 5 m/bend, gives an overall equivalent length for the pipeline as approximately 185 m. With a conveying line pressure drop of 2.5 bar the solids loading ratio will be of the order of sixty from Figure 18.5. From Figure 18.4 the appropriate conveying line inlet air velocity will be about 4.4 m/s.

From Equation (18.18), taking a conveying line inlet air pressure of 2.5 bar gauge, the air mass flow rate in a 53 mm bore pipeline will be:

$$\dot{m}_a = \frac{2.74 \times 351.3 \times 0.053^2 \times 4.4}{300} = 0.040 \text{ kg/s}$$

From Figure 18.2 the operating point corresponding to an air mass flow rate of 0.040 kg/s and a solids loading ratio of 60 gives a material flow rate of 8.7 tonne/h. From Equation (18.19) the diameter of pipeline required to achieve 30 tonne/h will be:

$$d = 53 \times \left[\frac{30}{8.7}\right]^{0.5} = 98.4 \text{ mm}$$

The calculation, therefore, will proceed on the basis of a 100 mm bore pipeline; 30 tonne/h in a 100 mm bore pipeline scaled down to 53 mm bore gives:

$$\dot{m}_{p53} = 30 \times \left[\frac{53}{100}\right]^2 = 8.4 \text{ tonne/h}$$

With this material flow rate and the above air flow rate, the operating point can be located on both Figures 18.2 and 18.3. This will now allow an evaluation of the three elements of pressure drop that need to be taken into account: (1) the pressure drop for conveying material through the pipeline, (2) the pressure drop due to the bends and (3) the air only pressure drop for the total pipeline.

1. From Figure 18.2 the pressure gradient is about 12.5 mbar/m and so as the equivalent length of the pipeline is 160 m once again, this element of pressure drop is 160 m × 12.5 mbar/m = 2.00 bar.
2. From Figure 18.3 the pressure drop for the bends is 66 mbar/bend and so for a total of five bends this element of pressure drop is 5 bends × 66 mbar/bend = 0.33 bar.
3. The air only pressure drop for the given conveying conditions can be obtained by applying Equation (18.16). The value of ψ comes to 30.8. The conveying line exit air velocity, C_2, can be determined approximately from C_1 from the relationship:

   $$p_1 \mathrm{C}_1 = p_2 C_2$$

since there is no change in pipeline bore or temperature and so

$$351.3 \times 4.4 = 101.3 \times C_2$$

from which

$$C_2 = 15.3 \text{ m/s}$$

and substituting the values for ψ and C_2 into Equation (18.16) gives a value for the air only pressure drop of 0.042 bar.

The total pressure drop, therefore, to convey 30 tonne/h comes to 2.00 + 0.33 + 0.04 = 2.37 bar.

Checks now need to be made. For the solids loading ratio the air mass flow rate is required and so from Equation (18.18):

$$\dot{m}_a = \frac{2.74 \times 338.3 \times 0.100^2 \times 4.4}{300} = 0.136 \text{ kg/s}$$

This relates to the 100 mm bore pipeline through which 30 tonne/h is to be conveyed and so the solids loading ratio, from Equation (18.1), is:

$$\phi = \frac{30}{3.6 \times 0.136} = 61$$

This is close enough to the original estimate of 60 and the pressure drop of 2.37 bar is sufficiently close to the 2.5 bar selected for repeat calculations not to be necessary, particularly as the solids loading ratio is higher than estimated and the pressure drop is lower than estimated.

A breakdown of the different elements of pressure drop for this case shows that about 2 per cent of the total is due to the air alone and 14 per cent is due to the five bends in the pipeline. The power requirements for this case are approximately 30 kW. These numbers are very different from those for the dilute phase conveying of the material at the same flow rate and through the same pipeline.

Chapter 19

Multiple use systems

19.1 Introduction

Not all pneumatic conveying systems are dedicated to the conveying of a single material over just one distance. In many cases several materials have to be conveyed to a number of different reception points. In a manufacturing process a single pipeline may be used to convey a diverse range of materials from a number of supply hoppers to a single delivery point for blending. In many industries, such as glass and food, a wide variety of materials have to be conveyed by a common system, since there is a requirement to deliver a given 'menu' for a particular process.

In ship off-loading a single line may be used to unload several different materials and to convey them to separate locations. Road and rail vehicles, and ships with their own off-loading facilities, are often required to discharge their materials into reception silos through pipelines of varying distances and geometry. In all of these cases it is essential that each material should be conveyed successfully, but each material may have different conveying characteristics and as a consequence the air requirements for the conveying of different materials, and the material flow rates achieved, can vary significantly. Conveying distance can also have a significant influence on conveying performance [1].

Some of the materials to be transported may be capable of being conveyed in dense phase, and hence at low velocity, while others may have no dense phase capability and will have to be conveyed in dilute phase with a high conveying air velocity. The conveying performance of different grades of the same material can also differ widely. Alumina and fly ash are two common materials that can come in a number of different grades. It is often necessary for different grades of either of these materials to be conveyed by a common system.

The design of these systems, therefore, requires very careful consideration. Fly ash, for example, collected in air pre-heater and economizer hoppers is usually coarse, and in general can only be conveyed in dilute phase, while the ash collected in the precipitator hoppers is usually fine and can normally be conveyed very easily in dense phase. By employing stepped pipelines, different materials such as these can be conveyed quite easily by a common pneumatic conveying system.

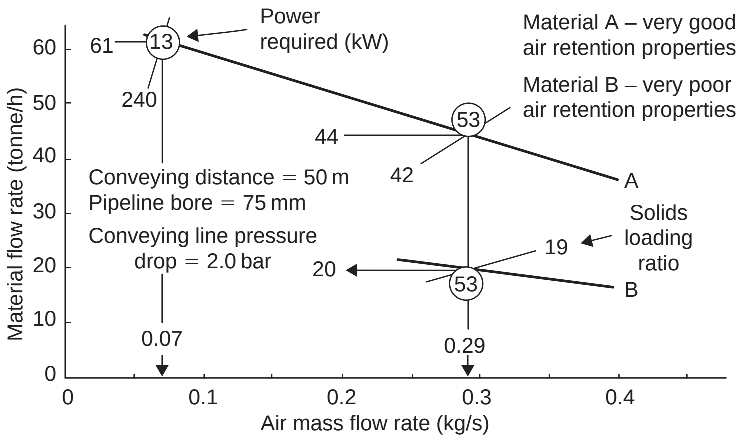


Figure 19.1 A comparison of the potential performance and air requirements of a system required to convey different materials over a distance of 50 m.

19.2 Multiple material handling

In many pneumatic conveying systems several materials may have to be handled by the one system and pipeline. The conveying characteristics present the necessary relationships between the main conveying parameters for a particular material in a specified pipeline and enable a system design to be carried out. If the materials have different conveying characteristics particular care will have to be taken in the specification of the correct air flow rate, and provision should be made for the control of the air flow rate. It is also most unlikely that it would be possible to achieve the same flow rate with each type of material.

These points can be explained by reference to Figures 19.1 and 19.2, which are plots of material flow rate against air mass flow rate. Lines of constant conveying line pressure drop have been drawn for two different materials. For Figure 19.1 the data for material A comes from Figure 15.5 and for material B from Figure 15.6.

If an air flow rate in excess of the minimum value is used to convey each material it will be seen from Figure 19.1 that material A will require 0.07 kg/s of air and material B 0.29 kg/s. In each case the material is conveyed through a 50 m long pipeline of 75 mm bore with a conveying line pressure drop of 2.0 bar.

If the air supply available to the system represented in Figure 19.1 was only specified for material A, at 0.07 kg/s, it would not be possible to convey material B at all. Thus the air supply for the system would have to be based on material B. If the full air flow rate of 0.29 kg/s was used to convey material A, however, the flow rate achieved would only be 44 tonne/h. With an air flow rate of 0.07 kg/s a flow rate of 61 tonne/h could be achieved with material A.

It should be noted that this much higher material flow rate can be achieved with only one quarter of the power required to convey material B, or material A at 44 tonne/h if the same air flow rate is used. A similar situation is shown in Figure 19.2

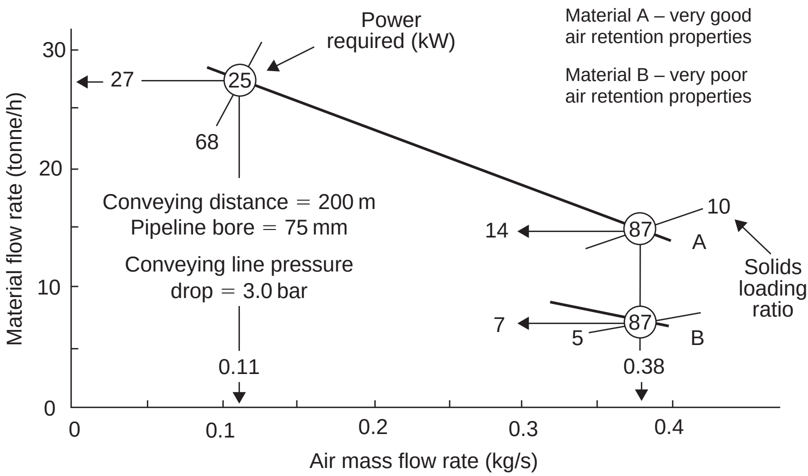


Figure 19.2 A comparison of the potential performance and air requirements of a system required to convey different materials over a distance of 200 m.

with a 200 m long pipeline of the same bore. In this case the potential reduction in flow rate of material A is particularly marked since this is a relatively long pipeline of small bore. Full sets of conveying characteristics for materials A and B conveyed over 200 m are presented in Figures 15.9 and 15.10.

It is clear from the data presented on Figures 19.1 and 19.2 that some form of control of the air supply is required. Control of the material flow rate is also required, of course. In both cases presented a considerable increase in the flow rate of material A could be achieved if the air flow rate could be reduced. Apart from the increase in material flow rate there is also the potential for considerable energy savings. In the case presented in Figure 19.1 the increase of 17 tonne/h could be achieved with a 40 kW saving in power, and in the case presented in Figure 19.2 the proportions are even greater.

19.2.1 Air supply control

The control that can be applied to the air supply depends to a large extent upon the type of air mover used or the source of air available. The performance characteristics of the air mover must be considered in order to determine the best means of control, as discussed in relation to Figures 6.5 and 6.6. The initial choice of air mover, of course, is particularly important, for in some cases it will not be possible for the one machine to meet the full range of duties.

With some machines it may not be possible to obtain independent control of flow rate and pressure, and with others it may prove difficult to achieve the potential energy saving. If a general high pressure air supply service is available, choked flow nozzles can be used most effectively to control the air flow rate at a given pressure, but the energy saving will depend upon the air supply system employed. The use of choked flow nozzles was considered in Section 10.4. With some pneumatic conveying systems operating with their own self-contained air supply, others using a general service supply, and with such a wide range of air movers available, each with it own operating characteristics, it is quite impossible to offer general recommendations on system control in this respect.

High, low and negative pressure systems all require separate treatment, with control of the air mover being necessary in some cases, and control by means of the air supply line being possible in other cases. The important points to bear in mind are that different materials are quite likely to have different volumetric air flow and power requirements, and that the air supply should be capable of meeting both the maximum demand and being conveniently controlled to lower demand levels.

19.2.2 Material flow control

Since different materials have different flow rate capabilities in a given conveying line, due consideration should be given to the material feeding device. Changes in material feed rate must clearly be made, for if a design was based on the conveying of material B only, for example, the pipeline would be considerably under-utilized for the conveying of material A. Alternatively, if the design was based on material A, the pipeline would almost certainly block when conveying material B, even if the air flow rate was correct.

The feeding device, therefore, should be capable of operating satisfactorily and conveniently over the range to be encountered. With volumetric feeders, such as rotary valves and screws, differences in material bulk densities should also be taken into account as well as differences in flow rate.

19.3 Multiple delivery points

Many pneumatic conveying systems are required to deliver a material to a number of different locations. For example, by means of diverter valves in a pipeline several hoppers or silos can be loaded from a given supply point. If the delivery points are at varying distances from the supply point, however, it is unlikely that it would be possible to achieve the same material flow rate to each point. With different material flow rates, and hence solids loading ratios, it is possible that air flow rates would also have to be adjusted for a material capable of being conveyed in dense phase.

These points can be explained with reference to Figures 19.3 and 19.4. These are plots of material flow rate against air mass flow rate, and lines of constant conveying line pressure drop have been drawn for conveying distances of 100 and 200 m.

Figure 19.3 shows the situation for a material having very good air retention properties and Figure 19.4 is for a material with very poor air retention properties. An air flow rate 20 per cent in excess of the minimum value required to convey each material is used for illustration purposes. Full sets of conveying characteristics for materials A and B in Figures 19.3 and 19.4 were presented in Figures 15.7–15.10.

19.3.1 Material influences

For materials capable of being conveyed in dense phase, an increase in conveying distance for a constant conveying line pressure drop will result in a reduction in material flow rate, and so the material will have to be conveyed at a lower solids loading ratio. At a lower value of solids loading ratio a higher minimum conveying air velocity will be

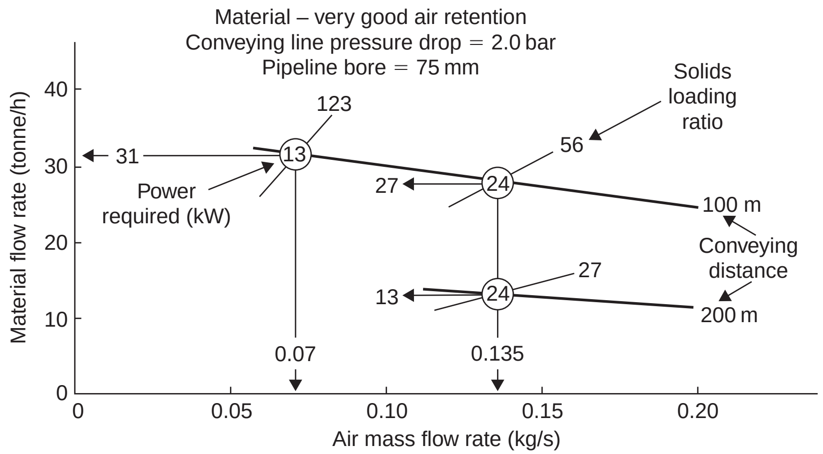


Figure 19.3 A comparison of the potential performance and air requirements of a system required to convey a material having very good air retention over different distances.

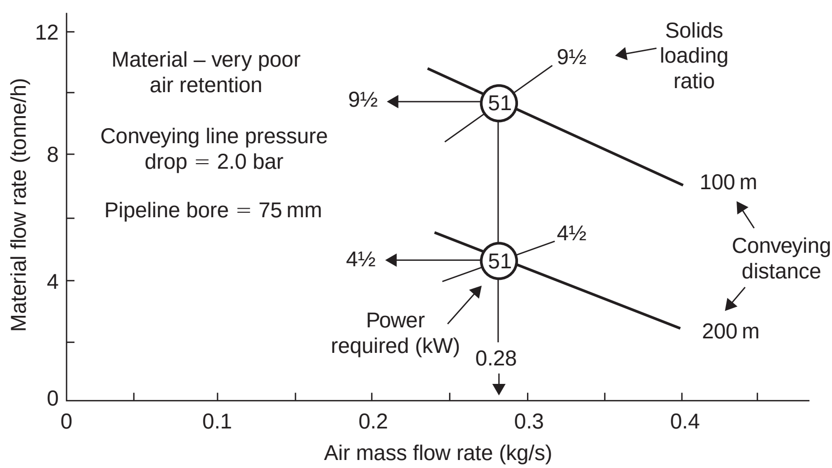


Figure 19.4 A comparison of the potential performance and air requirements of a system required to convey a material having very poor air retention over different distances.

required, and hence an increase in air flow rate will be necessary. For the case shown in Figure 19.3, 0.07 kg/s of air would be needed to convey the material over 100 m as the solids loading ratio is 123; 0.135 kg/s of air would be required to convey the material over 200 m for the solids loading ratio has reduced to about 27.

This is similar to the situation presented earlier with multiple material handling and presents the same design problems. If the air supply available to the system was specified only for a distance of 100 m, at 0.07 kg/s, it would not be possible to convey the material over a distance of 200 m, even if the air supply pressure were to be reduced to compensate. If the full air flow rate of 0.135 kg/s, necessary to convey the material over 200 m, was to be used to convey the material of 100 m, however, the flow rate would be less and the power required would be very much higher than that with the correct air flow rate.

A means of controlling the air flow rate to the value appropriate to the conveying distance, therefore, needs to be incorporated in the air supply system. Controls will also be necessary on the material feed, as discussed earlier with respect to multiple material handling. In the case of materials that can only be conveyed in dilute phase suspension flow no change in minimum conveying air velocity, and hence air flow rate, is necessary. There will, of course, be a change in material flow rate, as shown in Figure 19.4, and so material flow rate control will be required.

19.4 The use of stepped pipelines

The use of stepped pipelines is generally associated with the need to reduce the magnitude of the velocity of the conveying air towards the end of the pipeline of a high pressure, or high vacuum, pneumatic conveying system. This was considered in detail in Section 9.4. The problems of both erosive wear and material degradation increase exponentially with increase in conveying velocity, and so the use of stepped pipelines provides a means by which the excessively high velocities at the end of a conventional single bore pipeline can be reduced.

Stepped pipelines, however, can often be used in cases where different materials need to be conveyed by a common system and so simplify the system design and controls. In other cases it may be possible to use a common system but to feed into pipelines having a different bore. Some examples are given for reference.

19.4.1 Flour and sugar

There is often a requirement for a pneumatic conveying system to convey both flour and sugar. Although sugar comes in a number of grades, it is most commonly produced and available in granulated form. Granulated sugar has little dense phase conveying capability in a conventional pneumatic conveying system and normally must be conveyed with a minimum conveying air velocity of about 16 m/s. Flour, however, is usually produced as a fine material that can generally be conveyed very easily in dense phase and at low velocity in a conventional pneumatic conveying system.

Conveying data for granulated sugar and wheat flour were presented in Figure 12.11 and were derived from a programme of conveying trials conducted with a high pressure blow tank and conveyed through pipeline no. 3, shown in Figure 12.12. The conveying characteristics are reproduced here in Figure 19.5 for reference. From Figure 19.5a it will be seen that the granulated sugar could only be conveyed in dilute phase and at high velocity, despite the availability of high pressure air, and the maximum value of solids loading ratio achieved was little more than 15. The flour, however, could be conveyed at solids loading ratios up to 200 and with conveying air velocities down to about 3 m/s.

From Figures 19.5a and b it will be seen that the materials are very different in their conveying capability, and with a common pipeline it would not be possible to achieve

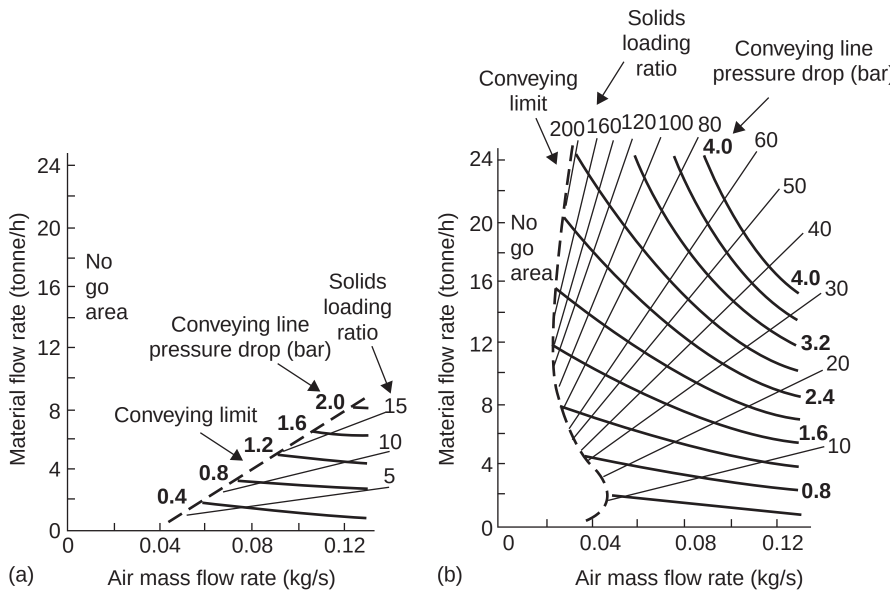


Figure 19.5 Conveying characteristics for materials conveyed through Pipeline no. 3: (a) granulated sugar and (b) wheat flour.

Table 19.1 Comparison of conveying parameters for granulated sugar and wheat flour conveyed through pipeline no. 3 with a conveying line pressure drop of 2.0 bar

Conveying parameters	Units	Material conveyed		
		Sugar	Flour	
		Minimum*	Minimum*	As sugar
Inlet air pressure	bar gauge	2.0	2.0	2.0
Inlet air velocity	m/s	19.2	3.6	19.2
Air mass flow rate	kg/s	0.154	0.029	0.154
Material flow rate	tonne/h	7	15	6
Solids loading ratio	–	12.6	144	10.8
Power required	kW	28	5.2	28
Specific energy	kJ/kg	14.4	1.25	16.8

* Conveying conditions

optimum conveying conditions for both materials. A compromise would have to be made, but because of the very much higher air requirements of the sugar, it would be the sugar that would dictate the design for the combined system. To illustrate the nature of the problem a design based on the use of an air supply pressure of 2 bar gauge and a conveying line inlet air velocity 20 per cent greater than the minimum conveying air velocity is assumed. The data for this situation is presented in Table 19.1 [2, 3].

With a minimum conveying air velocity of 16 m/s, a conveying line inlet air velocity of 19.2 m/s is required, and the corresponding material flow rate is about 7 tonne/h. For the same conveying line pressure drop and air flow rate the material flow rate for the flour will be about 6 tonne/h. If the flour was conveyed with a conveying line inlet air velocity of 3.6 m/s, however, the material flow rate achieved would be about 15 tonne/h and hence significantly more economical.

Approximate power requirements and specific energy values for the different cases are also given in Table 19.1. For the case considered it will be seen that the specific energy values for flour and sugar differ by a factor of about 11.5:1, based on optimum conveying conditions, and that the specific energy required for the flour must increase by a factor of about 13.4 in order to use the same air supply and pipeline. The magnitude of the potential differences is such that it is often more economical to install a separate conveying system for each material. By using a stepped pipeline, however, it is possible to achieve optimum conveying conditions for each material with a common conveying system. This is illustrated with two further sets of material below.

19.4.2 Alumina

Alumina comes in a range of grades and these are generally referred to as sandy or floury. The sandy grades are coarser than the floury grades, and in general the sandy grades can only be conveyed in dilute phase in a conventional conveying system, but the division between the two is often very close. Conveying characteristics for a typical sandy grade of alumina and for a typical floury grade of floury alumina were presented in Figure 13.21 and are reproduced in Figure 19.6 for reference. Both materials were conveyed through the same pipeline (pipeline no. 8) and a sketch of this is given in Figure 13.20.

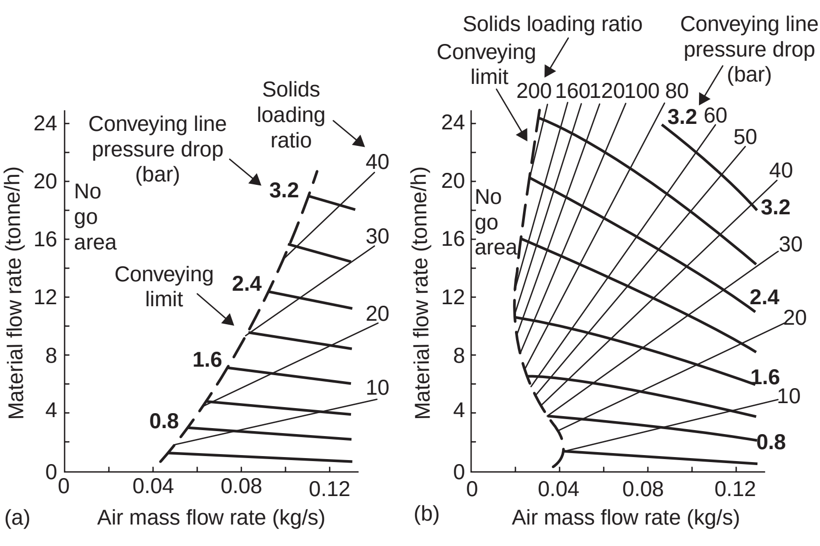


Figure 19.6 Conveying characteristics for alumina conveyed through Pipeline no. 8: (a) sandy alumina and (b) floury alumina.

Conveying trials were undertaken with air supply pressures up to 3.2 bar for each material. Despite the high pressure, the sandy alumina could only be conveyed in dilute phase, and a minimum conveying air velocity of 10 m/s had to be maintained for successful conveying. The floury alumina, however, could be conveyed in dense phase, and at only 3 m/s at high values of solids loading ratio. Unlike the flour and sugar, the two grades of alumina showed very similar conveying capabilities for high velocity dilute phase conveying, probably because there was little difference in particle size and shape between the two grades of the material.

Compared with the granulated sugar in Figure 19.5a, the sandy alumina tested was a very fine granular material and so could be conveyed at a much lower velocity than 16 m/s. As a consequence of this, together with a higher air supply pressure, a slightly shorter pipeline and fewer bends, solids loading ratios of just over 40 were achieved, but this is still dilute phase suspension flow. It is suspected that the material is just on the boundary of having dense phase conveying capability, and that a slightly finer grade would probably have the necessary air retention to make dense phase conveying a possibility.

If a 20 per cent margin is allowed on minimum conveying air velocity, in order to specify a conveying line inlet air velocity for design purposes, the minimum value for the sandy alumina will be 12.0 m/s and for the floury alumina it will be 3.6 m/s. To show how a common conveying system might be able to convey both materials, a graph is plotted of conveying air velocity against conveying air pressure and a series of curves for different pipeline bore is superimposed in Figure 19.7.

Figure 19.7 is drawn for a free air flow rate of 0.5 m^3/s and onto this are drawn possible velocity profiles for the two materials. Due to the extremely wide difference in conveying air velocities a single bore line is suggested for the floury alumina, and three

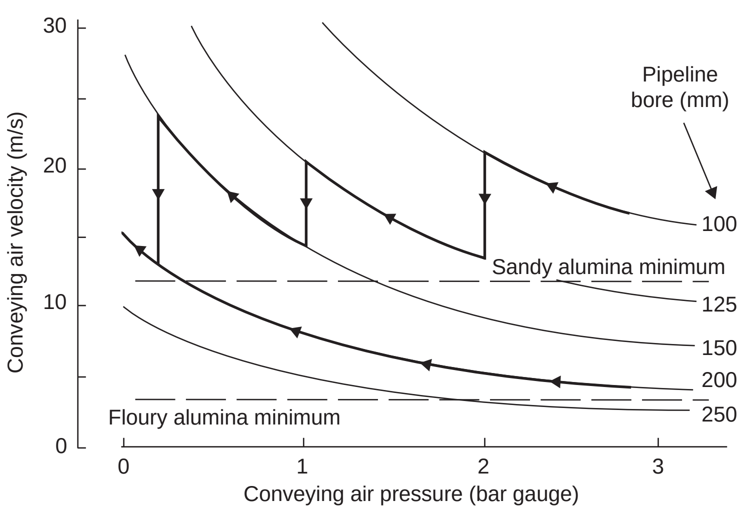


Figure 19.7 Pipeline conveying air velocity profiles for the conveying of both sandy and floury alumina in a common positive pressure conveying system.

steps are required in the pipeline for the sandy alumina, but it will be seen that the pipeline system meets the requirements of both materials. At entry to the silo a common bore pipe is possible, as illustrated, but this is not necessarily a requirement.

The use of two completely different pipelines is not likely to be a problem. The pipeline used for the floury alumina in Figure 19.7, therefore, could well be stepped part way along its length to 250 mm bore, which could not possibly be used with the sandy alumina. Consideration would have be to given in this case, however, to purging of the pipeline, since the maximum value of conveying air velocity in the pipeline would only be about 10 m/s.

19.4.3 Pulverized fuel ash

Fly ash is another material that can come in a very wide range of sizes, depending upon both the size distribution of the coal generated by the pulverizing mills for combustion in the boiler, and the location of collection hoppers within the boiler plant. The material is essentially the same, wherever it is collected, but the conveying capability of the different grades thus generated can be very considerable [4].

Conveying characteristics for a sample of coarse fly ash from an economizer hopper and those for a sample of fine fly ash from the second field of an electrostatic precipitator hopper were shown in Figure 13.25 and are reproduced here in Figure 19.8 [4,5]. Both materials were conveyed through the same pipeline and a sketch of this is given in Figure 13.24. A high pressure top discharge blow tank was also used for the conveying

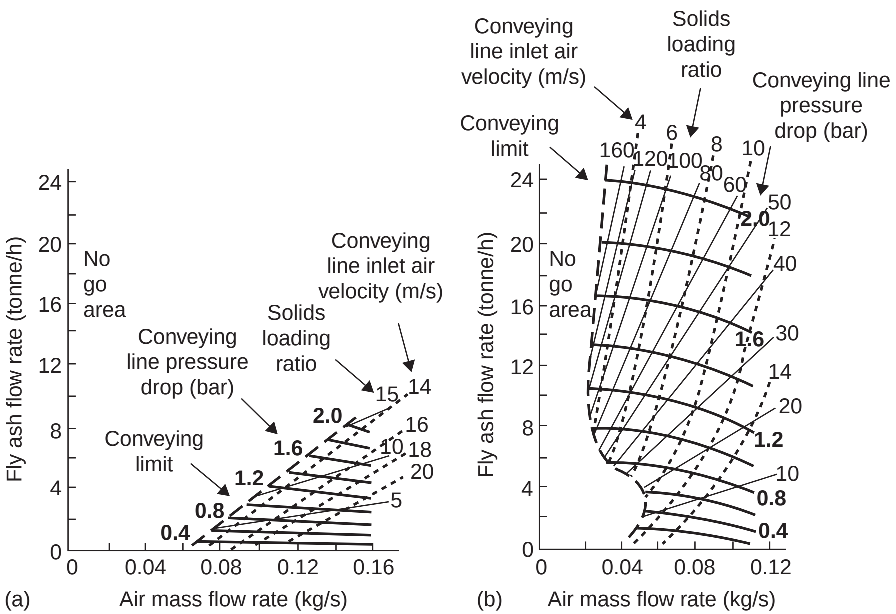


Figure 19.8 Conveying characteristics for materials conveyed through pipeline no. 3: (a) coarse fly ash and (b) fine fly ash.

of these materials, but the pipeline used was of a larger bore and significantly longer that those used for the two previous sets of materials.

The conveying characteristics are shown side by side once again so that a direct visual comparison of the two materials can be made. On these conveying characteristics lines of constant conveying line inlet air velocity have also been added for reference. For the coarse grade of fly ash it will be seen that the minimum conveying air velocity was about 13 m/s and that this did not vary with solids loading ratio. For the fine grade of the fly ash the minimum value of conveying air velocity was about 3 m/s. For the coarse fly ash the maximum value of solids loading ratio was about 15 and for the fine fly ash it was about 160.

Once again these values are dictated by a combination of air supply pressure, minimum conveying air velocity and conveying distance. It will be seen that the main operating area on the conveying characteristics for the fine fly ash occurs in the no go area for the coarse fly ash, and so the design of a common system for the conveying of both grades of the material may not be immediately obvious, particularly for a vacuum conveying system. Vacuum conveying systems are often used for the transferring of fly ash from the boiler hoppers to intermediate hoppers for onward transfer.

As with the alumina, a graph has been drawn of conveying air velocity against conveying air pressure, with lines of constant pipeline bore superimposed. Onto this has been drawn the conveying air velocity profiles for fine ash and coarse ash. A negative pressure conveying system has been considered, with an air flow rate of 1.0 m^3/s at inlet to the compressor at a pressure of 30 kN/m^2 absolute.

To avoid confusion an isothermal case has been considered with all temperatures at 300 K, as with the alumina considered above. For the coarse ash a minimum value of conveying air velocity of 16 m/s has been taken, and for the fine ash a value of 6 m/s has been used. The resulting velocity profiles are presented on Figure 19.9.

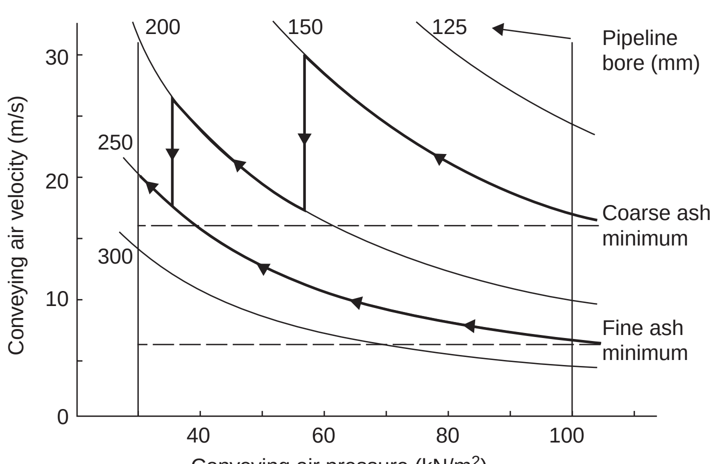


Figure 19.9 Pipeline conveying air velocity profiles for the conveying of both coarse fly ash and fine fly ash in a common negative pressure conveying system.

Once again a common pipeline bore has been used for entry to the reception silo, but as with the positive pressure conveying system considered for the alumina, this is not necessary for negative pressure conveying systems either. Two steps have been recommended for the coarse ash pipeline and this illustrates the general need for stepping pipelines to a larger bore in high vacuum conveying systems. Salient conveying parameters for the two pipelines at the material feed and discharge points are presented in Table 19.2 and a sketch of a typical plant layout is given in Figure 19.10.

A given pneumatic conveying system can be adapted to convey different materials, having widely differing conveying capabilities, quite simply by selecting an appropriate bore of pipeline to meet the minimum conveying air velocity requirements for the material, and for the given volumetric flow rate of air available. This will involve the use of different pipeline bores at the material feed point, but it will mean that it will be possible to convey the material.

By this means it will also be possible to convey each material at its optimum conveying conditions, and so convey materials in both dilute and dense phase with the same conveying system. With high pressure or high vacuum conveying systems it will be possible to step the pipelines to a larger bore along their length, and in these cases it may be possible to merge the pipelines into one and use a common section of pipeline at entry to the reception vessel.

Table 19.2 Summary of conveying parameters for fly ash pipelines considered

Conveying parameters	Units	Pipeline location		
		Feeding		Discharge
		Coarse ash	Fine ash	
Air flow rate	m^3/s	0.3	0.3	1.0
Air pressure	kN/m^2 abs	100	100	30
Temperature	K	300	300	300
Minimum air velocity	m/s	16	6	16
Pipeline bore	mm	150	250	250
Actual air velocity	m/s	17.0	6.1	20.4

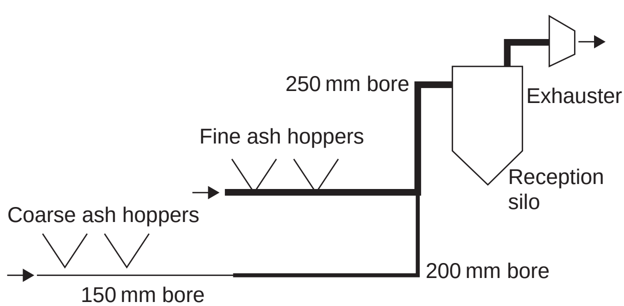


Figure 19.10 Sketch of typical vacuum conveying system for fly ash handling.

19.4.4 Step location

In all cases where stepped pipelines are employed it is essential that the step is located such that the conveying air velocity does not fall below the minimum conveying air velocity at the step, otherwise the pipeline is likely to block close to that point. If there is any doubt in assessing the correct location of a step it is always wise to position the step a little further down the pipeline where the pressure will be lower, and hence the conveying air velocity higher.

References

1. D Mills, J S Mason and P L Bransby. Design considerations for multiple use pneumatic conveying systems. Proc Solidex 84. pp 43–57. Harrogate, UK. April 1984.
2. D Mills. The use of stepped pipelines to enable different materials to be conveyed pneumatically by a common system. Proc 7th Int Conf on Bulk Materials Storage, Handling and Transportation. pp 751–760. The University of Newcastle. October 2001.
3. D Mills. How to convey diverse materials in a common pneumatic conveying system. Bulk Handling Review. Vol 6, No 4. pp 87–93. October/November 2001.
4. D Mills and V K Agarwal. Pneumatic Conveying Systems – design, selection, operation and troubleshooting with particular reference to pulverised fuel ash. Trans Tech Pub. 2001.
5. V K Agarwal, M D Bharathi and D Mills. The influence of material grade on pneumatic conveying system performance. Powder Handling and Processing. Vol 12, No 3, pp 239–246, July/September 2000.

This page intentionally left blank

Part C

System Operation

Chapter 20

Troubleshooting and material flow problems

20.1 Introduction

Despite being simple in concept, pneumatic conveying systems present significant design problems, not least because of the fact that the conveying medium is compressible. Any changes in pipeline geometry, whether horizontal runs, vertical lift or even bends can have a marked effect on performance. The properties of the material to be conveyed can have a significant influence on both the design and specification of components, and can also have a major influence on conveying performance.

One of the major difficulties with pneumatic conveying systems is that it is not always obvious what effect a change in operating conditions will have on system performance. A change of material or conveying distance, in particular, may require changes in both material feed rate and air flow rate. Unfortunately the cause of a particular problem in a pneumatic conveying system is not always obvious either. Particular note of changes in performance that might occur with respect to time should be made, for these should not occur with a pneumatic conveying system, and could well lead to failure over a period of time.

20.2 Pipeline blockage

One of the most frustrating problems encountered in system operation is that of pipeline blockage. This is by no means uncommon and there are a multitude of different circumstances and possible causes.

20.2.1 General

In any pipeline blockage situation the first thing to do is to check all the obvious system features:

- Is the reception point clear?
- Are the diverter valves operating satisfactorily?
- Is the full conveying air supply available?
- Was the pipeline clear on start up?
- Has a pipeline bend failed?

The problem may relate to system components, such as the feeding device or filtration plant. It may be a material related problem, such as particle size or moisture. The time of the day and year that it occurs, together with the prevailing weather conditions, and the nature of the blockage, are useful indicators of the potential cause.

20.2.1.1 Check list

Pipeline blockages generally present a serious problem in most bulk solids handling situations, and particularly so if continuous process operations are involved, and so there is usually a need for speed of solution. For this reason a check list of possible causes and actions to take is given in Table 20.1. Most of the reasons for pipeline blockage that are included are explained in detail in the notes that follow, but in the first instance the check list will provide ideas for immediate action.

20.2.2 On commissioning

If the pipeline blocks during commissioning trials with the pneumatic conveying system, it could indicate that there is either a serious design fault with the system, or some simple adjustment needs to be made to the plant.

Table 20.1 Check list of possible causes of pipeline blockage

Plant item	Possible cause	Action
Air mover	Incorrect	Check delivery pressure and rating
	Specification	Check conveying line inlet air velocity
	Relief valve	May be set too low
	Low air temperature	Check conveying line inlet air velocity
	Inlet filter	Check that this is clear
	Wear by dust ingress	Check rating against original specification
Air supply lines	Flow restriction	Check operation of all valves in air lines
Feeder	Air leakage too great	Check clearances
	Over-Feeding	Rotary valves and screws: reduce speed Blow tanks, suction nozzles: change proportion of air flows
	Non-steady feeding	Reduce operating pressure or increase power
	Wear	Check clearances, valve seatings, etc
Pipeline	Pipeline blocked previously	Ensure that the pipeline is thoroughly purged before conveying
	Diverter valve	Check for satisfactory operation
	Condensation in pipeline	Lag pipes, trace heat pipes, dry air or purge with warm air until dry
	Oversized material	Check material taken from blocked areas
	Wet materials	
	Pipeline coating	Moisture: dry air or material Fine material: shake or vibrate pipeline
Reception	Already full	Check level in reception hopper
System	Change of material Change of distance	Check air requirements, feed rate, etc

20.2.2.1 Incorrect air mover specification

If it is the former, the most likely reason is that the air mover is incorrectly sized for the duty. There are two possible reasons why the air mover may be incorrectly sized:

1. If the volumetric flow rate of air available for conveying the material in the pipeline is insufficient, it is unlikely that it will be possible to convey the material. A certain minimum value of conveying air velocity must be maintained at the material pick-up point at the start of the conveying line. The value depends upon the material being conveyed and, for materials that are capable of being conveyed in dense phase, in moving bed flow, varies with the solids loading ratio at which the material is conveyed.
2. The other possibility is that the incorrect conveying line inlet air pressure has been used in evaluating the volumetric flow rate required by the compressor. Since air is compressible it is extremely important that the pressure of the air at the material pick-up point, in absolute terms, is taken into account in evaluating the free air requirements for the air mover specification.

20.2.2.1.1 Conveying air velocity

One of two parameters is required here. These are the free air flow rate delivered, $\dot{V}_0$, and the conveying line inlet air velocity, C_1. For the design of a system C_1 must be specified and $\dot{V}_0$ is calculated on the basis of the value used. As air is compressible, with respect to both temperature and pressure, the starting point in the determination of any relationship for the determination of conveying air flow rate is the Ideal Gas Law. An expression for the volumetric flow rate of free air required was developed in Chapter 9 with Equation (9.10) and this is reproduced here in Equation (20.1) for reference:

$$\dot{V}_0 = 2.233 \times \frac{p_1 d^2 C_1}{T_1} \ \text{m}^3/\text{s} \tag{20.1}$$

where $\dot{V}_0$ is the free air flow rate (m^3/s); p_1, the conveying line inlet air pressure = 101.3 + gauge pressure (kN/m^2 abs); d, the pipeline bore (m); C_1, the conveying line inlet air velocity (m/s) and T_1, the conveying line inlet air temperature (K). Equation (20.1) can be used to check the specification of an air mover, given the conveying line inlet air velocity and other parameters.

Re-arranging Equation (20.1) in terms of conveying line inlet air velocity gives:

$$C_1 = 0.448 \times \frac{T_1 \dot{V}_0}{d^2 p_1} \ \text{m/s} \tag{20.2}$$

Equation (20.2) can be used to provide a check on the conveying line inlet air velocity, given the free air flow rate of the air mover being used on the plant and other parameters.

Pipeline bore influence

Pipeline bores quoted are 'nominal' sizes only since it is generally the outer diameter that is standardized because of the needs of flanging and threading. The diameter of a

4 in. nominal bore pipeline, however, is rarely 4 in. If a conveying air velocity is based on a diameter of 4 in., for example, and it is a schedule 10 pipeline, the actual bore will be 106.1 mm and not 101.6 mm. This difference will mean that the conveying air velocity will be about 9 per cent lower. If 16 m/s is the velocity in a 101.6 mm bore pipeline, it will only be 14.6 m/s in a 106.1 mm bore line and the pipeline is likely to block if the minimum conveying air velocity for the material is 15 m/s.

Conveying gas influences
Although air is used for the vast majority of pneumatic conveying systems, other gases such as carbon dioxide and superheated steam can be used for specific applications. Nitrogen is often used if the material is potentially explosive. The above equations, in terms of velocities and volumetric flow rates will apply to any gas, but because the characteristic gas constant, R, for each is different, then the density of each gas will be different. If densities or mass flow rates have to be used in any calculation, therefore, Equations (20.1) and (20.2) will have to be modified. This was considered in Chapter 9 with Equation (9.9) and Table 9.2.

20.2.2.1.2 Influence of solids loading ratio

It is the velocity at the material feed point, at the start of the conveying line that is important. If this velocity is too low the pipeline is likely to block. For materials conveyed in dilute phase, or suspension flow, it is necessary to maintain a minimum velocity, C_{min}, of about 11–16 m/s, depending upon conveyed material, as mentioned in Section 15.2.1.6. Typical values and data for C_{min} were presented in Figure 14.2. A 20 per cent margin on this value is generally recommended in terms of specifying a value for the actual conveying line inlet air velocity, C_1 to be employed. Typical values of C_1 were presented in Figure 18.4.

For fine powders, such as cement, flour and fly ash, that are capable of dense phase conveying in moving bed type flow, the value of minimum velocity is dependent upon the solids loading ratio at which the material is conveyed. Only at high values of solids loading ratio can the conveying air velocity be as low as 3 m/s. If the material is conveyed in dilute phase, at a low value of solids loading ratio, velocities appropriate to the dilute phase conveying of a fine material must be used. There is, therefore, a gradual transition between dilute and dense phase, with respect to minimum conveying air velocity. To ensure successful conveying, therefore, the conveying line inlet air velocity must be above these minimum values, whether the material is conveyed in dilute or dense phase.

20.2.2.1.3 Air mover change

If pipeline blockages occur and it is found that the conveying line inlet air velocity is too low, then an air mover with a higher volumetric flow rate will have to be used. If it is replaced with one having a higher delivery pressure, as well as a higher volumetric flow rate, Equation (20.2) must be checked again, because air supply pressure also has a significant influence on conveying line inlet air velocity.

It is equally important that any replacement is not over-rated. It is not generally necessary for the conveying line inlet air velocity to be any higher than about

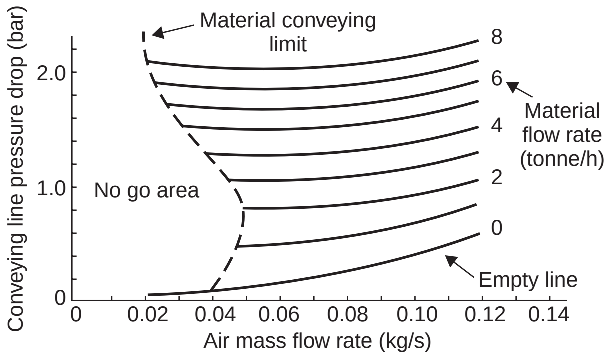


Figure 20.1 The influence of material and air flow rates on conveying line pressure drop for cement in pipeline no. 7.

20 per cent greater than the minimum conveying air velocity value. If it is in excess of this it is likely to have an adverse effect on the material flow rate, particularly for dilute phase conveying.

20.2.2.1.4 Conveying limitations

A useful graph to illustrate the influence of minimum conveying conditions is a plot of conveying line pressure drop drawn against air flow rate, with lines of conveying line pressure drop superimposed. Such a graph for cement conveyed through a 53 mm bore pipeline over a distance of 101 m and containing seventeen 90° bends, is presented in Figure 20.1. This is pipeline no. 7 shown earlier in Figure 13.4.

The empty line, or zero material flow rate curve, provides a useful datum for the relationship, for it shows just how much pressure is required to get the air through the given pipeline before any material is conveyed. This is a 'square law' relationship, and hence the gradual upward trend of pressure drop with increase in air flow rate, and hence velocity.

Apart from the lower limit of zero for material conveying capacity, which relates to the pressure drop requirements for the empty pipeline with air only, there are three other limitations on the plot in Figure 20.1. The first is the limit on the right hand side of the graph, which is set by the volumetric capacity of the blower or compressor used. This is not a real limit at all, therefore, and conveying is possible with higher values of air flow rate, but it would not be recommended. It will be seen from Figure 20.1 that for a given value of conveying line pressure drop, material flow rate gradually decreases as air flow rate, and hence power required, increases. Apart from this decrease in material flow rate and conveying efficiency, an increase in conveying air velocity will result in an increase in both material degradation and pipeline erosion.

The second limit is at the top of the graph. This is generally set by the pressure capability of the air mover. This is not a physical conveying limit either, and conveying with very much higher pressures is possible. The problem with using higher pressures, however, relates to the expansion of the conveying air, for in a single bore pipeline very high velocities will result at the end of the pipeline. This problem can be overcome by stepping the pipeline to a larger bore once or twice along the length of the pipeline so that higher pressures can be used.

The third limit is that on the left hand side of the graph and is clearly marked. This is a real conveying limit and it represents the minimum conditions for successful pneumatic conveying with the material. The lines of constant material flow rate actually terminate, and conveying is not possible in the area to the left, at lower air flow rates. Any attempt to convey with a lower air flow rate would generally result in blockage of the pipeline.

20.2.2.1.5 Influence of material type

This limit to conveying is influenced very significantly by material type. The cement data in Figure 20.1 follows the minimum limit set by the lower curve in Figure 14.2. As the cement is capable of being conveyed in dense phase, conveying with low values of air flow rate has been possible with high values of conveying line pressure drop.

In Figure 20.2 similar data for a material not capable of being conveyed in dense phase, in a conventional pneumatic conveying system, is presented. The limit to conveying for this material is set by the upper curve in Figure 14.2. The material was granular coke fines and was conveyed through exactly the same pipeline as the cement in Figure 20.1. A very significant difference in material flow rate capability will be noticed.

The minimum material conveying limit on Figure 20.2 is very regular. This is because it is defined only by a minimum conveying air velocity of 14 m/s. This means that the line drawn, representing the conveying limit, also represents a line of constant conveying line inlet air velocity of 14 m/s. This illustrates the influence of air supply pressure on conveying very well, and shows that great care must be exercised in operating such a conveying system, for it is very easy to cross the conveying limit and block the pipeline.

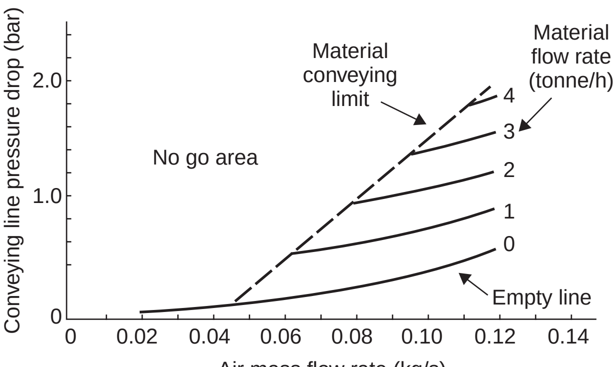


Figure 20.2 The influence of material and air flow rates on conveying line pressure drop for coke fines in pipeline no. 7.

20.2.2.1.6 Air leakage allowance

It is important that the $\dot{V}_0$ term in Equations (20.1) and (20.2) is the volumetric flow rate of the air used to convey the material in the pipeline. If, in a positive pressure conveying system, part of the air supply from the air mover is lost by leakage across the material feeding device, this must be taken into account. This point was illustrated with Figure 3.6. A similar situation occurs with negative pressure systems with ingress of air into the system. These points are considered further in subsequent sections of this chapter.

20.2.2.2 Over feeding of pipeline

The pressure drop in the conveying line is primarily dependent upon the concentration of the material in the pipeline, or the solids loading ratio. If too much material is fed into the conveying line it is possible that the pipeline could become blocked. There are two possible reasons for this. One is related to compressor delivery capability and the other is concerned with material conveying capability.

20.2.2.2.1 Compressor capability

If a pipeline is over fed the pressure required may exceed that available from the blower or compressor and the line will block. It will, therefore, be necessary to reduce the material feed rate to match the capability of the air mover or its drive motor. It could be either the compressor or the drive motor that imposes the limitation. The operating characteristics of the compressor and the specification of the motor could be checked to determine the exact cause of the problem. This problem relates to air mover characteristics such as those presented in Figure 6.5.

To illustrate the various problems with regard to the over feeding of a pipeline a section from each of the conveying characteristics presented in Figures 20.1 and 20.2 is re-drawn on Figure 20.3. A common axis was used for these two materials and so the air only curve could run continuously between the two sections.

Point (a) represents the coke fines successfully conveyed at 1.0 tonne/h with 0.10 kg/s of air and requiring a pressure drop of 0.8 bar. If 2 tonne/h were to be fed into the pipeline there would have to be a corresponding increase in air supply pressure because a pressure drop of about 1.1 bar would be needed. If a positive displacement blower was used to supply the air, having a maximum pressure capability of 1.0 bar gauge, it is quite possible that the new operating point could not be reached and the pipeline would block.

Point (b) represents the coke also being conveyed with a pressure drop of 0.8 bar. With a lower air flow rate a slightly higher material flow rate is achieved. The conveying air velocity is 20 per cent above the minimum at this operating point and the material conveys quite successfully. If the material flow rate is increased a corresponding increase in pressure drop will be required to meet the demand. In this case the pipeline will block, even if the air mover is capable of providing the air at a higher pressure, because the operating point has crossed the conveying limit into the ‘no go area’. This can be explained by reference to Equation (20.2). The air supply pressure, p_1, is on the bottom line of the equation and so as its value increases, the value of the conveying line inlet air velocity, C_1, will reduce and when the value drops below the minimum for the

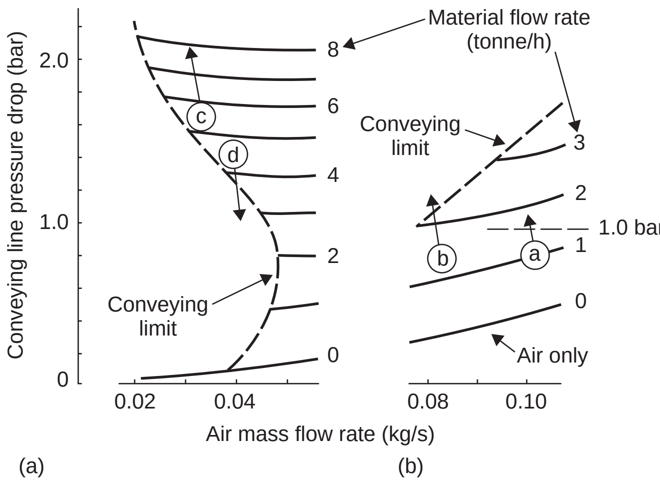


Figure 20.3 Influences of changes in material flow rate on conveying system performance: (a) cement and (b) coke fines.

material the pipeline will block. An air mover with a higher air flow rate capability would be needed to recover the situation.

It will be noticed that there is a slight reduction in the air flow rate as the pressure increases for points (a) and (b) on Figure 20.3. This is a consequence of the constant speed operating characteristics of the air mover, as considered with Figures 6.3 and 6.5. With the air flow rate being on the top line of Equation (20.2) this does aggravate the situation and mean that the conveying air velocity reduces very quickly. If it is known that there are likely to be times when surges in material flow rate are likely to occur, or that a slightly higher material flow rate will be required occasionally, then a margin much greater than 20 per cent must be built into the design specification.

20.2.2.2.2 Material capability

With a material such as cement the same situation will apply but with dense phase conveying at low velocity the lines of constant conveying line inlet air velocity, and hence the conveying limit itself, are very much steeper, as shown on Figure 16.1 for the cement. In the transition region between dilute and dense phase conveying, however, the situation is rather different, as will be seen from operating point (c) on Figure 20.3. An increase in material flow rate here will result in an increase in solids loading ratio and this in turn will result in a lowering of the conveying limit, as shown on Figure 16.5. As a consequence the new operating point is likely to be more than 20 per cent above the conveying limit, despite the slight reduction in air flow rate delivered by the compressor.

Point (d) on Figure 20.3 illustrates the reverse situation. This is pipeline blockage as a consequence of reducing the material flow rate, which can only occur with dense phase conveying. In the transition region between fully dense phase conveying and dilute phase conveying there is a switch from a minimum conveying air velocity of about 11 m/s, for the dilute phase conveying of this type of material, to a minimum conveying air velocity of about 3 m/s. It is in this region that such problems can occur. This was illustrated in detail with Figure 13.5 which shows the relationship between minimum conveying air velocity and solids loading ratio, and Figure 13.6 which shows the specific area on the conveying characteristics to a magnified scale. A reduction in material flow rate from point (d) will reduce the solids loading ratio which in turn will raise the value of conveying air velocity and the pipeline could block as a result.

20.2.2.2.3 Feeder control

Each type of pipeline feeding device has its own characteristic means of controlling the material flow. With positive displacement feeders this is achieved directly: either by means of speed control, as in the case of rotary valves and screws; or by frequency of operation, as in the case of double gate valves. In others, additional flow control devices are required, as with venturi feeders. In the case of blow tanks and suction nozzles, control is achieved by means of air supply proportioning.

Feed control is very important at the time of commissioning a plant, particularly with conveying systems employing positive displacement feeders. Due to the expense, these feeders are not generally supplied with a variable speed drive, unless there is a particular requirement during operation of the plant to be able to vary the feed rate. With rotary valves, for example, there is often a problem with achieving fine control of feed rate, since a change of just 1 or 2 rev/min can have a significant effect on material flow rate. On commissioning, therefore, it is essential that a means of obtaining a reasonable degree of speed control should be provided, either side of the estimated value, so that fine control of the flow rate can be achieved.

20.2.2.2.4 Performance monitoring

It is often difficult to assess whether a pipeline blockage results from an incorrect air mover specification, or over feeding of the pipeline. For a positive pressure system this can be established quite easily if there is a pressure gauge in the air supply line just before the material feed point into the conveying line. A typical arrangement is shown in Figure 20.4.

In a negative pressure, or vacuum conveying system, the pressure gauge would have to be located in the discharge air pipeline between the filtration unit and the inlet to the exhauster, as shown in Figure 20.5. Such a pressure gauge, in either the positive or negative pressure system, will give a reasonably close approximation to the conveying line pressure drop, for the pressure drop in the short section of the air supply line will be small in comparison. The pressure gauge will also work more reliably in the air line than it will in the material conveying line.

Note: Many of the comments that follow refer only to positive pressure conveying systems, but are equally applicable to negative pressure systems. This is simply to avoid making the text unnecessarily complicated in referring to two different cases at every juncture. The main difference between positive and negative pressure conveying systems is in the specification of the volumetric flow rate of the air, since that for exhausters is generally in terms of exhauster inlet conditions.

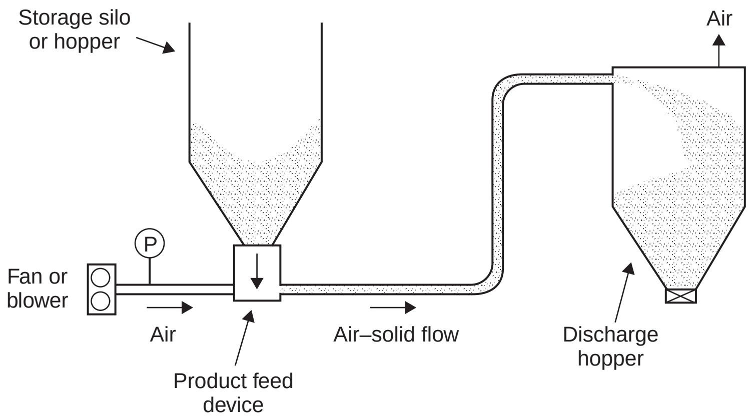


Figure 20.4 Performance monitoring of a positive pressure conveying system.

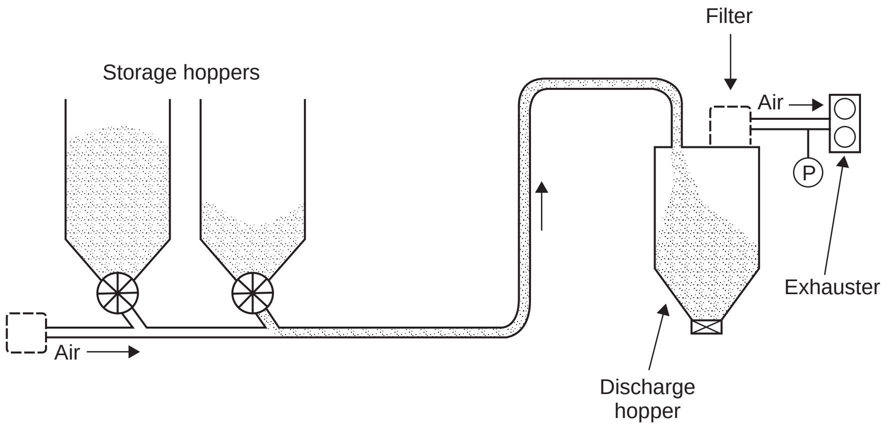


Figure 20.5 Performance monitoring of a vacuum or negative pressure conveying system.

If the reading on the pressure gauge is above the design value it would indicate that the pipeline is being over fed, and so the feed rate should be reduced. If the pressure is at the design value or below, and the pipeline blocks, it would indicate that the volumetric flow rate is insufficient. Pipeline blockage can occur very rapidly, particularly with high velocity dilute phase conveying. In a 100 m long pipeline, for example, with a mean conveying air velocity of 20 m/s the air will traverse the pipeline in 5 s. The particles are conveyed at a slightly lower velocity but they will only take a few seconds longer.

A pressure gauge in the air line is particularly useful for monitoring the performance of a system. If the pressure reading is below the design value, for example, it would indicate that the performance of the system has been under estimated and that it would be possible to feed more material into the pipeline. Care must be exercised here, however, and the air velocities should be checked as mentioned above, for an increase in air supply pressure will result in a lowering of the conveying line inlet air velocity.

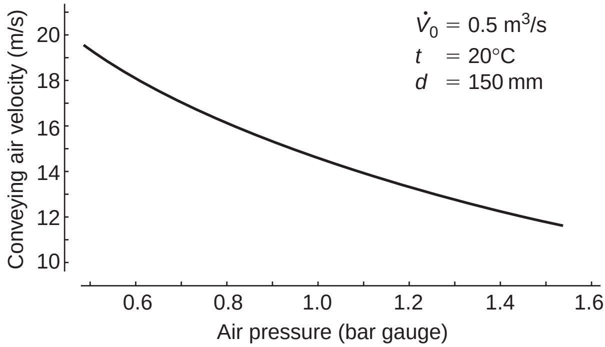


Figure 20.6 Influence of pressure on conveying air velocity.

The use of pressure gauges, such as those shown on Figures 20.4 and 20.5 would also be invaluable in achieving the correct balance between material feed rate, and air supply pressure and flow rate, if a change in either conveying distance or a change in material conveyed were to be made.

20.2.2.2.5 Influence of pressure

The influence of pressure, as it is such an important parameter, is illustrated further in Figure 20.6. This is a graph of conveying air velocity plotted against a narrow band of air pressure. It is derived from Equation (20.2), for a free air flow rate of 0.5 m^3/s at 20°C in a 150 mm bore pipeline. It should also be noted that with most positive displacement air movers there is a slight reduction in volumetric flow rate with increase in delivery pressure, as illustrated on Figure 20.3, and this will magnify the effect.

Figure 20.6 is drawn on a magnified scale and shows quite clearly the very significant effect that changes in pressure can have on conveying air velocity. Some fine granular materials, such as sand, sugar and alumina, are very sensitive to small changes in conveying air velocity.

Silica sand, for example, will convey very reliably with a conveying line inlet air velocity of 14 m/s, but if it drops to only 13.6 m/s the pipeline will block within seconds. Granulated sugar, having a mean particle size of about 460 μm, is a similar material that will convey reliably with a conveying line inlet air velocity of 16.2 m/s but will rapidly block the pipeline if the velocity falls to 15.8 m/s. It only requires a small change in air supply pressure, for a given air flow rate, to result in this change in conveying air velocity.

20.2.2.3 Non steady feeding of pipeline

If the pipeline blocks only occasionally, it is possible that this may be due to surges in the material feed rate. For a system that is operating close to its pressure limit, a momentary increase in feed rate could raise the material concentration to a level that may be sufficient to block the line.

This can be seen by reference to Figures 20.1 and 20.2 once again. Any increase in material flow rate will require a corresponding increase in conveying line pressure drop, and the response can be very rapid, as considered above. It is very approximately a linear relationship, and so a 10 per cent increase in material flow rate will require a 10 per cent increase in air supply pressure. If this pressure is not available, a momentary surge in feed rate could result in a blocked pipeline.

20.2.2.3.1 Commissioning

In addition to determining the mean flow rate on commissioning, the regularity of the flow rate over short periods of time should also be assessed. This is necessary to ensure that these fluctuations will not overload the system. It is essential, therefore, that both the compressor and the motor drive are specified with adequate margins. The compressor should be capable of delivering air at a pressure slightly higher than that required, and at a corresponding volumetric flow rate. The motor drive for the compressor should have sufficient spare power capacity to meet the demand of any possible surges.

A useful aid is to fit differential pressure switches to all air movers and link these to the material feeder so as to stop the feed in an over-pressure condition. This gives the system a chance to clear and it can be arranged to bring the feed back on again automatically, once the pressure has dropped to some specified value.

Material surges have to be considered in relation to the type of feeding device used. In this respect, positive displacement, volumetric devices need particular consideration. A rotary valve, for example, with eight blades and rotating at 23 rev/min will empty about three pockets of material every second. For most purposes this frequency is sufficiently high, but with a short pipeline due care should be taken with such a feeder. Double flap valve type feeders, cycling at 10–20 times a minute, clearly present a problem as this could be too coarse for many materials and duties.

20.2.3 On start up

If a pipeline has a tendency to block when the system is started up after a shut down period, some transient situation may be responsible. It is quite possible that the system will operate satisfactorily under normal load conditions.

20.2.3.1 Moisture in line

If material is blown into a cold pipeline it is possible that the inside surface could be wet as a result of condensation. This is liable to occur in pipelines that are subject to large temperature variations from day to night, particularly where there are pipe runs outside buildings. If air drying is not normally necessary, the problem can be overcome either by trace heating and insulation of exposed sections of the pipeline, or by blowing the conveying air through the pipeline for a short period to dry it out prior to introducing the material.

This point is illustrated in Figure 20.7. This is a graph which shows the variation, with temperature, of the mass of water that can be supported as vapour in saturated air. If the temperature rises, for a given mass of water vapour, the humidity will decrease and air will become drier. If the temperature falls, however, condensation will take place and the humidity will remain at 100 per cent. For initially saturated air, therefore,

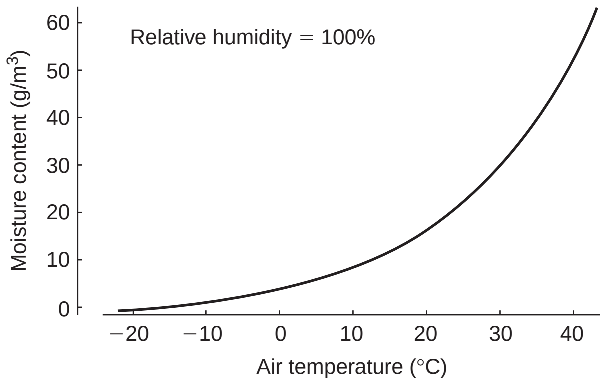


Figure 20.7 The influence of temperature on water vapour in air.

Figure 20.7 can be used to determine the mass of water vapour that will condense for a given change in temperature. The problem relates particularly to plant operating only on day shift where, at the end of the day, there could be warm moist air in the pipeline that could cool and possibly condense overnight to leave damp patches on the pipeline walls.

Moisture is often a problem in general high pressure plant air supplies. If such a plant air supply is used it would be wise to incorporate a moisture separating device. If the inside surface of a pipeline is wet, as a result of condensation, fine material will tend to stick to the wall surface. This is particularly a problem at bends prior to a vertical lift. Moisture condensing on the surface of the vertical pipeline will tend to drain down to the bend at the bottom and collect as a pool of water.

It depends upon the nature of the material being conveyed, and its interaction with water, as to what will happen when the material meets the water. In many cases a hard scale will form, and this will gradually accumulate with successive cycles of condensation and conveying, to a point where the build up adds significantly to the pipeline resistance. For a conveying system operating close to its pressure limit the added resistance could result in pipeline blockage.

As a matter of course the pressure gauge on a plant, as illustrated on Figures 20.4 and 20.5, should be checked regularly at convenient times to record the value of the air only pressure drop for the pipeline. The reference value for this should be obtained during commissioning of the plant. If the value rises the possible causes should be investigated, particularly if it continues to rise.

20.2.3.1.1 Air drying systems

Air can be dried either by refrigerating or by chemical means. The decision depends upon the level of drying required. The quantity of water in air, as a function of temperature, can be seen in Figure 20.7. The lower the air temperature (for refrigeration), or the dew point (for chemical dryers), the less moisture there will be in the air. Due to the problems of the free flow of the water to be removed, refrigerant dryers are normally designed to cool the air down to about 2°C. For most purposes this is sufficient. For those cases where this is not adequate, however, chemical dryers have to be used.

These are capable of reducing the dew point temperature of the air down to −40°C, and at this temperature moisture levels are very small indeed.

The capability of air for supporting moisture will decrease with both a decrease in temperature and an increase in pressure. If air is compressed isothermally, or is compressed and allowed to cool before use, condensation will occur if the ambient air being compressed has a sufficiently high relative humidity. Provision, therefore, must be made to drain this condensate. The compression process, however, occurs very quickly and complete condensation may not take place. Condensed water in the form of a fog or mist is often conveyed with the air and can be transported through pipelines over long distances. It is not always advisable, therefore, to rely on the compression process to dry the air. Moisture and condensation are considered in more detail in Chapter 25.

20.2.3.2 Cold air

The density of air decreases with increase in temperature. In normal operation the delivery temperature of the air from an air mover, such as a positive displacement blower, could be some 60°C higher than the inlet temperature. This means that the volumetric flow rate, and hence the conveying air velocity, will be 25–30 per cent greater than the value at ambient temperature. On start up the air will initially be fairly cold for conveying the material, and so if the resulting conveying air velocity is below that necessary for the material, the pipeline could block.

This point is illustrated in Figure 20.8. This is a graph of conveying air velocity plotted against a narrow band of air temperature. It is derived from Equation (20.2) once again, for a free air flow rate of 0.5 m^3/s at a pressure of 1.0 bar gauge in a 150 mm bore pipeline. Figure 20.8 shows that conveying air velocity is quite sensitive to temperature, as well as pressure. Since air density increases with decrease in temperature, it is essential that air requirements are based on the lowest temperature that is likely to be experienced. Thus a cold start up in winter with the lowest possible air and material temperatures must be catered for. This is particularly important in plant where the material, under normal circumstances, may be at a high temperature. If the plant is shut

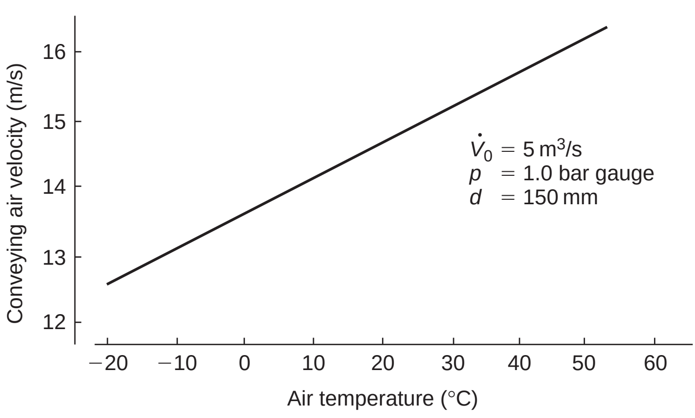


Figure 20.8 The influence of temperature on conveying air velocity.

down and re-started with cold material it could have a significant effect on the conveying air velocity.

If meeting the air flow requirements for the lowest temperature results in excessively high conveying air velocities during normal operation, then some means of controlling the air flow rate to the conveying line must be incorporated. Variable speed control of the air mover, choked flow nozzles in a by-pass air supply line and the discharge of part of the air to atmosphere via a control valve, are some of the methods that could be considered for the control of the air flow rate to the pipeline for normal operation.

20.2.3.3 Material in pipeline

If, when the plant is shut down, the pipeline is not purged, a quantity of material could be left in the pipeline. If the conveying line incorporates a long vertical lift section, sufficient material could accumulate in the bend at the bottom to prevent the system from being re-started. It is always a wise precaution on start up to blow air through the pipeline before material is introduced. If the pipeline was not purged on shut down, there may be sufficient material left in the pipeline to cause blockage of the pipeline during start up. If the pipeline is already blocked it will considerably aggravate the situation if more material is blown into the pipeline. This reinforces the need to monitor the air only pressure drop for the pipeline.

20.2.3.4 After unexpected shut down

If conveying stops unexpectedly due, for example, to a power supply failure, it may not be possible to start the system again, particularly if the pipeline incorporates a large vertical lift. If the bends at the bottom of any vertical sections are taken out, to remove the material at these points, it may be possible to purge the line clear, if the pipeline is not too long. Should this be a common occurrence on a plant, an air receiver could be fitted between the air mover and the material feeding device. Such an arrangement is illustrated in Figure 20.9. If the material feed into the pipeline is stopped at the instant the power supply fails, the air stored in the receiver could be sufficient to purge the line clear of material.

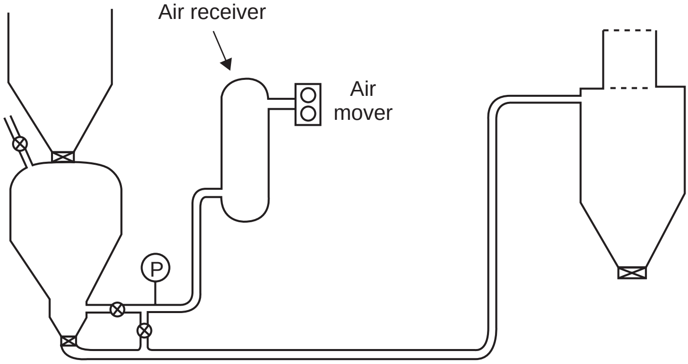


Figure 20.9 Use of air receiver in air supply line for pipeline purging.

Alternatively a parallel line with connecting valves to the pipeline could be fitted so that the pipeline could be cleared slowly from the end, one section at a time. It should be noted that in the various sketches used to illustrate the points being discussed, different types of system and material feeding arrangements are shown. This is simply to add variety to the notes and avoid repetition. In most cases the modifications to the plant suggested can be applied to any type of pneumatic conveying system and can be utilized with any type of feeder.

In Figure 20.9 a blow tank is specifically shown to illustrate the point that consideration should also be given to the material feeder. With a rotary valve and screw, the material feed will automatically be stopped, but it may not be with a blow tank. It is essential that the material feed should be stopped if the power to the air mover fails. In this event an outlet valve should be provided on the blow tank, with arrangements made for this to close in the event of a power failure.

20.2.4 After a period of time

If a system, that has operated satisfactorily for a long period of time, starts to give trouble with blocked pipelines, wear of the feeding device could be the cause of the problem in the case of positive pressure systems. If the air leakage across the feeding device increases, the air available for conveying the material will decrease. If the loss of air is too great, it is possible that the volumetric flow rate of air that is left will be insufficient to convey the material and the pipeline will block.

A very similar situation exists with regard to vacuum conveying systems. In this case it is the leakage of air into the system, particularly through the discharge valve on the reception hopper. This leakage air is drawn directly into the exhauster and so by-passes the conveying line.

Wear of screw flights, valve seatings of gate lock valves, and rotary valve blades and housings, will all result in a greater leakage of air across the respective feeding device. It is also possible that gradual deterioration in performance of the air mover will have a similar effect, both for positive and negative pressure conveying systems. Most positive displacement air movers operate with very fine clearances and cannot tolerate dust. If they are operated in a dusty environment, and inlet filters are not maintained, wear will occur, particularly if the dust is abrasive. Exhausters on negative pressure conveying systems, and blowers used with closed loop conveying systems, are particularly vulnerable in this respect.

20.2.4.1 Component wear

The situation with respect to a rotary valve feeding a positive pressure pneumatic conveying system pipeline is shown in Figure 20.10 by way of an example. Air will leak across the rotary valve, via the empty pockets and the blade tip clearances, because of the pressure drop across the valve. In low pressure rotary valves, without end plate sealing, air will also leak between the ends of the rotor blades, or the end plate, and the rotor housing. The volumetric flow rate of air delivered from the blower or compressor should be specified to take this leakage into account, in order to ensure that there is sufficient air to convey the material through the pipeline.

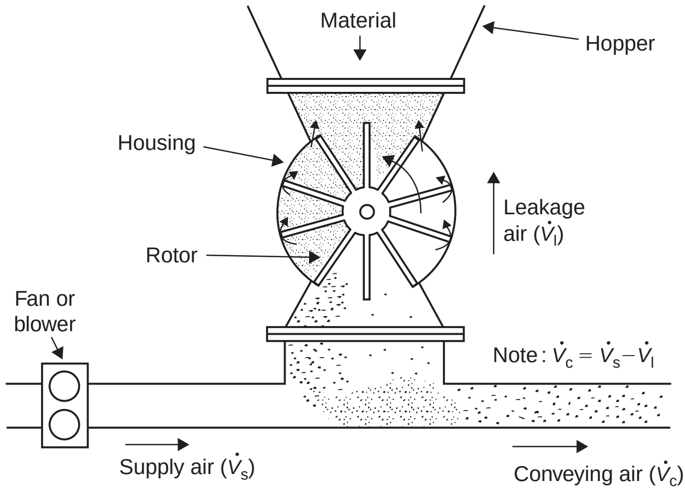


Figure 20.10 Air flow rate analysis for positive pressure conveying system having a rotary valve feeder.

Most manufacturers of rotary valve feeders provide data on air leakage across their rotary valves so that this can be taken into account in the specification of air requirements for air movers. The air flow rates to be taken into account are illustrated on Figure 20.10. The leakage rate depends primarily on the size of the rotary valve, the blade tip clearance and the pressure drop across the valve. Rotor speed and the nature of the material being handled can also have an influence.

If there is wear, because of handling an abrasive material, blade tip clearances will increase, and there will be an increase in air leakage. If the air leakage increases, less air will be available to convey the material. If the leakage is such that it results in the conveying air velocity falling below the minimum value, the pipeline will block. These components should be checked for wear. The performance of the air mover should also be checked, as this might be responsible, as mentioned above. In the short term an increase in air loss across a feeding device can be compensated by increasing the air flow rate. In the long term, however, it is recommended that worn components should be replaced.

20.2.4.2 Pipeline effects

The influence of a gradual increase in air leakage across a feeding device, or a gradual reduction in performance of an air mover, is depicted on Figure 20.11. The conveying characteristics relate to cement conveyed through an 81 mm bore pipeline.

From this it will be seen that the system would operate with a conveying line pressure drop of 0.7 bar, and 0.10 kg/s of air was initially available for conveying the material. This is well above the minimum necessary for the successful conveying of cement, for the conveying line inlet air velocity would be about 10 m/s and the solids loading ratio, as will be seen from Figure 20.11 would be about 26. Cement is an abrasive

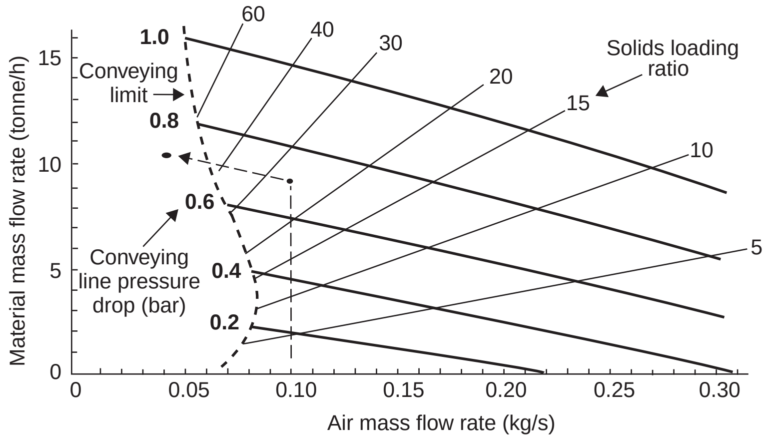


Figure 20.11 The influence of a gradual reduction in conveying air flow rate on system performance.

material and with continual wear the air available would gradually reduce until it became insufficient to convey the cement and the pipeline would block.

This can also be a major problem with vacuum conveying systems if filtration units are not maintained and the dust is carried through the exhauster such that its performance deteriorates.

20.2.5 With new material

It is quite possible that a system that operates satisfactorily with one material will be completely unable to convey another material, or even a different grade of the same material. Minimum conveying air velocities can differ markedly from one material to another, as was illustrated in many of the chapters in Part B of this Design Guide. For given conveying conditions, of air flow rate and air supply pressure, different flow rates will be achieved with different materials. Particular care must be exercised in designing any system in which more than one material is to be conveyed, as considered in Chapter 19.

20.2.5.1 Conveying capability

This point is illustrated in Figure 20.12. This is a plot of material flow rate drawn against air flow rate for a range of materials. The curves represent constant pressure drop lines of 1.5 bar taken from the conveying characteristics for each material. They are for a single bore pipeline, 50 m long, 53 mm bore and containing nine 90° bends (pipeline no. 3 in Figure 12.12).

The problem is illustrated very well with Figure 20.12. The materials tested cover a very wide range of material types, sizes and densities, and include representatives of each of the three main modes of conveying. Sugar and coal are typical of materials that can only be conveyed in dilute phase, despite the fact that a high air supply pressure

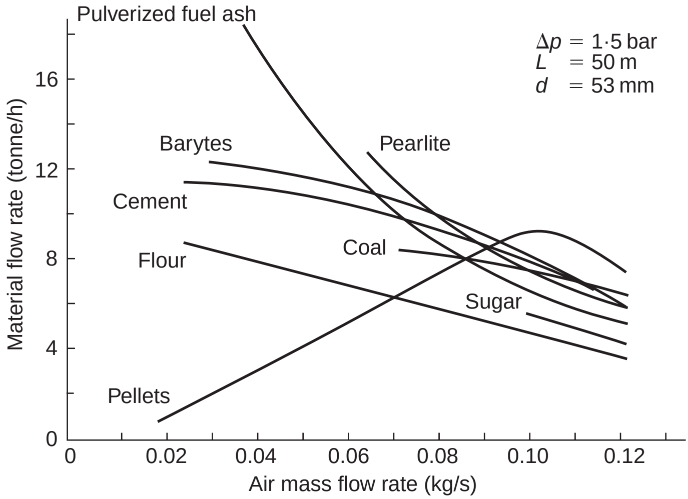


Figure 20.12 Influence of material on conveying capability for identical pipeline and conveying conditions.

was used and the pipeline was relatively short. Pulverized fuel ash, barytes, cement and flour were all capable of being conveyed at very low velocity in dense phase in a moving bed type flow. The polyethylene pellets were also capable of being conveyed at very low velocity in dense phase, but in this case it was plug type flow.

It will be seen that the dilute phase materials needed very much higher values of air flow rate than the dense phase materials, and that the coal, with a mean particle size of about 10 mm, could be conveyed at a lower velocity than the granulated sugar. On the right hand side of Figure 20.12, at high air flow rates, all the materials are conveyed in dilute phase suspension flow, and it will be seen that there is a wide spread of material flow rates, for identical conveying conditions, over the range of materials tested. At low air flow rates there is an even wider spread of material flow rates.

It is also possible for different grades of the same material to give totally different conveying line performances, and operating problems resulting from this source can be particularly difficult to recognize. A slight change in particle size distribution or particle shape with some materials can result in a significant change in conveying capability. Particular consideration to this particular problem was given in Section 13.4. As mentioned before, most manufacturers of pneumatic conveying systems have test facilities so that they can convey a material for which a design is required, and so obtain the necessary data. Figure 20.12 will help to reinforce both the need for such design measures, and the need for good troubleshooting procedures.

20.2.5.2 Air requirements

If a different material is to be conveyed its performance will depend very much upon the air flow rate available, as will be seen from Figure 20.12. If there is insufficient air, it will not be possible to convey the material, unless the pressure is reduced, or more

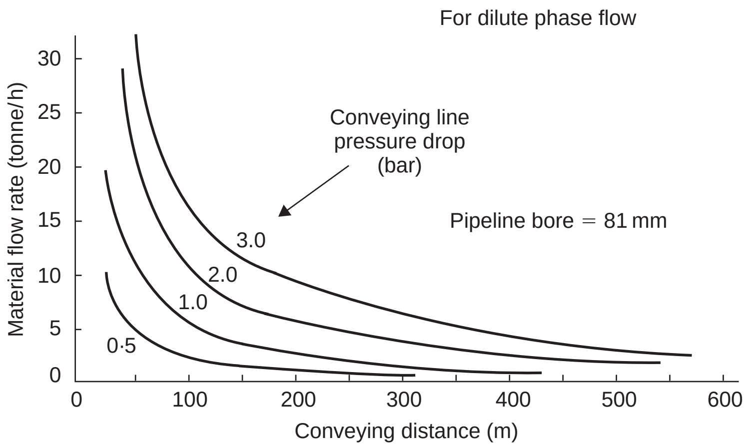


Figure 20.13 The influence of conveying distance on the conveying potential of pneumatic conveying system pipelines.

air is provided. In either case the material flow rate achieved is likely to be much lower and so consideration must be given to the capability of the material feeding device for the new duty. If the air flow rate is increased this might have an adverse effect on the performance of the filtration plant. As will be seen, a change of material can have an influence on many aspects of system design and operation.

20.2.6 With change of distance

If a system operates satisfactorily in conveying a material over a given distance it is quite possible that the pipeline will block if the pipeline is extended and it is required to convey the material over a longer distance. A change of pipeline routing that requires an increase in the number of bends in the pipeline can also affect performance. Even a change of existing bends in a pipeline, to bends having a different geometry for example, can influence performance, as considered in Section 14.5.2.

20.2.6.1 Material feed rate

For a given value of conveying line pressure drop, the conveying capacity of a pipeline will decrease with increase in distance. For a change in conveying distance, therefore, there must be a corresponding change of material feed rate into the pipeline.

This point is illustrated in Figure 20.13. This is a plot of material flow rate drawn against conveying distance, with the influence of conveying line pressure drop shown. It represents the approximate capability of an 81 mm bore pipeline with a material only capable of being conveyed in dilute phase in a conventional conveying system. It shows that for a given conveying line pressure drop the material flow rate is approximately inversely proportional to conveying distance. This is for illustrative purposes only, since it is the 'equivalent length' of a pipeline that is the important parameter and this includes allowances for vertical lift and number and geometry of bends.

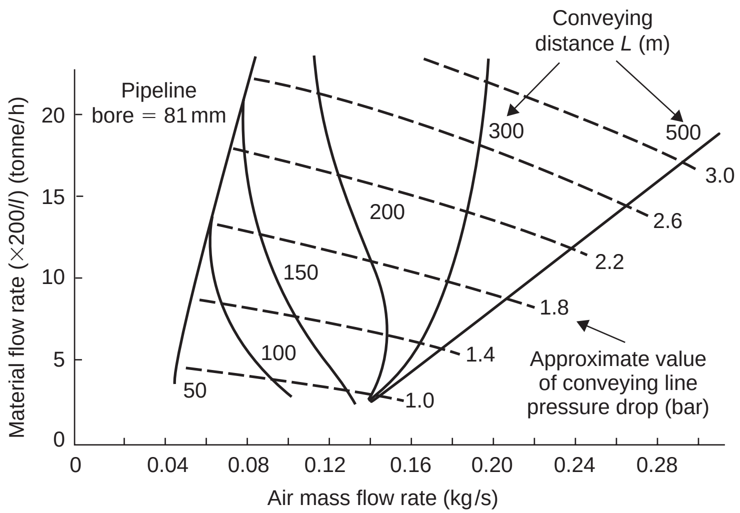


Figure 20.14 The influence of conveying distance on conveying limits for materials capable of dense phase conveying.

From Figure 20.13 it will be seen that the lines slope steeply for short conveying distances. For a given conveying line pressure drop, therefore, material flow rate capability will change significantly for just small increases in conveying distance with short pipelines. This is a direct consequence of the scaling model for conveying length, as considered in Section 14.3.2.2. To maintain the same material flow rate over a longer distance will require a significant increase in pressure drop. If a higher pressure is not available the pipeline will block if the material flow rate is not reduced to compensate.

20.2.6.2 Air flow rate

If the conveying distance is increased, the material flow rate will have to decrease. This will result in the material being conveyed at a lower value of solids loading ratio. For a material capable of being conveyed in dense phase, in a conventional system, this will mean that a slightly higher value of conveying line inlet air velocity will have to be employed. This, in turn, means that a higher flow rate of air will have to be used to convey the material. The potential influence of solids loading ratio on conveying line inlet air velocity for dense phase flow was illustrated earlier in Figure 18.4.

This point is illustrated with Figure 20.14. This is a plot of material flow rate against air flow rate for an 81 mm bore pipeline. It is presented for illustrative purposes only once again, since an 81 mm bore pipeline would not be appropriate for the very long distances considered. The change in the limit to conveying with increase in conveying distance is due to the gradual change from dense to dilute phase conveying that results from the gradual decrease in pressure gradient available for material conveying.

20.2.6.3 Conveying potential

In terms of conveying potential it is conveying line pressure gradient and material properties that are the important parameters. To convey in dense phase requires a high pressure gradient, because of the high concentration of the material in the air. Due to the compressibility problems with air, and expansion effects in particular, air supply pressures greater than about 5 bar gauge are rarely employed. If it is required to convey over a long distance, therefore, the pressure gradient must be reduced if it is not possible to utilise a higher air supply pressure to compensate. If the pressure gradient has to be reduced it will not be possible to convey in dense phase.

Thus even if a material is capable of being conveyed in dense phase and at low velocity, the material will have to be conveyed in dilute phase, and at a much higher velocity, if it is required to convey the material over a long distance. A larger bore pipeline will have to be used, as an alternative to a higher air supply pressure, in order to achieve the material flow rate required.

If the properties of the material are such that it can only be conveyed in dilute phase, suspension flow, the use of high pressure air for conveying will have no effect at all in changing this to dense phase, unless a totally different conveying system is employed. The transition that occurs with dense phase materials that is depicted on Figure 20.14 is only appropriate for dense phase conveying. For materials that are only capable of dilute phase conveying the conveying limit will not vary with respect to conveying distance.

Chapter 21

Optimizing and up-rating of existing systems

21.1 Introduction

There is often a need in industry for an existing plant to be up-rated to meet a demand for increased output or production. If part of a process plant includes pneumatic conveying facilities it is not always obvious as to how this might be achieved. It may be possible to increase capacity simply be optimizing the existing system. Alternatively it might be necessary to add or replace some of the plant.

All too often, when it is required to increase the capacity of an existing pneumatic conveying system, an attempt is made at improving output by increasing the amount of air used for conveying the material in a pipeline. This is usually done by adding another blower in parallel, by changing the existing blower for one with a much higher volumetric flow rate, or by changing the drive such that the rotor speed of the blower is increased. In nearly all cases, however, the net result of these simple modifications is that the material flow rate through the pipeline does not increase at all, but decreases, and often by a considerable amount.

There are many different solutions to the problem and consideration is given to some of the alternatives that are available. An explanation is also given as to how an existing system could be tested in order to check whether it is operating under optimum conditions. Various methods are compared, in terms of potential material flow rates, and the effect that the changing of one plant item can have on the rest of the system are considered. Although low pressure continuously operating systems using positive displacement blowers are generally used for reference purposes in this chapter, the underlying principles and points considered will generally apply equally to any other type of system.

21.1.1 Optimizing conveying conditions

Engineers asked to undertake the design of a pneumatic conveying system are usually aware of the situation with respect to air flow rate, but are often not certain of the relationship between conveying air flow rate, or velocity, and material flow rate, air supply pressure and pipeline layout. The problem, of course, is that different materials can have totally different conveying characteristics and that conveying distance can also influence these characteristics, as illustrated at many points in Part B of this 'Design guide'.

Unless conveying trials are carried out with a material, or previous experience with the material is available, it is unlikely that the plant could be built to achieve the required output without over-design in certain areas. They will know that a dilute phase conveying system will not operate if the velocity is below the saltation or choking velocity. They are equally aware, however, that the system will operate reasonably well, although inefficiently, if the velocity is on the high side.

The tendency, therefore, is to 'play safe' and either install a pipeline with a larger bore than necessary, or to install a blower having a capacity much greater than is actually necessary. If, on commissioning the plant, the design flow rates are not achieved, the situation can usually be rectified by changing the V-belt drive gear ratio to achieve a lower volume output. It is quite likely, therefore, that the output of an existing conveying plant could be increased quite simply by adjusting the air flow rate and optimizing the conveying of the material in the existing pipeline.

21.1.2 Modifying plant components

If the conveying line is already operating under optimum conditions, or if optimization does not achieve the desired increase in material flow rate, it is possible that a modification to one or two of the plant components will result in an increase in capacity. For a given system, the material flow rate is dependent to a large extent upon the conveying line pressure drop available. It is necessary, therefore, to either provide the system with more pressure or to minimize the pressure drop associated with some of the plant components and thereby make more available for the conveying of the material.

The total pressure drop for the conveying system is made up of that due to the feeding device, that due to the conveying line and that due to the filtration plant at the end of the line. If the pressure drop associated with the material feeding and filtration units can be reduced, a greater pressure drop will be available for conveying the material in the pipeline, which will enable more material to be conveyed. Air supply and extraction lines, particularly if they are long, should also be included in this review.

Increasing the pipeline to a larger bore will almost certainly achieve an improvement in performance. An increase to the next standard size, however, may achieve a material flow rate higher than necessary. If the conveying line pressure drop is greater than about 0.8 bar for a positive pressure system, or more than about 0.4 bar for a vacuum system, the possibility of stepping the pipeline to a larger bore part way along its length would be well worthwhile exploring.

This is certainly the case for virtually all materials conveyed in dilute phase and for most materials conveyed in dense phase in sliding bed flow. It is only where materials exhibit a pressure minimum point in their conveying characteristics that the benefits would need to be reviewed carefully. Stepping of the pipeline will reduce the high values of conveying air velocity that can result towards the end of single bore pipelines. Since pressure drop is dependent upon both pipe bore and velocity the stepping of the pipeline to a larger bore will generally help on both accounts. The stepping of pipeline systems was considered in Section 9.4 in relation to conveying air velocities, and in Section 14.8 in relation to conveying performance.

21.1.3 Replacing plant components

If optimizing the conveying conditions and modifying plant items does not result in the desired increase in performance it will probably be necessary to replace one or more of the plant items. One of the easiest items to replace is probably the blower or compressor. It is important to realise, however, that if no other changes are made to the plant the output of the new air mover will only need to be increased in terms of delivery pressure. Only a relatively small increase in volumetric flow rate will be required in order to compensate for the increase in delivery pressure to maintain the necessary conveying line inlet air velocity. If a rotary valve is used in such a system it may also be necessary to take into account the corresponding increase in air leakage that is likely to result.

There are, of course, limits as to what can be achieved by replacing the blower or compressor. For negative pressure, or vacuum systems, the increase in available pressure drop may only be marginal. With positive pressure systems the material feeding device may impose a limit on the maximum supply pressure, particularly with low pressure rotary valves and venturi feeders. An increase in conveying line pressure drop can result in an increase in material flow rate as has been shown with the various material conveying characteristics presented but there is clearly a limit on the improvement that can be achieved.

If a significant improvement in performance is required then an increase in pipeline bore will be required. It is quite likely, however, that a new blower or compressor will be required as well, unless the original one installed was grossly over-rated. The possibility of increasing the speed of an existing machine to deliver a higher air flow rate could be explored, along with the capability of the existing drive motor. The capability of the existing filtration plant would also have to be examined for the higher air flow rate.

21.2 System not capable of duty

As with the problem of pipeline blockage, considered in the previous chapter, the inability of a system to achieve the rated duty could result from an error in the system design. Alternatively, it is possible that the problem could be rectified by some simple adjustment to the plant. It is particularly important to determine whether the limitation on material flow rate is due to the material feeding device or to the pipeline and air supply.

21.2.1 Material feeding

The first check to be made is on the conveying line pressure drop. If this is below the capability of the air mover it is probable that insufficient material is being fed into the pipeline. This may be rectified by adjusting the controls on the feeding device. If the maximum output of the feeder does not meet the conveying capability of the pipeline, however, it will probably be necessary to fit a larger feeder.

In the case of feeders delivering material into positive pressure conveying systems, there will be a leakage of air across the device. It should be checked that the feeder is operating satisfactorily with the material before recommending a larger size. In the case of rotary valves, for example, leakage air can restrict the flow of material into the valve. The leakage air might also aerate the material to such an extent that there is a significant reduction in bulk density. The effectiveness of air vents and the clearances on all moving parts should also be checked.

If the conveying line pressure drop is at the design value, however, it would indicate that it is the pipeline or the air supply that is the main cause of the system not being able to achieve the required material flow rate.

21.2.2 Air filtration

Another check to be made should be on the filtration unit. If this is incorrectly sized for the duty it is possible that the pressure drop across the filter will be unnecessarily high. Filter cloth surface areas are sized primarily on volumetric air flow rate. If it is incorrectly sized an additional unit could be installed, if there is sufficient space. If there is not sufficient room, then the filter unit will probably have to be replaced with a larger unit.

Before going to this length, however, a check should be made that cleaning cycles are satisfactory, cleaning is effective, and that the filter cloths do not need replacing. The pressure drop across a filtration unit should be low and so this element of pressure drop is only likely to be significant on low pressure conveying systems.

21.2.3 Reduce air flow rate

An improvement in system performance will often be obtained by reducing the quantity of air that is used for conveying the material, particularly if the system is overrated in terms of the volumetric flow rate of air that is supplied. This, however, must be carefully considered before being undertaken. It is essentially a programme of optimization that is required and it must be carefully planned.

21.3 Optimizing existing systems

In the majority of cases optimization of an existing system will be achieved by reducing the amount of air used for conveying the material. The problem with existing plants, however, is the potential disruption of production, particularly if a change in conditions results in a pipeline blockage. A large degree of control, therefore, is required so that changes can be made gradually and their effects can be carefully monitored.

21.3.1 Control and instrumentation

Although reducing the speed of the blower can produce the additional benefit of a slight increase in delivery pressure, it is not very convenient in terms of control and gradual adjustment. An off-take to atmosphere in the air supply line between the blower and the point at which the material is fed into the pipeline provides much more flexibility.

This can easily be arranged by fitting a Tee-piece into the line, with a control valve on the off-take. If there is not already a pressure gauge on the air supply line one could be fitted at the same time, as this will be needed to record the air supply pressure, or conveying line pressure drop.

If a rotameter, or some other form of air flow rate measuring device, is also fitted so that the air is discharged through it to atmosphere, a measure of the air flow rate discharged will be obtained as well. As many valves have non-linear characteristics, a rotameter would be particularly useful in ensuring that the desired proportion of air was discharged. By this means it will be possible to exercise full control over the air flow rate and quite accurately determine the amount actually used for conveying. Once this off-take is installed, tests can be carried out on the plant with little disruption to production.

In most plants the supply or receiving hoppers are mounted on load cells, or have some other weighing mechanism, and so material flow rates can be determined reasonably quickly and accurately, whether conveying is continuous or batch-wise. By gradually opening the off-take valve a number of tests can be carried out, and if the air supply pressure and the material flow rates are recorded for each test, it will be possible to construct a small part of the conveying characteristics. Depending upon the method of feeding the material into the pipeline it may be necessary to make adjustments to the feed rate so that this can be varied as well.

It is recommended that the amount of air by-passed to atmosphere should not exceed more than about 15 per cent of the total supply from the blower. When this point is reached the speed of the blower should be reduced to match the reduced air flow rate required before discharging any more air to the atmosphere. This is necessary to prevent the possibility of a surge in material feed from blocking the pipeline. A momentary increase in material flow rate will demand an increase in pressure, and if the off-take valve is wide open a much higher proportion of air will be lost than intended in the transient situation that follows. As a result the conveying line could be starved of air and the line could block.

21.3.2 Feeder considerations

Screw feeders and rotary valves are positive displacement devices and so the feed rate is unlikely to change. In this case an improvement in performance will be recognized in terms of a reduction in conveying line pressure drop. This, of course, will provide a perfectly valid alternative data point. If a significant reduction in conveying line pressure drop is achieved it would be recommended that the speed of the screw or rotary valve should be increased to give a higher material flow rate. This will then provide another data point.

By making gradual changes in air off-take, blower speed, and material flow rate, and determining the conveying line inlet air velocity at each stage, if should be possible to establish the capability of a system without risk of disrupting production on an existing plant.

21.3.3 The use of a sight glass

Ideally some of the tests should be carried out with conveying air velocities as close to the minimum as possible. For this purpose it would be a distinct advantage if there was a short length of sight glass in the pipeline so that the material being conveyed could be observed. With a sight glass in the line it would be possible to detect when conveying was being carried out close to the minimum conditions, and so tests could be carried out in this region with much more confidence.

Such a sight glass should be positioned as close as possible to the point at which the material is fed into the pipeline, for as the conveying air expands through the line the velocity will be a minimum at the material feed point, as this is the point of minimum velocity. Ideally the sight glass should be in a straight length of pipeline and be a couple of metres from any bend or valve in the line. A sight glass in a vertical line is possibly better than one in a horizontal line, for minimum conditions are much easier to detect.

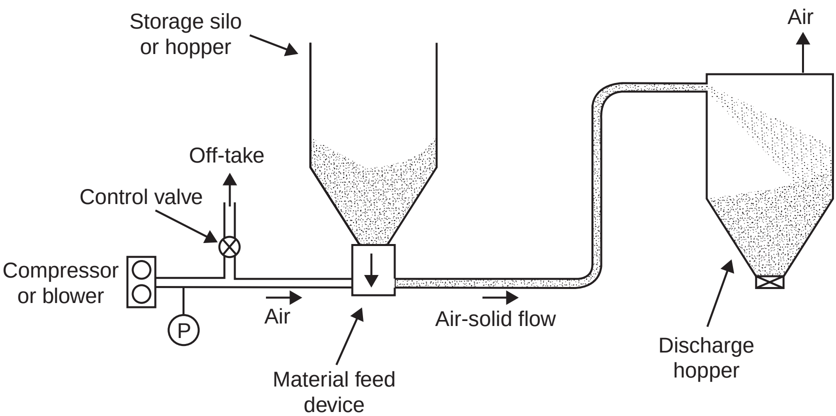


Figure 21.1 The use of an off-take to monitor the performance of a positive pressure pneumatic conveying system.

In a vertical line the flow is across the full bore of the pipe and at very low velocities some of the material will be observed to drop out of suspension, fall down past the sight glass, and be re-entrained in the conveying air. In some cases the material will start to build up on the wall of the sight glass. If all that can be seen is a blur it will be obvious that the conveying air velocity is far too high.

By carrying out tests over as wide a range of conveying conditions as can be achieved, it should be possible to obtain a reasonable indication of the nature of the conveying characteristics in the region of interest. If an improvement in material flow rate was indicated with a reduced air flow rate, the off-take valve could be shut and the speed of the blower could be reduced to provide the optimum value of air flow rate, and it is possible that an improvement in air supply pressure would result. If no improvement in material flow rate was achieved, the exercise would at least confirm that the material was already being conveyed under optimum conditions, and this would provide useful information about conveying air velocities and pressure drops so that the influence of alternative means of increasing the output could be assessed, such as using a larger bore pipeline.

21.3.4 Off-take systems

Figure 21.1 shows how part of the air supply can be discharged to atmosphere so that it is not used for conveying the material in the pipeline. This is a sketch of a simple positive pressure conveying system and shows the off-take positioned between the air mover and the material feeding device.

In a negative pressure system it would be positioned between the filtration unit and the exhauster. Air is drawn into the system and so it is an air intake rather than an off-take. By this means the exhauster discharges the rated air flow, but less air is drawn through the pipeline to convey the material. A sketch of a negative pressure system with such a Tee-piece and valve is given in Figure 21.2.

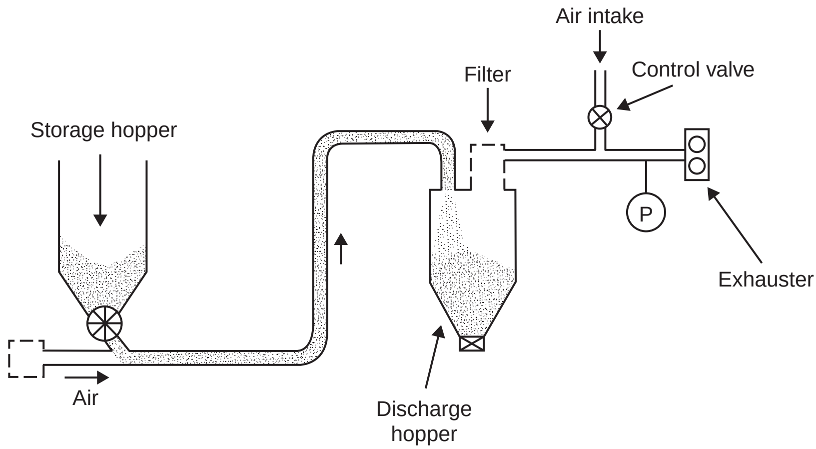


Figure 21.2 The use of a system by-pass to monitor the performance of a negative pressure pneumatic conveying system.

The same optimizing procedure can be applied to combined positive and negative pressure systems (see Figure 2.5). Each part would have to be assessed individually and be provided with its own Tee-piece and valve. Only if both parts of the system were to be found to be equally over-rated would it be possible to change the speed of the blower to provide the desired air flow rate. If there is any in-balance, one Tee-piece would have to be set and left open.

21.4 Case study

To illustrate some of the points discussed above, and to reinforce the procedures, a case study is considered. From the extent of the introduction earlier it will be clear that it will not be possible to cover all types of conveying system and every combination of plant item that could comprise a pneumatic conveying system. The same applies to the material conveyed and so the conveying characteristics presented in Figure 20.11 for a material capable of being conveyed in dense phase are used here for illustrative purposes.

The material was cement and was conveyed through a 50 m long pipeline of 76 mm bore that incorporated nine 90°bends and was limited to low positive pressure conveying. As a consequence the use of a positive displacement blower is considered. This combination is probably the most common found in industry. Despite the necessary restriction on the specific cases considered, much of the work is of a very general nature and so the underlying principles can be widely applied.

21.4.1 The influence of changing air flow rate

In order to show how the conveying characteristics can be used to assess the results of any changes that are made in operating conditions, the influence of changing air flow rates are demonstrated. Two cases are considered: one to show the adverse effect that generally results from increasing the air flow rate, and the other to show the benefit that can often be obtained by decreasing the air flow rate, particularly if the blower is over-rated for the required conveying duty.

The conveying characteristics presented in Figure 20.11 are used for this purpose and it is assumed that the conveying line pressure drop is 0.6 bar and that the air mass flow rate is 0.18 kg/s. Figure 20.11 is reproduced in Figure 21.3 and this conveying condition is located on the conveying characteristics by reference point A. The cement flow rate is 5.5 tonne/h and the solids loading ratio is about 8½.

It will be useful to know the value of the conveying air velocity for the various operating points being considered and so in Figure 21.4 a graph is included of conveying air velocity plotted against air mass flow rate, with lines of constant air pressure drawn and the various operating points being investigated are identified on this graph. Values can, of course, be calculated by using Equations such as (9.11) or (9.20).

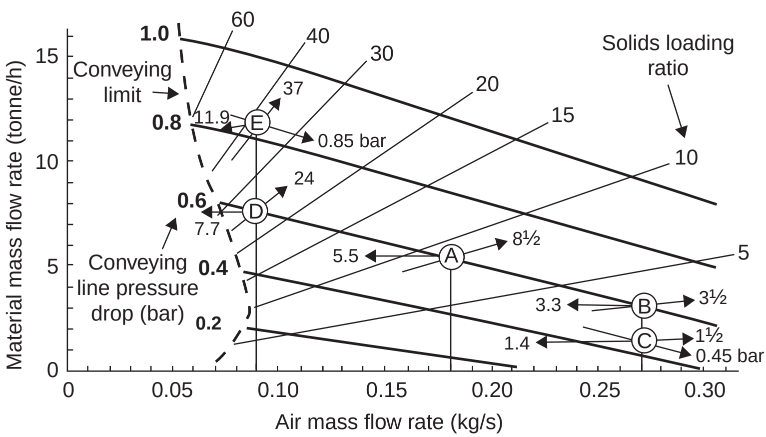


Figure 21.3 Case study points on conveying characteristics.

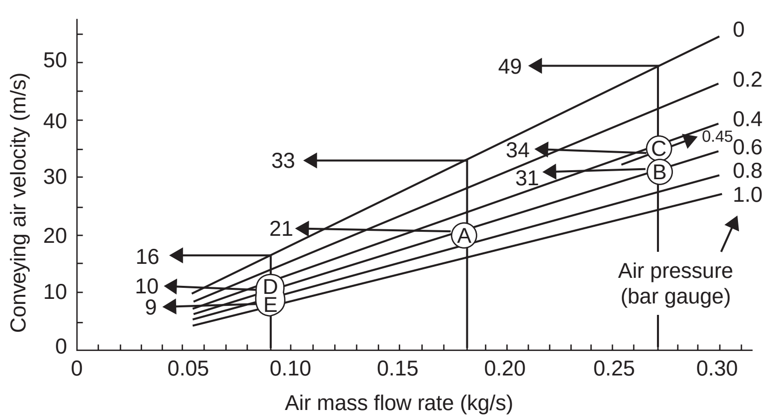


Figure 21.4 Conveying air velocity values for case study.

From Figure 21.4 it will be seen that with 0.18 kg/s of air in the 76 mm bore pipeline the conveying line inlet air velocity will be about 21 m/s, at a pressure of 0.6 bar gauge, and at exit from the pipeline at atmospheric pressure the velocity will be about 33 m/s. For this particular material these velocities are unnecessarily high and so the blower would be over-rated for the duty.

21.4.1.1 Increasing air flow rate

There are two ways of increasing air flow rate: one is to change the blower and the other is to increase the rotational speed of the existing blower, if it still comes within the operating characteristics for the machine. It will be assumed that the air flow rate is increased by 50 per cent and the net result of both alternatives will be investigated. If the existing blower is replaced by one that will supply 50 per cent more air, with the same delivery pressure, the operating point on the conveying characteristics will simply transfer along the same constant pressure drop line to the appropriate air mass flow rate at point B. From Figure 21.3 it will be seen that the material flow rate will reduce by about 40 per cent to 3.3 tonne/h as a result. The reason for this is the excessively high conveying air velocity.

From Figure 21.4 it will be seen that the conveying line inlet air velocity is now 31 m/s and the exit air velocity is up to 48 m/s. With such high values of velocity most of the pressure drop is used in blowing the air though the conveying line and little is left for conveying the material. From the blower characteristics, presented in Figure 21.5, it will be seen that the power required to supply the increased air flow rate at this same pressure is 21 kW, and so the 40 per cent reduction in material flow rate would be achieved with a 30 per cent increase in power.

If the air flow rate is increased by increasing the rotational speed of the existing blower, this will necessarily result in a lower delivery pressure if there is no change in drive power. From the blower characteristics in Figure 21.5 it will be seen that the rotational speed will have to be increased to about 2000 rev/min and, assuming that there

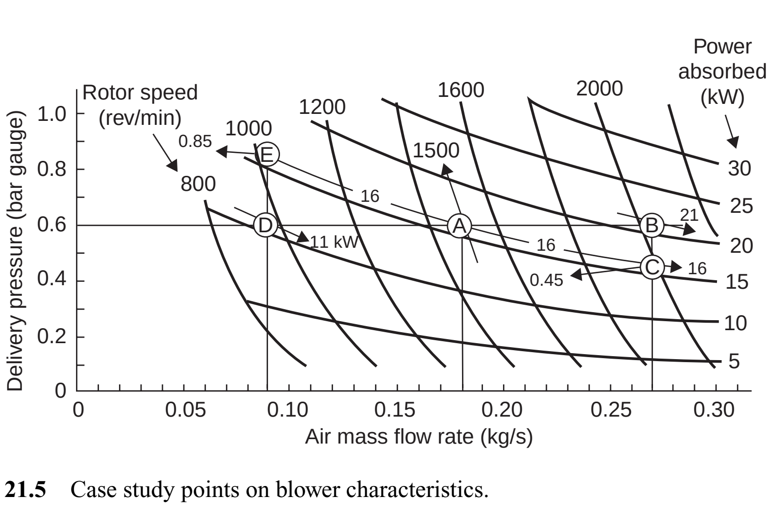


Figure 21.5 Case study points on blower characteristics.

is no additional reduction in pressure due to transmission losses, etc, the delivery pressure will be down to about 0.45 bar. This operating condition is located on Figure 21.5 at point C.

With an air mass flow rate of 0.27 kg/s supplied at a pressure of 0.45 bar, the equivalent point on the conveying characteristics in Figure 21.3 shows that the material flow rate will be only 1.4 tonne/h. With the same air flow rate as in Case B, the conveying line exit air velocity will also be 49 m/s. Due to the slightly lower air supply pressure, however, the conveying line inlet air velocity will be slightly higher at 34 m/s. The 75 per cent reduction in material flow rate can be attributed to the adverse effect of the excessively high conveying air velocities, as in Case B. The power supply, of course, is the same as in Case A.

21.4.1.2 Decreasing air flow rate

Two methods of decreasing the air flow rate are also considered. One is to provide a by-pass in the air line at outlet from the blower and to discharge part of the air supply to atmosphere so that it is not used for conveying. The other is to reduce the rotational speed of the blower. It will be assumed that the air flow rate is reduced by 50 per cent and the net result of these two methods is investigated.

If 50 per cent of the air is discharged to atmosphere, the operating point on the conveying characteristics will simply transfer along the 0.6 bar pressure drop line to the appropriate mass flow rate value at point D. From Figure 21.3 it will be seen that the material flow rate will increase by about 40 per cent to 7.7 tonne/h. Since the blower was over-rated in terms of volumetric flow rate the conveying air velocity was unnecessarily high.

With 50 per cent less air the pressure drop required to blow the air through the line is reduced. This means that more is available for conveying the material, and so its mass flow rate can be increased. From Figure 21.4 it will be seen that the conveying line inlet air velocity has reduced to about 10 m/s, and the conveying line exit air velocity is only 16 m/s. From the blower characteristics in Figure 21.5 it will be seen that the power required to supply the reduced air flow rate at this same pressure is 11 kW, and so the 40 per cent increase in material flow rate could be achieved with a 30 per cent decrease in power.

If the air flow rate is achieved by decreasing the rotational speed of the existing blower it is possible that the reduced flow rate will be at a higher delivery pressure. From the blower characteristics in Figure 21.5 it will be seen that the rotational speed will need to be reduced to about 1000 rev/min. On the assumption that this gain in pressure drop can be fully realised, the delivery pressure will be about 0.85 bar. This operating condition is located on Figure 21.5 at point E. With an air mass flow rate of 0.09 kg/s supplied at a pressure of 0.85 bar, the equivalent point on the conveying characteristics in Figure 21.3 shows that the material flow rate will now be 11.9 tonne/h.

With the same air flow rate as in Case D the conveying line exit air velocity will also be 16 m/s. Due to the slightly higher air supply pressure, however, the conveying line inlet air velocity will be a little lower at 9 m/s. The considerable increase in material flow rate can be attributed to the fact that the full 16 kW is available to the system and that with these low inlet and exit air velocities the system is operating very close to its point of maximum efficiency.

It will be noticed from Figure 21.3 that the operating point is still within the body of the conveying characteristics and so there is unlikely to be any problems of pipeline blockage. It will also be noticed from Figure 21.5 that point E is only just within the operating limits of the blower. It is, however, a valid operating point on the conveying characteristics and a smaller blower is likely to meet the duty as specified.

21.4.1.2.1 The effects of solids loading ratio

The minimum conveying air velocity, as a result of this increase in pressure with Case E is now down to about 9 m/s. The solids loading ratio of the material in the pipeline, however, has increased to about 37 as can be seen from point E on Figure 21.3. The minimum air velocity that can be achieved for conveying a material in a pipeline depends to a large extent upon the solids loading ratio of the material being conveyed. As the solids loading ratio is increased, the minimum conveying air velocity that can be employed decreases for a material that is capable of being conveyed in dense phase. At a solids loading ratio of 37, therefore, it should be possible to convey the material with air velocities lower than 9 m/s without risk of blocking the pipeline.

The influence of solids loading ratio on the minimum conveying air velocity for the cement is given in Figure 21.6. Points D and E from the above case study are superimposed on this plot and it can be seen that they are both above the conveying limit by a reasonable margin.

21.4.1.2.2 Power requirements

It will be noticed from the blower characteristics in Figure 21.5 that points A, C and E all lie on a line of constant power. These same points, therefore, form a line of constant

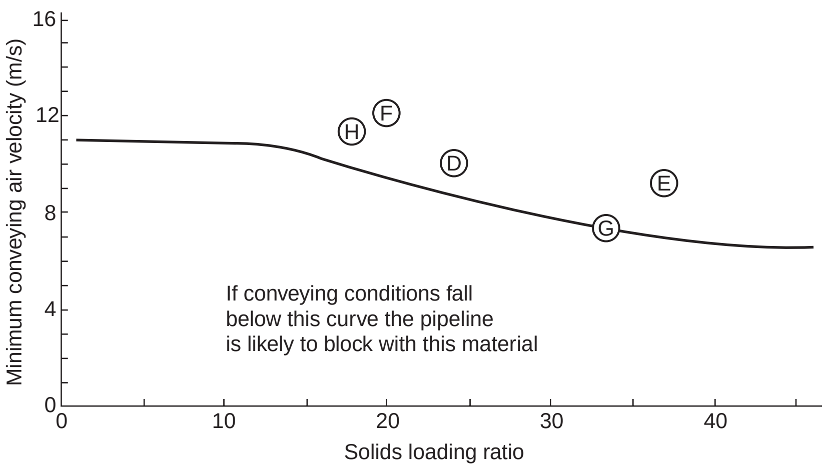


Figure 21.6 The influence of solids loading ratio on the minimum conveying air velocity for the material.

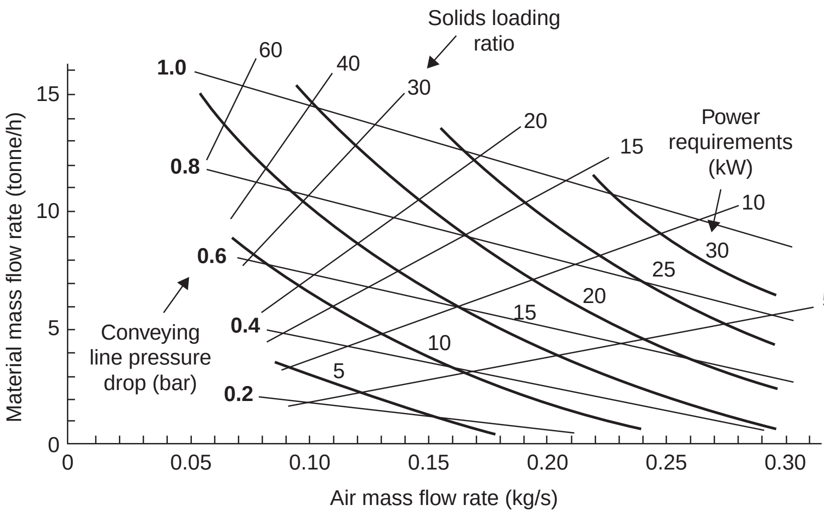


Figure 21.7 Influence of conveying parameters on power requirements.

power on the conveying characteristics in Figure 21.3. Lines of constant power can be superimposed on the conveying characteristics quite easily, as illustrated in Section 11.5.2, and so to illustrate this point the conveying characteristics in Figure 21.3 are reproduced with lines of constant power requirements in Figure 21.7. It can be seen from Figure 21.7 that, for a material that has conveying characteristics of this type, that a reduction in air flow rate, for a constant value of conveying line pressure drop leads to a significant reduction in power requirements as well as an increase in material flow rate.

21.4.2 The influence of changing pipeline diameter

If the required increase in material flow rate is greater than that which can reasonably be obtained by optimizing the existing system, it will probably be necessary to increase the size of the pipeline. If it can be established that the blower is over-rated for the existing plant, in terms of volumetric flow rate, it is possible that the same blower could be used with a larger bore line. In order to investigate this possibility, conveying characteristics for different sizes of pipe are necessary. For the purposes of demonstrating the potential influence of pipe bore the conveying characteristics for the cement in the 76 mm bore line in Figure 21.3 have been scaled in proportion to pipe section area.

In Figure 21.8 the conveying characteristics for the material conveyed through a 100 mm bore pipe are presented. If the reference condition used in Figure 21.3, to show the influence of air mass flow rate, is taken again, both the possibility of using the same blower with a larger size pipe and the influence of pipe bore can be investigated. In the earlier case a blower capable of delivering 0.18 kg/s of air at 0.6 bar gauge was considered. For the 76 mm bore line in Figure 21.3 it was shown that the material flow rate would be 5.5 tonne/h. This, however, could be increased to 7.7 tonne/h by

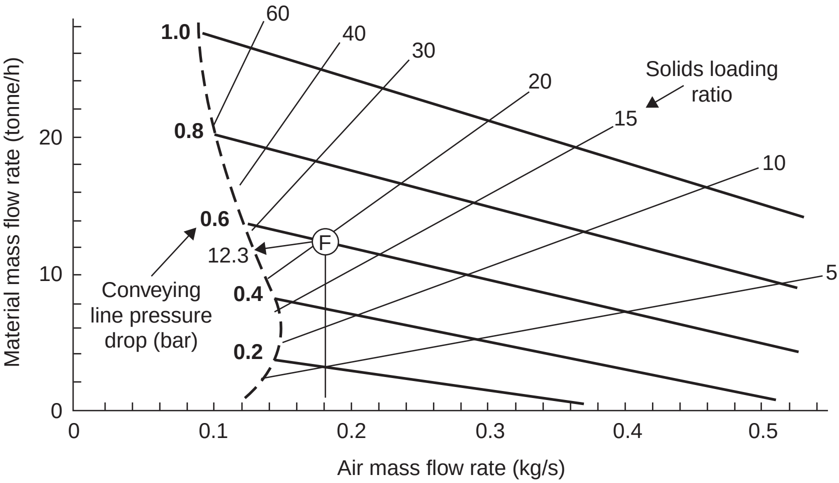


Figure 21.8 Conveying characteristics for material in 100 mm bore pipeline.

using an off-take for 50 per cent of the air, and to 11.9 tonne/h by reducing the speed of the blower, since the blower was over-rated.

The reference condition in Figure 21.8 is denoted by point F. With an air mass flow rate of 0.18 kg/s and a supply pressure of 0.6 bar gauge it will be seen that conveying of the cement in a 100 mm bore line is close to the ideal condition. The velocity of the air at the material feed point into the pipeline would be about 12 m/s. This provides an adequate safety margin in terms of the minimum conveying air velocity for the material, as shown in Figure 21.6, and so no change in blower operating conditions would need to be made. The solids loading ratio of the cement would be about 20 and the material flow rate 12.3 tonne/h. There is even scope for an improvement on this by reducing the speed of the blower as the operating condition is well above the minimum.

In Figure 21.9 the conveying characteristics for the material conveyed through a 125 mm bore pipeline are presented. If the same blower supply conditions of 0.18 kg/s at 0.6 bar gauge are superimposed it will be seen that the operating point, denoted by the reference G, is beyond the range of the conveying characteristics. The velocity of the air at the material feed point would only be about 7 m/s and so it is unlike that conveying would be possible. The theoretical value of solids loading ratio would be about 33. The point is also shown on Figure 21.6.

If the rotor speed of the blower is increased to about 1900 rev/min, the air mass flow rate would be increased to 0.25 kg/s and this should be ideal for conveying the cement through a 125 mm bore pipeline. From the blower characteristics in Figure 21.5 it will be seen that the delivery pressure would be reduced to about 0.50 bar with the same 16 kW power input. The new blower operating conditions are shown on Figure 21.9 at point H.

From this it will be seen that the material flow rate would be about 15.7 tonne/h. The solids loading ratio of the material would be about 18 and the conveying

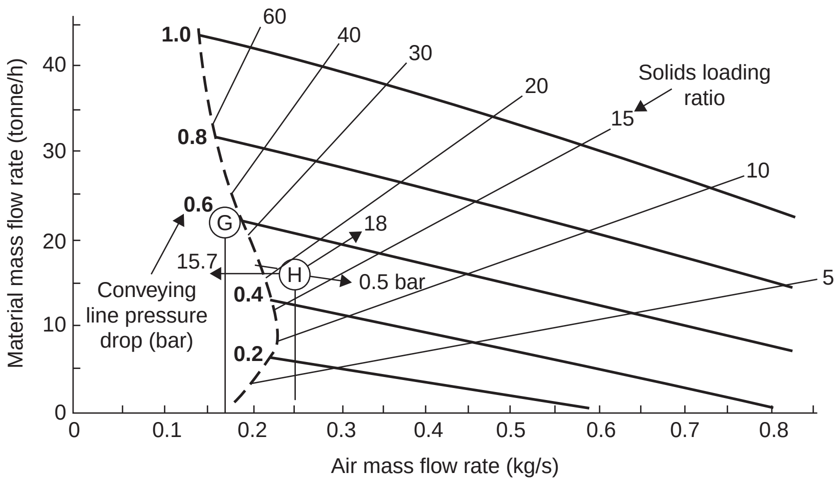


Figure 21.9 Conveying characteristics for material in 125 mm bore pipeline.

line inlet air velocity about 11 m/s, which would be quite satisfactory as shown on Figure 21.6.

21.4.2.1 System potential

If the required material mass flow rate is greater than that which can be achieved with the existing blower, then a larger bore line and a new blower would be required. From Figure 21.9 the potential conveying capacity of a 125 mm bore pipeline can be seen. If a blower capable of supplying 0.25 kg/s at 0.8 bar gauge is used, for example, a material flow rate of almost 30 tonne/h could be achieved.

If such a large increase in material flow rate is required, however, it would also be necessary to check whether the existing feeding device is capable of delivering at such a rate, and whether the filtration unit is capable of handling the increase in both air and material satisfactorily. In the above case study it has been assumed that the feeding device would deliver the appropriate flow rate into the conveying line each time. It is, of course, essential that this should be the case. If insufficient material is fed into the conveying line the capability of the blower, in terms of pressure, will not be achieved for the resistance of the line will be insufficient.

21.5 Alternative methods of up-rating

From the work presented above it is quite clear that the first thing that should be done in any attempt to up-rate an existing pneumatic conveying plant is to optimize the system. If the plant has been over-designed it should be possible to alter the conveying conditions and obtain a significant increase in material flow rate as a result. If it is found that the plant is operating fairly close to its optimum condition, or if an even greater increase in material flow rate is required, then a number of alternative ways of increasing the throughput can be considered.

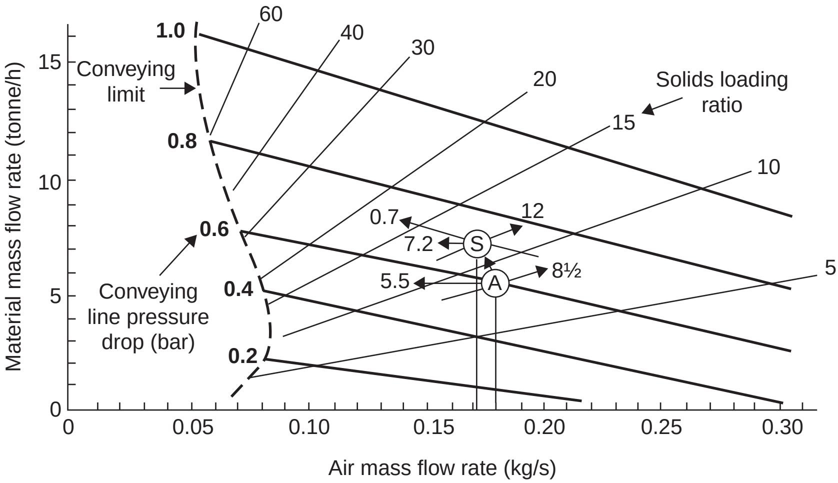


Figure 21.10 The influence of a surge in material feed rate.

21.5.1 Pipeline feeding

The feeding of material into the pipeline is particularly important, for if this is not done at a steady rate a blocked line may result. A surge of material into a pipeline will require an increase in pressure to clear it, and the line will probably block if the maximum pressure of the blower is exceeded. A certain amount of the available capacity of the blower, in terms of delivery pressure, must be kept in hand in order to accommodate slight fluctuations in feeding rate. If these fluctuations can be kept to a minimum it will be possible to operate the blower at a pressure much closer to its maximum, without risk of blocking the line.

The effect of a surge in material feed rate can be demonstrated on any of the conveying characteristics. Those from Figure 21.3 are used for this purpose and these are reproduced in Figure 21.10 with the point A being taken as the reference condition once again. At this point the air flow rate is 0.18 kg/s, the material flow rate is 5.5 tonne/h and the conveying line pressure drop is 0.6 bar. If there is a surge in material feed rate of about 30 per cent, the flow rate will increase momentarily from 5.5 to about 7.2 tonne/h. This will cause an increase in concentration of the material in the air and so there will have to be a corresponding increase in pressure to compensate.

With positive displacement blowers, and most similar compressors and exhausters, an increase in demand for pressure results in only a small reduction in the air flow rate that is delivered. They are essentially constant volume machines as the characteristics in Figure 21.5 show. The operating point on the material conveying characteristics, therefore, will jump to point S on Figure 21.10. At this point the solids loading ratio is 12 and the conveying line pressure drop required is about 0.7 bar. The equivalent point on the blower characteristics is shown on Figure 21.11. If the blower is not capable of supplying the air at this pressure it is likely that the surge in material flow rate would result in the pipeline being blocked. From Figure 21.11 it will be seen that the power

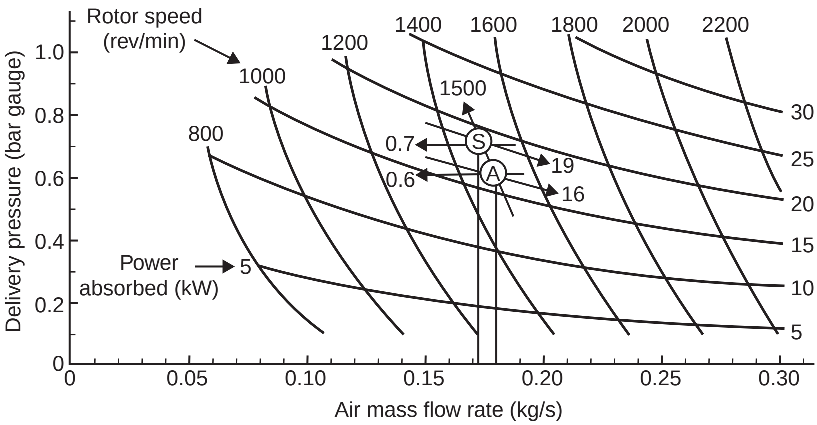


Figure 21.11 The influence of a surge on blower performance.

required has to jump from 16 to 19 kW, and so this represents the spare capacity that must be available to prevent such a surge from blocking the pipeline.

At point A the conveying line inlet and outlet air velocities, determined from Figure 21.4, were 21 and 33 m/s. It would, therefore, take less than two seconds for the air to traverse a pipeline 50 m long, and so the avoidance of even short material surges is very important. If such surges could be eliminated or be substantially reduced it would be possible to use part of the margin to supply pressure for the conveying of the material at an increased flow rate.

21.5.2 Pipeline modifications

A number of modifications can be made to the pipeline that may help to reduce the pressure drop and enable more material to be conveyed. The most obvious one is to reduce the length of the line, although this is rarely possible. If re-routing is practicable so that some of the bends in the line could be eliminated, this would certainly help in reducing the line pressure drop. It would also help if very short radius and pocketed bends were to be replaced with slightly longer radius bends.

A stepping of the pipeline to a larger bore part way along its length would reduce the mean conveying air velocity in the line. This would be an advantage in cases where the air supply is at a high pressure, for very high exit velocities can result if only a single bore line is used. The sizing must be carried out carefully, however, for the velocity must not be allowed to drop below the minimum conveying air velocity at the start of the new section.

The improvements that can be achieved by many of these suggested pipeline modifications, however, will only be marginal with a low pressure system. If a significant increase in material flow rate is required, therefore, it is unlikely to be met by simple modifications such as these. The most drastic change to a pipeline would be to increase the bore, but this would result in a significant increase in material flow rate. The conveying characteristics for the 76 mm bore pipeline presented in Figure 21.3 were scaled up to 100 mm bore in Figure 21.8 and to a 125 mm bore line in Figure 21.9. These show quite clearly the potential of pipe bore, but as mentioned earlier, the subsidiary influences of material feeding and filtration must be given due consideration.

21.5.3 Air supply pressure

The influence of air supply pressure has already been mentioned in relation to pipeline feeding. In the example given above it was stated that a 30 per cent increase in material flow rate would require an increase in the conveying line pressure drop from 0.6 to 0.7 bar. The increase in pressure required for a given increase in material flow rate, therefore, can be determined very easily from the conveying characteristics.

If the blower is replaced with another, the output of the replacement will only need to be increased in terms of delivery pressure. There may need to be a small increase in volumetric flow rate in order to compensate for the increase in delivery pressure and so maintain the same conveying line inlet air velocity. If a rotary valve is used to feed the material into the conveying line it may also be necessary to allow for a small increase in air leakage across the valve. The increase in blower rating, therefore, is essentially in terms of delivery pressure only if no other changes are made to the plant.

Chapter 22

Operating problems

22.1 Introduction

Since the cause of any operating problem is not always obvious, this chapter has been subdivided into four major areas to help in the identification and solving processes. In the first section problems related to particular types of system are considered. The second section is devoted to problems that can be associated with system components, including air movers, feeders and filtration systems. The next deals with system-related problems and includes effects that the material can have on the system. The last concerns material-related problems and includes effects that the system can have on the conveyed material.

Although the specific problem of pipeline blockage was considered in detail in Chapter 20, and that of systems not capable of achieving the rated duty in Chapter 21, many of the items considered may also have an influence on material flow rate. A number of the problems that are considered to be are either very common in the industry, or need more detailed treatment, have an entire chapter devoted to them later in this part of the Design Guide.

In trying to identify any particular problem it is suggested that each section should be consulted since cross-referencing and repetition have been kept to a minimum. Those items that relate to the particular problems experienced, type of plant and components used, and material conveyed, should all be referred to in order to obtain a clear picture of the problem in relation to the entire system and the material handled.

22.1.1 Existing plant

This section of the Guide is directed essentially at identifying operating problems that occur with an established plant, or one that has just been installed. It is not intended to support system design by way of problem anticipation so that counter measures or appropriate equipment selection are dealt with before the plant is built. If a new system is designed correctly, and potential problem areas are recognized at the design stage, there should be no need to refer to this section at all. This part of the Guide can, of course, be used as a checklist to ensure that all possible sources of problems have been considered at the design stage, and should prove to be invaluable when commissioning a plant.

22.2 Types of system

In this section, problems that relate specifically to a particular type of pneumatic conveying system are considered. System types were considered mainly in Chapter 2 and reference will be made to particular figures included there.

22.2.1 Positive pressure systems

The most common problems associated with pneumatic conveying systems relate to the fact that the material to be conveyed has to be fed into a pipeline in which the conveying air is maintained at pressure. Air requirements have to be specified, taking account of both the compressibility of the air, and air leakage from or into the system.

22.2.1.1 Multi point feeding

Multi point feeding of a positive pressure pneumatic conveying system is not generally recommended unless particular attention has been paid to the problem of air leakage. For feeders subject to air leakage, air loss from a single feeder can be a significant proportion of that required for conveying the material. The air loss from a number of feeders, therefore, would be seriously detrimental to the performance of the system.

The air loss from multiple feeding points would be difficult to accurately estimate and so the air flow rate available for conveying could not be guaranteed. Apart from the problem of having too little or too much air for conveying the material, the loss of a large quantity of air from multiple feeding points would represent a very significant energy loss from the system.

22.2.2 Negative pressure systems

A common fault with negative pressure, or vacuum conveying systems, is the loss of vacuum, particularly with batch and intermittently operating systems. The cause of the problem is often that the discharge flap fails to seat at the base of the receiver vessel. Another common problem is similar to that experienced with positive pressure systems, in that the compressibility of the air is not taken into account correctly. In vacuum systems, however, this can affect the specification of the filter, as well as the conveying line inlet air velocity and the specification of the air mover.

22.2.2.1 Air filtration

With negative pressure systems, the entire discharge system operates under vacuum, and this includes the filtration plant. Filters are generally sized in terms of the surface area of filter cloth, and the surface area required is evaluated in terms of a given air velocity across the fabric surface. Under vacuum, therefore, the volumetric flow rate of air to be handled is very much higher than it is for a positive pressure conveying system discharging to atmospheric pressure.

The size of filter required for a vacuum conveying system will depend upon the exhauster pressure, and for a vacuum of 0.5 bar, for example, it will need to be about twice the size of that required for an equivalent positive pressure system. If the filtration plant is not sized, taking this into account, it will be too small for the duty and system performance and operating problems can be expected as a result.

22.2.2.1.1 Back-up filters

It is generally recommended that a secondary filter, often referred to as a policeman filter, should be fitted to negative pressure conveying systems. This is a particular requirement if a positive displacement blower, screw compressor or a sliding vane rotary compressor is used as an exhauster. These exhausters operate with very fine clearances between the moving parts and cannot tolerate dust, particularly if it is abrasive.

A back-up filter is required in case an element in the main filter unit should fail. If an abrasive material such as silica sand, cement, alumina or fly ash, is being conveyed, and the main filter unit fails, considerable damage will be caused to any of the above exhausters in a very short space of time. A back-up filter will allow time for the conveying system to be shut down safely so that repairs can be carried out. A similar situation occurs with combined 'suck-blow' systems and with closed loop conveying systems.

22.2.2.2 Multi point discharge

Vacuum conveying systems are not generally recommended if multi point discharging of materials is required, since a complex arrangement of pipe-work and isolating valves is necessary. The problem is essentially the reverse of that associated with multiple point feeding of positive pressure conveying systems considered above. They are sometimes used in low pressure systems, where ductwork is used. Valves in the ductwork, however, have to seal effectively, otherwise the air leakage into the system will have an adverse effect on the conveying of the material.

22.2.2.3 Air ingress

If air leaks into a vacuum or negative pressure system it will alter the balance of conveying air velocities along the length of the pipeline. The problems that occur here can generally be considered to be a mirror image of those that exist on similar positive pressure systems.

22.2.2.3.1 Into reception hopper

If air leaks into the reception hopper, and thereby bypasses the conveying pipeline, air velocities in the conveying line will fall and the pipeline could block if the ingress of air is not allowed for in the specification of the air mover. This can occur if the material in the reception hopper is discharged by means of a rotary valve, for example. The rotary valve will typically discharge the material into a vessel at atmospheric pressure, and so there will be a pressure difference across the valve. As with rotary valves feeding positive pressure pneumatic conveying systems, there will be a leakage of air across the valve because of the pressure difference. In a vacuum system this air will leak into the system, and so it must be taken into account (see Figure 3.7).

22.2.2.3.2 Into pipeline

Air ingress is likely to occur along a pipeline at flexible sections, such as those used in ship off-loading systems, particularly if the conveyed material is erosive and the flexible joint has to be made from hard metal or ceramic materials. If air leaks into a pipeline part way along its length in this way, it will result in a lowering of the conveying air velocity at the material feed point into the pipeline. This is the critical point in a pipeline and so could result in pipeline blockage.

If a bend in a pipeline fails, or if pipeline joints are not securely tightened in a positive pressure conveying system, clouds of dust will result and the situation is likely to be dealt with very quickly. In terms of conveying performance it is unlikely to present a problem, for downstream of the feed point the velocity increases and such air loss could be a benefit to the system. In a vacuum system dust is not likely to be released in this situation, as air is drawn into the system, and so the problem may not be recognized. Air drawn into the system, however, will starve the pipeline inlet of air and the pipeline could block as a consequence.

22.2.2.4 Stepped pipelines

With a vacuum of only 0.5 bar there will be a doubling in conveying air velocity through the pipeline. Stepped pipelines, therefore, are well worth considering for vacuum systems, particularly if high vacuum is employed (see Figure 9.13). Reduced erosive wear, particle degradation and improved conveying performance are all possible benefits.

22.2.2.5 Air mover specification

Care must be exercised in specifying exhausters. The rating of an exhauster is not usually in terms of free air conditions, as with positive pressure systems, but in terms of the volumetric flow rate of air at inlet to the exhauster. This, however, is not significantly different from the means by which positive pressure air movers are specified, for they are both in terms of the displacement volume of the air mover at inlet conditions. The value, of course, will vary with the vacuum drawn and so the conveying line inlet air velocity will have to be carefully evaluated and the influence of the vacuum determined. This, however, is very similar to the analysis that must be made for positive pressure systems and considered in Chapter 9.

22.2.3 Combined systems

It must be appreciated that the available power for a combined positive and negative pressure conveying system has to be shared between the two parts of the system (see Figure 2.5). If a positive displacement blower/exhauster is used, the pressure capability on both the vacuum and blowing sides will be lower than that which can be achieved with an equivalent machine used for the single duty. With a blower, for example, a pressure ratio of 2:1 is generally considered to be the upper operating limit, regardless of the application.

This means that for a positive pressure system the maximum delivery pressure is about 1 bar gauge (2 bar abs/1 bar abs = 2). For a negative pressure system the maximum exhaust pressure is about −0.5 bar gauge (1 bar abs/0.5 bar abs = 2). For a combined system the limit on pressures is approximately 0.4 bar gauge on blowing and −0.3 bar gauge on vacuum (1.4 bar abs/0.7 bar abs = 2).

A sketch of a typical system is given in Figure 2.5 and velocity profiles through such a system were presented in Figure 9.7. Even though a common air mover is used for both parts of the system, the diameter of pipeline employed for the vacuum side of the system is generally larger than that for the positive pressure side. If an improvement in performance is required or there is an imbalance in conveying distances between the two sections, two separate systems and a dedicated air mover for each would be better. By this means the pressure rating and air flow rate can be chosen to match the requirements of each section more closely.

22.2.4 Fan systems

As a result of the performance characteristics of fans, conveying air velocities will be high at low material flow rates, and low at high material flow rates. A comparison of the operating characteristics of fans and positive displacement machines is shown in Figure 6.3. If a fan system is overfed, the pressure demand on the fan will increase. This will cause a decrease in volumetric flow rate and it is possible that the pipeline will block.

The ideal characteristics for an air mover, for a pneumatic conveying system, are those that result in no change in volumetric flow rate with increase in pressure. Positive displacement machines come close to this, as shown in Figure 6.5, and hence this type of air mover is widely used for pneumatic conveying systems. They are almost exclusively used for high material flow rate and long distance conveying duties.

22.2.5 Single plug blow tank systems

With some materials the plug of material that is conveyed will be accelerated along the length of the system pipeline. If there is no check on the volumetric flow rate of air supplied, additional air and hence energy will be expended unnecessarily on the material. If the volumetric flow rate of air needs to be controlled a choked flow nozzle or orifice plate can be used in the air supply line.

When a plug of material is discharged from a pipeline at a high pressure, a large volume of pressurized air is released, particularly if it is a long pipeline. A certain amount of material is almost certain to be left in the pipeline. This will tail off the end of the plug being conveyed, to be swept up by the front of the next plug. The high pressure air in the pipeline will suddenly be vented from the end of the pipeline when the plug is discharged. The venting air, which can reach an exceptionally high velocity, will pick up deposited material and cause severe erosion problems if the material is abrasive.

22.3 System components

Many of the problems encountered in pneumatic conveying systems are associated with the various components that go to comprise the system itself. The problems generally result from either incorrect specification, or a failure to take account of the properties of the material to be conveyed. Not all types of system components are mentioned individually. Most of the problems associated with screw feeders, for example, are common to rotary valves, and so simple representative components are considered.

22.3.1 Blowers

The rotary lobes in blowers are machined to close tolerances, as are moving parts in many other air compressors. Any ingress of dust or material into the machine will have a serious effect on the performance of the blower. Downstream of the blower, or any other air mover, non-return valves should be fitted into the air supply lines to prevent the possibility of backflushing of materials. This is always a possibility if the pipeline blocks.

Some materials that have very poor permeability are capable of holding back air pressures of 6 bar gauge with just a short plug of material in the pipeline. If the pipeline blocks and the air mover is switched off while the pipeline is being cleared, the material in the pipeline could easily be backflushed to the compressor if it was not protected with non-return valves.

22.3.1.1 Air filters

If a blower, or any other positive displacement air mover, is operating in a dusty environment a filter should be fitted to the air inlet. This filter should be cleaned or changed periodically, for if it becomes choked with dust, the added resistance will have an adverse effect on the blower performance. A source of air away from the plant or outside the building is generally recommended in these circumstances.

In negative pressure, closed loop and combined systems, blowers have to operate with air that has been used for conveying material. In these cases it is essential that the air is effectively filtered. Unless the filtration unit is 100 per cent reliable, it is generally advisable to add a back-up filter in order to provide a measure of protection for the blower in the event of a rupture of one of the filter elements. If a gradual change in performance of a conveying system is observed over a period of time, it could be due to wear of the blower. Ingress of dusty air into the blower will cause a gradual change in its operating characteristics.

22.3.2 Blow tanks

Of all systems components, the operation and control of blow tanks is probably least understood. The transient nature of their operation must be taken into account in specifying material flow rate (see Figure 2.7) and air requirements. A variety of blow tank designs and configurations exist and these were considered in both Chapters 3 and 4. A particular advantage of blow tanks is that they have no moving parts, which makes them ideal for the feeding of abrasive materials, but the means by which material feed rate is controlled is by no means obvious.

22.3.2.1 Control

The discharge rate of a blow tank is controlled by means of proportioning the air supply between the fluidizing and supplementary air lines as considered with Figure 3.28. A control system fitted to a blow tank was presented in Figure 4.16. For complete system control the blow tank characteristics need to be considered in conjunction with the pipeline conveying characteristics and Figure 22.1 is included to illustrate the interaction between the two.

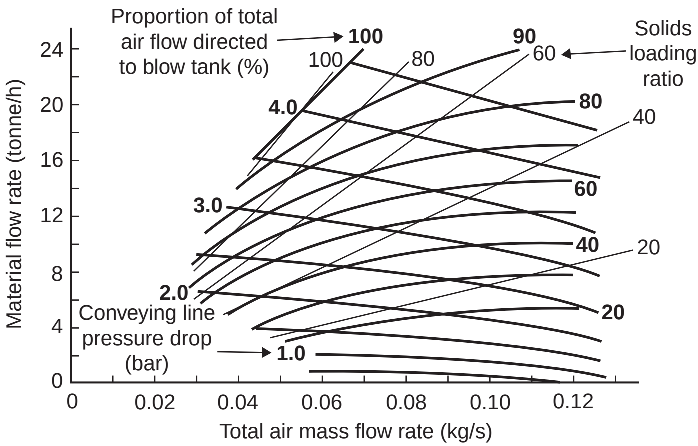


Figure 22.1 Typical operating characteristics for blow tank fed pipeline conveying system.

Figure 22.1 combines the discharge characteristics of the blow tank as a feeder and the potential of a given pipeline for conveying material. The blow tank was a top discharge type having a fluidizing membrane and the material conveyed was cement. The conveying system relates to pipeline no 7 shown in Figure 13.4. This was 101 m long, of 53 mm bore and incorporated seventeen 90° bends. By combining the blow tank and conveying line characteristics in this way it can be seen how the total conveying system can be controlled to achieve a given material delivery rate. It is important that the required conveying duty can be achieved by both the blow tank and the pipeline.

22.3.2.2 Discharge limits

The upper discharge limit of a blow tank will be reached when all the air is directed to the blow tank. If a further increase in material flow rate is required, this can be achieved by increasing the volumetric flow rate of air, although this may have an adverse effect on the conveying of the material in the pipeline. The alternative is to increase the diameter of the blow tank discharge pipe. The diameter of the discharge pipe within the blow tank does not have to be the same as that of the pipeline.

If an attempt is made to convey a material at a low flow rate from a top discharge blow tank with only a small proportion of the air flow rate directed to the blow tank, the blow tank could 'stall' and cease to discharge material into the conveying line. This is because the air velocity in the blow tank discharge line will be very much lower than that at the material pick-up point. For a material having poor permeability and air retention properties this could result in blockage of the discharge pipe. If this occurs a smaller diameter discharge pipe should be used.

22.3.2.3 Change of distance or material

If a blow tank is to be used to convey a material over a range of distances it will be necessary to change the proportion of the air according to the distance conveyed. If this is not done the pipeline will be under-utilized for shorter distances, and may block on longer distances. Feeder control, with respect to a change of distance, is an issue that must be considered with regard to any type of feeder. The same applies to a change of material but is particularly critical with regard to blow tanks as illustrated with Figure 4.15. An automatic control system, as mentioned above, would be recommended in both of these cases.

22.3.2.4 Discharge valve

If the conveyed material is abrasive, any valve in the conveying line will be subject to wear. With top discharge blow tanks, discharge valves are not necessary. They will, however, enable a blow tank to be pressurized quickly and so give an overall increase in the conveying efficiency and material flow rate (see Section 4.4.2). In bottom discharge blow tanks the discharge valve may be necessary to prevent flooding of free flowing materials into the conveying line, and hence overload the conveying system on start-up.

22.3.2.5 Moisture in air

When air is compressed, its capacity for supporting water vapour decreases. Even relatively dry air may reach its saturation point and condensation may occur as the pressure is increased. With moist air the quantity of water precipitated can be very high, particularly with respect to a change in temperature (see Chapter 25). Unless positive measures are taken to remove this water, drops of water will be transported through the air supply lines with the conveying air. If a fluidizing membrane is used in a blow tank, this water can cause blinding of the membrane with certain materials and this can affect system performance.

Since most blow tanks are used for batch conveying, it is possible for water to accumulate in the supply lines as a result of the intermittent operation. On start up with the next batch, a small pool of water could be blown into the blow tank. With materials such as cement and fly ash this could cause the material to set in the discharge area and cause a major restriction to the flow. Most problems associated with moisture can be overcome by drying the air. If the material is hygroscopic it will probably be necessary to incorporate a desiccant type dryer. If moisture and condensation are to be avoided, then a refrigerant dryer should be satisfactory for most applications.

22.3.2.6 Pressure drop

Both the blinding of a fluidizing membrane and a restriction in the discharge pipe will add to the pressure drop across a blow tank. If the pressure drop across the material feeder increases, the pressure drop available for the material in the pipeline will decrease, and result in a decrease in conveying capacity, if it is taken into account, and pipeline blockage if not.

Part of the blow tank pressure drop occurs in discharging the material from the blow tank. This is particularly a problem in top discharge blow tanks where a long length of discharge pipe may be required. The conveying air should be introduced as close to the blow tank as possible in order to minimize this pressure drop. In a tall blow tank it may be necessary to bring the discharge line out through the side of the blow tank in order to reduce its length.

22.3.2.7 Performance monitoring

The performance of a blow tank can be monitored quite easily by means of pressure gauges. If a pressure gauge is installed in the supplementary air supply line this will effectively give a measure of the conveying line pressure drop, and hence the utilization of the pipeline in conveying the material. A pressure gauge in the blow tank will then give an indication of the pressure drop across the blow tank discharge line. If the blow tank has a fluidizing membrane, a further pressure gauge in the air supply line to the blow tank will help to monitor the state of the membrane. A sketch of a top discharge blow tank, with a discharge valve, arranged with pressure gauges for performance monitoring, is shown in Figure 22.2.

22.3.2.8 Granular materials

Difficulty may be experienced in discharging granular materials from a top discharge blow tank. Air permeates very easily through these materials and it is possible that insufficient resistance will be built up to discharge the material. Bottom discharge blow tanks are generally recommended for granular materials. Granular materials with a high percentage of fines are very much less permeable. These materials are not generally capable of dense phase conveying in conventional systems. They will require very little air for their discharge from a blow tank, and so if the discharge line is unnecessarily long or has a long horizontal section, the discharge line is likely to block.

22.3.3 Rotary valves

Rotary valves are probably the most commonly used device for feeding pipelines, particularly in low pressure conveying systems. They are available in a wide range of sizes and there are many different types for free flowing, granular and cohesive materials, as

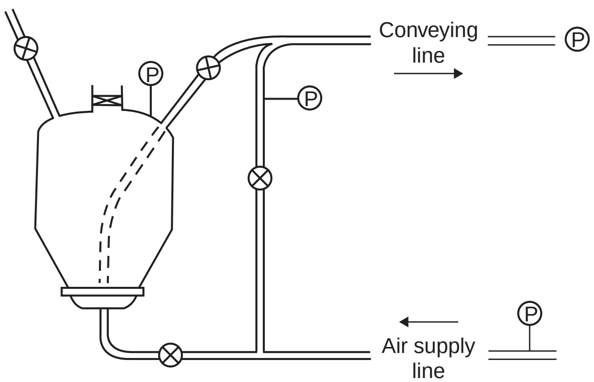


Figure 22.2 The use of pressure gauges for monitoring the performance of a blow tank system.

considered in Section 3.2. The mechanism of feeding, however, gives rise to a number of problems, and in positive pressure systems allowance must be made for air leakage.

23.3.3.1 Flow control

It is essential that the pipeline should be fed at the correct rate. If the feed rate is too low the pipeline will be under-utilized, and if the feed rate is too high the pipeline could block. Flow control can be achieved by varying the rotational speed of the rotor. There is an upper limit for any given size of valve however, for the pocket filling efficiency will decrease with increase in speed. If a variable speed drive is provided the flow rate will be infinitely variable, as it is with a blow tank, up to its maximum capability with a material. If some form of gearing is provided only step changes will be possible.

Many rotary valves are dedicated to a single material and duty, and no means of speed control is incorporated. If a material is to be conveyed over a different distance, a corresponding change in feed rate will be required. If a different material is to be conveyed it is quite likely that both the pipeline and rotary valve feeding characteristics for the material will be different. As it is a volumetric feeder, those for the rotary valve will be particularly influenced by the bulk density of the material.

22.3.3.2 Air leakage

Air leakage across a rotary valve depends primarily upon the rotor tip clearance and the pressure drop across the valve. Air leakage also depends upon the material being fed. A cohesive material, for example, will help to seal the various clearances and so reduce the leakage rate. The influence of these parameters was illustrated with Figures 3.8 and 9. If air leaks across a rotary valve, less will be available to convey material through the pipeline. In specifying the air requirements for the air mover this must be taken into account. Air leakage will also increase with increase in size of the rotary valve. If a valve is used which is larger than that necessary for the required duty, the air leakage will be unnecessarily high as a result.

22.3.3.2.1 Venting

The air leaking across the valve may interfere with the feeding of material into the rotary valve, as it will have to flow in the opposite direction to the flow of material in order to exit from the system. This reverse flow of air may restrict the material flow and prevent the pockets from being fully filled. This air may also fluidize the material and lower its bulk density, which will also reduce the feed rate. In this case the problem may be alleviated by venting. Some material is likely to be carried over with the vented air and so the vent line must be kept clear. The vent should preferably discharge into the feed hopper above, where the air can be filtered. The vent line must not be allowed to become blocked and so it must be designed as a miniature pneumatic conveying system itself.

A sketch of a vented rotary valve is given in Figure 22.3. The vent should be positioned on the side of the body such that there is always one rotor blade positioned between the material feed and the vent to prevent a direct flow of material from the hopper to the vent.

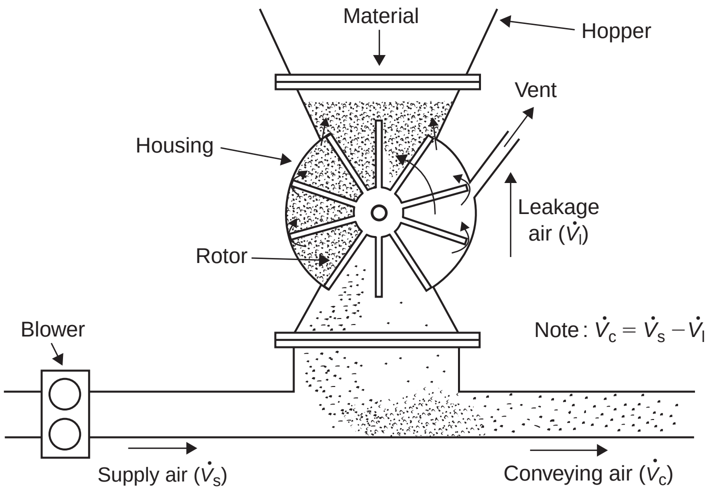


Figure 22.3 Sketch of vented rotary valve.

22.3.3.3 Valve seizure

Valve seizure could be caused by the trapping of granular materials or by some foreign body in the material. If hot material is conveyed seizure could be caused by differential expansion problems. Particular care should be taken on start up with a cold valve. Insulation and trace heating may be necessary to maintain blade tip clearances, for if clearances become too great in such transient situations the pipeline could block because of a loss of too much air. If bearings are not protected and maintained, dust ingress could cause serious problems. If a bearing ran hot before seizure it could provide the necessary source of ignition for an explosion in a dusty environment (see Chapter 26).

22.3.3.4 Valve wear

Rotary valves are not generally recommended for handling abrasive materials, although they can be manufactured with wear resistant materials. Apart from abrasive wear of the sliding surfaces, erosive wear will be severe as a result of the very high velocities achieved by the air leaking through the valve. Wear will result in an increase in rotor tip clearances and hence an increase in air leakage. This, in turn, will cause a loss of air to the conveying line, which could ultimately result in pipeline blockage. This point was discussed in Section 20.2.4 and with Figure 20.11.

22.3.4 Filters

Most problems that occur with filters generally result from incorrect specification, either in terms of the air flow rate or the particle size distribution to be expected.

22.3.4.1 Material degradation

Filter cloths and screens will rapidly block if they have to cope with unexpectedly high flow rates of fine powder. The net result is that there is usually an increase in pressure

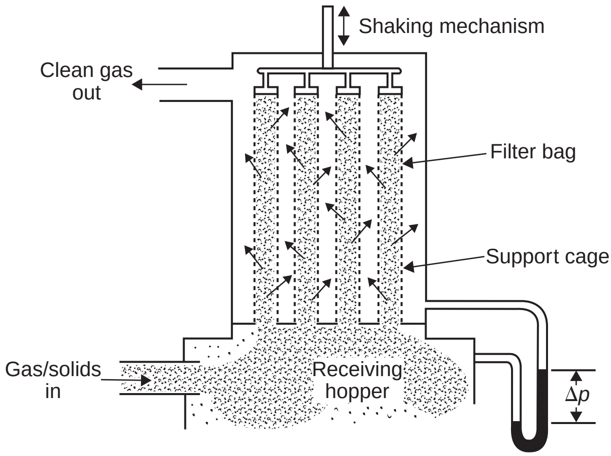


Figure 22.4 Typical shaken bag filter unit with manometer for performance monitoring.

drop across the filter. The sample of material to be conveyed, and hence filtered, that is supplied to a filter manufacturer for selection and sizing purposes, could differ significantly from that which has to be handled by the plant filter installed. The sample provided may be representative of the material to be conveyed, but if it is a friable material, and the conveying air velocity is unnecessarily high, the material at the end of the conveying line could be very different.

22.3.4.2 Maintenance

Cloth filters will gradually block with fine material which cannot be shaken free, and their performance will be less effective. Filter bags are an item, therefore, that require periodic replacement. The performance of a filter can be monitored to a certain extent by noting the empty line pressure drop values. If there is a pressure gauge in the air supply or extraction lines the empty line pressure drop can be checked. This pressure drop represents the combined resistance of the pipeline and filtration unit. If the pipeline is purged clear of material, any changes in pressure drop can generally be attributed to the filter. An increase in this pressure drop would indicate that cleaning of the filter is not as effective as it should be and should be checked.

Alternatively an additional pressure gauge could be positioned on the receiving hopper. Most filter units are provided with a pressure tapping for this purpose and so with a pressure tapping on the receiving hopper a differential value for the filter can be obtained. Such a device is illustrated in Figure 22.4 on a mechanically shaken unit. With reverse air jet filters a check should be made to ensure that the air supply for the filter bags and pulsing is correctly connected and of adequate capacity, and that the timer for cleaning is set and operating correctly.

22.3.4.3 Sizing

The surface area of filter cloth required is based to a large extent on the volumetric flow rate of the air to be handled. The value of the air flow rate, at the local pressure and temperature conditions, divided by the cloth area gives an approximate face velocity. Typical values for felted fabrics are in the region of about 0.025 m/s for fine particulate materials and up to about 0.050 m/s when handling coarser or granular materials.

It must be remembered that if the filter is used in a negative pressure system, the volumetric flow rate to be handled will be significantly higher, because of the very low pressure, and so the cloth area will have to be much greater than that in an equivalent positive pressure system exhausting to atmospheric pressure, in order to maintain the same face velocity. The same considerations will have to be given to the filters in a system that operates at a high altitude, and to any system in which high temperature material has to be handled.

22.3.4.4 Batch cycles

In batch conveying cycles, such as those associated with blow tanks, the air flow rate is not uniform with respect to time. At the end of the cycle, when the blow tank is just empty, a very large volume of air is stored under pressure in the blow tank and pipeline. The venting of this air, together with the regular compressor output for conveying, will result in a significantly higher filter duty at this time. This high air flow rate should be taken into account in the specification of the conveying line filter.

The resulting surge can be reduced by isolating the blow tank from the conveying line when it is empty, and venting the blow tank separately. If this is done, however, the filter on the material feed hopper above the blow tank will have to be appropriately sized for this intermittent high flow rate duty. Alternatively the supply from the air mover can be isolated when the blow tank is empty and the pressurized air in the blow tank can be used to purge the conveying line.

22.3.5 Vacuum nozzles

Vacuum nozzles are widely used for feeding negative pressure, or vacuum systems, since they enable material to be transported from open storage, such as from stockpiles and from the holds of ships. They can equally be used in hoppers as an alternative to rotary valves and screw feeders as illustrated in Figure 3.25.

22.3.5.1 Flow control

Vacuum nozzles, unlike rotary valves and screws, are not positive displacement feeders. Their control, therefore, is based on proportioning of the air, in a similar manner to that of a blow tank. The main requirement is that primary air should be provided at the pick-up point and that this should be sleeved to provide a free passage of air directly from the atmosphere, as shown in Figure 3.22. For continuous operation the nozzle needs to be plunged into the material. Air may permeate through the material but it is unlikely to be sufficient for conveying alone.

The primary air, together with any that might permeate through the material, will pick the material up and transfer it into the conveying line. If the concentration of material is too great, the secondary air can be used to provide the necessary dilution. This proportioning of the air is essential if the pipeline is to operate at the maximum material flow rate with the available pressure drop generated by the exhauster. The location of the outer sleeve in relation to the pipeline (see Figure 3.23) is also important in terms of feed rate control as illustrated in Figure 3.24.

22.4 System related

In this section problems relating to the system are considered, other than throughput problems which were considered in Chapters 20 and 21. One part is concerned essentially with environmental factors such as altitude, temperature variations and condensation. Another part deals with physical problems that can happen to the system such as an explosion, bends eroding and electrostatic discharges. Many of these problems are caused directly by the material being conveyed. They are considered in this section since the problem may not initially be recognized in terms of the material being conveyed.

22.4.1 Altitude

The operation of a pneumatic conveying system at altitude should present no problems at all, provided that due account has been taken of the local air pressure, and hence density of the air. This will influence the specification of the air mover since the volumetric flow rate is generally quoted in terms of free air (see Equation (9.10) and Figure 9.21). It will also influence the size of the filter required, as discussed above in the section on component related problems.

For a plant located at an elevation of 1000 m above sea level, for example, there is a reduction in ambient pressure of about 11.4 kN/m^2 or 85 mmHg, which is more than 10 per cent of the standard atmospheric pressure at sea level. The normal atmospheric pressure at sea level can fluctuate quite naturally by $\pm$25 mmHg on a day to day basis, which equates to a change in elevation of about 300 m.

22.4.2 Condensation

Condensation is liable to occur in pipelines that are subject to large temperature variations, particularly where there are pipe runs outside buildings, and air drying is not employed. This problem is considered in detail in Chapter 25.

22.4.3 Electrostatics

Pneumatic conveying systems are known to be prolific generators of static electricity. In a large number of cases the amount of charge generated is too small to have any noticeable effect, but sometimes appreciable generation can occur. Very often, this is just a nuisance, but occasionally it can present a hazard. The electrostatic problem can be reduced by earthing the pipeline and ensuring that electrical continuity is maintained across all flanged joints. The humidity of the conveying air can also be used as a means of controlling static build-up. The use of humidity for charge control, however, is clearly not suitable if the material being conveyed is hygroscopic, or where condensation might be a problem.

22.4.4 Erosive wear

If the hardness of the particles to be conveyed is higher than that of the system components, such as feeders and pipeline bends, then erosive wear will occur at all surfaces against which the particles impact. Erosion is wear caused by the impact of particles against surfaces, and the angle of impact is a major variable in the wear process. Abrasive wear is caused by the sliding of particles against surfaces. Abrasive wear can be a problem with hoppers, chutes and cyclones, but in pneumatic conveying systems erosive wear can be an order of magnitude more serious. As a consequence Chapter 23 is devoted entirely to the subject of Erosive Wear.

22.4.5 Explosions

There is a wide range of material which, in a finely divided state, dispersed in air, will propagate a flame through the suspension if ignited. These materials include foodstuffs such as flour, sugar and cocoa, synthetic materials such as plastics, chemical and pharmaceutical materials, metal powders and fuels such as coal and wood. Research has shown that the particle size must be below about 200 μm for a hazard to exist.

It is virtually impossible to avoid dust cloud formations in pneumatic conveying. Even when the material being conveyed consists of particles larger than 200 μm, consideration must be given to the production of fines during conveying which may result in an explosion hazard being created in the receiving vessel. This is another topic that clearly requires serious consideration and so the problem is reviewed and a range of solutions are presented in Chapter 26.

22.4.6 Pipeline purging

With foodstuffs and perishable commodities there is generally a need to purge the pipeline clear of material. With dilute phase conveying this is rarely a problem, for although the conveying line inlet air velocity may only be 12 m/s while conveying, during purging of the pipeline the conveying line pressure drop will be little more than the air only pressure drop value. As a consequence the air velocity for purging will be close to the conveying line exit air velocity and this is generally sufficient to ensure a pipeline will be purged clear in a matter of minutes.

Difficulties can be experienced with low velocity dense phase conveying, however, since conveying line inlet air velocities can be very much lower. In a programme of tests carried out with a 1260 kg batch of cement a note of the mass of cement that could not be conveyed to the reception hopper was made, as part of the recorded information taken in determining the conveying characteristics for the material in the test pipeline. The results are presented in Figure 22.5 [1].

A sketch of the 95 m long pipeline of 105 mm bore is given in Figure 22.6. It will be seen that in addition to the usual lines of constant conveying line pressure drop and solids loading ratio, lines of constant conveying line inlet air velocity have been added. The horizontal axis has been doubled to provide conveying line exit air velocity values and lines of constant percentage of batch conveyed have also been superimposed. The purging of the pipeline was limited to about 1 min in all cases.

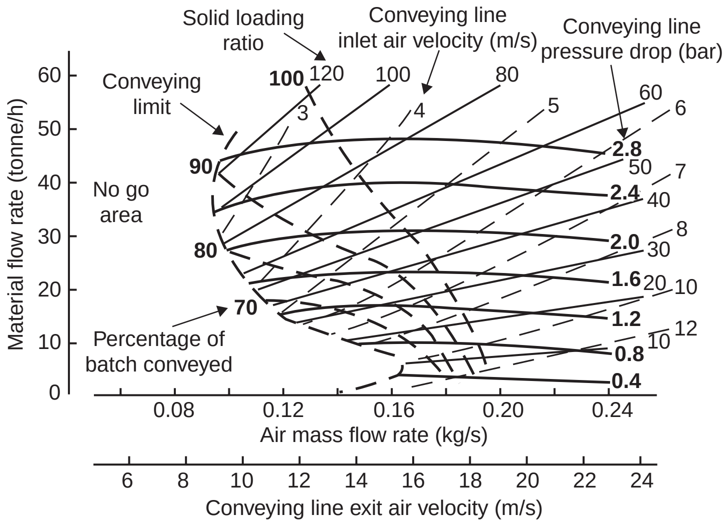


Figure 22.5 Conveying characteristics for cement in Pipeline no. 16.

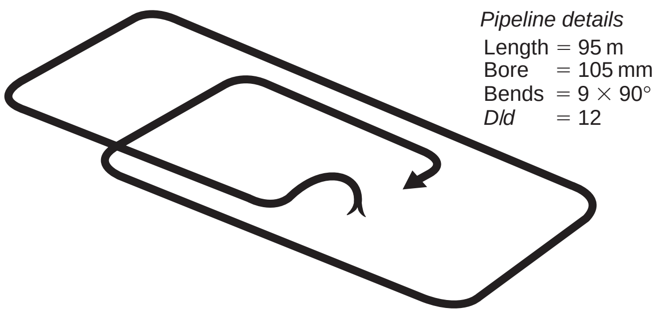


Figure 22.6 Sketch of Pipeline no. 16.

The curves present an interesting trend. With the cement conveyed at a solids loading ratio of 120 and a conveying line inlet air velocity of 3 m/s, the pipeline was purged clear with a conveying line exit air velocity of 12 m/s. In dilute phase suspension flow a conveying line exit air velocity of 19 m/s was required to purge the pipeline clear of material. This was a single bore pipeline. The situation can be very different with stepped pipelines, for both dilute and dense phase conveying, for conveying line exit air velocities can be very much lower. This particular situation was considered in Section 9.5.

The bends in the test pipeline were of quite long radius and so did not present a problem in purging. Some of the bends used in pneumatic conveying pipelines, however, such as the pocketed bends, may take a considerable time to be purged clear of material. This is particularly the case with bind tee bends such as that shown in Figure 5.1a.

A residue of material may also be left in the feeding device and this is particularly so with top discharge blow tanks as mentioned in Section 4.4.1.1. This is a particular advantage of the bottom discharge type since the entire contents can usually be discharged.

This entire problem of purging must be given serious consideration if a system is required to convey a number of different materials and cross-contamination must be avoided.

22.4.7 Plant wear

To recap briefly on some of the points made earlier; if the material being handled is abrasive, wear of feeding devices, such as screws and rotary valves, will occur. This will result in an increase in air leakage across the feeder and hence a reduction in the air flow rate available to convey the material. In vacuum, closed loop and combined systems, wear of the air mover may occur if the filtration system is not sufficiently efficient. This will result in a gradual deterioration in performance of the air mover. Pipelines and bends are considered in Chapter 23.

22.4.8 Temperature variations

For a plant subject to operating in extremes of temperature, from summer to winter and/or day to night, consideration will have to be given to the problems of condensation and changes in conveying air velocity. Air density increases with decrease in temperature, and so if a conveying air velocity is 15 m/s at 40°C, it will be about 12 m/s at −20°C for the same free air flow rate. The influence of conveyed material temperature must also be taken into account as considered in Section 9.6.1. Condensation may occur in pipelines subject to large temperature variations as discussed in Section 20.2.3.1. Chapter 25 is devoted to the topic of moisture and condensation in pneumatic conveying systems.

22.5 Material related

In this section problems relating to the conveyed material are considered. In the previous section some of the problems were as a direct result of the materials being conveyed, but the problems were recognized in terms of the effects that the materials had on the system. This section includes problems that result from the effect that the system can have on the material being conveyed, such as absorption of moisture, the formation of angel hairs and particle degradation. The more obvious material properties such as particle size, temperature and moisture content are also considered here.

22.5.1 Angel hairs

The formation of angel hairs is a problem that can occur with plastic materials such as nylons, polyethylene and polyesters, particularly in pelletized form. The presence of angel hairs is undesirable since they can cause blockages at line diverters and in filters. Angel hairs are generally caused by sliding contact between the particle and the pipeline. The frictional heat generated is sufficient to cause melting of that part of the particle in contact with the pipeline surface. This problem is considered in Chapter 24 along with other particle degradation problems.

22.5.2 Coating of pipelines

Certain moist materials, pigments and similar ultra-fine materials, hygroscopic materials, and food products with a high fat content, may have a tendency to stick to or coat the walls of a pipeline. If the coating builds up it will gradually reduce the section area of the pipeline and generally results in blockage. Conveying with a very much higher air velocity is often successful with some materials. One method that often works is to convey the material through a rubber hose capable of withstanding the conveying air pressure. The natural flexing of the hose with the conveying of the material and pressurizing and de-pressurizing is often sufficient to dislodge any build-up of material.

22.5.3 Cohesive materials

With cohesive materials the problems often relate to the difficulty of feeding the material into the pipeline. If difficulties are encountered in achieving flow rates with a system, and the conveying line pressure drop is below the expected value, the problem could well relate to the discharge of the material from the supply hopper, rather than the capability of the feeding device or the pipeline. In this case, the use of a suitable bin discharge aid should be considered. In the case of rotary valves, a blow through type should be used if there is any difficulty in discharging a cohesive material into a conveying line.

22.5.4 Consolidation of materials

Many bulk materials increase in strength with time. This is a particular problem with the storage of bulk solids in hoppers and silos. A material stored for 1 day may well flow freely from a hopper but refuse to flow at all after being stored for two days. Bulk density can also increase with time, and significantly so with some materials. If a material has consolidated in a hopper and is fed into a positive displacement feeder, the pipeline could block due to being overfed.

This can occur with rotary valve fed systems on start-up. The bulk density of materials such as barytes, cement and fly ash can increase by 30 to 40 per cent with compaction. The discharge rate of a rotary valve was given in Equation (3.1) and it will be seen that it is directly proportional to the bulk density of the material. Once the material in the hopper has been disturbed by flowing down into the rotary valve, and with aeration from a proportion of the air leaking across the rotary valve, operation could be back to normal once the blockage has been cleared and the system re-started.

Aeration of the material before being conveyed would always be recommended in road and rail vehicle transport systems. By the time such a vehicle arrives at a depot for off-loading a considerable degree of compaction will have resulted. This is one of the advantages of pressurizing bottom discharge blow tanks from the bottom, as shown in Figure 4.16. The air required to pressurize the vessel must pass through the material and this will aerate the material very effectively.

22.5.5 Degradation of materials

The fracture and breakage of pneumatically conveyed materials is a problem with all friable materials. Even if the presence of fines in the material is not a problem with respect to product quality, the fines produced will add unnecessarily to the duty on the filtration unit. The problem is influenced to a large extent by conveying air velocity. Since this is a major problem in the industry Chapter 24 is devoted to the subject.

22.5.6 Granular materials

If a granular material has to be conveyed, difficulties may be experienced in discharging the material into the conveying line. Rotary valves and blow tanks may cause problems here, and so reference should be made to the appropriate items in Chapters 3 and 4. Once the granular material is fed into the pipeline there should be no problem with its conveying, although it is almost certain that it will have to be conveyed in dilute phase suspension flow, unless the material has a very narrow particle size distribution and good permeability.

22.5.7 Hygroscopic materials

If a hygroscopic material is pneumatically conveyed it may absorb moisture from the air used to convey the material and become very cohesive, and have poor flowability as a result. Although the specific humidity of the air will reduce if it is compressed isothermally beyond the saturation point, its relative humidity will increase and is likely to be 100 per cent after compression. The added moisture will not only affect material quality but could cause subsequent handling problems.

Problems of moisture in conveying air are not so serious in negative pressure systems. Although the specific humidity will remain constant, the relative humidity of the air will constantly reduce along the pipeline as the conveying air pressure reduces. The problem can be overcome altogether by drying the air that is used for conveying the material, either by refrigeration or desiccant devices. The subject of moisture in air with respect to pneumatic conveying systems is considered in detail in Chapter 25.

22.5.8 Large particles

Large particles can be conveyed quite successfully in pneumatic conveying systems but a general recommendation is that the diameter of the pipeline should be about three times that of the larger particles. This is simply an expedient measure to ensure that the pipeline will not block by the wedging action of two 'rigid' particles. There are exceptions to this rule, of course, and with very 'pliable' materials such as fish, it is possible to convey 'particles' that are slightly larger than that of the pipeline bore. With 'rigid' particles, shape may present a problem if a mean particle value is used in sizing, and the particles have an irregular shape.

Care must be exercised with the feeding of these materials in all cases. With materials such as coal, clinker and iron ore, gate valves are often used because they are very rugged, and heavy duty closing devices are employed. The trapping of these particles must be avoided for they may damage the seals. Trapped particles and damaged seals will both allow air to leak through the feeder and so affect the performance of the conveying system.

22.5.9 Material grade

If a system is dedicated to a single duty with a single material, and the system has been optimized to the lowest specific energy, operating difficulties may be experienced if there is a change in material grade or quality. If a material is produced with a slightly different shape or size it could be sufficient to cause the pipeline to be blocked. It must be appreciated that different grades of the same material can have very different conveying characteristics, and even the pneumatic conveying of a material can change its conveying characteristics. This was illustrated in Chapter 13 with light soda ash and a number of other materials.

22.5.10 Temperature

High temperature materials can be conveyed quite successfully and conveying gas at any temperature can be used. Compatibility with system components is the determining factor. Conveying air velocities also have to be guaranteed if there are significant temperature changes. It is the evaluation of gas and conveyed material temperature that presents the difficulty, as discussed in Section 9.6.1.

At the feeding point, for example, cold air may be used to convey a high temperature material. Along the conveying line there will be a move towards thermal equilibrium between the air and the material, and there will be heat transfer from the pipeline to the surroundings. Since conveying times are very short it is unlikely that equilibrium will be established. It is quite possible, therefore, for the surface of the particles to be 'cold' and the inner core to be 'hot'. Due to this it is often possible to use filter cloths in these high temperature situations. By the same reasoning the material in the reception hopper could be very hot once equilibrium has been established there.

The maintenance of conveying air velocities is particularly important in these situations but their evaluation can be difficult. Particle temperature transients represent a complex convection, radiation and three-dimensional conduction heat transfer problem. Since air density increases with decrease in temperature, however, the maintenance of air velocities is only likely to be a problem in situations where a very high temperature gas is used to convey a cold material. In this case the temperature gradient effect could over-ride the pressure gradient influence on air density.

22.5.11 Wet materials

Fine materials that are wet will tend to coat the pipeline and gradually block the pipeline. The problem can be relieved by heating the conveying air if the material is not too wet. Greater difficulty may be experienced in discharging a material from a hopper if it is wet. When wet granular materials are fed into a pipeline bends present a particular difficulty since these can become wet with moisture centrifuged off particles on impact, and fine material will adhere and gradually block the line at the bend. Single plug blow tanks, as illustrated in Figure 2.9, often work well with wet materials since the retarding force is wall friction, and the higher the moisture content the lower the wall friction.

Reference

1. D Mills, V K Agarwal and M D Bharathi. The pneumatic conveying of fly ash and cement at low velocity. Proc 24th Powder and Bulk Solids Conf. pp 147–163. Chicago. May 1999.

Chapter 23

Erosive wear

23.1 Introduction

Erosive wear results from the impact of particles against surfaces. Typical erosive wear situations in bulk solids handling plant are in the loading and off-loading of materials, and with free fall onto surfaces. The blowing of materials into cyclones, their loading into hoppers and onto chutes, off-loading from hoppers, conveyor belts and bucket elevators, are common examples. These are all cases where particles impact against surfaces and cause erosive wear, rather than slide against a retaining surface and cause abrasive wear.

Erosion represents a major problem, not only in bulk solids handling plant, but in many other areas. In thermal power plant pulverized fuel causes erosive wear of supply lines and nozzles, and the resulting fly ash is a problem with respect to boiler tubes. Both pneumatic and hydraulic conveying of particulate materials in pipelines can result in severe erosion problems, and aircraft, rockets and missiles are eroded by rain drops and ice particles. The area that has probably received most attention, however, is aircraft engines, and in particular helicopters, for dust ingestion can cause considerable damage, and has resulted in several catastrophic failures in service.

It is a major feature in the wear of pneumatic and hydraulic pipeline transport systems. In pneumatic conveying, in particular, it can be a severe problem because of the high velocities required for conveying bulk particulate materials. The erosion of surfaces by solid particles in a fluid stream is probably the main reason why industry is often reluctant to install pneumatic conveying systems, particularly when abrasive materials have to be handled. In several other areas, however, erosion has many practical uses and advantages, such as in erosive cleaning of surfaces and erosive drilling and cutting.

23.1.1 Data sources

Information on erosive wear comes from a very wide range of sources, therefore. Until recent years little was known of the fundamental mechanisms of the erosion process or of the variables that influence the problem. There are, in fact, so many variables that influence the problem that advances have only been made by the development and use of specially designed erosive wear testing rigs. In these a wide range of powdered and granular materials have been impacted against a wide range of surface materials over carefully controlled conditions of velocity, particle concentration, temperature, impact angle, etc.

Many studies have been of a general nature with a view to getting a better understanding of the basic mechanisms of the process, and for this purpose numerous single particle impact investigations have been undertaken. Other studies have been conducted for specific purposes, and so the range of variables investigated can be extremely wide. For particle impact velocity, for example, tests have been carried out at about 1–3 m/s for hydraulic transport, from 15 to 35 m/s for pneumatic conveying, from 100 to 500 m/s for aircraft applications and up to 8000 m/s for rockets.

23.1.2 Issues considered

The information presented on erosive wear, therefore, is in two sections. In the first the influence of the major variables in the problem of erosive wear is presented, and the data for this has been obtained from a very wide range of sources. This provides general information on the basic mechanisms of the erosive wear process and influence of the variables involved, and will provide a useful background and basis for subsequent decisions in relation to the wear of pneumatic conveying system pipelines and components.

In the second part a review of industrial solutions to the problem of pipeline wear is presented, with particular reference to bend wear. Bends in pneumatic conveying system pipelines are probably the most vulnerable of all components to wear. If silica sand is conveyed through a pipeline with a conveying air velocity of about 25 m/s, for example, an ordinary mild steel bend could fail well within 2 h. This review, therefore, covers issues such as bend geometry and the use of wear resistant materials.

23.2 Influence of variables

There are many parameters associated with both the impacting particles and the surface material that will have an effect on erosive wear. In some cases the variables are inter-related and so need to be considered in groups in these situations.

23.2.1 Impact angle and surface material

A curve presented by Tilly [1] and shown in Figure 23.1 illustrates the variation of erosion with impact angle for two different surface materials and is typical of the early work carried out to investigate the influence of these variables.

Both materials showed very significant differences in both erosion rate and the effect of impact angle. These materials do, in fact, exhibit characteristic types of behaviour that are now well recognized. The aluminium alloy is typical of ductile materials: it suffers maximum erosion at an impact angle of about 20° and offers good erosion resistance to normal impact. The glass is typical of brittle materials: it suffers severe erosion under normal impact but offers good erosion resistance to low angle, glancing impact. These particular tests were carried out with sand particles sieved to between 60 and 125 μm and impacted at about 100 m/s. That brittle and ductile materials respond to erosion in very different ways can be clearly seen from Figure 23.1, and it is obvious that different mechanisms of material removal must be involved.

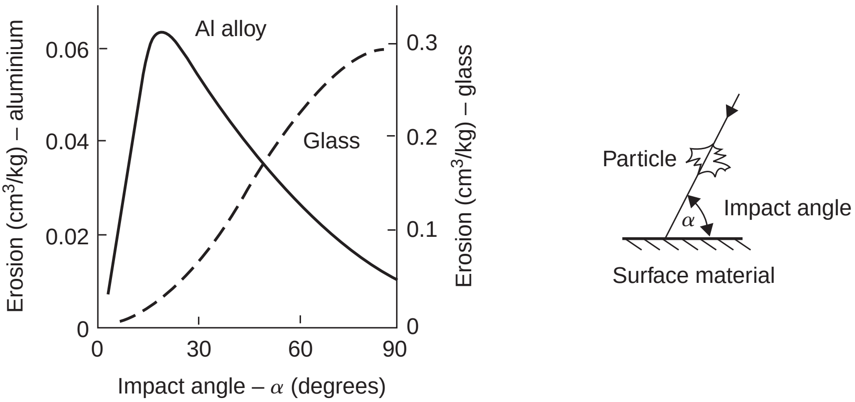


Figure 23.1 Variation of erosion with impact angle for various surface materials.

The influence of impact angle and the different response of ductile and brittle materials to erosive wear is an aspect of the problem that will be considered at many different points. The relationships can be used to explain a number of observed phenomena in erosive wear, and are particularly useful in predicting the possible behaviour in new and untried situations.

23.2.1.1 Theories proposed

From early thoughts on the matter it was suggested that for ductile materials (annealed low carbon steel, copper, aluminium, etc.) material removal is predominantly by plastic deformation. No cracks propagate ahead of the cutting particle and the volume removed is due entirely to the cutting action of the particle, rather like the cutting edge of a machine tool. For brittle materials (glass, basalt, ceramics, cast iron, concrete, etc.) it was thought that material removal is in a large part due to the propagation of fracture surfaces into the material.

These erosion processes, however, have subsequently proved to be not quite as straightforward as this. Photographs taken of impact craters, produced as a result of single particle impact studies, have shown clear evidence that melting has taken place [2, 3]. The melting only occurs over a small part of the impact crater, but it must be considered as being contributory to the erosive wear process. This is considered later in relation to heat treated surface materials.

23.2.2 Velocity

Of all the variables that influence the problem of erosive wear, velocity is probably the most important of all. It is generally recognized that erosive wear is dependent upon a simple power of velocity, such as:

$$\text{Erosion} = \text{constant} \times (\text{velocity})^n$$

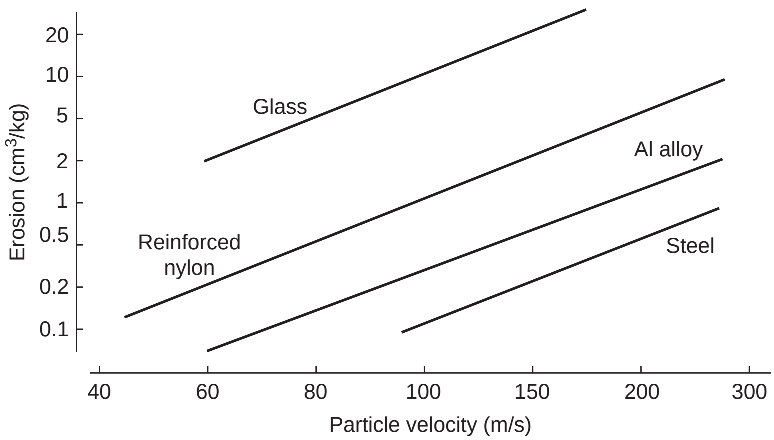


Figure 23.2 Variation of erosion with velocity for various surface materials.

23.2.2.1 Surface material

There is much confusion as to the value of the exponent, and values of n ranging from 2–6 have been reported. Tilly and Sage [4] tested a wide range of different materials and obtained very good agreement with respect to the exponent, n, in each case. Their results are reproduced in Figure 23.2. This is a log plot and the slope of all the lines was approximately 2.3. The velocities, of course, are well above those generally encountered in pneumatic conveying systems, even at the lower end of their range.

The velocity exponent is now generally considered to be approximately 2½, and although erosive wear resistance varies widely for different surface materials, as shown in Figures 23.1 and 23.2, the value of the velocity exponent remains reasonably constant at about 2½ for all surface materials.

23.2.2.2 Bend wear

Few comprehensive erosion studies have been carried out exclusively in the velocity range appropriate to pneumatic conveying. The author, however, has carried out several extensive research programmes into the erosion of pipe bends in an actual pneumatic conveying system, at velocities appropriate to dilute phase suspension flow [5]. Tests were carried out over a range of conveying air velocities from 15–35 m/s and at solids loading ratios from 0.5 to 8. Steel bends of 53 mm bore having a bend diameter, D, to pipe bore, d, ratio of about 5:1 were eroded by 70 and 230 μm sand, and over the ranges tested the velocity exponent was found to be consistent at 2.65. A graph showing the influence of conveying air velocity on the specific erosion of the bends is given in Figure 23.3.

The erosion is in terms of the mass of metal eroded from a bend per tonne of sand conveyed through the bend. With a velocity exponent of 2.65 it means that the wear rate will increase by a factor of six with a doubling of the air velocity. This explains why the curve rises so steeply in Figure 23.3. If a positive pressure conveying system

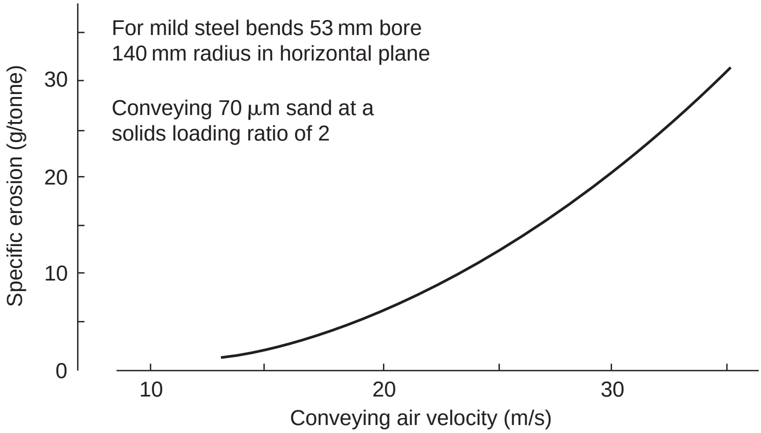


Figure 23.3 The influence of velocity on the erosive wear of bends in a pneumatic conveying system pipeline.

operates at a pressure of 1 bar gauge, a doubling of the velocity will be achieved in a single bore pipeline discharging to atmospheric pressure. With a vacuum conveying system a doubling in velocity will be achieved with a system exhausting at 0.5 bar absolute. In such a system a bend at the end of the pipeline will wear approximately six times as fast as a bend at the start of the pipeline.

If an abrasive material is to be conveyed, therefore, it would always be recommended that the pipeline be stepped to a larger bore part way along its length in order to limit the maximum value of velocity that is achieved, in order to minimize the erosive wear of bends towards the end of the pipeline. It is essential, of course, that the step to the larger bore pipeline is correctly positioned along the pipeline, for if the velocity falls below the minimum value of conveying air velocity at the step, the pipeline is likely to block at this point.

Figure 23.3 shows quite clearly that excessively high conveying air velocities should be avoided. It also shows the benefits of conveying with low velocity air, and hence the potential of low velocity flow in this respect. With the bends reported in Figure 23.3, tested at a solids loading ratio of 2, bend failure occurred when about 60 g of metal was eroded from the bend. The bend wall thickness was about 4 mm. In Figure 23.4 the conveying capacity of these bends, in terms of the mass of sand that could be conveyed through the pipeline before bend failure occurred, is presented. From this it will be seen that with a conveying air velocity of about 30 m/s only 3 tonne of sand could be conveyed before bend failure.

23.2.3 Particle size

The general consensus of opinion with regard to particle size is that there is a threshold value of wear rate which, for velocities appropriate to pneumatic conveying, occurs at a particle size of about 60 μm. Below this size wear rate reduces, but for

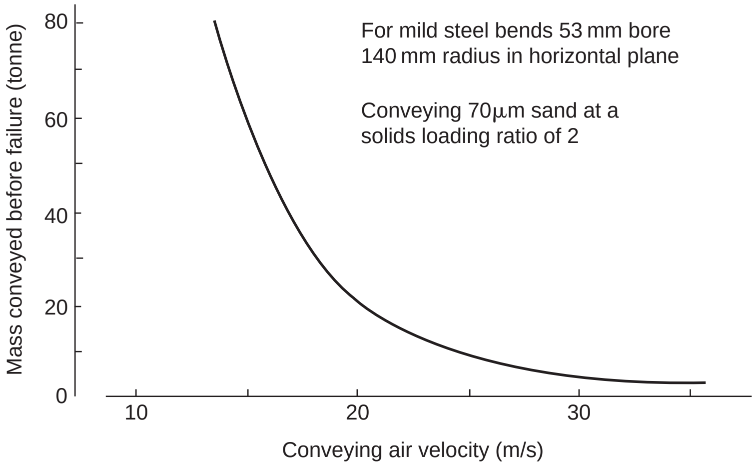


Figure 23.4 The influence of velocity on the conveying capacity of the bends shown in Figure 23.3.

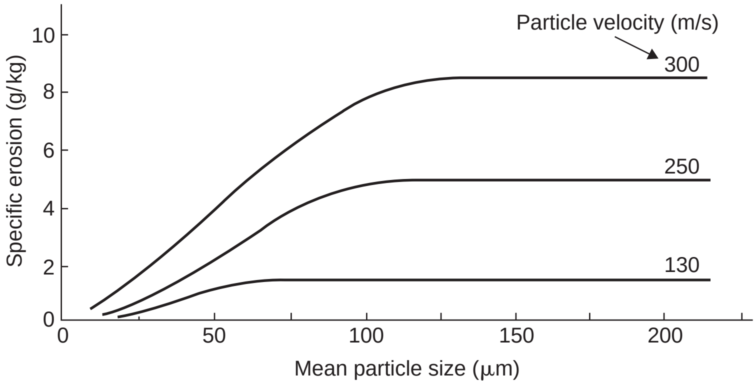


Figure 23.5 The influence of particle size and velocity on erosion.

particle sizes greater than 60 μm it remains constant. Results of work carried out by Tilly [6] are presented in Figure 23.5.

Figure 23.5 shows that the threshold value increases with increase in velocity. The work was carried out for an investigation into the erosion of aircraft engines, which explains the high velocity range. A shot blast type of test rig, in which abrasive particles were impacted against flat plates, was used for the purpose.

Wear rate here is expressed in specific terms, that is the mass (or volume) of surface material eroded per unit mass of particles impacted. In a given mass of particles, the number of particles will reduce as the particle size increases, and so although the specific erosion remains constant with increase in particle size, the erosive wear per particle will increase approximately with the cube of the particle size. Little work has been undertaken with particles much larger than about 1 mm in size and so it is not known to what particle size the threshold value remains constant.

23.2.3.1 Bend wear

Work carried out on actual pipe bends in pneumatic conveying system pipelines would tend to confirm this [7]. Batches of sand with mean particle sizes ranging from 70 to 280 μm were used in a programme of conveying trials. Six test bends in the one pipeline were monitored for erosive wear, and the average mass eroded from each bend was found to be independent of particle size. On an individual basis, however, the bends showed a very interesting trend. The degree of scatter in the results increased markedly with decrease in particle size, as shown in Figure 23.6. With the larger particles the wear rates were remarkably consistent, but with the finer particles the spread of the results was very wide.

It is believed that the finer particles are influenced by the secondary flows and turbulence that can be generated by the bends and that this causes accelerated wear of some bends, although there is no obvious reason why some bends were more vulnerable than others in the pipeline. This could well account for some of the premature failures that have been reported in situations where very fine materials have been conveyed. It was also found that the depth of penetration of the particles into the bend walls was a factor of two greater for the 70 μm sand compared with the 280 μm sand. Since failure occurs when a given thickness of material is eroded, this parameter is potentially as important as specific erosion in pipe wear situations.

23.2.4 Particle hardness

The value of the particle hardness of the material being conveyed is the major indicator of the potential erosiveness of the material. Goodwin et al. [8] investigated the influence of particle hardness on erosive wear with a rig in which abrasive particles

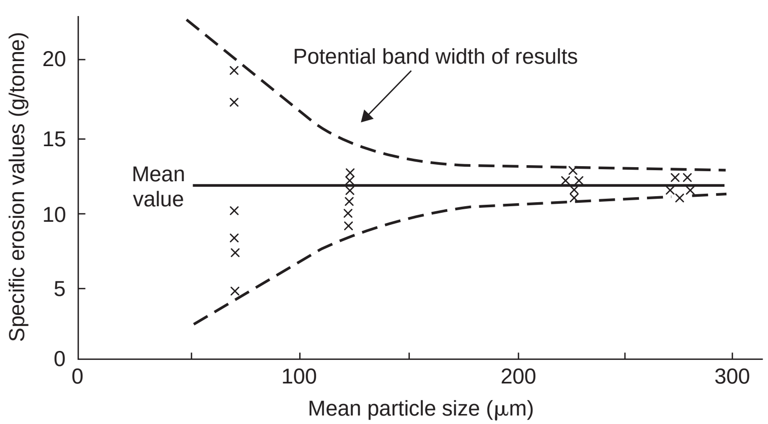


Figure 23.6 The variation of individual specific erosion values with mean particle size for bends in a pneumatic conveying system pipeline.

were impacted against test plates. They found that erosion is related to hardness by the expression:

$$\text{Erosion} = \textit{constant} \times H_{\mathrm{p}}^{2.4}$$

where H_{p} is the particle hardness (kg/mm^2).

It is generally considered, however, that there is a threshold value of particle hardness beyond which erosion remains essentially constant. This occurs at a particle hardness of about 800 kg/mm^2, and so materials with hardness values much greater than this would not be substantially more erosive than sand particles.

23.2.4.1 Bend wear

A sketch of the potential influence of particle hardness on the erosion of mild steel bends, from work of the author, is given in Figure 23.7. The hardness values of typical materials, both potential conveyed materials and bend surface materials, have been superimposed for reference.

It will be noticed from this that coal is a very soft material and is unlikely to be a problem with respect to erosion. In reality, of course, both pulverized and granular coal are erosive materials. This, however, is due to the presence of non-combustible minerals, such as quartz and alumina in the coal, and not to the coal itself. With large tonnage flows, even small percentages of these highly abrasive minerals will cause severe wear. A similar situation applies to pulverized fuel ash, and other materials containing small percentages of similar contaminants, such as barytes and wood chips.

23.2.4.2 Hardness measurement

Knowledge of particle hardness is essential, therefore, particularly at the design stage of a plant, since it gives an indication of the need to take steps to avoid excessive wear of key system components. Scratch hardness is the earliest known type of hardness

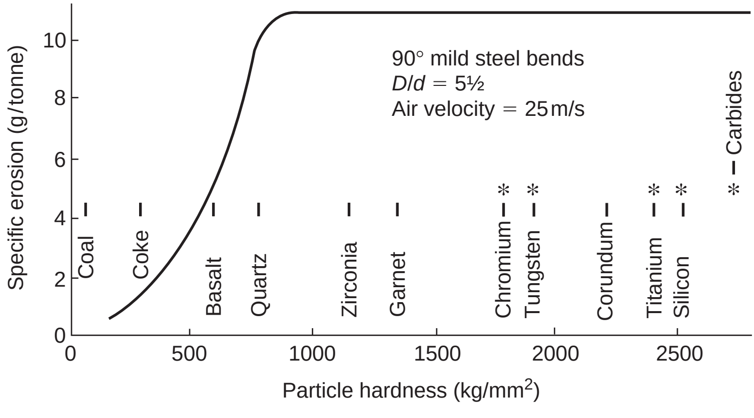


Figure 23.7 The influence of particle hardness on the erosion of bends in a pneumatic conveying system pipeline.

Table 23.1 Mohs' scale of hardness

Mohs' scale of hardness	Material	Chemical formula	Explanation
1	Talc	$Mg_3(OH)_2(Si_2O_5)_2$	Very soft, can be powdered with finger
2	Gypsum	$CaSO_4$	Moderately soft, but can scratch lead
3	Calcite`	$CaCO_3$	Can scratch a fingernail
4	Fluorite	CaF_2	Can scratch a copper coin
5	Apatite	$Ca_5(PO_4)_3(Cl_2F)$	Can only just scratch a knife blade
6	Feldspar	$KAlSi_3O_8$	Can scratch a knife blade
7	Quartz	SiO_2	
8	Topaz	$Al_2F_2SiO_4$	All materials harder than 6
9	Corundum	Al_2O_3	will scratch window glass
10	Diamond	C	

test, and in its simplest form is the ability of one solid to scratch, or be scratched, by another. The method was first proposed on a semi-quantitative basis in 1822 by Mohs, who selected 10 mineral standards, starting with the softest – talc (scratch hardness 1) – and ending with the hardest – diamond (scratch hardness 10). Due to its simplicity it is still widely used today as a reference for potential erosive wear of plant by conveyed materials. This has become known as the Mohs' hardness scale and is shown in its complete form in Table 23.1.

It should be noted that divisions along the scale are clearly not all of the same magnitude. If a Mohs' number of a material is unknown, an indication of its value, and hence its potential abrasiveness, can be obtained by conducting a series of quick tests of the type indicated in Table 23.1. Thus cement clinker, for example, has a Mohs' number of 6, since it can scratch any substance as hard as apatite (Mohs' no. 5), but cannot scratch any substance as hard as quartz (Mohs' no. 7). A convenient method of carrying out a hardness test is by the use of a set of 'hardness pencils'. At the tip of each pencil is mounted a piece of one of the materials from the Mohs' list. By starting with the hardest pencil, undertaking a scratch test and then repeating this with progressively less hard pencils, the Mohs' hardness of the material can be determined.

Since the Mohs' scale proved too coarse for the measurement of the hardness of general engineering metals, quantitative tests of the static indentation type were devised, mostly based on the use of pyramids. Equipment is available for carrying out such tests with fine particulate materials, but because of its complexity, the Mohs' scale is still used today for many bulk solids handling applications. Metal hardness, of course, is usually referred to in terms of the value indicated by one of these indentation methods. Fortunately sufficient research has been undertaken to relate the hardness as measured by any of these methods to the Mohs' scale number. Such a relationship is shown in Figure 23.8.

23.2.5 Surface material

A number of surface materials were included in Figures 23.1 and 23.2. In Figure 23.2 it was shown that, for a given impact angle, the effect of velocity was similar for each

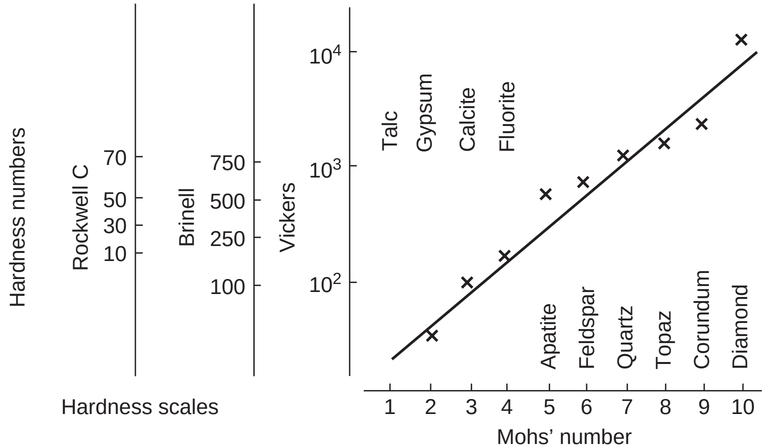


Figure 23.8 Relationship between Mohs, Vickers, Brinell and Rockwell hardness scales.

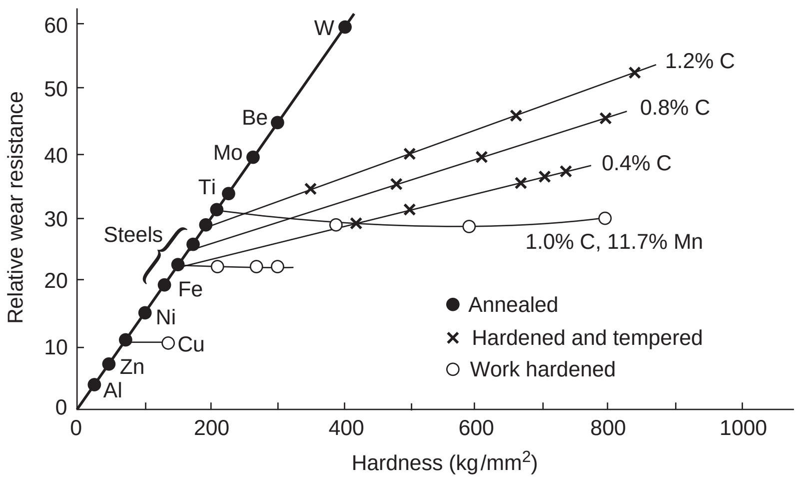


Figure 23.9 Variation of relative abrasive wear resistance with indentation hardness for various surface materials.

material. Figure 23.1, however, showed that impact angle could have a very different effect, with the ranking of different materials changing significantly with impact angle. From these figures it is clear that surface hardness is not necessarily the main parameter to be considered in selecting materials for erosive wear resistance.

23.2.5.1 Steels – heat treated

There is a wealth of information in the field of abrasive wear on the relationship between surface material hardness and wear resistance for metals. One of the earliest of these is shown in Figure 23.9 [9]. The ordinate in this case is the relative wear resistance, which

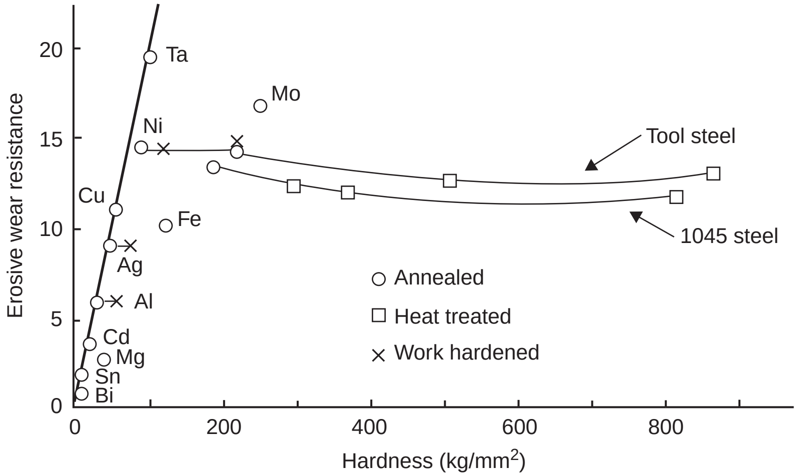


Figure 23.10 Variation of erosive wear resistance with indentation hardness for various surface materials.

is the inverse of wear rate. This shows that the hardness value of annealed metals provides an approximate estimate of their resistance to abrasive wear. Cold working fcc metals to higher hardness values has essentially no effect on abrasive wear resistance, and hardening and tempering carbon steels to achieve higher hardness levels does not result in a corresponding increase in wear resistance.

Finnie [10] was the first to show that such a relationship might exist in the field of erosive wear, but Finnie et al. [11] were the first to produce a hardness to wear resistance relationship similar to those presented for abrasive wear. Results of their work are presented in Figure 23.10. The range of materials that they considered was rather limited but the shape and trends of the curves were similar. Several researchers have commented on the possibility of micro-melting occurring over a small part of the indented surface, as mentioned in relation to Theories Proposed above at Section 23.2.1.1. This could partially over-ride the effect of heat treatment and consequent micro-structural changes.

The author has also carried out tests to determine the influence of surface hardness on erosive wear resistance [12]. An acceleration tube device was used, with silica as the abrasive material. The surface material employed was an alloy tool steel and this was hardened, and tempered over a range of temperatures, to produce a range of surface hardness values up to 830 kg/mm^2. In the annealed, or 'as received', condition the steel had a Vickers hardness of about 230 kg/mm^2.

A comparison of the two hardness extremes, with respect to impact angle, is presented in Figure 23.11. This clearly shows an impact angle effect and reinforces the point that the reference conditions for any comparison with respect to erosive wear performance should always be clearly stated.

Although there is little or no difference in wear rate at very high values of impact angle, at low impact angles the heat treated material shows a significant improvement.

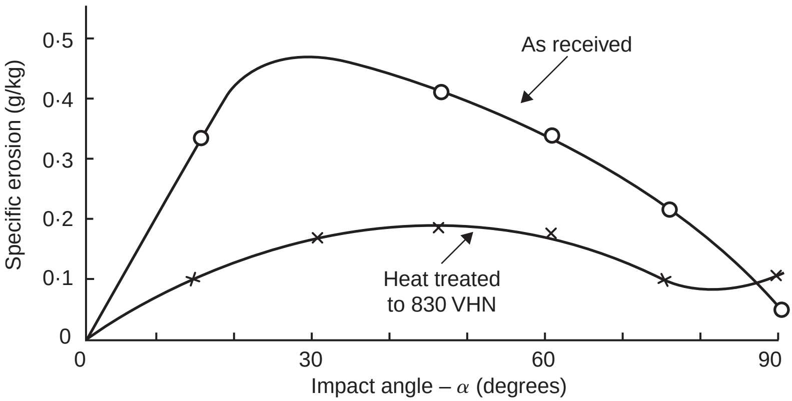


Figure 23.11 Variation of specific erosion with impact angle for 'as received' and heat treated alloy tool steel.

Pipeline is available that has been heat treated on the inner surface to high hardness values, and since straight pipeline is generally only subject to low angle glancing blows, this could offer added protection in this situation.

23.2.5.2 Resilient materials

Resilient materials, such as rubber and polyurethane, are often used in erosive wear situations. Although the hardness of the surface material is generally far lower than that of the particles impacting against the surface, they derive their erosive wear resistance from the fact that they are able to absorb most of the energy of impact by virtue of their resilience. Mason et al. [13] tested mild steel, nylon and Linatex (a proprietary material containing 95 per cent natural rubber) in a shot blast impact testing machine. Alumina particles were impacted at different angles over a range of velocities. They showed that the nylon and rubber exhibited typically ductile behaviour, with respect to impact angle, similar to mild steel.

Their erosive wear results, with respect to air velocity, are shown in Figure 23.12. These show that natural rubber is superior to mild steel at velocities below about 120 m/s, but above this value the performance of the rubber rapidly deteriorated. It is suspected that beyond a certain impact energy level the rubber is no longer able to absorb the energy. As a result the wear mechanism probably changes to one of tearing and possibly burning because of the heat generation. This point is considered further in Section 23.3.2.6, where the use of rubber is considered as a bend wall material.

23.2.5.3 Hard materials

Hard brittle materials are generally used in cases of severe erosive wear. Materials used include Ni-hard, basalt and ceramics. Ni-hard is an abrasion resistant white cast iron. It contains about 6 per cent Ni, 8.5 per cent Cr, 1.7 per cent Si and 0.5 per cent Mn and the structure can be refined by chill casting. The material has a Brinell hardness of 550–650, which is equivalent to a Vickers hardness of about 750 kg/mm^2.

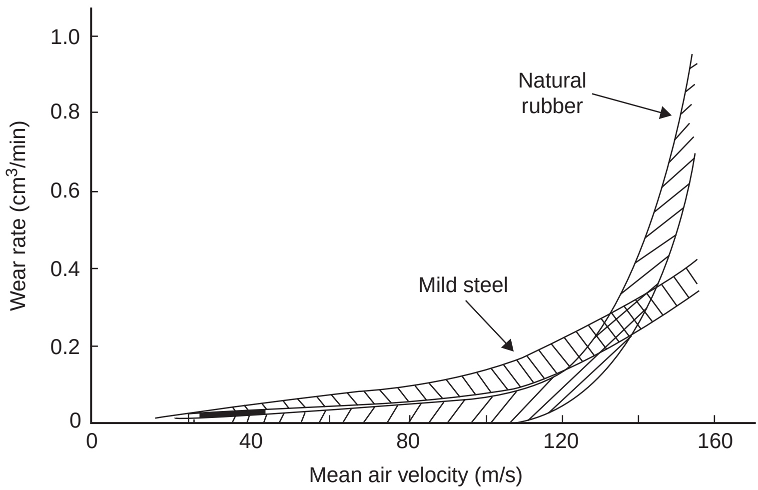


Figure 23.12 The influence of air velocity on wear rate for mild steel and rubber surfaces.

Basalt is a volcanic rock which can be cast into sections and used for lining surfaces, and although widely used for lining chutes and hoppers, it is often used for straight pipeline and bends. After casting, the material is heat treated to transform it from an amorphous into a crystalline structure. This is a naturally hard material with a hardness, according to the Mohs' scale of 7–8, which is equivalent to a Vickers hardness of about 720 kg/mm^2. Basalt consists of approximately 45 per cent silica and 15 per cent alumina, with the rest made up of oxides of iron, calcium, magnesium, potassium, sodium and titanium.

Of the materials used for providing erosion resistance, alumina based materials are probably most common. A typical material consists of 50 per cent aluminium oxide, 33 per cent zirconium oxide and 16 per cent silicon oxide. The general industry specification today is an alumina content of 85 per cent, although higher alumina contents can be supplied. It has a hardness of 9 on the Mohs' scale, which is equivalent a Vickers hardness of about 2000 kg/mm^2. Like basalt, these materials can also be cast into moulds of the required shape.

23.2.6 Particle concentration

Particle concentration is a variable that has received little attention in basic research work on the subject, with the general opinion being that erosion decreases only very slightly for a large increase in concentration. Concentrations investigated, however, have generally been very much lower than those encountered in pneumatic conveying, even with dilute phase conveying. In pneumatic conveying the term used for particle concentration is generally solids loading ratio (see Equation (1.3)). Its particular advantages over particle concentration are that it is a dimensionless quantity and that its value does not vary with conveying air velocity or pressure, so that it remains essentially constant along the length of a pipeline.

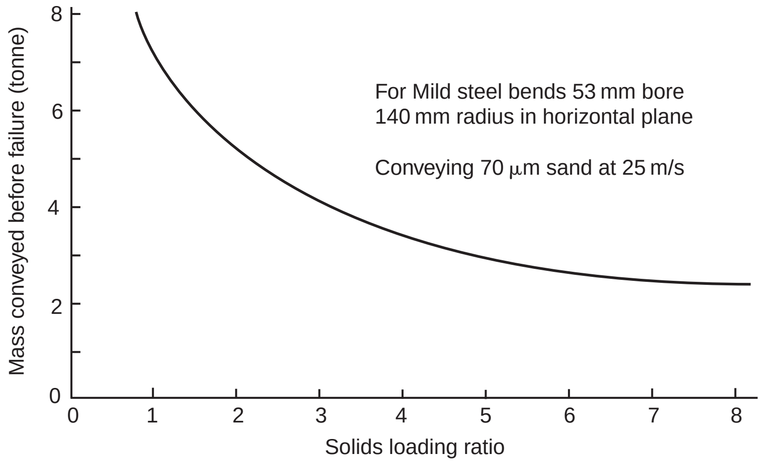


Figure 23.13 The influence of solids loading ratio on the conveying capacity of bends.

23.2.6.1 Bend wear

The general explanation for the gradual reduction in erosive wear with increase in solids loading ratio is that as the particle concentration increases, fewer impacts occur between the particles and the bend wall surface due to the interference of an increasing number of other particles. From work on the erosive wear of pipe bends the author has derived the following relationship for erosive wear:

$$\text{Mass eroded} = \textit{constant} \times (\text{solids loading ratio})^{-0.16}$$

The author has also found that the depth of penetration of particles into the bend wall surface varies with particle concentration, as with particle size reported in Section 23.2.3. As the solids loading ratio increases the particles tend to focus on a smaller area of bend wall surface such that the rate of penetration of the particles increases. In terms of the mass of metal that has to be eroded from a bend before failure occurs the author has derived the following relationship:

$$\text{Mass eroded at failure} = \textit{constant} \times (\text{solids loading ratio})^{-0.74}$$

By combining the data on the mass eroded from the bends, with that on the depth of penetration of the conveyed material into the bends, it is possible to determine a relationship for the mass of material that can be conveyed through a bend before failure occurs [14]. Data for the bends investigated is presented in Figure 23.13. This is similar to the data presented on the influence of velocity in Figure 23.4. It will be seen from Figure 23.13 that as the solids loading ratio increases the life expectancy of the bends reduces quite considerably. Although the specific erosion decreases with increase in solids loading ratio, the influence of the increase in penetration rate has an over-riding effect.

It was reported earlier, with respect to particle size, and Figure 23.6, that the degree of scatter of the results increased considerably with decrease in particle size. A similar phenomenon was observed with regard to solids loading ratio, with the degree of scatter increasing considerably with increase in solids loading ratio. In terms of component life, therefore, both particle penetration rate and possible scatter in the results are potentially as important as mass eroded. Once again there was no obvious explanation for the occurrence, but it is possible that eddies produced and turbulence generated increase with increase in concentration.

23.2.7 Particle shape

The influence of particle shape on mass eroded has been reported by many researchers. The result is much as one might expect, for smooth and rounded particles do not cause as much erosion as sharp angular particles, under similar conditions of impact velocity and surface and particle hardnesses. For test work on the erosive wear of pipe bends in pneumatic conveying system pipelines there is generally a need to re-circulate the conveyed material. As a result of re-circulating the material, it degrades and the sharp angular corners and edges of the fresh material are gradually worn away, and they become more rounded and hence significantly less erosive [15]. This is a major problem when test facilities are used to assess component life.

23.2.8 Surface finish

It is generally thought that a highly polished surface will reduce the rate of erosive wear, but it must be emphasized that this is effectively just an incubation period. It will generally only have the effect of reducing the wear rate initially. Once the material surface starts to wear it will have little further influence on the steady state erosion rate. Brittle materials that have porous surfaces are particularly vulnerable to erosive wear. This can result in the casting process of these materials if gas bubbles are allowed to form. If a gas bubble results in particles impacting at an angle close to 90° extremely rapid wear will result in that area [16].

23.3 Industrial solutions and practical issues

To a certain extent the problem of bend wear in pneumatic conveying system pipelines is a problem with which industry has learnt to live. There are a number of ways by which the severity of the problem can be reduced, but a number of factors relating to the material conveyed and the system itself have to be taken into account. Expense is obviously a consideration, some methods may lead to a reduction in the conveying capability of the plant, and if the material being conveyed is friable then a solution that minimizes the effect of degradation must be sought.

23.3.1 Pipeline considerations

The volumetric flow rate of air specified and the pipeline bore chosen are of major importance, for the two have to be selected so that the resulting conveying air velocity is acceptable. The problem is that air is compressible and so its value is significantly affected by pressure. This represents a particular difficulty in high pressure systems, where the air pressure can drop from several bar at the start of the pipeline to atmospheric at the other end. As the pressure of the conveying air decreases along the length of the pipeline its density decreases, with a corresponding increase in volumetric flow rate, and hence velocity. In order to keep the velocity to within reasonable limits, stepped pipelines are often employed. A similar situation exists with negative pressure systems when operating under high vacuum. These issues were considered in detail in Chapter 9.

If, for example, the air supply pressure in a positive pressure conveying system is 3 bar gauge, and the conveying line inlet air velocity is 15 m/s, the conveying air velocity will approximately quadruple to about 60 m/s at the end of the pipeline in a single bore line. A 4-fold increase in velocity will result in an almost 40-fold increase in mass eroded from the bends. This explains why bends near the end of a pipeline will generally fail in a much shorter time than those near the start of the pipeline. If a dense phase system was specifically installed to overcome the problem of erosion, a stepped pipeline for such a system would be almost essential if a high air supply pressure was used.

23.3.2 Bend wear

By the very nature of the transport process, pipelines used for pneumatic conveying systems are prone to wear when abrasive materials have to be conveyed. In dilute phase, materials are conveyed in suspension in the air, and a high conveying air velocity must be maintained in order to keep the material moving, and so avoid pipeline blockage. The main problem relates to the wear of bends in the pipeline, and any other surfaces where particles are likely to impact as a result of a change in flow direction. Bends provide pneumatic conveying systems with their flexibility in routing, but if the material is abrasive and the velocity is high, rapid wear can occur.

23.3.2.1 Influence of bend geometry

Bends are available in a wide range of geometries, in terms of bend curvature, from long radius bends to tight elbows and mitred bends. As bends are so vulnerable to wear there have been many developments and innovations for reducing the problem. The author has investigated the influence of bend geometry [17]. A wide range of D/d values were investigated and the results for 90° mild steel bends are shown in Figure 23.14. The bends were eroded by sand, conveyed at a solids loading ratio of two and with a conveying air velocity of 25 m/s.

The results can, to a certain extent, be predicted from the data presented in Figure 23.1 on the influence of impact angle on erosive wear for a ductile material. With sharp bends, having a low D/d ratio, the majority of the particles will impact against the bend wall at a fairly steep angle. At a high impact angle erosive wear will not be too severe for a ductile material and so it can be expected that the bend will not wear too rapidly.

A bend with a D/d ratio of about 6:1 corresponds closely to the worst case from the data in Figure 23.14. The majority of the particles will impact against the bend wall at an angle of about 20°. For a ductile material this will result in maximum erosion and so the bend can be expected to fail quickly. Particle impact against the wall for bends

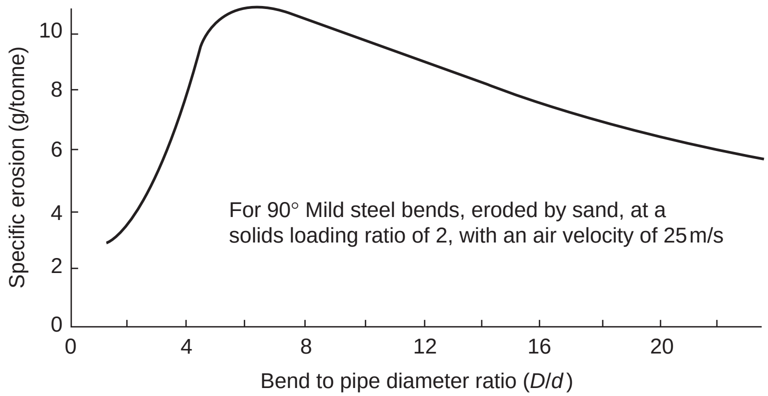


Figure 23.14 The influence of bend geometry on the erosive wear of pipeline bends.

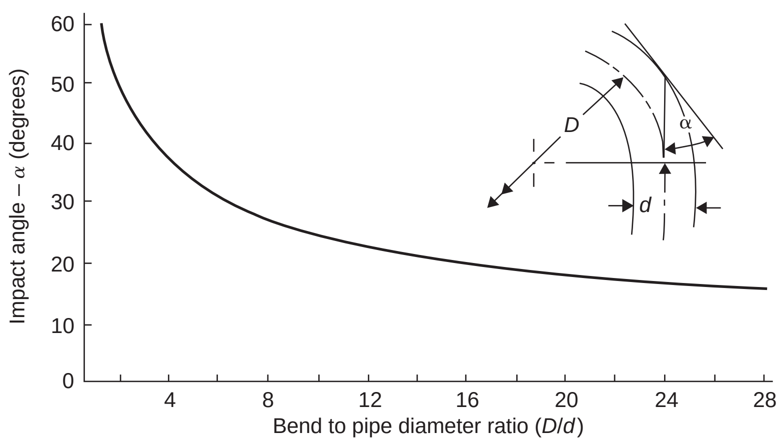


Figure 23.15 Influence of bend geometry on particle impact angle.

with a *D*/*d* ratio greater than about 20:1 is at a much shallower angle. If the impact angle is relatively small the erosion will not be too severe, and so for this case also it can be expected that the bend will not wear too rapidly.

23.3.2.2 Long radius bends

A very low impact angle is an essential pre-requisite for minimizing erosion, particularly in the case of brittle surface materials. In the case of ductile materials, because of the remarkably steep increase in erosion with very small increase in impact angle, as shown in Figure 23.1, exceptionally long radius bends would be required. It is possible to calculate the relationship between the bend geometry (*D*/*d*) and the impact angle. The results of such an analysis are given in Figure 23.15 and this clearly shows the nature of the problem.

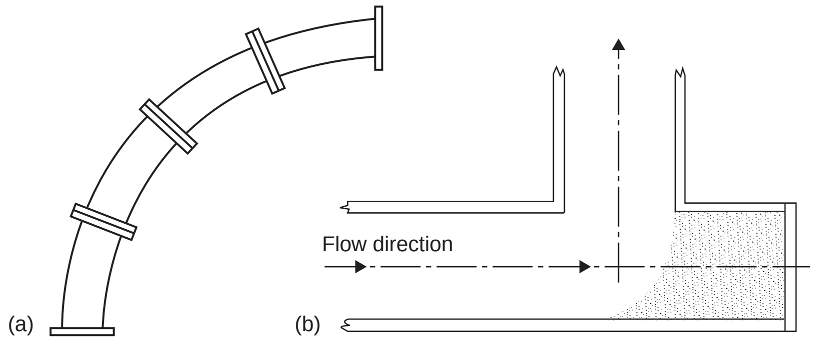


Figure 23.16 Regular geometry bends used in pneumatic conveying system pipelines: (a) bend with replaceable and interchangeable 22½° segments and (b) sketch of tee-piece bend.

For ductile materials long radius bends are not likely to be a viable proposition. For brittle materials, however, such as basalt and cast iron, they are essential, as mentioned above. A common method of providing a long radius bend is to make the bend in segments. By this means the bend will be lighter and much easier to fit into the pipeline. Since the majority of the wear will be at the primary impact point only one or two sections need to be replaced should the bend fail. It is also possible to reverse and interchange segments and so extend the overall life of the bend. Segments can be made in 45°, 30° and 22½° sections. A four section long radius bend is shown in Figure 23.16a.

23.3.2.3 Short radius bends

With very short radius bends the angle at which the material impacts against the bend wall will be fairly high, as shown in Figure 23.15. Although this will not be suitable for brittle surface materials, ductile materials, because of their improved erosion resistance at high impact angle often gives reasonable service in use, if the conveyed materials is not too abrasive.

Three major problems have to be taken into account, however, before using very short radius and similar bends. The more severe the impact of the material against the bend wall the greater will be the problem of degradation if the material is friable (see Chapter 24). The introduction of a very short radius bend will probably also increase the conveying line pressure drop, which will mean that the material mass flow rate will have to be reduced to compensate (see Section 14.5.2). A very short radius bend, and those that are designed to trap the conveyed material, may require a slightly higher value of conveying line inlet air velocity to ensure that the pipeline does not block.

A very cheap and often effective solution to the erosion problem is to use a blanked tee-piece or mitred bend ($D/d = 0$). Such a bend is shown in Figure 23.16b. This gives a simple right-angled bend in the line, and so consideration has to be given to even greater problems of added degradation and pressure drop. The material being conveyed, however, fills the blanked section of the tee and part of the bend so that much of the material being conveyed impacts against itself and not against the pipe wall.

Should the line block at the bend, access can easily be gained from the blanked section to facilitate clearing.

A more sophisticated version of this was developed about 30 years ago and is known as the Booth bend after its originator. This is a very short radius cast bend which incorporates a shallow depression. This allows material to collect in the bend and so subsequent material flowing through the pipeline will impact against itself. A sketch of the bend is given in Figure 23.17a.

Another more recent version is a short radius bend with a large recessed chamber in the area of the primary wear point. It is claimed that this acts as a vortice and that material is constantly on the move in this pocket, thereby providing a cushioning effect. Consideration, however, has to be given to the orientation of the bend. A sketch of the bend is given in Figure 23.17b.

23.3.2.4 Air injection

A number of bend protection devices have been proposed that incorporate the injection of air into a bend. The object of these is to deflect the impacting particles away from the bend wall. The main problem with this type of device in a pneumatic conveying line is that air injection has to be continuous at each bend. In a pipeline of constant bore this will result in a further increase in velocity, and since erosion is highly dependent upon velocity, this method does tend to aggravate the problem. The pipeline can be stepped to a larger diameter part way along its length to compensate, but this adds considerably to the cost of the plant and the complexity of its design, and so this method is rarely used.

23.3.2.5 The use of hard materials

Hard, brittle materials are generally used in cases of severe wear. Materials used include Ni-hard, basalt and ceramics, as discussed in Section 23.2.5.3. These materials can generally be cast or formed into sections, and in the case of non-metals, are used for lining pipes and bends. Care must be taken with cast materials, however, as mentioned above

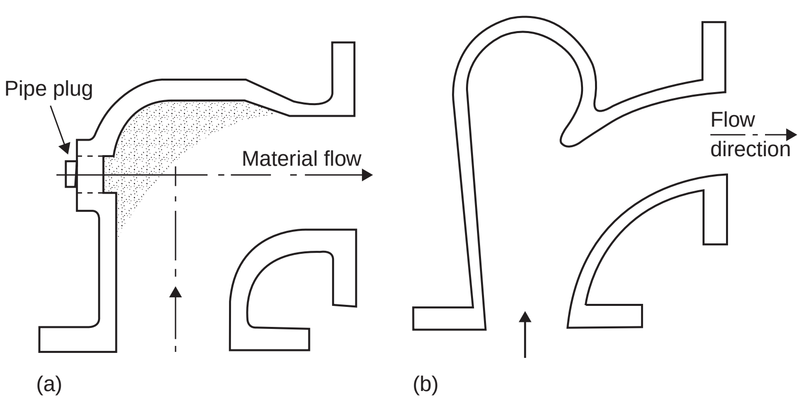


Figure 23.17 Sketch of some specially developed bends for pneumatic conveying: (a) short radius bend with shallow depression and (b) vortice pocket bend.

in relation to Surface Finish at Section 23.2.8, for if a porous surface if obtained, rapid erosion can result.

23.3.2.6 The use of resilient materials

Resilient materials such as rubber and polyurethane are widely used in erosive wear situations. Although the hardness of the surface is often far lower than that of the material being conveyed, and impacting against the surface, they derive their erosive wear resistance from the fact that they are able to absorb much of the impact energy, without being permanently damaged, by virtue of their resilience, as mentioned earlier.

The author has carried out several programmes of tests to compare rubber and steel bends [18]. In one such programme a pipeline was built in which several rubber and steel bends were alternately positioned at the corners of a test loop so that they could be tested at the same time for a direct comparison. Tests were carried out with lump coke and fine silica sand, each conveyed at a solids loading ratio of 10 and with a conveying air velocity of about 25 m/s. Figures 23.18 and 23.19 show the comparative wear effects of the coke and sand on the rubber and steel bends very well.

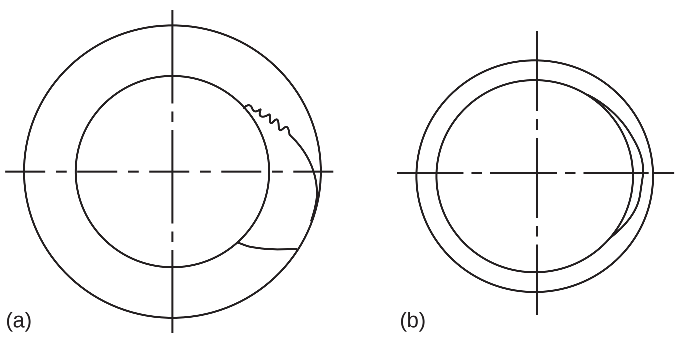


Figure 23.18 Comparison of bend section wear profiles for bends eroded by coke: (a) synthetic rubber and (b) steel bend.

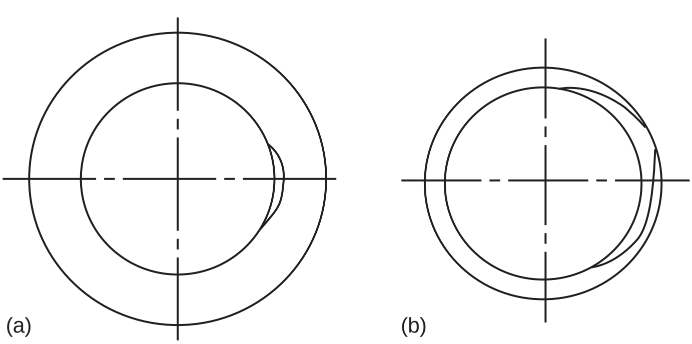


Figure 23.19 Comparison of pipe section wear profiles for bends eroded by sand: (a) synthetic rubber and (b) steel bend.

These are pipe section profiles taken at the point around the bend where either the bend failed or where the penetrative wear was a maximum. Each bend was 53 mm bore, with a pipe wall thickness of 4 mm in the case of the steel bends and 10 mm in the case of the rubber bends. To illustrate the different erosive wear profiles the pipe wall has been magnified by a factor of 1.5 in relation to the pipe bore.

Figure 23.18 compares the pipe section profiles of the steel and rubber bends when eroded by coke. The rubber bends failed after 50 tonne of coke had been conveyed through them, at which time about 56 g had been eroded from the bends. Only 32 g has been eroded from the steel bends, however, and they would probably be capable of conveying another 50 tonne before they would fail. In terms of potential service life, therefore, the 4 mm thick steel bends could be expected to last twice as long as the 10 mm thick rubber bends for the conveying of the coke.

Figure 23.19 compares the pipe section profiles of the steel and rubber bends when eroded by the sand. In this case the steel bends failed after only 3.5 tonne of the sand had been conveyed through them, at which time about 54 g had been eroded from the bends. Only 10 g was eroded from the rubber bends at this stage, and they were quite clearly capable of handling considerably more sand before they would fail. In terms of potential service life, therefore, the rubber bends could be expected to last about five times as long as the steel bends for the conveying of the sand.

Thus for bulk materials having a large particle size, such as lump coal, coke and mined and quarried products, rubber bends cannot be recommended for erosive wear applications. It is believed that there is a threshold value of impact energy that resilient materials such as rubber can withstand without suffering significant damage, as discussed in the section on Resilient Materials above. As either particle size or impact velocity increase, the impact energy of a particle will increase. In relation to velocity this effect was shown quite clearly in Figure 23.12.

23.3.2.7 Surface coatings

A wide range of materials can be applied to existing surfaces, and in many cases they are applied to erosion resistant surfaces, such as Ni-hard, to give added protection. Polyurethane, which cures at ambient temperature, is often used. This can be sprayed, or applied in putty form by trowel, which is particularly useful for repairing eroded surfaces. Hardfacing metal alloys, tungsten carbide and a range of oxide ceramics can be applied to surfaces by means of flame spray coating. Some of these materials have very high hardness values, and combined with the fact that the surfaces can also be very smooth, they can provide good erosion resistance. The surface coatings, however, can generally be applied only in thin layers and so once this is penetrated the bend will rapidly fail.

23.3.2.8 Wear back methods

Wear back methods are potentially the cheapest and most effective means of suppressing erosion. A channel welded to the back of a bend and filled with concrete, as shown in Figure 23.20a, is probably the most common method adopted. When the outer surface of the original steel bend erodes, the concrete will generally extend the

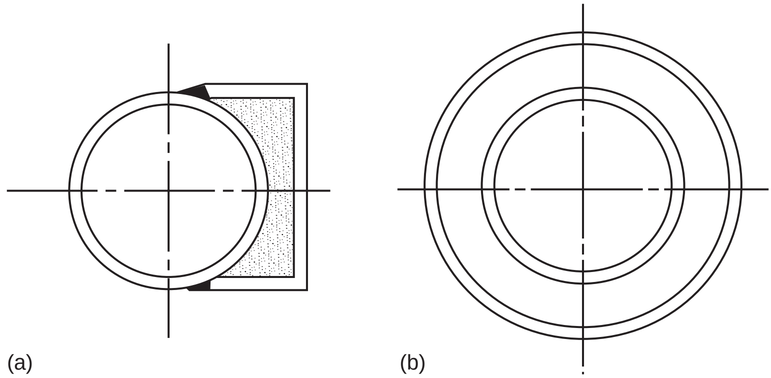


Figure 23.20 Wear back methods of bend reinforcement: (a) concrete filled channel and (b) pressure-tight sleeve over bend.

life of the bend for a reasonably long time. It is essential however, that the wear back covers as much as possible of the outer bend surface, for bends can be holed over a wide range of both bend and pipe angles.

The only problem with this type of solution is that when a primary wear point is established in the concrete at the initial impact point, deflection of particles can result, and these may cause erosion of the inside surface of the bend. The bend may well fail through erosion of the inside surface long before the material has penetrated the concrete. Secondary and tertiary wear pockets in long radius bends may also cause the material to be deflected against the wall of the following straight length of pipe and cause this to fail. These points are considered in more detail below. A similar method of prolonging bend life is to sleeve the main bend with another pressure-tight bend, which is shown in Figure 23.20b. When the inner bend fails the space will fill with the material being conveyed.

23.3.2.9 The use of inserts

Considerable protection can be provided for a bend by positioning a sacrificial insert in the pipeline just prior to the bend. An insert made of a flat strip twisted through 180°, for example, and shown in Figure 23.21, will ensure that the material impacts against the insert prior to impact against the bend. The velocity of the particles will be reduced after impact with the strip and the presence of the strip will prevent the particles from focusing on a small area of the bend. Such a strip should offer little resistance to flow and should last for a reasonable period of time, since the wear would be very evenly distributed over the entire surface of the strip [19].

23.3.2.10 Ease of maintenance

In terms of ease of maintenance, very short radius bends have the particular advantage of their much lighter weight. These can generally be removed and changed by two people without the use of special lifting equipment. Bends with the provision of replaceable

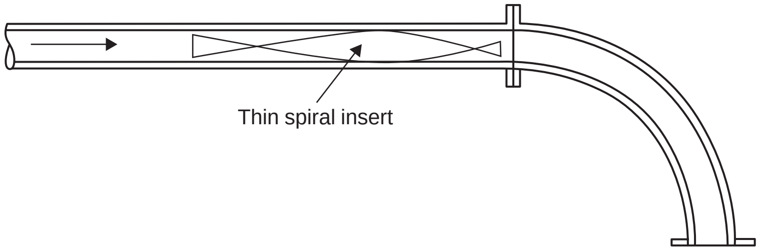


Figure 23.21 Bend protection by use of sacrificial inserts in preceding straight pipeline.

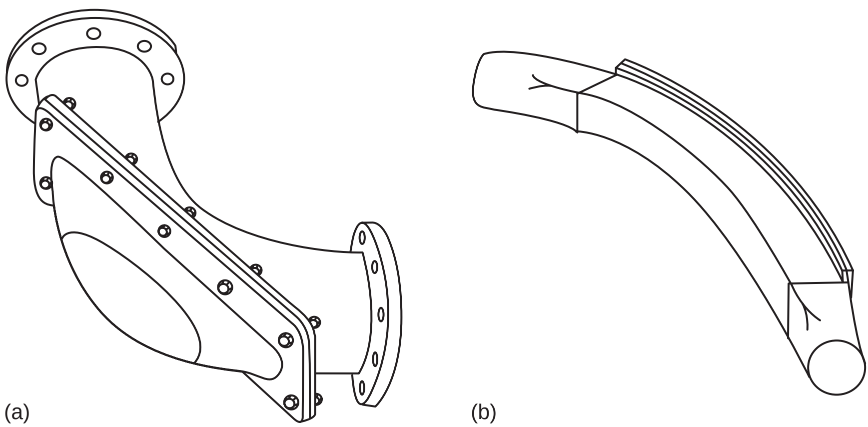


Figure 23.22 Bends with replaceable backs: (a) regular bend and (b) square section bend.

wear backs are also very useful in this respect, such as those shown in Figure 23.22, as the bend itself does not have to be removed or replaced.

For regular radiused bends, as shown in Figure 23.22a, the wear backs are usually made of Ni-hard or similar material. The backs must be replaced on a regular basis, however, and not when failure occurs. If they are left until failure occurs, much of the body may have worn away and it may not be possible to guarantee an air-tight seating. If the material being conveyed is potentially explosive, the possibility of this type of bend wearing to a point where it will be incapable of withstanding the explosion pressure generated must also be considered.

With large bore pipelines square section bends are often fabricated, and in such a manner that the outer wall can be removed, as illustrated in Figure 23.22b. This allows for easy replacement. Alternatively the backing plate can be made of a different material, or be given a lining of a costlier material, to resist the erosive wear.

23.3.3 Wear patterns and deflecting flows

Mason and Smith [20] carried out tests on 25 and 50 mm square section 90° bends with a flow of alumina particles from vertically up to horizontal. The bends were made of Perspex and were constructed with substantial backing pieces in order that the

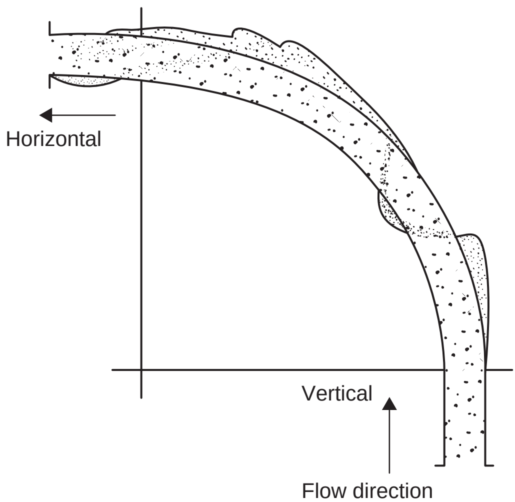


Figure 23.23 Wear and flow pattern for an eroded bend.

change in flow pattern and wear over a period of time could be visually observed. The results from one of their tests are given in Figure 23.23.

With a new bend the particles tend to travel straight on from the preceding straight pipeline until they impact against the bend wall. After impact they tend to be swept round the outside surface of the bend. They are then gradually entrained in the air in the following straight length of pipe. In Figure 23.23 the flow pattern is shown after substantial wear has occurred. This shows quite clearly the gradual wearing process of a bend and the effect of impact angle on the material in the process. Erosion first occurred at a bend angle of 21° which became the primary wear point, as one would expect. After a certain depth of wear pocket had been established, however, the particles were deflected sufficiently to promote wear on the inside surface of the bend, and then to promote a secondary wear point at a bend angle of 76°.

A small tertiary wear point was subsequently created at an angle of 87°. If such a well reinforced bend were to be used in industry, in preference to replacing worn bends, the deflection from the latter wear points would probably cause erosion of the straight pipe section downstream of the bend. As this pattern of particle deflection in worn bends is now well recognized, some companies manufacture steel bends with thicker walls and a typical example is shown in Figure 23.24. This particular bend is also slightly thicker on the inside surface to allow for the fact that particles can be deflected to the inside surface, as illustrated in Figure 23.23.

23.3.3.1 Influence of impact angle

The curve in Figure 23.1 of erosion against impact angle, for the aluminium alloy, provides a means by which an interpretation of the type of wear shown in Figure 23.23 can be obtained. The outer wall of the bend presents a surface at a low impact angle to the particles issuing from the preceding vertical straight pipe run, and as Perspex is a

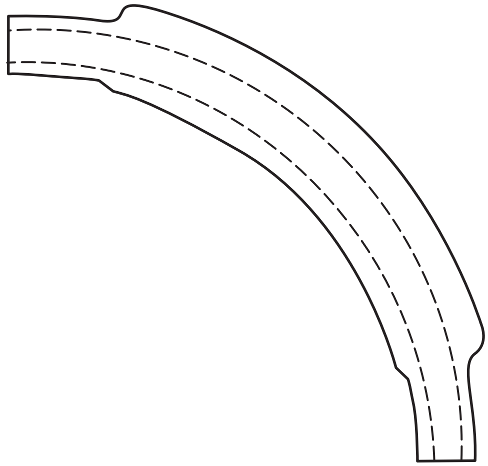


Figure 23.24 Bend with reinforced walls.

ductile material rapid erosion takes place. Gradually the impact angle at this primary wear point changes to almost 90°. From Figure 23.1 it will be seen that ductile materials suffer relatively little erosion under normal impact, and this explains why little further erosion takes place at this point.

The conveyed material can be seen quite clearly to be deflected out of this primary wear pocket. Due to this abrupt change in direction, however, it is no longer swept around the bend as before, but impacts on the inside surface of the bend. It is then deflected to the outer wall again, and because the low impact angle is maintained here, the erosion at this point is far greater than that at the primary wear point.

Mason and Smith [20] also mention that a conventional bend design, used to avoid plant shut down due to wear, is to reinforce the outside of the bend with a mild steel channel backing filled with a suitable concrete, as illustrated in Figure 23.20a. They included a radiograph of such a 100 mm bore pipeline bend and this showed a primary wear pocket developing in precisely the same manner as for the Perspex bend tested. It is believed that the bend ultimately failed through erosion of the inner surface due to material deflection from the primary wear point.

23.3.4 Wear of straight pipeline

Straight pipeline is rarely a problem with regard to erosive wear, although there are specific circumstances where it should be taken into account. Reference has already been made above to the deflection of particles issuing from a well reinforced eroded bend. Similar deflections can be promoted from poorly aligned pipe sections, and large abrasive particles present a particular problem.

23.3.4.1 Following bends

It will be seen from Figure 23.23 that the straight section of pipeline, following a well reinforced bend, is liable to erosive wear. Although the angle of impact of the particles

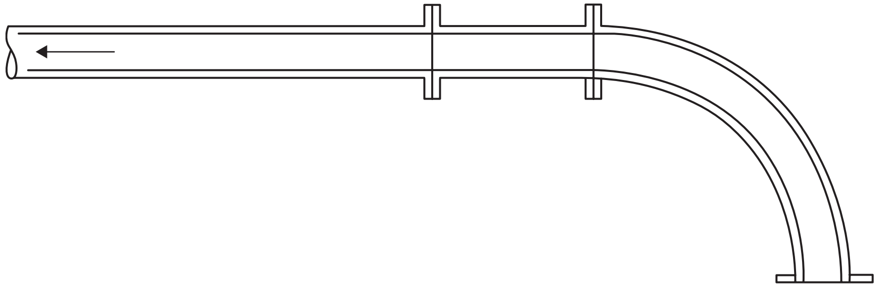


Figure 23.25 Thick walled section of straight pipeline following reinforced bend.

is generally low, for a ductile material low angle impact is likely to result in significant wear, because of the remarkably steep increase in erosion with very small increase in impact angle, as illustrated in Figure 23.1. To extend the life of the pipeline following a bend, therefore, it is suggested that a short section of thick walled pipe should be placed between the bend and the main pipeline, as illustrated in Figure 23.25.

It is also recommended that a short section of thick walled pipe should be used after a blind tee bend, such as that shown in Figure 23.16b. The turbulence generated in such a bend is quite significant and ultimate failure generally occurs a short distance downstream of the bend. The section of thick walled pipe following a bend does not have to be very long for the deflecting flow is soon dampened out. A 2 m section is generally long enough for small bore pipelines, and something of the order of 20 pipe diameters should be allowed for larger bore pipelines.

Since the flow of deflected particles issuing from a bend will generally impinge constantly on the same area of the thick walled pipe it is also recommended that this short section of pipe should be connected by flanges to the bend and the following section of regular pipeline so that it can be rotated on a regular basis. This will both help to extend the life of this section of pipe and prevent a large wear pocket forming which could result in a further site for particle deflection to occur.

Hot dust laden gases from boilers and reactors are often passed through heat exchangers for generating steam. The tubes through which the gases flow often wear, and are generally very expensive to repair. The wear is usually only at the start of the tube. This is because the dusty gases on entry to the tube are in a very turbulent state and numerous particle impacts occur. After a short distance the flow is effectively straightened out and little further pipeline wear occurs. An effective solution to the problem is to provide a sacrificial extension to the pipe prior to the tube plate and the heat exchange section for flow straightening purposes.

23.3.4.2 Pipe section joints

Misaligned flange joints, and welded joints with weld metal protruding inside the pipeline, as illustrated in Figure 23.26, can often lead to straight pipeline failure, particularly in small bore pipelines. It is a similar situation to the wear pockets formed in bends, since the step produced can result in particle streaming. This is particularly a

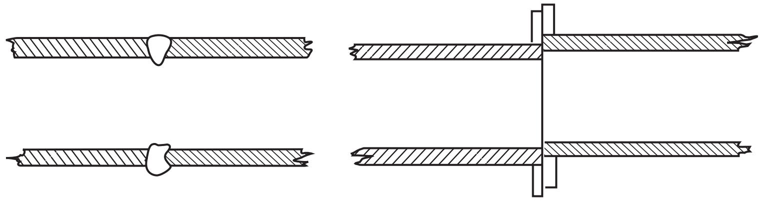


Figure 23.26 Examples of erosion promoting sites at poorly jointed sections: (a) welded pipe joints and (b) flanged pipe joints.

problem if rubber hose is attached to steel pipe by means of pushing the hose over the steel pipe. A small step will be formed and this can cause severe streaming of particles.

23.3.4.3 Large particles

Small particles will generally be conveyed through a pipeline with little contact with the pipeline wall in dilute phase suspension flow, in the absence of flow streaming and turbulence promoting sites. With large particles, however, gravitational force has a much greater effect. Large particles can be conveyed quite successfully, but in horizontal flow they will tend to skip along the pipeline. They will convey in suspension, but gravity will give them a low trajectory in their flow, and hence they will impact fairly frequently with the pipeline wall. The impact angle will be very low but, as has been discussed before, wear of ductile pipeline materials can be significant as a result of glancing impact from abrasive particles.

Erosive wear, as a result, will be concentrated along the bottom of the pipeline. Since it is not generally very convenient to reinforce a pipeline along its entire length, in order to overcome this problem, it is recommended that the pipeline should be rotated periodically. By this means the pipeline will last for a very much longer period of time. It is important to recognize this problem when the pipeline routing is being planned, however, for the horizontal sections of pipeline need to be located where convenient access can be gained to carry out the rotating process.

References

1. G P Tilly. Erosion caused by impact of solid particles. Treatise on Materials Science and Technology. Vol 13, pp 287–319. Academic Press Inc. 1979.
2. B J Hockey and S M Wiederhorn. Erosion of ceramic materials: the role of plastic flow. Proc 5th ELSI Conf. Paper 26. Cambridge. September 1979.
3. E E Smeltzer et al. Mechanics of metal removal by impacting dust particles. ASME Winter An Mtg. Los Angeles. Paper 69-WA/Met-8. November 1969.
4. G P Tilly and W Sage. The interaction of particle and material behaviour in erosion processes. Wear. Vol 16, pp 447–465. 1970.
5. D Mills and J S Mason. Conveying velocity effects in bend erosion. Journal of Pipelines. Vol 1, pp 69–81. 1981.
6. G P Tilly. Erosion caused by airborne particles. Wear. Vol 14, pp 64–69. 1969.

7. D Mills and J S Mason. The effect of particle size on erosion of pipe bends in pneumatic conveying systems. Proc Powtech '79. NEC Birmingham. March 1979.
8. J E Goodwin, W Sage and G P Tilly. Study of erosion by solid particles. Proc IMechE, Vol 183, No 15, pp 279–292. 1969–70.
9. M M Khruschof. Resistance of metals to wear by abrasion, as related to hardness. Proc IMechE Conf on Lub and Wear. pp 655–659. 1959.
10. I Finnie. Erosion by solid particles in a fluid stream. Spec Tech Pub No 307 of Am Soc for Testing Materials. pp 70–82. June 1961.
11. I Finnie, J Wolak and T Kabil. Erosion of metals by solid particles. ASTM Journal of Materials. Vol 2, pp 682–700. September 1967.
12. D Mills and J S Mason. The erosive wear of hardened and tempered steels in pneumatic conveying system pipelines. Proc 7th ELSI Conf. Paper 81. Cambridge. September 1987.
13. J S Mason et al. The rapid erosion of various pipe wall materials by a stream of abrasive alumina particles. Proc Pneumotransport 2. Paper E1. Guildford. 1973.
14. D Mills and J S Mason. Evaluating the conveying capacity and service life of pipe bends in pneumatic conveying systems. Journal of Powder and Bulk Solids Technology. Vol 3, No 2, pp 13–20. 1979.
15. D Mills and J S Mason. Particle size effects in bend erosion. Wear. Vol 44, pp 311–328. 1977.
16. E Raask. Impact erosion wear caused by pulverised coal and ash. Proc 5th ELSI Conf. Paper 41. Cambridge. September 1979.
17. K N Tong, D Mills and J S Mason. The influence of bend radius on the erosion of pipe bends in pneumatic conveying systems. Proc 5th Powder and Bulk Solids Conf. Chicago. May 1980.
18. V K Agarwal, D Mills and J S Mason. A comparison of the erosive wear of steel and rubber bends in pneumatic conveying system pipelines. Proc 6th ELSI Conf. Paper 60. Cambridge. September 1983.
19. V K Agarwal and D Mills. The use of inserts for reducing bend wear in pneumatic conveying system pipelines. Proc 14th Powder and Bulk Solids Conf. Chicago. May 1989.
20. J S Mason and B V Smith. The erosion of bends by pneumatically conveyed suspensions of abrasive particles. Powder Technol, Vol 6, pp 323–335. 1973.

Chapter 24

Particle degradation

24.1 Introduction

In some bulk solids handling processes intentional breakdown of the material is required, as in crushing, grinding and comminution. In many handling and storage situations, however, unintentional breakage occurs. This is usually termed degradation or attrition, depending on the mechanism of particle breakage. Bulk materials, when pneumatically conveyed, will impact against bends in the pipeline, and there may be a significant amount of particle to particle interaction. There may also be frequent impacts against the pipeline walls, and particles sliding along the pipeline walls in low velocity dense phase flows. These collisions and interactions will produce forces on the particles that may lead to their breakage.

24.1.1 Particle breakage

If particle breakdown occurs easily the bulk solid is said to be friable. Tendency to particle breakdown covers three main situations. The first is a tendency to shatter or degrade when the bulk solid is subject to impact or compressive loading. The second is the tendency for fines and small pieces to be worn away by attrition when bulk solids either rub against each other or against some surface, such as a pipeline wall or bend. The third is the tendency for materials such as nylons and polymers to form angel hairs when conveyed, as a result of micro-melting occurring, due to the frictional heat of particles sliding against pipeline walls.

Of all conveying systems, dilute phase probably results in more material degradation and attrition than any other. This is because particle velocity is a major variable in the problem and, in dilute phase conveying, high velocities have to be maintained. The potential influence of a pneumatic conveying system on a material is demonstrated in Figures 24.1 and 24.2. This is a consequence of conveying a friable material at an excessively high velocity in dilute phase suspension flow in a conveying system with a large number of small radius bends.

Figure 24.1 shows the influence on the cumulative particle size distribution for the material before and after conveying. The mean particle size, based on the 50 per cent value, has changed from about 177–152 μm. The really significant effect, however, is shown in the fractional size distribution plot in Figure 24.2. In this magnified plot the effect of degradation on the material can be clearly seen. A considerable number of

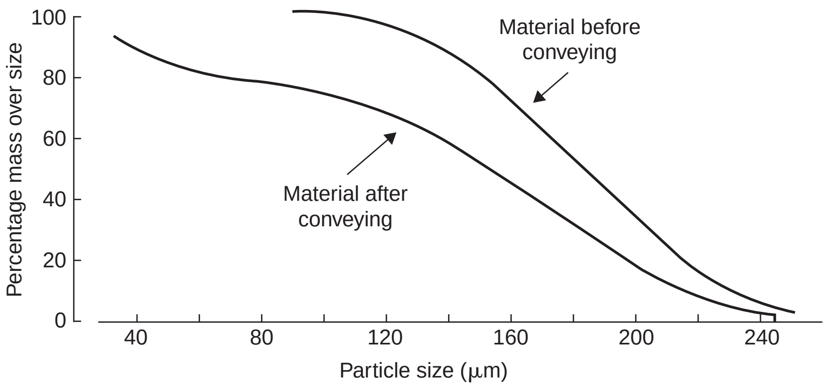


Figure 24.1 Possible influence of pneumatic conveying on cumulative particle size distribution of a friable material.

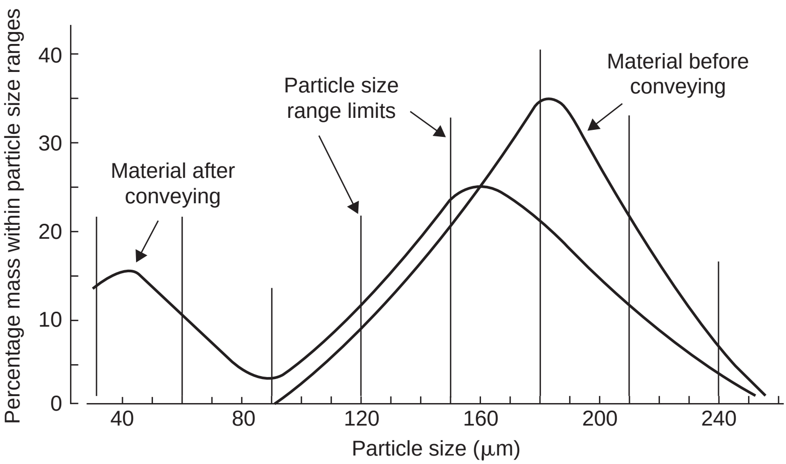


Figure 24.2 Possible influence of pneumatic conveying on fractional size distribution of a friable material.

fines are produced and even on a percentage mass basis these cause a significant secondary peak in the particle size distribution.

24.1.2 Operating problems

Particle degradation can cause problems in a number of areas on account of the changes in particle shape and particle size distribution that can result. It is a particular problem with chemical materials that are coated, for it is the coating that is generally the friable element of the resulting material. Plant operating difficulties are often experienced because of the fines produced, and problems in handling operations can also result after the material has been conveyed.

Apart from the obvious problems of quality control with friable materials, changes in particle shape can also lead to subsequent process difficulties with certain materials. The appearance of the material may also change so that it is not so readily sold. Changes in particle size distribution can affect flow characteristics, which in the extreme can change a free-flowing material into one which will only handle with great difficulty, and with materials for subsequent sale this can lead to customer problems.

24.1.2.1 Filtration problems

In pneumatic conveying systems plant operating difficulties can result if degradation causes a large percentage of fines to be produced, particularly if the filtration equipment is not capable of handling the fines satisfactorily. Filter cloths and screens will rapidly block if they have to cope with unexpectedly high flow rates of fine powder. The net result is that there is usually an increase in pressure drop across the filter, and this could be a significant proportion of the total pressure available in a low pressure system.

This means that the pressure drop available for conveying the material will be reduced, which in turn means that the mass flow rate of the material will probably have to be reduced in order to compensate. If this is not done there will be the risk of blocking the pipeline. Alternatively, if the filtration plant is correctly specified, with material degradation taken into account, it is likely to cost very much more as a result. This, therefore, provides a direct financial incentive to ensure that particle degradation is minimized, even if it does not represent a problem with respect to the material itself [1].

24.1.2.2 Flow problems

In many systems there is a need to store the conveyed material in a hopper or silo. Flow functions can be determined for bulk particulate materials, from which hopper wall angles and opening sizes can be evaluated, to ensure that the material flows reliably at the rate required. A change in particle size distribution of a material, as a result of conveying operations, however, can result in a significant change in flow properties. Thus a hopper designed for a material in the 'as received' condition may be totally unsuitable for the material after it has been conveyed. As a result it may be necessary to fit an expensive flow aid to the hopper to recover the situation.

24.1.2.3 Potential explosion problems

Many materials, in a dust cloud, can ignite and cause an explosion. Dust clouds are clearly quite impossible to avoid somewhere in a pneumatic conveying system, and so this poses a problem with regard to the safe operation of such systems. Of those materials that are potentially explosive, research has shown that it is only the fraction with a particle size less than about 200 μm that poses the problem. Degradation and attrition caused by pneumatic conveying, however, can result in the generation of a considerable number of fines, particularly if the material is friable. Even if the material did not represent a problem with respect to explosions in the 'as received' condition, the situation could be very different after the material has been conveyed.

24.1.3 Test rigs and data sources

Little data is available on the degradation of materials in pneumatic conveying systems. This is partly due to the complexity of obtaining and analysing the data, but mainly to the fact that so many variables are involved, together with the problem of relating the data from one material and situation to another. A particular problem with data obtained from a pneumatic conveying system pipeline is that it is very difficult to separate the individual contributions made by the bends and the straight pipeline. A further problem is that in a pipeline there is a gradual expansion of the conveying air, which means that the particle velocity is constantly changing. Velocity is a major variable in particle degradation and so this makes attempts at analysis almost impossible.

The major source of information is probably from the basic research that has been undertaken with small bench scale test rigs in which particles have been impacted against test materials under controlled conditions. This work has often been carried out to assist in an understanding of erosive wear problems and to investigate problems of comminution. Although much of this work cannot be related directly to pneumatic conveying situations, it can provide valuable information of a comparative nature on a number of the variables in the process.

24.1.3.1 Acceleration tube device

Test facilities employed are very similar to those used in erosive wear research, such as whirling arm and acceleration tube devices. A device used by Salman et al [2] and reported by the author is shown in Figure 24.3 and consists of a linear air gun. One particle was tested at a time. Compressed air was used to accelerate the particles, and particle velocity could be varied by adjusting the air pressure. A cage was used to collect the particles and fragments after impact. The particle impact velocity was determined by measuring the time required for a particle to travel from the end of the barrel

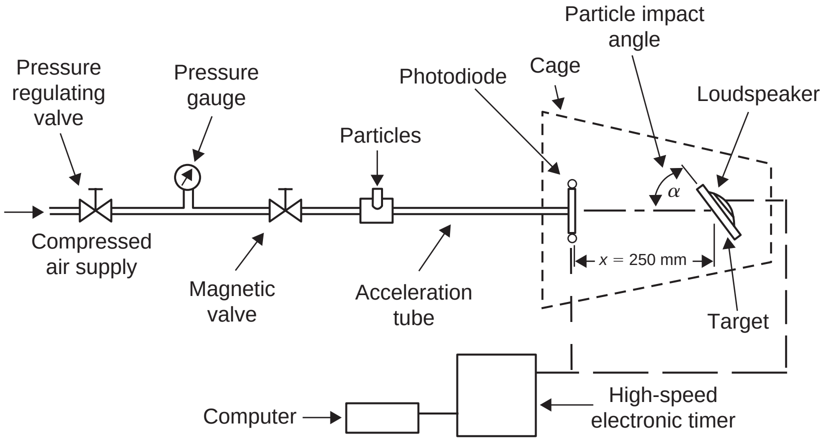


Figure 24.3 Schematic arrangement of acceleration tube test apparatus and measuring system for particle impact studies.

to the target. A photodiode was located at the end of the barrel and a loudspeaker was mounted behind the target.

In order to study the particle degradation process, brittle materials were used to ensure that no plastic deformation should take place. Three types of particle were used and tested. These were aluminium oxide, polystyrene and glass, and all the particles were spherical. The majority of the work was carried out with 5 mm diameter aluminium oxide particles, with particle velocities up to about 30 m/s. Much of the information reported here on the influence of conveying parameters is derived from this programme of work. For every test, 100 particles were impacted, and the number of unbroken particles was counted to provide an assessment of the degradation.

24.2 Influence of variables

The variables involved in particle degradation are similar to those associated with erosive wear. Velocity, once again, is probably the most important variable, but particle size and concentration also play a part. Particle impact angle is equally important, and has a major influence with respect to the selection of pipeline bend geometry. The influence of both particle materials and surface materials must also be given due consideration. As with erosive wear, much of the research work into the subject has been carried out for various other purposes, and so the range of parameters investigated is often beyond those associated with pneumatic conveying, but it does provide useful information on the general trends of the variables involved.

24.2.1 Velocity

The relative velocity between particles and surfaces has a major influence on the nature and extent of the degradation and is probably the most important variable in particle degradation. In any collision the kinetic energy of the particles has to be absorbed and may provide sufficient energy for fracture. If the collision is elastic, with a high coefficient of restitution, much of the kinetic energy will reappear as particle velocity. In plastic collisions much of the kinetic energy will be converted to heat.

Low velocity impacts tend to knock small chips from the edges of particles, whereas high velocity collisions are more likely to shatter particles. In general the rate of damage has been found to be a power law function of velocity, in much the same way as the erosive wear process. The range in value of the power coefficient is also large, and can vary between one and five, depending upon the conveyed material and the system being considered. The possibility of there being a threshold value of velocity, below which no degradation occurs, is also a possibility.

24.2.1.1 Peas

Agricultural products have been widely used in test work. Segler [3] investigated the effects of air velocity, moisture content, pipeline diameter and material concentration on the damage of peas, as a result of pneumatic conveying. His test loop was 73 m long, 112 mm bore and contained four bends. The results of his tests on the effect of

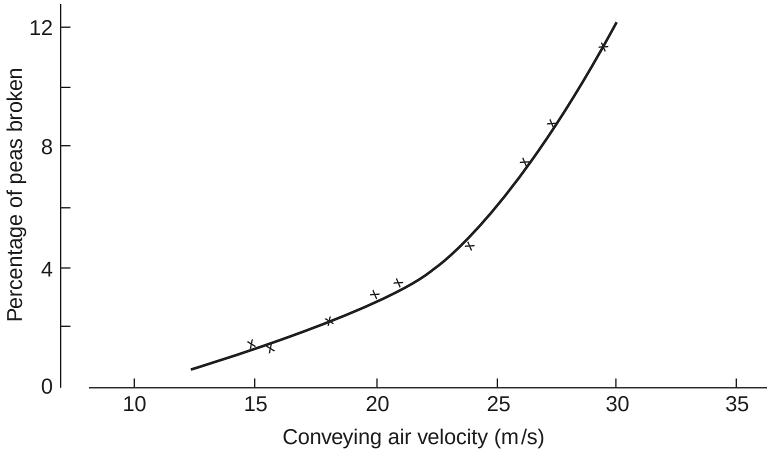


Figure 24.4 The influence of air velocity on the breakage of peas.

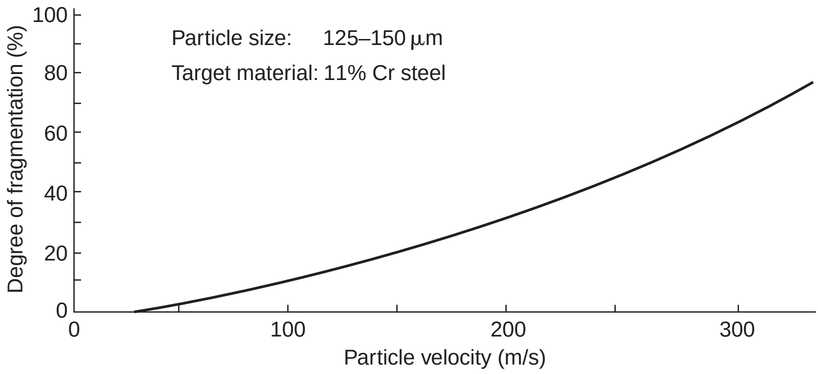


Figure 24.5 The influence of particle velocity on the degradation of quartz particles.

air velocity are presented in Figure 24.4. These showed that the damage increased approximately with the cube of air velocity.

24.2.1.2 Quartz

Tilly [4] carried out impact studies with quartz particles against an alloy steel target in a rotating arm test rig. He found that the particles incurred a substantial degree of fragmentation which was dependent upon the velocity of impact. His results are presented in Figure 24.5.

The velocity range comes as a result of their work being applied to aircraft engines. From this it would appear that for fragmentation to occur it is necessary to exceed a threshold velocity of about 15 m/s. Below this velocity the particles may be considered to behave elastically.

In work by Tilly and Sage [5] they impacted quartz particles in the size range of 100–225 μm at velocities of 60, 130 and 300 m/s. Their results, in terms of particle size distribution, are presented in Figure 24.6. Although this data is for conveying velocities much higher than those that would be encountered in a pneumatic conveying system, they relate to just a single impact and so help to illustrate the nature of the problem, for many materials that are conveyed are significantly more friable than quartz.

24.2.1.3 Aluminium oxide

The results of a programme of tests carried out with 5 mm aluminium oxide particles impacted at 90° against a steel target are presented in Figure 24.7 [2].

In this plot the experimental data has been included to show how the relationship was derived and to show the limits of scatter in the results. The relationship is typical of the results obtained and so where families of curves are presented in subsequent figures from this programme of work, experimental data has been omitted for clarity.

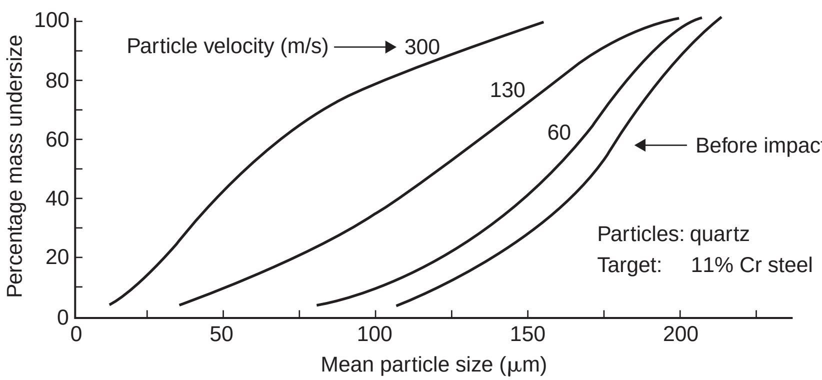


Figure 24.6 Influence of particle velocity on size distribution generated with quartz.

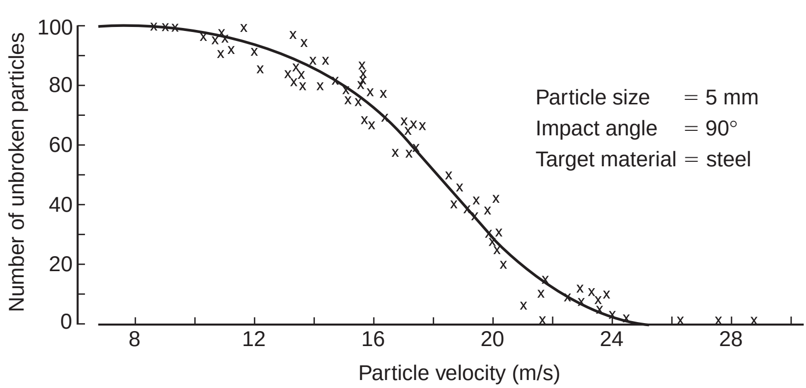


Figure 24.7 The influence of particle velocity on the degradation of aluminium oxide particles.

It will be seen from Figure 24.7 that there is a very rapid transition in particle velocity from zero breakage to total degradation. Below a particle velocity of about 9 m/s only elastic deformation occurs and there is no particle degradation. Above a particle velocity of about 25 m/s, however, the stress induced by the impact is always sufficient to damage every particle. It is interesting to note that within the transition region the number of unbroken particles at any given velocity is very consistent and that a smooth transition is obtained from one extreme to the other over this range of velocity.

24.2.2 Particle size

Tilly [4] carried out impact studies with quartz particles against an alloy steel target in a rotating arm test rig. He found that the particles incurred a substantial degree of fragmentation which was dependent upon the initial particle size. His results are presented in Figure 24.8. From this it would appear that for fragmentation to occur it is necessary for the particles to exceed a threshold size of about 10 μm. Below this size the particles probably behave elastically, for in their test rig the particles would have impacted the target since the tests were carried out in a vacuum.

The results of tests carried out with three different sizes of aluminium oxide particles are shown in Figure 24.9 [2]. The data for the 5 mm particles, which was the reference material in the work, was presented earlier in Figure 24.7. Results from similar tests with 3 and 7 mm aluminium oxide particles, also impacted at 90° against the same steel target are additionally presented in Figure 24.9. A very significant particle size effect is shown. As the particle size increases, the maximum velocity at which no degradation occurs decreases. The transition from no degradation to total degradation also changes, with the transition occurring over a narrower velocity range with increase in particle size.

24.2.2.1 Particle velocity influence

In more recent work on the influence of particle size, fertiliser particles, also having particle diameters of 3, 5 and 7 mm, were pneumatically conveyed in a test facility to

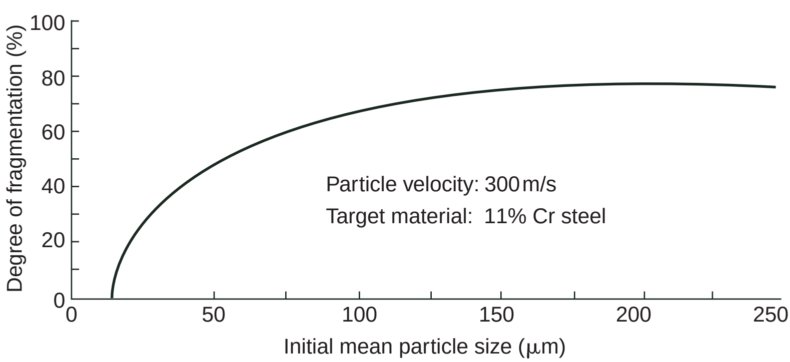


Figure 24.8 The influence of initial particle size on the degradation of quartz particles.

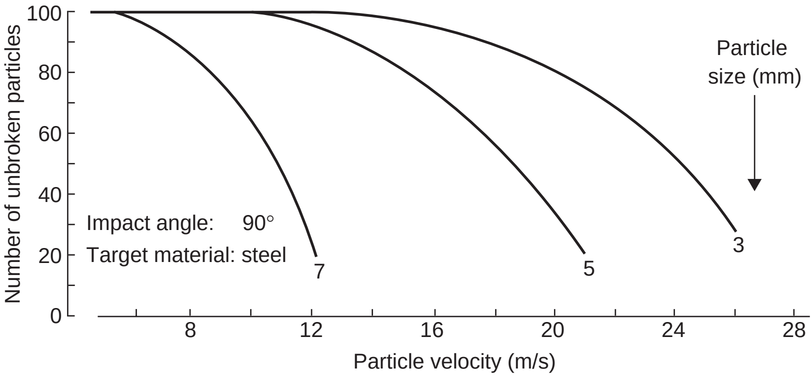


Figure 24.9 The influence of particle velocity and particle size on the degradation of aluminium oxide particles.

assess their degradation [6]. In this case the velocity used was that of the conveying air and not that of the particles. In terms of air velocity the 3 mm particles degraded the most and the 7 mm particles the least. The reason for this is that when it is the air velocity that is held constant, the smaller particles are accelerated to a higher velocity than the larger particles. It is because particle velocity has a greater influence on degradation than particle size that a reversal in the influence of particle size has occurred.

24.2.3 Surface material

With erosive wear of surface materials it has been found that the resilience of the surface material can have a significant influence on erosive wear, and that rubber and polymers can offer better wear resistance than metals having a very high hardness value in certain cases. Since the mechanisms of erosion and degradation have many similarities, it is quite possible that resilient materials could offer very good resistance to particle degradation.

24.2.3.1 Material type

Further work by Tilly and Sage [5] showed that fragmentation is also dependent upon the type of target material. Figure 24.10 shows a comparison of their results for quartz impacted against nylon and fibreglass, which with their earlier results for alloy steel demonstrates the complex nature of the problem. Degradation in terms of the influence of initial particle size is used for the comparison in this case.

The results of tests carried out on four different target materials are presented in Figure 24.11 [2]. In each case the targets were 5 mm thick and they were impacted by 5 mm aluminium oxide particles at an angle of 90°. This also shows very clearly that target material can have a very marked effect on degradation. Although there is little difference in the maximum value of particle velocity at which no degradation occurs, varying from 9 m/s for steel to about 14 m/s for Plexiglas and aluminium, very significant differences exist in the transition region between no degradation and total degradation.

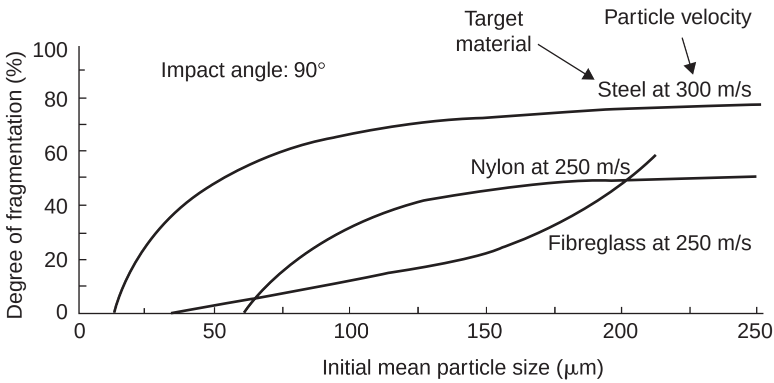


Figure 24.10 The influence of initial particle size and target material on the degradation of quartz particles.

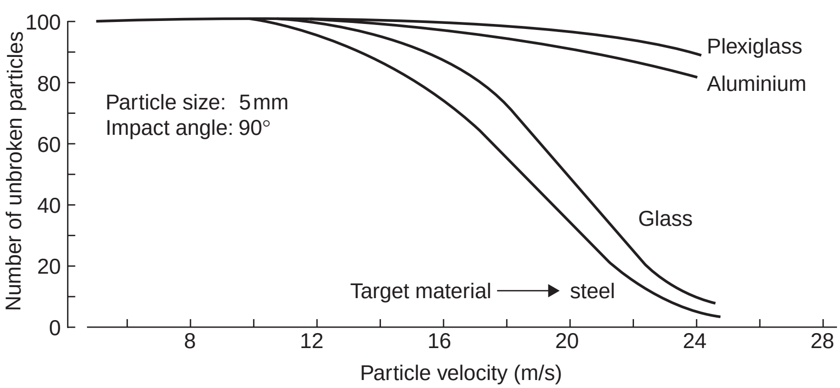


Figure 24.11 The influence of particle velocity and target material on the degradation of aluminium oxide particles.

In the case of the steel and glass targets the transition is very rapid. For the aluminium and Plexiglas, however, the transition is very slow, and so a high velocity impact against these materials would only result in limited damage occurring.

24.2.3.2 Surface thickness

A similar programme to that reported in relation to Figure 24.11 was carried out with steel targets of varying thickness [6]. If the conveyed material is not erosive, in addition, a thin walled surface would also help reduce degradation, for the work showed a significant reduction in degradation of the particles with a 1 mm thick target as compared with a 2 mm thick target. The force acting on a particle is equal to its mass times the rate of deceleration. This force must be reduced in order to reduce the damage to particles on impact against a surface. This can be achieved to a certain extent by using either a resilient surface material or a surface material that will flex on impact.

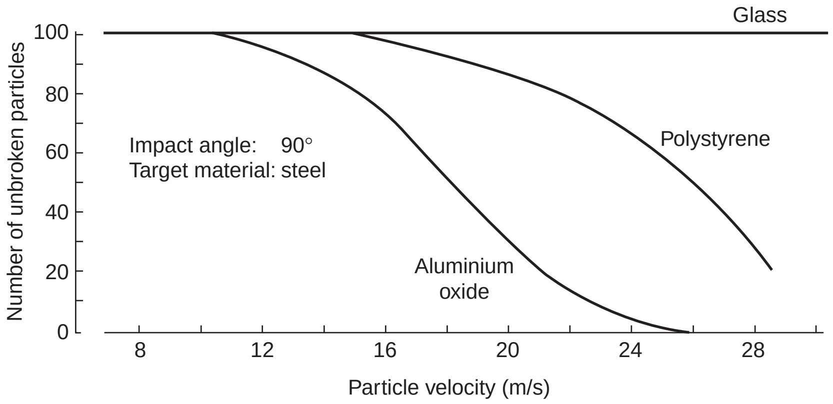


Figure 24.12 The influence of particle velocity on the degradation of various particulate materials.

24.2.4 Particulate material

In Figure 24.12 the data for the aluminium oxide of Salman et al [2] is presented again, together with the results from identical tests carried out with polystyrene and glass particles. It will be seen from this that polystyrene particles suffer a similar transition from zero breakage to total degradation, but at a slightly higher velocity range than the aluminium oxide. That different particulate materials can respond in totally different ways is clearly demonstrated by the glass particles. No damage was observed to any of the particles tested up to the maximum particle velocity investigated of 30 m/s.

24.2.5 Particle impact angle

Particle impact angle, α, was defined on the sketch of the acceleration tube test device shown earlier in Figure 24.3, and is the same as that used in erosive wear work. Impact angle has been shown to be a major variable with regard to the erosive wear of surface materials, and hence is an important consideration in terms of material selection and the specification of components such as pipeline bends. In relation to particle degradation it is equally important, for as the impact angle reduces, so the normal component of velocity decreases [7]. This will have a direct bearing on the deceleration force on the particles, as discussed above in relation to Surface Thickness in Section 24.2.3.2.

The results of a comprehensive programme of tests carried out to investigate the influence of particle impact angle are presented in Figure 24.13 [2]. Five millimetres of aluminium oxide particles were impacted against a steel target, which is the reference point in this particular programme of work, and so the data for 90° impact is the same as that presented earlier in Figures 24.7, 24.9, 24.11 and 24.12. It will be seen from Figure 24.13 that there is little change in the response to degradation until the impact angle is below about 50°. There is then a very marked difference in performance with only small incremental changes in impact angle.

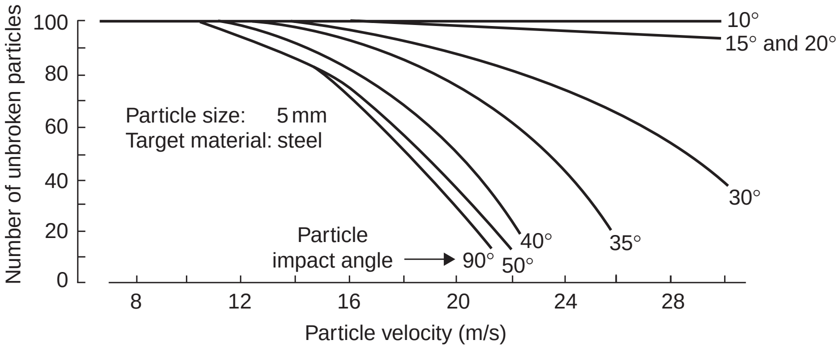


Figure 24.13 The influence of particle velocity and impact angle on the degradation of aluminium oxide particles.

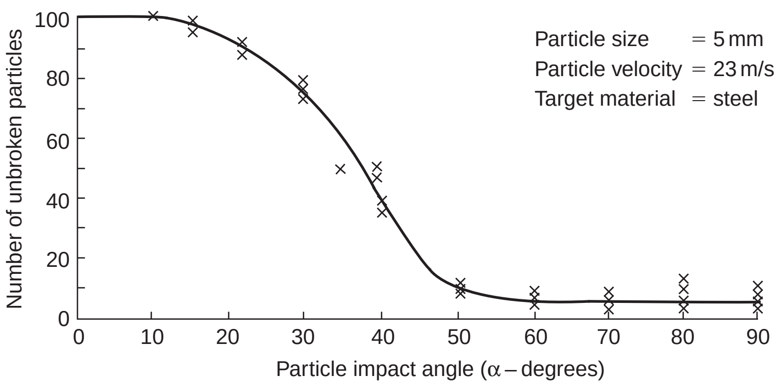


Figure 24.14 The influence of particle impact angle on the degradation of aluminium oxide particles.

With a decrease in particle impact angle it would appear that there is little change in the particle velocity at which the onset of degradation occurs. The transition from zero degradation to total degradation, however, becomes an increasingly more gradual process as the particle impact angle reduces. At impact angles of 15° and 20° it would appear that this transitional process will be spread over a very wide range of velocity values. At an impact angle of 10°, however, there is a significant change once again, in that no particle degradation was recorded at all up to 30 m/s.

In Figure 24.14 an alternative plot of the data in this programme of tests is presented. This is effectively a slice taken from Figure 24.13 at a particle velocity of 23 m/s. It will be seen from this that tests were carried out at regular increments of impact angle of about 10° between 10° and 90°. This plot shows quite clearly that at impact angles below about 12° no degradation occurs, and that at impact angles above about 55° the degradation remains essentially constant at the maximum value for this particular impact velocity.

24.2.6 Other variables

Segler [3] investigated the influence of moisture content on particle degradation and showed that degradation can increase dramatically with decrease in moisture content. The results of the following three tests with peas show the sensitivity to this variable:

Moisture content (%)	17.1	16.1	15.4
Broken particles (%)	0.1	1.1	11.1

Segler investigated the effect of particle concentration and found that the damage decreased as the solids loading increased. The damage produced when the peas were introduced individually was four times higher than in dense flow. A similar effect is found in erosive wear and can be attributed to the cushioning effect of dense flows.

He also examined the damage to the peas in identical pipelines having bores of 46 and 270 mm. It was found that the damage in the 46 mm bore pipeline was two to three times greater than that in the 270 mm bore pipeline. His explanation was that the frequency of pipe wall impacts, for such large particles, would be more frequent for the small bore pipeline.

24.3 Recommendations and practical issues

The results from the various programmes of work reported here have produced some very interesting relationships with respect to many of the variables investigated, and should provide useful guidance to the design engineer who has to ensure that material degradation is reduced to a minimum in pneumatic conveying system pipelines.

24.3.1 Particle velocity

Particle velocity has been a major consideration in this presentation and it has been shown quite clearly that there is a threshold value of particle velocity below which no degradation occurs. The value of this particle velocity for the aluminium oxide was about 10 m/s and was influenced only slightly by particle size, target material, and particle impact angle above about 15°.

24.3.1.1 Dense phase conveying

At velocities only slightly lower than this, however, the mode of conveying changes from dilute phase, suspension flow, to dense phase, non-suspension flow, for many of those materials capable of being conveyed in dense phase. In dense phase conveying little impact occurs in horizontal pipelines and the mode of conveying mostly involves sliding of the particles through the pipeline. With materials having good permeability, conveying is in plugs and slugs, and for materials having good air retention, it is as a moving bed along the bottom of the pipeline.

When particles slide through a pipeline the interaction results in attrition rather than degradation of the material. In dilute phase there may be little particle to pipe wall interaction, and it is suspected that most of the damage results from impact with pipeline bends. In dense phase, although the velocity is low, there is a significant amount of particle to pipe wall interaction and this is likely to cause more damage to the particles than the bends. As a consequence it is possible for some materials to suffer a greater amount of damage in low velocity dense phase flow than they would in higher velocity dilute phase flow. It is important, therefore, to examine the relative effects of degradation and attrition on the conveyed material before deciding upon the type of pneumatic conveying system to be employed.

24.3.1.2 Dilute phase conveying

For many materials dense phase conveying is not an option, for the majority of materials cannot be conveyed at low velocity in a conventional conveying system. For these materials conveying has to be in suspension flow and so if the material is friable, degradation must be limited. To this end the material should be conveyed at as low a velocity as possible, consistent with reliable conveying, and the pipeline should be stepped to a larger bore part way along its length to reduce the high conveying air velocities that result at the end of the pipeline.

With a 1 bar pressure drop in a positive pressure system, discharging to atmospheric pressure, the conveying air velocity will approximately double from the material feed point to discharge. For the situation presented in Figure 24.7 it will be seen that at 10 m/s no damage occurs, but at 20 m/s 80 per cent of the particles are broken. As the air expands through the pipeline, therefore, it is the bends at the end of the pipeline, in a single bore line, that are likely to cause the majority of the damage. By stepping the pipeline the maximum velocity in the pipeline could possibly be limited to 15 or 16 m/s, at which the degradation would be limited to only 30 per cent.

24.3.2 Particle impact angle

For given conveying conditions, particle impact angle is probably the most important variable with respect to pneumatic conveying system pipelines. Particle impact angles against pipeline walls will generally be very low since particles will only suffer a glancing impact. From the data presented here it would appear that little degradation will occur in straight pipeline, even for long pipelines and repeated impacts.

It is clearly major changes in flow direction, and in particular bends, that are likely to result in the majority of degradation occurring. In this respect, particle impact angle can be related approximately to the radius of curvature of a bend. In a short radius bend the particles will impact at a high value of angle, but in a long radius bend the impact angle will be much lower, as illustrated in Figure 23.15. Since degradation reduces significantly with reduction in impact angle, the use of long radius bends would be recommended in any system where particle degradation needs to be minimized.

24.3.3 Bend material

The choice of material for the pipeline, and in particular the bends, provides another means by which particle degradation can be minimized. Although there is little change in the value of the lower threshold velocity, below which no degradation occurs, with respect to target material, there is a very significant effect on the upper threshold value. Thus, for a given particle impact velocity, very much less damage will result to particles if they impact against a surface such as Plexiglas or aluminium, than will occur if they impact against steel or glass. If it is possible to use a more resilient material, such as rubber or polyurethane, an even more significant reduction in particle degradation may be achieved.

24.4 Pneumatic conveying data

To provide some data on the potential order of magnitude of the problem of degradation, for materials conveyed in dilute phase suspension flow in a pneumatic conveying system, four different materials were pneumatically conveyed and the resulting degradation was monitored. A large scale pneumatic conveying facility was used and on-line samples were taken for analysis. Each material was re-circulated through the test loop a number of times so that the influence of conveying distance could also be investigated. The work was carried out by the author for the British Materials Handling Board [8].

24.4.1 Experimental details

A large scale pneumatic conveying test facility was used for this programme of work. Materials were fed into the conveying line by means of a 1 m^3 capacity bottom discharge blow tank, with a similar sized receiving hopper mounted on load cells above. The pipeline was 37.5 m long, 53 mm bore and incorporated seven 90° bends. The bend diameter to pipe bore ratio for all seven bends was about 6:1. A sketch of the pipeline and conveying facility is given in Figure 24.15.

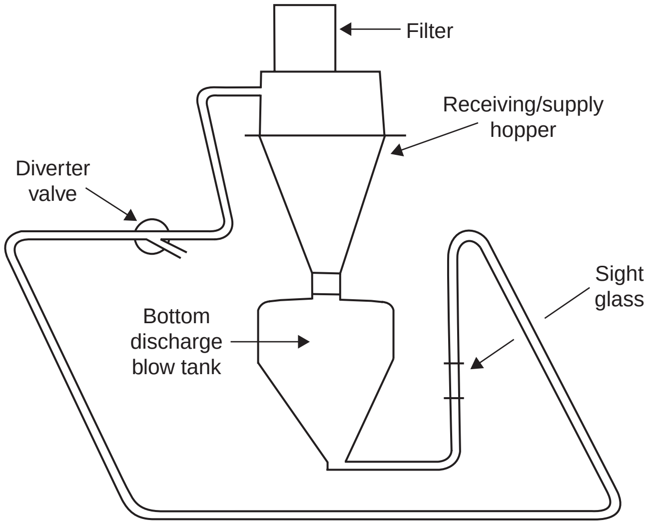


Figure 24.15 Sketch of conveying line used for material degradation trials.

The diverter valve in the pipeline was used for material sampling. The most reliable way to ensure that a truly representative sample is obtained from a bulk solid is to sample the material while it is moving or being conveyed. With the diverter valve the full bore flow of the material being conveyed was sampled, and although a large sample was obtained, it was representative and easily reduced in quantity by means of a riffling device.

24.4.2 Materials tested

Four materials were tested in the programme of work. One was dried silica sand, another was sodium chloride (salt), the third was sodium carbonate (heavy soda ash) and the fourth was coal. Particle size distributions for the four materials are presented in Figure 24.16. A list of the various property values for the materials tested is given in Table 24.1 for reference.

The pipeline shown in Figure 24.15 and used for this particle degradation study is a slightly modified version of Pipeline no. 1 shown in Figure 12.2. Conveying

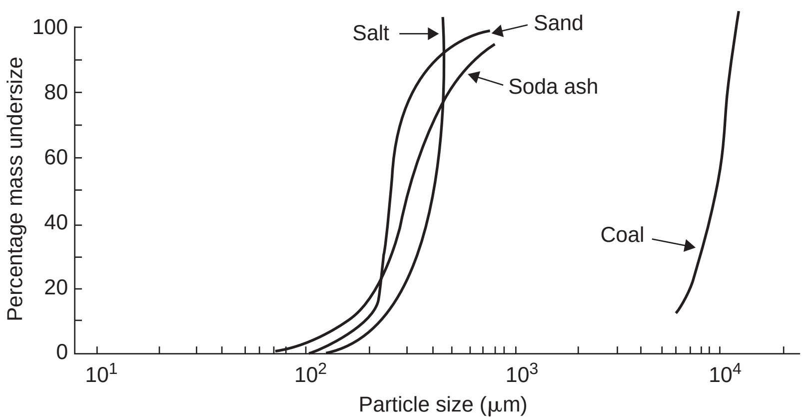


Figure 24.16 Particle size distributions of materials tested.

Table 24.1 Properties of materials considered

Material	Mean particle size (μm)	Density (kg/m^3)			Angle of repose (degrees)
		Particle	Bulk		
			Poured	Tapped	
Sand	260	2570	1500	1510	35
Salt	366	2630	1220	1260	35
Soda ash	343	2505	1155	1250	38
Coal	10 300	1320	690	692	33

Table 24.2 Cumulative distances and numbers of bends for conveyed materials

Number of times material circulated	Conveying distance (m)	Number of 90° bends
1	31.5	5
2	69.0	12
3	106.0	19
4	144.0	26
5	181.0	33

Table 24.3 Conveying conditions employed for each material tested

Material	Solids loading ratio	Conveying air velocity (m/s)	
		Minimum	Maximum
Sand	4.2	17.7	22.9
Salt	5.1	17.0	22.1
Soda ash	4.4	17.4	22.5
Coal	5.7	17.8	22.3

characteristics for the sand conveyed through Pipeline No 1 will be found in Appendix 2 and those for the other three materials are included in Figure 12.1.

24.4.3 Conveying details

Each material was circulated a total of five times and samples were obtained during every pass. By re-circulating and sampling in this way the influence of conveying distance could be determined. By the last sample, after the materials had been circulated five times, they had been conveyed through a total of 181.5 m of pipeline and through 33 90° bends. A summary of the total conveying distance and number of bends after each circulation is given in Table 24.2.

For consistency, an attempt was made to convey each material under similar conditions. It was not possible, of course, to employ identical conveying conditions for each material because the conveying characteristics of the materials differed so much. The actual conveying conditions employed for each material, in terms of the solids loading ratio and the maximum and minimum values of conveying air velocity are given in Table 24.3 for reference.

24.4.4 Test results

Results of the sieve analysis of the samples of coal after each of the five conveying runs, together with the as received analysis for reference, are presented in Figure 24.17. It will be seen that very significant degradation occurred, particularly for the early passes, after which the rate of degradation decreased. The mean particle size was reduced by 6.95 mm in total, which is about 67 per cent of the original mean particle size value.

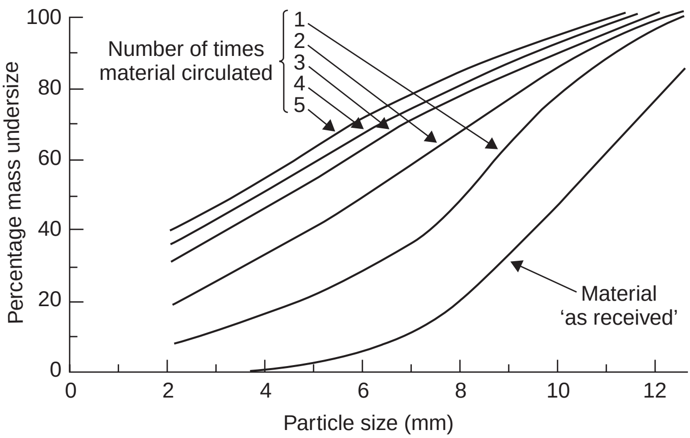


Figure 24.17 Influence of pneumatic conveying on the degradation of coal.

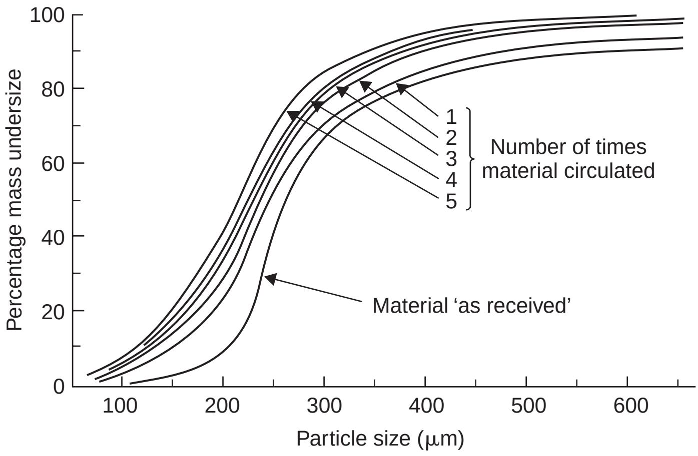


Figure 24.18 Influence of pneumatic conveying on the degradation of silica sand.

Similar results for the silica sand, for each of the five cumulative test runs, together with the fresh material, are presented in Figure 24.18.

The degradation of this abrasive material was quite significant, and separate lines could be drawn on the graph for each sample. There was an overall reduction of about 47 μm in the mean particle size, which represents approximately 18 per cent of the as received value. Results for the salt and soda ash were similar to those for the sand. The overall reduction in mean particle size for the salt and the soda ash both amounted to approximately 20 per cent of the as received values. Mean particle size data for each of the materials, after each time they were circulated, are presented in Table 24.4, and these mean values are shown plotted against the number of times circulated in Figure 24.19.

Table 24.4 Mean particle sizes for materials after being pneumatically conveyed

Material condition	Mean particle size (μm)			
	Sand	Salt	Soda ash	Coal
As received	260	388	343	10 300
Times circulated				
1	242	363	330	8 100
2	234	352	320	6 050
3	228	335	305	4 400
4	223	320	290	3 800
5	213	310	275	3 350

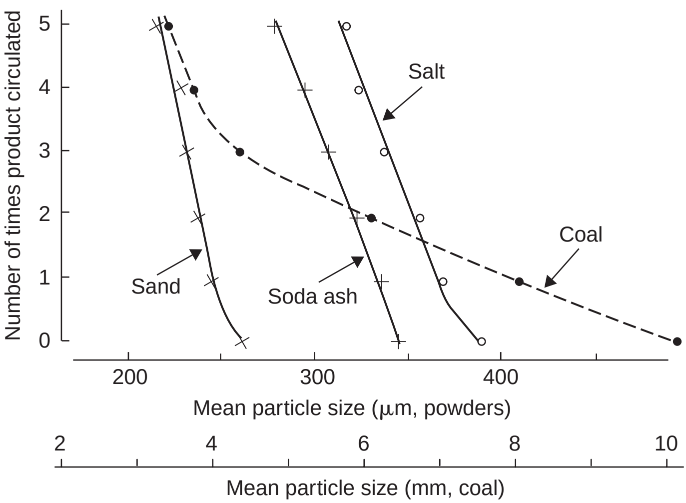


Figure 24.19 Influence of material circulation on mean particle size.

24.5 Particle melting

Particle melting is a form of material degradation that often occurs in pneumatic conveying plant handling plastic type materials, particularly in pelletized form. If conventional pipeline is used, materials such as polyethylene, nylon and polyesters can form cobweb-like agglomerates. They are variously given names such as 'angel hairs', 'raffia', 'snake skins' and 'streamers'.

They frequently cause blockages at line diverters and filters which require plant interruption to remove them. Equipment is generally installed at the terminating end of the system for this purpose. Such equipment is necessary because they also cause material rejection by customers, for the presence of these contaminants in the product is undesirable.

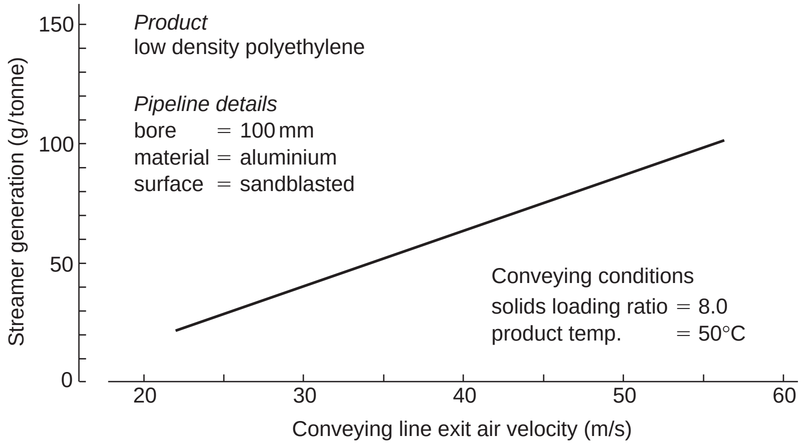


Figure 24.20 Influence of velocity on the degradation of LDPE.

24.5.1 Mechanics of the process

The streamers are caused by the pellets impacting against the bends and pipe walls. A considerable amount of energy is converted into heat by the friction of the two surfaces when they touch. If the surface of the pipe is smooth, the pellet will slide. This contact, though momentary, decelerates the particle by friction which is transformed into heat. This is generally sufficient to raise the temperature at the surface of the pellet to its melting point. To a certain extent this is analogous to the thermal model proposed for erosive wear.

24.5.2 Influence of variables

The onset of the formation of these angel hairs or streamers is the result of a combination of conditions. Particle velocity is the most important, but it also depends upon the temperature of the pipeline, the temperature of the pellets, and the solids loading ratio of the conveyed material. The influence of conveying line exit air velocity for low density polyethylene is shown in Figure 24.20 and the influence of solids loading ratio for this same material is given in Figure 24.21 [9]. In each case the degradation of the material is expressed in terms of the mass of streamers and fines produced, in grams, per tonne of low density polyethylene conveyed.

24.5.3 Pipeline treatment

The formation of streamers and fines can be reduced quite considerably by suitably treating the pipe wall surface. A roughened surface is necessary in order to prevent the pellets from sliding. If the surface is too rough, however, small pieces will be torn away from the pellets instead, and a large percentage of fines will result. It will also have an adverse effect on the pressure drop, and hence on material conveying capacity.

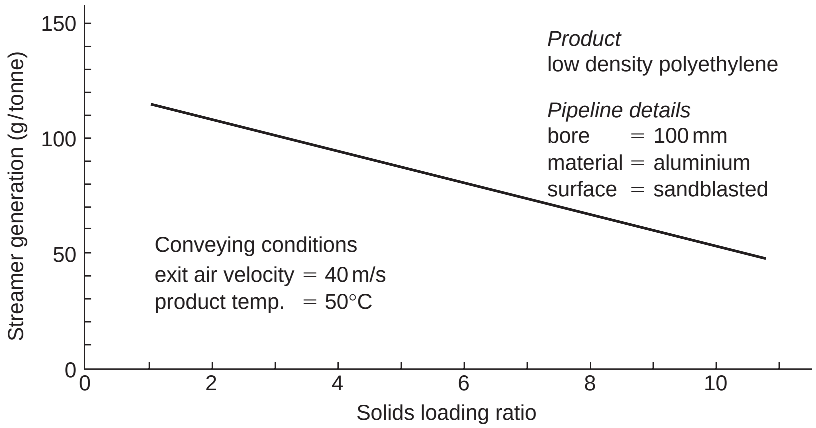


Figure 24.21 Influence of solids loading ratio on the degradation of LDPE.

Although the results presented in Figures 24.20 and 24.21 were obtained from tests carried out with pipe surfaces roughened by sand blasting, this treatment is not recommended as it will result in the generation of a large percentage of fines. Also, this roughness is relatively shallow in depth and an aluminium surface will wear so that the pipe must be retreated in six to twelve months [9].

References

1. D Mills and J S Mason. The effect of pipe bends and conveying length upon particle degradation in pneumatic conveying systems. Proc 3rd Powder and Bulk Solids Conf. Chicago. May 1978.
2. A D Salman, M Szabo, I Angyal, A Verba and D Mills. The design of pneumatic conveying systems to minimise product degradation. Proc 13th Powder and Bulk Solids Conf. Chicago. May 1988.
3. G Segler. Pneumatic grain conveying with special reference to agricultural applications. Germany. 1951.
4. G P Tilly. Erosion caused by impact of solid particles. Treatise on Materials Science and Technology, Vol 13, pp 287–319. New York: Academic Press Inc. 1979.
5. G P Tilly and W Sage. The interaction of particle and material behaviour in erosion processes. Wear, Vol 16, pp 447–465. 1970.
6. A D Salman, A Verba and D Mills. Particle degradation in dilute phase pneumatic conveying systems. Proc 17th Powder and Bulk Solids Conf. Chicago. May 1992.
7. D Mills. Particle degradation in pneumatic conveying. Freight Pipelines. Ed. G F Round. Amsterdam: Elsevier. pp 31–48. 1993.
8. D Mills. The degradation of bulk solids by pneumatic conveying and its simulation by small scale rigs. BMHB Report. February 1988.
9. J Paulson. Effective means for reducing formation of fines and streamers. Proc Conf on Polyolefins. Soc of Plastic Engineers. Houston. 1978.

Chapter 25

Moisture and condensation

25.1 Introduction

Atmospheric air naturally contains a certain amount of water vapour. The amount of water vapour that air can contain depends upon both temperature and pressure. A decrease in temperature or an increase in pressure can result in condensation occurring when the air passes through the saturation point. The problem with condensation, however, is that it can sometimes be very difficult to predict. The presence of moisture may even be unknown if it cannot be seen, although its effects will certainly be evident.

The addition of water to a bulk solid can have a significant effect on its flowability. Condensation usually occurs on the walls of containing vessels and surfaces such as hoppers, silos and pipelines. Although the effect might be localized, the material/surface interface is critical to the smooth operation of most bulk solids handling plants. Some materials are hygroscopic and will naturally absorb moisture from the air without condensation occurring. For these materials it is generally necessary to dry the air that comes into contact with the material, to a value of relative humidity below that at which the material is capable of absorbing atmospheric moisture.

25.2 Humidity

The amount of water vapour that air can support is not constant but varies with both temperature and pressure. Once air is saturated, a change in either temperature or pressure can result in condensation occurring. The terms used here are relative humidity and specific humidity, and the Ideal Gas Law, commonly used for air, provides the basis for modelling moist air.

Specific humidity is the ratio of the mass of water vapour to the mass of dry air in any given volume, or volumetric flow rate, of the mixture. It is usually expressed in terms of grams of water per kg of dry air, and so it is strictly not a dimensionless quantity. Relative humidity is the ratio of the partial pressure of the vapour actually present to the partial pressure of the vapour when the air is saturated at the same temperature. It is usually expressed as a percentage, with 100 per cent representing saturated air.

Thus, specific humidity is a measure of the moisture content of the air, and relative humidity is a measure of the ease with which the atmosphere will take up moisture. Relative humidity is usually obtained by means of wet- and dry-bulb thermometers or some other form of hygrometer and specific humidity can be calculated.

25.2.1 Specific humidity

Specific humidity, ω, is the ratio of the mass of water vapour to the mass of dry air in any given volume of the mixture:

$$\omega = \frac{m_v}{m_a} \ g_v/kg_a \tag{25.1}$$

where m_v is the mass of vapour (g) and m_a, the mass of air (kg).

From the Ideal Gas Law (first presented in Equation (9.4)):

$$p_a V = m_a R_a T \tag{25.2}$$

At low values of partial pressure, water vapour can also be treated as an ideal gas, and so:

$$p_v V = m_v R_v T \tag{25.3}$$

where p_a is the partial pressure of air; p_v, the partial pressure of water vapour; V, the volume of mixture; R_a, the characteristic gas constant for air; R_v, the characteristic gas constant for vapour and T, the absolute temperature of mixture.

And note that V and T will be the same, for both the air and the vapour, since the two constituents are intimately mixed.

The partial pressure of water vapour, p_v, varies with temperature. For reference, values are given on Figure 25.1. The partial pressure of water vapour increases exponentially with increase in temperature and so the partial pressure axis on Figure 25.1 is split in two. The axis on the right hand side, for high temperature air, is magnified by a factor of ten, compared with that on the left hand side for low temperature air. It will also be seen that at 0°C, the freezing point for water, that a significant quantity of

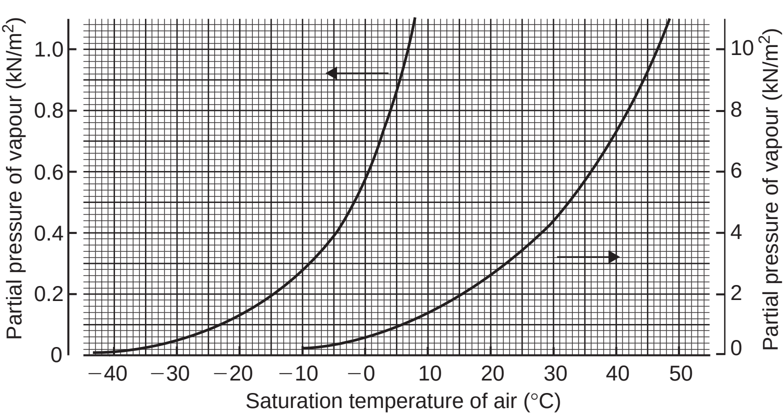


Figure 25.1 The variation of saturation vapour pressure with temperature.

vapour still exists in the air. At temperatures below 0°C, therefore, water vapour will precipitate as ice onto cold surfaces, without passing through the liquid phase. By the same reasoning, wet surfaces that are frozen can be dried, for the ice evaporates directly into vapour, without the surface becoming wet.

The characteristic gas constants for the two constituents can be obtained from Equation (9.9) and is included here as Equation (25.4):

$$R = \frac{R_0}{M} \text{ kJ/kg} \cdot \text{K} \tag{25.4}$$

Values for various gases, including steam, are given in Table 9.2.

By substituting for R from Equation (25.4) into (25.2) and (25.3) gives:

$$m_a = \frac{p_a V M_a}{R_0 T} \tag{25.5}$$

and

$$m_v = \frac{p_v V M_v}{R_0 T} \tag{25.6}$$

Substituting Equations (25.5) and (25.6) into (25.1) gives:

$$\omega = \frac{p_v M_v}{p_a M_a} \tag{25.7}$$

since V and T are common to both constituents.

From Dalton's Law of Partial Pressures:

$$p = p_a + p_v \tag{25.8}$$

where p is the total pressure, which for most applications is equal to atmospheric pressure (kN/m^2 abs).

Thus specific humidity, ω, is given by:

$$\omega = \frac{18 p_v}{29(p - p_v)} \text{ kg}_v/\text{kg}_a \tag{25.9}$$

Alternatively:

$$\omega = \frac{622 p_v}{p - p_v} \text{ g}_v/\text{kg}_a \tag{25.10}$$

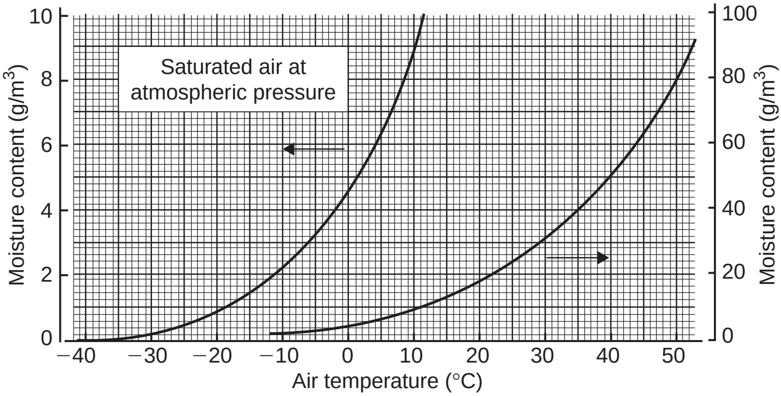


Figure 25.2 The influence of temperature on the moisture content of saturated air.

25.2.1.1 The influence of temperature

A graphical representation of this equation is given in Figure 25.2. This is a graph of moisture content of air, in grams of water per cubic metre of air, plotted against air temperature. This graph is also plotted with a split moisture content axis in a similar manner to Figure 25.1, with the two sections covering cold and warm air. It will be seen from these that the capability of air for absorbing moisture increases very considerably with increase in temperature. Figure 25.2 is drawn for saturated air at atmospheric pressure.

The moisture content, in volumetric terms, is obtained by multiplying Equation (25.10) by the density of air, which, for air at free air conditions, is 1.225 kg/m^3. The density of air, however, varies with temperature and so this is not a very convenient parameter to use for process calculations. Specific humidity is better for this purpose since the mass flow rate of air will remain constant. The moisture content of air can also be expressed in flow rate terms. This is done simply by using the flow rate form of the Ideal Gas Law, rather than the static form in Equations (25.2) and (25.3). Figure 25.3 is such a plot and shows the magnitude of the potential moisture problem, of water associated with air, very well.

Figure 25.3 is also drawn for saturated air at standard atmospheric pressure and shows how the quantity of water in the air is influenced by both the volumetric flow rate of the air and its temperature. The influence of the volumetric air flow rate is linear, of course, but that of temperature is not, as illustrated with Figure 25.2. Air temperatures down to minus 20°C have been included on Figure 25.3 to reinforce the point that significant quantities of moisture can be associated with air at temperatures below 0°C.

25.2.1.2 The influence of pressure

Two further graphical representations of Equation (25.10) are given in Figures 25.4 and 25.5. These are graphs of moisture content of air, in grams of water per kg of air,

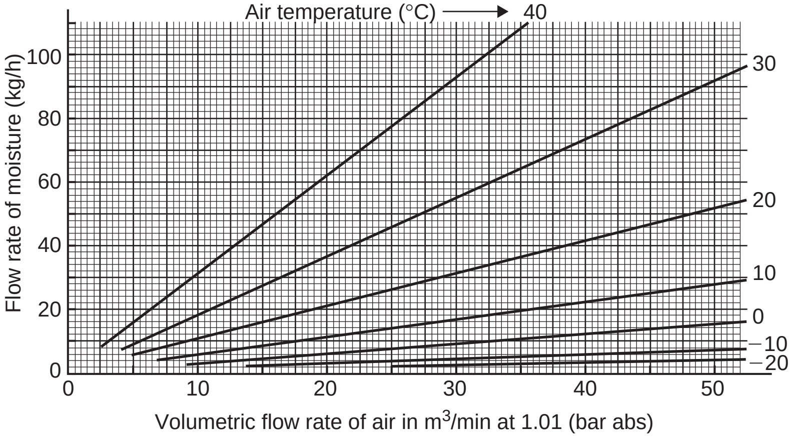


Figure 25.3 The influence of temperature on the flow rate of moisture associated with saturated air.

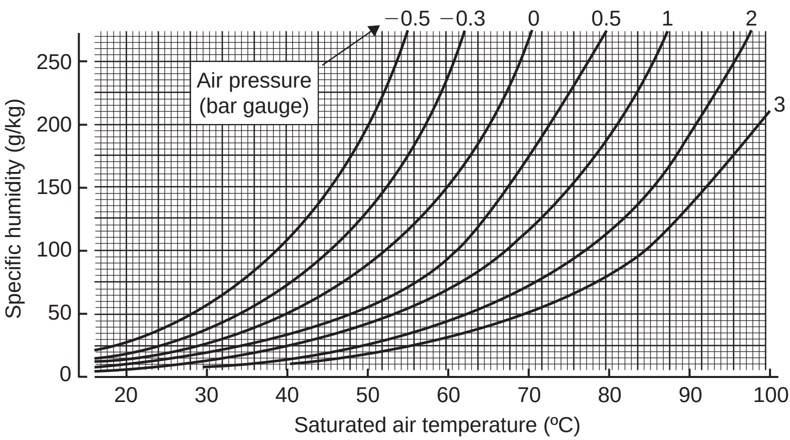


Figure 25.4 The influence of temperature and pressure on the moisture content of saturated air.

drawn to illustrate the influence of air pressure. Figure 25.4 is a graph of specific humidity plotted against temperature, with lines of constant pressure drawn. The pressures cover a range from −0.5 to 3 bar gauge and so are appropriate to both positive and negative pressure conveying systems.

Figure 25.5 is a similar plot, but with the *x*-axis and the family of curves interchanged. Both plots are for saturated air. These show that pressure also has a significant effect on the amount of water vapour that air can absorb, decreasing with increase in pressure. Figure 25.5 shows the influence of pressure on the moisture content capability of air very well, particularly at low pressures and under vacuum conditions.

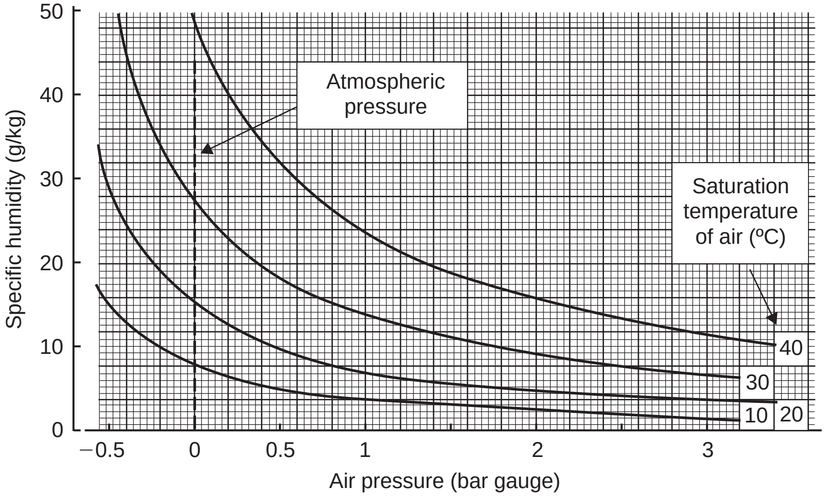


Figure 25.5 The influence of pressure and temperature on the moisture content of saturated air.

25.2.2 Relative humidity

Relative humidity, ϕ, is the ratio of the partial pressure of the vapour actually present, to the partial pressure of the vapour when the air is saturated at the same temperature:

$$\phi = \frac{p_v}{p_g} \tag{25.11}$$

where p_v is the partial pressure of vapour and p_g, the partial pressure of vapour at saturation.

This is usually expressed as a percentage.

This situation can be best represented with lines of constant pressure superimposed on a temperature vs. entropy plot for H_2O. Such a plot is given in Figure 25.6. This also shows the saturation lines for both liquid and vapour and how these separate the various phases or regions. Air saturated with water vapour, and having a relative humidity of 100 per cent, will lie on the saturated vapour line, g. The vapour in air having a relative humidity less than 100 per cent is effectively superheated steam and so the point will lie in the vapour region.

Point A represents the actual condition of the vapour in the air and it will be seen that it is in the superheated steam region. On the saturation line for the vapour, at the same temperature (point B), the pressure is p_1. If the air is cooled from point A it will follow the p_2 curve to the saturation line at C, which is the dew point at this pressure. From Figure 25.6 the relative humidity is given as:

$$\phi = \frac{p_2}{p_1}$$

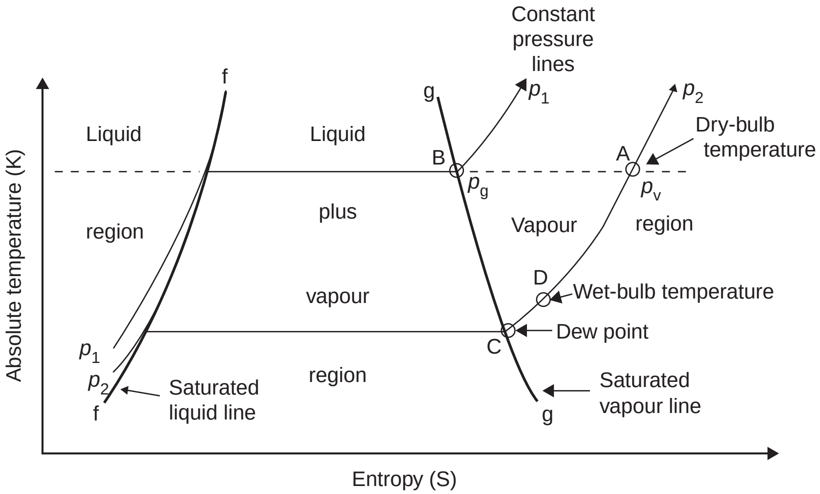


Figure 25.6 Temperature vs. entropy plot for H_2O.

The pressures p_1 and p_2 can be obtained from Figure 25.1, knowing the corresponding saturation temperatures T_B and T_C.

25.2.2.1 Psychrometric chart

The above expression, in terms of pressures, and other equations that can be derived from the Ideal Gas Law are however of little practical use in the process of determining relative humidity. For this we generally use wet- and dry-bulb thermometers or a hygrometer. The actual, or dry-bulb temperature, of the air is represented by point B on Figure 25.6 and point D represents the approximate location of the wet-bulb temperature for unsaturated air.

Since this method depends upon equilibrium between heat and mass transfer rates, the equations are rather complicated, and so data is given in charts and tables. The information is usually presented in a psychrometric chart. Such a chart, for air at atmospheric pressure, is shown in Figure 25.7. This is a graph of specific humidity plotted against dry-bulb temperature.

The saturation line is presented on this chart and this represents a relative humidity of 100 per cent. This is the same line as that drawn on Figure 25.2. Dry air, or air with a relative humidity below 100 per cent, is represented in the area to the right of the saturation line. Lines of both constant wet-bulb temperature and relative humidity are superimposed on the chart. Thus, if the wet- and dry-bulb temperatures are known, for a given sample of air, both relative humidity and specific humidity can be determined quite simply.

On some psychrometric charts lines of constant specific enthalpy and specific volume are also superimposed so that this data can also be obtained quickly if required.

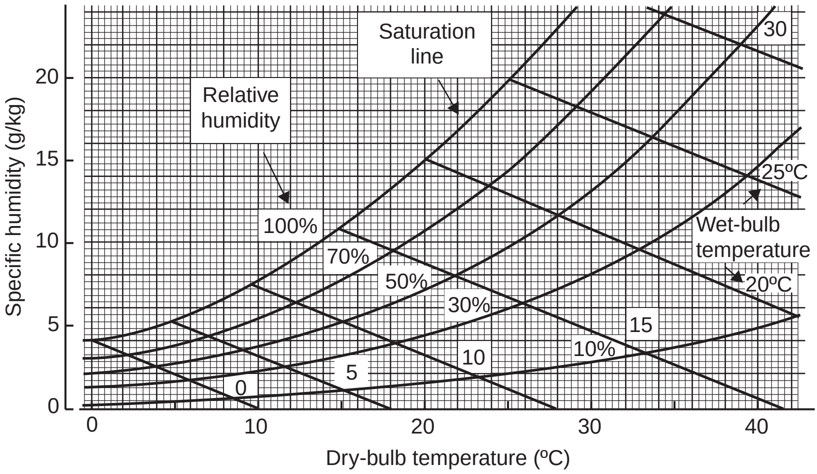


Figure 25.7 Psychrometric chart for air at atmospheric pressure.

25.2.3 Universal model

By combining Equations (25.10) and (25.11) an equation is obtained in which both relative humidity and specific humidity appear. This is:

$$\omega = \frac{622\phi p_g}{p - \phi p_g} \ g_v/kg_a \tag{25.12}$$

Thus, with relative humidity, ϕ, obtained from a hygrometer, the pressure, p, obtained from a barometer or pressure gauge, and the saturation pressure, p_g, obtained from Figure 25.1 or an appropriate set of tables, the specific humidity of any sample of air can be readily evaluated.

25.3 Air processes

Since there is the possibility of condensation occurring, if either the temperature of the air decreases, or the pressure increases, the effect of various processes that air might undergo needs to be considered. Such processes include heating, cooling, compressing and drying.

25.3.1 Heating

If air is heated at constant pressure, its relative humidity will decrease and it will become drier. This effect can be seen from the psychrometric chart in Figure 25.7, reproduced in Figure 25.8 with two cases illustrated.

If no further moisture is added to the air its specific humidity will remain constant. Thus an increase in temperature will result in a horizontal shift to the right and give a

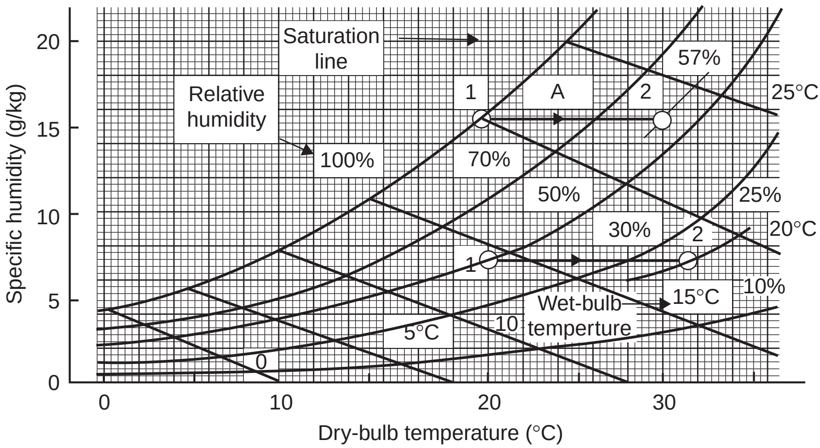


Figure 25.8 Psychrometric chart for air at atmospheric pressure illustrating the drying effect of heating air.

decrease in relative humidity, regardless of the starting point. In case A the starting point is saturated air at a temperature of 20°C. If it is heated to 30°C the relative humidity will drop to about 57 per cent. In case B the starting point is also air at 20°C but with a relative humidity of 50 per cent. If it is heated to 32°C the relative humidity will fall to about 25 per cent.

25.3.2 Cooling

If moist air is cooled at constant pressure, the reverse of the above process will occur, until the saturation line is reached. During this part of the cooling process the partial pressure of the vapour will remain constant. This can be explained as follows:

For the vapour in a mixture of air and vapour at temperature, T, we have, from Equation (25.3):

$$p_v = \frac{m_v R_v T}{V}$$

and for the mixture

$$p = \frac{mRT}{V}$$

from which:

$$\frac{p_v}{p} = \frac{m_v R_v}{mR} \tag{25.13}$$

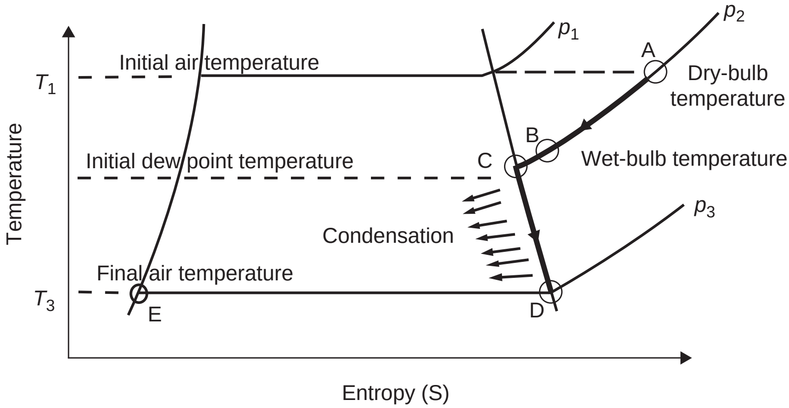


Figure 25.9 Sketch showing cooling and condensing process on temperature vs. entropy diagram.

The ratio of m_v/m will remain constant until the saturation line is reached, and so provided the total system pressure remains constant, the partial pressure of the vapour will remain constant. This entire cooling process can be illustrated on the temperature vs. entropy diagram shown in Figure 25.9.

If the starting point is at A, the air will have a relative humidity given by p_2/p_1. T_A is the dry-bulb temperature. As the air cools the constant pressure line will be followed to the saturation line at point C, where the relative humidity will be 100 per cent. Point C is known as the dew point and the corresponding temperature, T_C, is the dew point temperature. T_B is the wet-bulb temperature. It should be noted that the wet-bulb temperature is not at the point C, but between A and C on the constant pressure line, as explained above.

Any further cooling beyond point C will result in condensation. Condensation will result in a loss in water vapour, and hence the partial pressure of the vapour will fall, as can be seen from Equation (25.13). If the final temperature is T_3, point D on the temperature – entropy diagram will represent the saturated vapour and point E will represent the saturated water that has condensed. From point C to D the relative humidity will always be 100 per cent.

25.3.2.1 Condensation in reception hopper

Condensation can be a major problem in hoppers and silos, even if they are full of material. Condensation can also be a problem in conveying pipelines. When bulk solids are poured and stored there are always gaps between the particles, and these interstitial spaces naturally fill with air. This voidage is typically about 50 per cent for most bulk solids, which means that a 100 m^3 capacity hopper will still retain approximately 50 m^3 of air when it is completely full of material.

If, at the time of pneumatically loading a material into a hopper, the conveying air was warm, and the temperature subsequently fell, usually overnight, condensation could occur. If the temperature of the air was 30°C and the air was saturated, it would contain

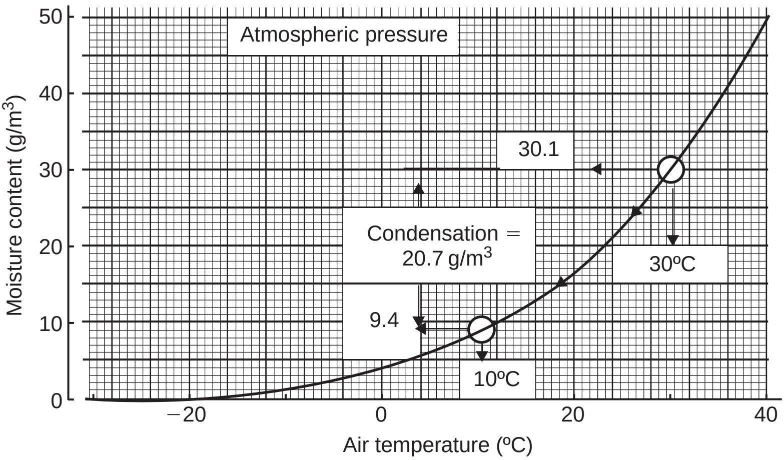


Figure 25.10 Condensation of saturated air on cooling.

about 30.1 g of water per cubic metre of air. If the temperature fell to 10°C, the air would only be able to support 9.4 g/m^3, and so the difference would condense. This is shown diagrammatically in Figure 25.10. If the hopper had a capacity of 100 m^3 and was full of material having a voidage of 50 per cent, the condensation for the given change in temperature would be about:

$$50\ \text{m}^3 \times (30.1 - 9.4)\,\text{g/m}^3 = 1035\,\text{g of water}$$

This amounts to more than 1 l of water, and most of it is likely to condense on the inside surface of the hopper, being the coldest surface on cooling, and the water will gradually drain down the walls, if it is not taken up by the stored material. Depending upon the mode of interaction between the material in the hopper, the water, and the hopper walls, this could have a very significant effect on the subsequent discharge of the material from the hopper.

It is possible that with a daily cycle of emptying and re-filling the hopper, the effect, in terms of moisture condensation, will be cumulative. Much of the condensed water will remain in the hopper, unless it drains out, because a subsequent rise in temperature will cause little evaporation of this water. Thus on the next filling another litre of water could be condensed under similar climatic conditions.

25.3.3 Compressing

Two basic models of air compression can be considered. One is isentropic, or adiabatic, and the other is isothermal. The mode of compression is dictated essentially by the type of compressor or exhauster used. If compression is carried out very quickly, such as in a positive displacement blower or screw compressor, with negligible heat transfer

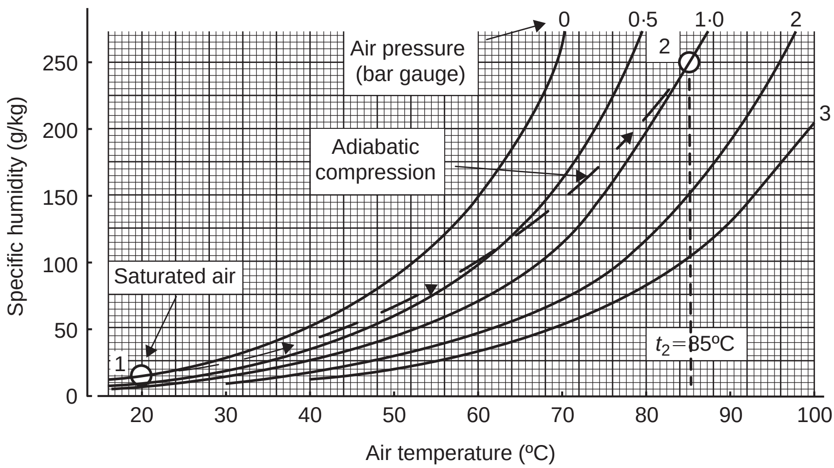


Figure 25.11 Simulation of adiabatic compression of saturated air.

to the surroundings, the compression will be adiabatic. If the compression is carried out slowly, as in some reciprocating compressors, the compression could be isothermal, particularly if the cylinder walls are water cooled and inter-cooling is employed between compression stages.

25.3.3.1 Adiabatic compression

Thermodynamic models for adiabatic compression were considered with Equations (6.3) and (6.4), and Figure 6.9 in the Chapter on Air movers. From this it was shown that if air at atmospheric pressure and 20°C was compressed to 1 bar gauge (201.3 kN/m^2 abs), the minimum temperature that it would reach after compression would be about 85°C. This compression process, for initially saturated air is simulated diagrammatically on Figure 25.11.

From Figure 25.11 it will be seen that at a temperature of 85°C and pressure of 1 bar gauge, air can support about 250 g of moisture per kg of air. Saturated air at atmospheric pressure and 20°C will have a specific humidity of about 14.7 g/kg. Thus after compression the air will be very dry and there will be no possibility of condensation occurring during the compression process.

It should be noted that this process cannot be represented correctly on Figure 25.11 because the constant pressure lines are drawn for saturated air. It is, therefore, not possible to locate the point after compression. Although the temperature and pressure are both correct, the specific humidity is not. Knowing that the specific humidity is 14.7 g/kg, however, since it will be the same as at inlet to the compressor, it is possible to determine the relative humidity from Equation (25.12):

$$\omega = \frac{622\phi p_g}{p - \phi p_g}$$

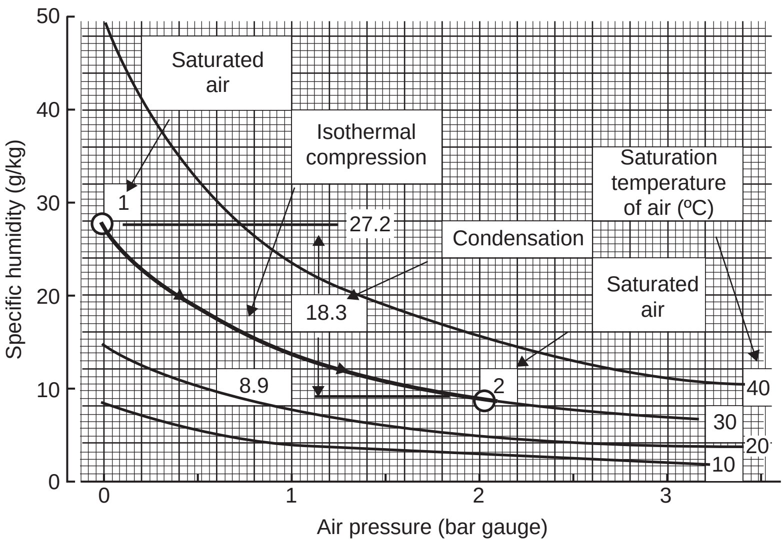


Figure 25.12 Isothermal compression of saturated air.

The saturation pressure of water vapour at 85°C is 57.8 kN/m^2 and so:

$$14.7 = \frac{622 \times \phi \times 57.8}{201.3 - (57.8 \times \phi)}$$

from which

$$\phi = 8\%$$

Thus the air will be extremely dry after compression.

Note also that these models cannot be used with reliable accuracy at such high partial pressures, but the calculation and Figure 25.11 do help to illustrate the point being made.

25.3.3.2 Isothermal compression

Since the specific humidity of air decreases with increase in pressure it is possible that condensation could occur during isothermal compression. A typical process is illustrated on Figure 25.12. This is a graph of specific humidity plotted against pressure, with lines of constant saturation temperature drawn. The process illustrated is that of compressing saturated air at 30°C and atmospheric pressure, isothermally to a pressure of 2 bar gauge.

The specific humidity of saturated air at 30°C and atmospheric pressure is 27.2 g/kg, and at a pressure of 2 bar gauge it is 8.9 g/kg. Thus 18.3 g of moisture will condense per kg of air compressed isothermally at 30°C. Starting with saturated air presents the worst case. If the air was not initially saturated, but had a relative humidity below 100 per cent, less moisture would be condensed. Using Equation (25.12) in a similar manner to that above, for adiabatic compression, it can be shown that if the air at inlet to the compressor had a relative humidity below 34 per cent, no condensation would occur during compression. The psychrometric chart presented in Figure 25.7 can also be used to evaluate this relative humidity level.

If, in the above case, 0.5 m^3/s of saturated air was compressed, having a density of 1.165 kg/m^3:

$$0.5\ m^3/s \times 1.165\ kg/m^3 \times 18.3\ g/kg = 10.66\ g/s \text{ of moisture would condense}$$

which equates to 38.4 kg/h, which is more than 8 gallon/h. For an air supply with a relative humidity below 34 per cent, however, there would be no condensation.

Relative humidity and air temperature are both liable to vary on a day-to-day basis, and with seasonal changes, and so large fluctuations in moisture levels can be expected. If measures must be taken to remove the moisture from the compressed air, the equipment used must be sized on the basis of the worst combination of climatic conditions to be expected.

25.3.4 Compression and cooling

If the air from an adiabatic machine is too hot to be used directly, an after-cooler is often used. Although no condensation will occur in the compression process, it is possible that it could occur on cooling. For illustration an example is simulated on Figure 25.13. This is for atmospheric air, initially saturated at 40°C. The air is compressed to a pressure of 2 bar gauge with a resulting temperature of 96°C. It is then cooled at constant pressure.

After compression the air will be very dry, but cooling can have an even greater effect, and condensation could occur, as in the case illustrated. It should be noted that the process is only simulated on Figure 25.13, since the constant pressure lines relate to saturation conditions, but this does help to illustrate the point being made once again.

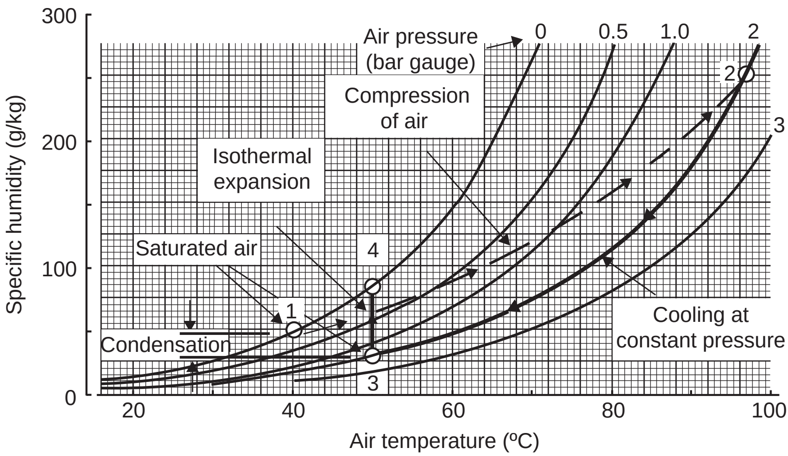


Figure 25.13 Compression, cooling and expansion of initially saturated air.

Only two variables can be represented at a time on a graph and in this case, as with Figure 25.11, temperature, pressure and humidity are all variables.

25.3.5 Expanding

In Figure 25.13 the case illustrated is that of atmospheric air (point 1) being compressed to 2 bar gauge (point 2) and then cooled at constant pressure to a temperature of 50°C (point 3). At point 3 the air will be saturated, as shown above, and so will have a relative humidity of 100 per cent. In expanding from point 3, at a pressure of 2 bar gauge, to atmospheric pressure at point 4, the air will gradually become drier. This is because air is capable of absorbing more moisture as the pressure decreases, as illustrated earlier with Figure 25.5.

25.3.5.1 Vacuum conveying

A similar situation occurs automatically with vacuum conveying. In a negative pressure conveying system the air is drawn into the conveying pipeline at atmospheric pressure and expands through the line to the exhauster. Figure 25.14 illustrates the situation for a negative pressure conveying system, having an exhauster capable of achieving a vacuum of 0.7 bar. An inlet air temperature of 15°C has been considered, and if the material fed into the pipeline is also at 15°C, the conveying process will be essentially isothermal.

Saturated air at the pipeline inlet has been considered and so the specific humidity of the air at inlet will be 10.6 g/kg. Since the capability of air for absorbing moisture increases with decrease in pressure no condensation will occur and the specific humidity of the conveying air at the pipeline exit will also be 10.6 g/kg, unless there is a transfer of moisture to or from the conveyed material and the air during the conveying process.

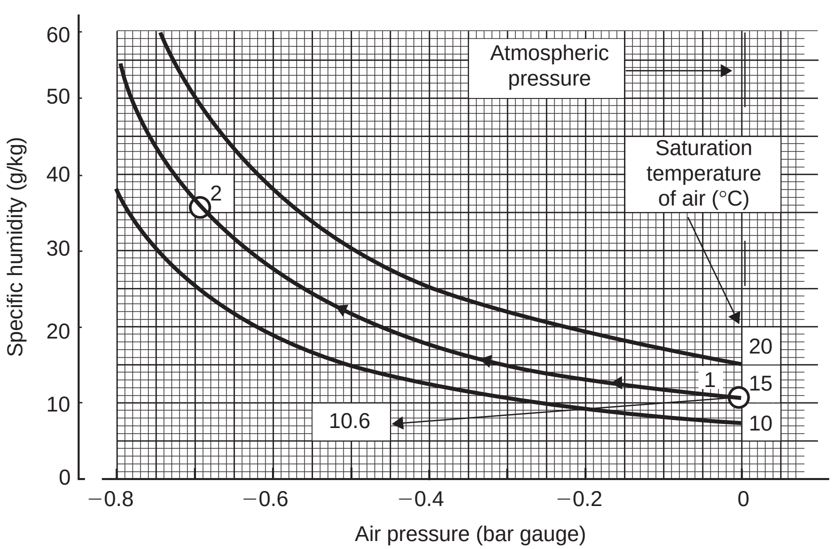


Figure 25.14 Simulation of expansion of saturated air in a vacuum conveying system.

It will be seen from Figure 25.14 that the specific humidity of saturated air at a pressure of −0.7 bar gauge and a temperature of 15°C is 35.8 g/kg, and so the air will be very dry at exit. Once again the relative humidity of the air at the pipeline exit can be obtained from Equation (25.12):

$$\omega = \frac{622\phi p_{\mathrm{g}}}{p - \phi p_{\mathrm{g}}} \, \mathrm{g/kg}$$

The specific humidity, ω, is 10.8 g/kg, the saturation pressure of water vapour, p_{g}, at 15°C is 1.704 kN/m^2 and the total pressure is −0.7 bar gauge (31.3 kN/m^2 abs) and so:

$$14.7 = \frac{622 \times \phi \times 1.704}{31.3 - (1.704 \times \phi)}$$

from which

$$\phi = 31\%$$

Once again it should be noted that this process cannot be represented correctly on Figure 25.14 because the constant temperature lines are drawn for saturated air. It is, therefore, not possible to locate the point after expansion. Although the temperature and pressure are both correct, the specific humidity is not, as shown above.

25.3.6 Drying

If condensation must be avoided in a bulk solids handling plant, or if dry air must be used because a material to be conveyed is hygroscopic, it may be necessary to dry the air. There are three possibilities here, depending upon the degree of dryness to be achieved. These are filters, refrigerants and desiccants.

25.3.6.1 Filters

Owing to the speed at which both compression and cooling processes occur it is quite possible for droplets of water, in the form of fine mist, to be carried through the pipeline with the compressed air. The removal of droplets of water in suspension is a relatively simple process, although the efficiency of removal is significantly influenced by droplet size, being increasingly more difficult for smaller drop sizes. Filters were considered earlier in Chapter 6 on Air movers at Section 6.3.3.1.

25.3.6.2 Refrigerants

Drying by refrigerant cooling is essentially an extension of the process shown above in Figure 25.13, for the constant pressure cooling of high temperature compressed air. Refrigerant dryers usually have two stages of heat exchange. In the first, the warm compressed air is pre-cooled by the cold, dry, outgoing air. It then passes to a refrigerant heat exchanger where it is cooled to the required dew point. This is usually about 2°C, at

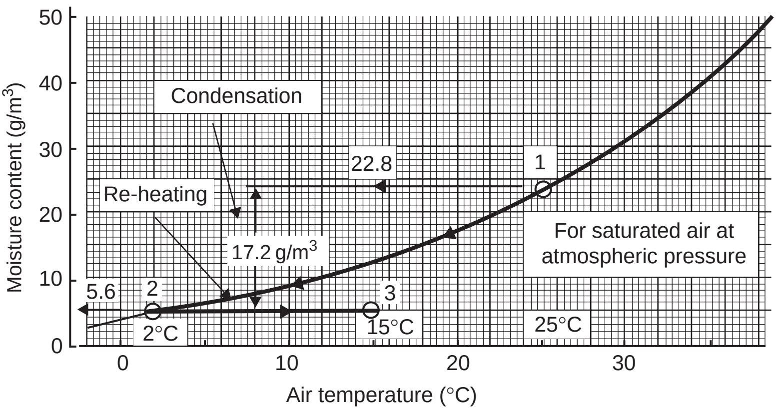


Figure 25.15 Condensation in refrigeration drying of saturated air.

which temperature the specific humidity of the air is about 4.36 g/kg. Drying down to this level of moisture avoids problems of ice formation and freezing. If any further drying is required much lower temperatures would have to be achieved, and this would make a refrigerant unit very expensive. This process can be illustrated on a graph of moisture content plotted against air temperature. Such a graph is shown in Figure 25.15.

Figure 25.15 considers saturated air at 25°C being cooled to 2°C. At 25°C the moisture content will be 22.8 g/m^3 and at 2°C it will be 5.6 g/m^3. Thus 17.2 g/m^3 will be condensed. If the air flow rate is 0.5 m^3/s, the condensation rate will be 8.6 g/s or 31.0 kg/h, which is almost 7 gallon/h. If the air is then re-heated to 15°C, 5.6 g/m^3 represents a specific humidity of 4.87 g/kg, and from the psychrometric chart in Figure 25.7 it will be seen that the relative humidity will be about 40 per cent

On Figure 25.16 a similar process is plotted to show how the psychrometric chart can be used for this type of evaluation. In this case air at 30°C, with a relative humidity of 50 per cent, is cooled to 2°C, and then re-heated to 20°C. As the inlet air is fairly dry it has to be cooled down to 18°C before reaching its dew point temperature, after which condensation will occur. From Figure 25.16 it will be seen that the air, after re-heating from 2°C to 20°C, at constant specific humidity, will have a relative humidity of about 30 per cent.

25.3.6.3 Desiccants

If air having a specific humidity of less than 4.36g/kg, or a dew point below 2°C, is required, a desiccant type air drier would generally be recommended. These are capable of reducing the moisture level of air to an equivalent dew point temperature of 260ºC, at which temperature the specific humidity will be about 0.0055g/kg.

It should be noted that there is no significant reduction in air temperature with desiccant type dryers as this is entirely a chemical absorption process. In order to reduce the moisture loading on a desiccant type dryer, if such a low air dryness level is required, it would generally be recommended that a refrigerant dryer should be used prior to a desiccant type.

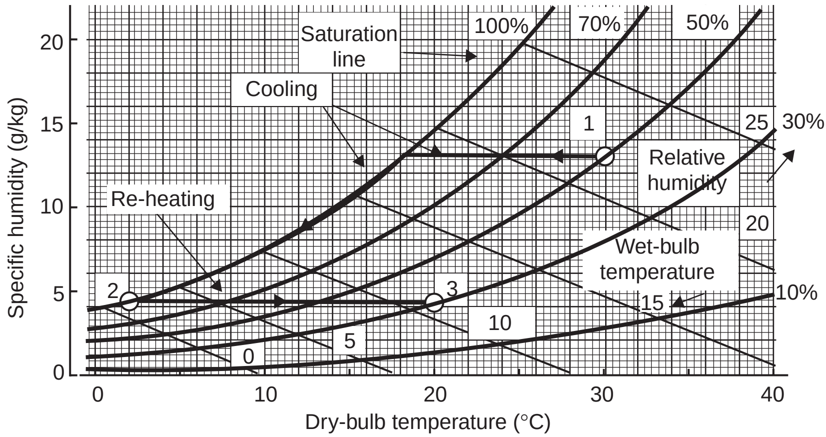


Figure 25.16 Cooling, condensing and re-heating atmospheric air.

25.4 Energy considerations

In Chapter 6 on Air movers, the use of pre-cooling systems for compressors was introduced and it was mentioned that significant energy savings could be made. In order to be able to assess the energy requirements for this type of system the energy model is presented here. From the above consideration of moisture and condensation it will be seen that the analysis will have to include elements for air, water and steam.

25.4.1 Steady Flow Energy Equation

The Steady Flow Energy Equation in its full form is as follows:

$$\dot{Q} - \dot{W} = \dot{m}(h_2 - h_1) + \frac{\dot{m}}{2000}\left(C_2^2 - C_1^2\right) + \frac{\dot{m}g}{1000}\left(z_2 - z_1\right) \tag{25.14}$$

where $\dot{Q}$ is the heat transfer (kW); $\dot{W}$, the work transfer (kW); $\dot{m}$, the mass flow rate (kg/s); h, the specific enthalpy (kJ/kg); C, the velocity (m/s); g, the gravitational acceleration (m/s^2); z, the elevation (m) and subscripts 1 and 2 relate to inlet and outlet conditions.

Some of these energy quantities may be zero, such as heat and work transfers, and many will be negligibly small, such as changes in kinetic and potential energy. The mass flow rate, $\dot{m}$, terms will apply to each constituent; air, water and steam.

Note that:

$$h = u + pv \text{ kJ/kg} \tag{25.15}$$

$$= C_p t \text{ kJ/kg} \tag{25.16}$$

where

$$u \text{ (specific internal energy)} = C_v t \text{ (kJ/kg)} \tag{25.17}$$

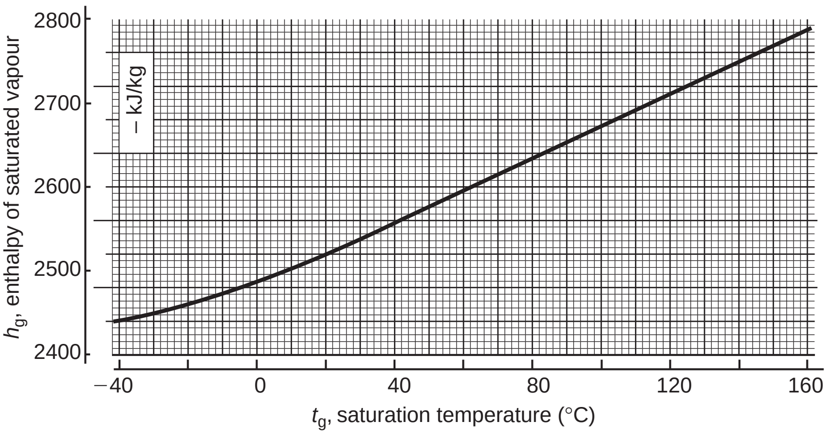


Figure 25.17 Variation of specific enthalpy of saturated vapour with saturation temperature – for steam.

p is the pressure (kN/m^2); t, the temperature (°C); v, the specific volume (m^3/kg); C_p, the specific heat at constant pressure (kJ/kg) and C_v, the specific heat at constant volume (kJ/kg).

Approximate values of specific heats, for this type of application, are as follows:
For air $C_p = 1.0\,\text{kJ/kg}\cdot\text{K}$ and $C_v = 0.72\,\text{kJ/kg}\cdot\text{K}$
For H_2O $C_{pf} = 4.18\,\text{kJ/kg}\cdot\text{K}$ (i.e. for water)
and $C_{pg} = 1.88\,\text{kJ/kg}\cdot\text{K}$ (i.e. for superheated steam)

$$\text{For water vapour } h_v = h_g + C_{pg}(t - t_g)\ \text{kJ/kg}\cdot\text{K} \tag{25.18}$$

where h_v is the enthalpy of superheated vapour (kJ/kg); h_g, the enthalpy of saturated vapour (kJ/kg); t, the actual temperature °C; and t_g, the saturation temperature °C.

Values of h_g are given in Figure 25.17. Although values of specific humidity may be low, it will be seen from Figure 25.17 that specific enthalpy values of the vapour are extremely high, and so the energy quantities associated with the vapour can be very significant.

The datum for the specific enthalpy values in Figure 25.17 is taken as 273.16 K, which is the 'triple point' of water, which is 0.01°C, and so 0°C is taken as the datum for all thermal energy quantities in the Steady Flow Energy Equation. This means that Celsius temperatures can be used directly, as shown in Equations (25.16)–(25.18), instead of absolute values, which are essential for the Ideal Gas Law.

25.4.1.1 Evaporative cooling

In dealing with the staging of positive displacement blowers, in Chapter 6 on Air movers, it was mentioned that water sprays could be used to reduce the temperature of the outlet air, instead of a conventional heat exchanger. A water consumption figure was given as 2 per cent of the air flow rate. This case will be used as an example of applying the Steady Flow Energy Equation.

It will be assumed that 0.5 kg/s of air (24.5 m^3/min at free air conditions), having a relative humidity of 70 per cent, is drawn into the compressor at a pressure of 101.3 kN/m^2 absolute (standard atmospheric pressure) and at a temperature of 20°C. The air is delivered at a pressure of 201.3 kN/m^2 absolute (1 bar gauge) and at a temperature of 100°C; 0.01 kg/s of water (2 per cent of 0.5) at a temperature of 20°C is sprayed into the air stream at exit from the compressor.

General

$t = 20°C$

$p = 101.3\,\text{kN/m}^2$

Air

$\dot{m}_a = 0.5\,\text{kg/s}$

Vapour

$\phi = 70\%$

$\omega = 10\,g_v/kg_a$ from Figure 25.8

$\dot{m}_v = 0.01 \times 0.5 = 0.005\,\text{kg/s}$

$t_{sat} = 14°C$ from Figure 25.8.

At outlet from the compressor and inlet to the evaporative cooler at ①:

General

$t = 100°C$

$p = 201.3\,\text{kN/m}^2$ 1 bar gauge

Air

$\dot{m}_a = 0.5\,\text{kg/s}$ this will remain constant

$H_{a1} = \dot{m}_a \times C_p \times t = 0.5 \times 1.0 \times 100 = 50.0\,\text{kW}$

Vapour

$\dot{m}_v = 0.005\,\text{kg/s}$

$H_{v1} = \dot{m}_v\,[h_g + C_p(t_1 - t_g)]$ obtain h_g from Figure 25.17

$= 0.005\,[2510 + 1.88(100 - 14)] = 13.4\,\text{kW}$

Water

$t = 20°C$

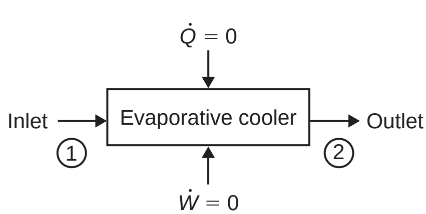
$\dot{m}_w = 0.01\,\text{kg/s}$

$H_{w1} = \dot{m}_{w1} \times C_p \times t = 0.01 \times 4.18 \times 20 = 0.8\,\text{kW}$

Total

$= H_{a1} + H_{v1} + H_{w1} = 50.0 + 13.4 + 0.8 = 64.2\,\text{kW}$

For the evaporative cooler



For the evaporative cooler it can be assumed that there will be no work done, and heat exchange with the surroundings can be neglected. It can also be assumed that all kinetic and potential energies can be disregarded. Thus the only energy into the system is that of the enthalpies of the air, water and vapour, as evaluated above at 64.2 kW. At outlet it will be assumed that all the water is evaporated and so only the enthalpies of the air and vapour need be taken into account.

At outlet from the evaporative cooler at ②:

General
$t = t_2$ this is unknown and has to be evaluated
$p = 201.3\,\text{kN/m}^2$

Air
$\dot{m}_a = 0.5\,\text{kg/s}$
$H_{a2} = \dot{m}_a \times C_p \times t_2 = 0.5 \times 1.0 \times t_2 = 0.5t_2\,\text{kW}$

Water
$\dot{m}_w = 0$ assume all evaporated

Vapour
$\dot{m}_v = 0.005 + 0.01 = 0.015\,\text{kg/s}$
$H_{v2} = \dot{m}_{v2}[h_g + C_p(t_2 - t_g)]$

This will be a 'trial and error' solution since h_g is a function of t_2.

If, for a first approximation, it is assumed that the vapour leaving the evaporative cooler is saturated, and that t_2 will be approximately 50°C, h_g can be taken as 2590 kJ/kg (from Figure 25.17) and a balance gives:

$$64.2 = 0.5t_2 + (0.015 \times 2590)$$

from which

$$t_2 = 50.7°\text{C}$$

To provide a check on this temperature, and the fact that the water has all evaporated, Equation (25.12) can be used to evaluate the relative humidity.

The specific humidity of the air leaving the evaporative cooler, if all the water has evaporated, will be, from Equation (25.1):

$$\omega = \frac{\dot{m}_v}{\dot{m}_a} = \frac{0.015}{0.5} \times 1000 = 30\ \text{g}_v/\text{kg}_a$$

Substituting this into Equation (25.12) gives:

$$30 = \frac{622 \times 12.33\phi}{201.3 - 12.33\phi}$$

From which the relative humidity is 75 per cent, and so all the water will have evaporated, residence time permitting. From this it will be seen that the cooling effect of water, because of the very high enthalpy of evaporation, h_{fg}, can be very effective, and that the enthalpy term for vapour should always be included in any energy analysis of a system.

25.4.1.2 Flash drying

A flash dryer is essentially a pneumatic conveying system. It consists mainly of a vertically upward section of duct. Wet material is fed in at the bottom and is conveyed up by hot air or gas. The dried material is removed either by cyclone separator or bag filter. The vertically upward flow allows intimate mixing, and a reasonable residence time for the necessary mass transfer process to take place. The evaporation of the moisture from the wet material rapidly cools the hot air, and so the method of drying is generally suitable for most powdered and granular materials, including many heat sensitive products.

The Steady Flow Energy Equation can be used to model this type of system also, knowing the moisture content and flow rate of the feed material. As with the evaporative cooling case considered above, there will be no work transfer, heat transfer to the surroundings can be neglected, and changes in kinetic and potential energy can generally be neglected. In addition to allowing for flows of water, air and vapour, however, account also has to be taken of the conveyed material. Specific heat values of a number of materials were given in Table 9.4.

25.4.1.3 Vacuum drying

In the heating of a material the driving force is temperature difference, and the greater the temperature difference the faster the material will be heated, or cooled. For the flow of a fluid the driving force is pressure difference. In the case of the drying of wet bulk particulate materials the driving force is the difference in vapour pressure, and this can reasonably be related to relative humidity difference. When the material is wet, or frozen, the air in intimate contact with the material, in the boundary layer, will be saturated and have a relative humidity of 100 per cent. The lower the relative humidity of the body of drying air in contact with the material, the greater the drying effect will be.

In the flash dryer, considered above, the drying air is given an extremely low value of relative humidity by means of heating to a high temperature. Saturated air at 20°C, when heated to 100°C, for example, will have a relative humidity of about 2 per cent. Relative humidity, however, can be lowered in a similar manner by reducing pressure, and this effect was shown earlier in Figure 25.5. Saturated air, at 20°C and atmospheric pressure, will have a relative humidity of about 20 per cent when the pressure is reduced to -0.8 bar of vacuum (21.3 kN/m^2 absolute). A difference in temperature, therefore, is not a necessary requirement for drying. Dehumidified air, dried with a desiccant type dryer, can also be used to dry wet materials at atmospheric temperature. Combinations of any of these three methods of reducing the relative humidity of the drying air can be used to speed the process.

Vacuum drying of materials at very low pressures is usually a batch operation, and as extremely low values of relative humidity can be achieved, the drying process is reasonably quick. With no requirement for heat it is ideal for heat sensitive materials. With the potential for achieving very low values of relative humidity, particularly when the atmospheric air is fairly dry, consideration must be given to the drying of materials when pneumatically conveyed in vacuum conveying systems.

25.5 Nomenclature

C	Conveying air velocity	m/s
C_p	Specific heat at constant pressure	kJ/kg·K
C_v	Specific heat at constant volume	kJ/kg·K
g	Gravitational acceleration	m/s^2
h	Specific enthalpy	kJ/kg
H	Enthalpy	kJ
m	Mass	kg
$\dot{m}$	Mass flow rate	kg/s
M	Molecular weight	–
p	Air pressure	kN/m^2 (bar)
	Note: 1 bar = 100 kN/m^2	
$\dot{Q}$	Heat transfer	kJ/s (kW)
R	Characteristic gas constant	kJ/kg-K
R_0	Universal gas constant = 8.3143kJ/kg-mol	kJ/kg-mol K
t	Actual temperature	°C
T	Absolute temperature = $t + 273$	K
u	Specific internal energy	kJ/kg
v	Specific volume	m^3/kg
V	Volume	m^3
$\dot{V}$	Volumetric flow rate	m^3/s
$\dot{W}$	Work transfer	kJ/s (kW)
z	Elevation	m

25.5.1 Greek

γ	Ratio of specific heats = C_p/C_v	–
ϕ	Relative humidity	–
ω	Specific humidity	g_v/kg_a

25.5.2 Subscripts

a	Air
f	Saturated liquid
fg	Change of phase (evaporation) (= g − f)
g	Saturated vapour
sat	Saturation value or conditions
v	Water vapour
1, 2	Actual conditions, generally inlet and outlet.

Chapter 26

Health and safety

26.1 Introduction

Pneumatic conveying systems are basically quite simple and are eminently suitable for the safe transport of powdered and granular materials in factory, site and plant situations. The system requirements are a source of compressed gas, usually air, a feed device, a conveying pipeline, and a receiver to disengage the conveyed material and carrier gas. The system is totally enclosed, and if it is required, the system can operate entirely without moving parts coming into contact with the conveyed material. High, low or negative pressure air can be used to convey materials. For explosible materials, an inert gas such as nitrogen can be employed instead of air.

26.1.1 System flexibility

With a suitable choice and arrangement of equipment, materials can be conveyed from a hopper or silo in one location, to another location some distance away. Considerable flexibility in both plant layout and operation are possible, such that multiple point feeding can be made into a common line, and a single line can be discharged into a number of receiving hoppers. With vacuum systems, materials can be picked up from open storage or stockpiles, and they are ideal for clearing dust accumulations and spillages.

Pneumatic conveying systems are particularly versatile. A very wide range of materials can be handled, and they are totally enclosed by the system and pipeline. This means that potentially hazardous materials can be conveyed quite safely, with the correct choice of system and components. There is minimal risk of dust generation, and so these systems generally meet the requirements of any local Health and Safety legislation with little or no difficulty.

26.1.2 Industries and materials

A wide variety of materials are handled in powdered and granular form, and a large number of different industries have processes that involve their transfer and storage. Some of the industries in which bulk materials are conveyed include agriculture, mining, chemicals, pharmaceuticals, paint, rubber and metal refining and processing. In agriculture very large tonnages of harvested materials such as grain and rice are handled, as well as processed materials such as animal feed. Fertilizers represent a large allied industry with a wide variety of materials. A vast range of food products, from flour to sugar and tea to coffee and milk powder, are conveyed pneumatically in numerous manufacturing processes. Confectionery is an industry in which many of these materials are also handled.

26.1.3 Mode of conveying

Much confusion exists over how materials are conveyed through a pipeline and to the terminology given to the mode of flow. First it must be recognized that materials can either be conveyed in batches through a pipeline, or they can be conveyed on a continuous basis, 24 h a day if necessary. In batch conveying the material may be conveyed as a single plug if the batch size is relatively small. For continuous conveying, and batch conveying if the batch size is large, two modes of conveying are recognized. These are dilute and dense phase flow and are considered in detail in Section 1.2.3.

26.1.4 System integration

Dust, mess and spillage that are often found surrounding bulk solids handling plant are not generally caused by pneumatic conveying systems. Feeders for pneumatic conveying systems, for example, usually fit under hoppers, and these in turn are fed from above by other systems, such as belts, bucket elevators and chain and flight (en-masse) conveyors. Dust and mess in the area often comes from poor integration of the mechanical conveyor with the hopper, and not with the pneumatic conveyor. In terms of plant safety, therefore, due consideration must be given to the interfacing of different systems, particularly if they are operating in series.

Pneumatic conveying systems provide a totally enclosed environment throughout for the transport of materials, and along the conveying route there are no moving parts at all, unless diverter valves are employed for multiple point off-loading. Some feeding devices, such as blow tanks, venturis and vacuum nozzles have no moving parts, apart from valves opening and closing at the start and end of the process. Although pneumatic conveying systems are capable of releasing dust into the atmosphere, it generally occurs only as a result of a fault situation, and is not an endemic problem with the conveying system.

26.2 Dust risks

Many dusts represent a very significant health hazard. If these materials are to be conveyed it is essential that any dust associated with the material should remain within the conveying system while being transported. If any material is deemed to be toxic to any degree there should be no possibility of any dust being released into the atmosphere. There is also a wide range of materials, which, in a finely divided state, dispersed in air, will propagate a flame through the suspension if ignited.

These materials include foodstuffs such as sugar, flour and cocoa, synthetic materials such as plastics, chemical and pharmaceutical products, metal powders, and fuels such as coal, coke and sawdust. If conveyed with air there is the possibility of a dust explosion within the system. If the dust is released from the system there is the possibility of a dust explosion external to the conveying system.

The potential magnitude of the problem can be illustrated by the fact that during the 17 years from 1962 to 1979 there were 474 recorded dust explosions in the UK, resulting in 25 deaths [1]. This covers the whole area of bulk solids handling, transport and storage and the number of explosions that could be attributed directly to pneumatic conveying systems is not known. In just 2 years (1976 and 1977), dust explosions in grain handling plant in the United States claimed the lives of 87 workers and caused injuries to over 150 more [2]. It is believed that most of these explosions were in bucket elevators and not pneumatic conveying systems, but these statistics highlight the potential for dust explosions, regardless of the source.

26.2.1 Dust emission

Excepting the potentially explosive materials, the most undesirable dusts are those that are so fine that they present a health hazard by remaining suspended in the air for long periods of time. The terminal velocity of a 1 μm particle of silica, for example, is about 1 mm in 30 s, whereas that of a 100 μm particle is about 300 mm/s. The terminal velocity of an object depends upon its density, size and shape, and is approximately proportional to the square of its size. Comparative size ranges of some familiar airborne particles are illustrated in Figure 26.1.

Particles falling in the size range of approximately 0.5–5 μm, if inhaled, can reach the lower regions of the lungs where they may be retained. Prolonged exposure to such dusts can cause permanent damage to the lung tissues, symtomized by shortness of breath and increased susceptibility to respiratory infection. Prevention of the emission of these fine particles into the atmosphere is thus of paramount importance. Emissions of larger particles may also give rise to complaints, in a social context, created by the deposition of the particles on neighbouring properties or on vehicles belonging to a company's own employees.

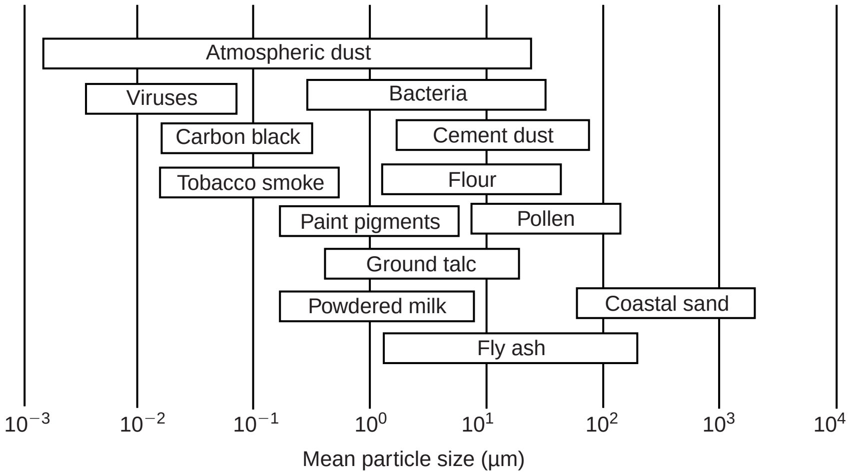


Figure 26.1 Approximate size range of some familiar types of airborne particulate materials.

26.2.1.1 Dust as a health hazard

When suspended in air the smallest particle visible to the naked eye is about 50–100 μm in diameter, but it is the particles of 0.2–5 μm diameter that are most dangerous for the lungs, as mentioned above. Thus the existence of visible dust gives only indirect evidence of danger, as finer invisible particles will almost certainly be present as well. The fact that no dust can be seen is no reliable indication that dangerous dust may not be present in the air. The large visible particles in a dust cloud will quickly fall to the floor, but it will take many hours for the fine dangerous particles to reach the ground.

Airborne dusts that may be encountered in industrial situations are generally less than about 10 μm in size and can be taken into the body by ingestion, skin absorption or inhalation. The former is rarely a serious problem, but diseases of the skin are of not infrequent occurrence. Allergic reactions are known to be caused by powders containing, for example, metals such as chrome, nickel and cobalt. It is, however, inhalation that presents the greatest hazards for workers in a dusty environment.

Relatively large particles of dust that have been inhaled and become deposited in the respiratory system will usually be carried back to the mouth by cilliary action and be subsequently swallowed or expectorated. At the other extreme, ultra-fine particles (less than about 0.2 μm) that become deposited are likely to pass relatively quickly, generally into solution in the extra-cellular fluids of the lung tissues. Much of this is excreted by the kidneys, either unchanged or after detoxication by the liver. This is the fate of many systemic poisons, for example lead, which gain entry to the body via the lungs [3].

Inhaled particles with the approximate size range of 0.2–5 μm can reach the lower regions of the lungs where they will probably be retained. Prolonged exposure to such dusts can cause various diseases, most of them potentially serious, and often resulting in permanent damage to the lung tissues. The best known are probably the diseases collectively designated 'pneumoconiosis' and characterized by chronic fibrosis of the lungs as a result of continuous inhalation of mineral dusts such as silica, asbestos and coal. Generally the symptoms are a chronic shortage of breath and increased susceptibility to respiratory infection. Other dust-related diseases include pneumonitis (an acute inflammation of the lung tissue or bronchioles) and lung cancer.

The relative dangers of some common dusts are compared in Table 26.1 in which the minerals are conveniently classified in Groups I–IV [3].

26.2.1.2 Dust concentration limits

One of the criteria used in monitoring the compliance of companies with the 1974 Health and Safety at Work Act, and other relevant statutory provisions, is the concentration of airborne dust. The measured concentration is compared with variously defined 'threshold limit values' (TLVs) which are also functions of the duration of exposure of personnel to the dust. The most commonly used definitions of threshold limit value are [4]:

- TLV-TWA: time-weighted average concentration for a normal 8 h working day or 40 h week, to which most workers can be repeatedly exposed day after day, without adverse effect.

Table 26.1 Relative dangers of some common dust

Group I: Very dangerous
Expert advice should always be sought
- Beryllium: particularly as the oxide
- Silica (SiO_2) which has been heated: in these circumstances silica undergoes modification into biologically active forms calcined kieselguhr (diatomaceous earth) is dangerous on this account
- Crocidolite (blue asbestos): evidence associates this variety of asbestos with the development of malignant tumours of pleura and peritoneum

Group II: Dangerous
A visible haze of any of these dusts is intolerable and no possible source of such should be ignored whether or not there is a visible cloud
- Asbestos, other than crocidolite: the two important varieties in commerce are amosite (brown asbestos) and chrysotile (white asbestos)
- Silica: (e.g.) as quartz, ganister, gritstone, etc.
- Mixed dusts: containing 20% or more of free silica, (e.g.) pottery dust, granite dust and foundry dust
- Fireclay dust: with a total silicate (as silica) content in excess of 60%

Group III: Moderate risk
Emission of any of these dusts to form a dense local cloud should cause concern
- Mixed dusts: containing some free silica but arbitrarily less than 20%. In this group are included the dusts of iron and non-ferrous foundries
- Coal dust
- Kaolin (china clay, fullers earth)
- Non-crystalline silica: including unheated kieselguhr
- Carbides of some metals
- Cotton dust: and other dusts of vegetable origin
- Aluminous fireclay
- Synthetic silicas
- Graphite
- Talc
- Asbestine
- Mica

Group IV: Minimal risk
Visible concentrations of these dusts, although inexcusable on general grounds, probably represent more danger to welfare than to health
- Alumina (‘aloxite’, corundum)
- Glass (including glass fibre)
- Mineral wool and slag wool
- Pearlite and dusts from other basic rocks
- Silicates other than those already mentioned
- Tin ore and oxides
- Zirconium silicate and oxide
- Barytes
- Carborundum
- Cement
- Emery
- Ferrosilicon
- Iron oxide
- Limestone
- Magnesium oxide
- Zinc oxide

- TLV-STEL: Short-term exposure limit. This is the maximum concentration in which workers can be exposed for a period of up to 15 minutes, provided that no more than four excursions to this value occur each day.
- TLV-C: Threshold limit ceiling. This is the concentration that should not be exceeded, even instantaneously.

For further information on actual threshold limit values, Ref [5] should be consulted.

26.2.1.2 Dust suppression

Where a test for dustiness, or previous experience with a material, indicates that the generation of dust is likely to present a problem, serious consideration should be given to methods of reducing the material's dustability. It may be appropriate to re-examine the manufacturing process to see if the proportion of fines could be lessened. Agglomeration of the particles, for example by pelletizing, should have a significant effect. If dust is generated during transport, it may be possible to change routing or conveying parameters.

Total enclosure of the processing and handling plant is probably the most desirable approach but, in addition to the high cost, there are obvious problems over accessibility. A generally more satisfactory arrangement is to use some kind of partial enclosure or hood in conjunction with an exhaust system which will draw off the dusty air and so minimize the dispersion of solid particles into the atmosphere. Dusty air collected from a booth, hood or other type of partial or total enclosure must then be filtered, or otherwise cleaned, before it can be released into the atmosphere.

26.2.2 Explosion risks

Apart from choking lungs, irritating eyes and blocking pores, some seemingly innocuous dusts can ignite to cause fires. Many materials, in a dust cloud, can ignite and cause an explosion which could be capable of demolishing a factory. A corn starch powder explosion at General Foods, Banbury did just this in 1981. The company pneumatically conveyed corn starch, used in custard powder production, from a transfer hopper to feed bins, via a diverter valve.

An accumulation of corn starch on the operating cylinder caused a malfunction of this diverter valve. When one hopper was full, the flow should have been diverted to the next one. An already full hopper, therefore, was over-filled causing powder to be dispersed into the surrounding atmosphere. The actual explosion therefore occurred, external to the processing plant where the dust cloud was ignited by electrical arcing from nearby electrical switchgear, burning nine men and blowing out brickwork and windows on all four walls [6].

When an explosible dust cloud is ignited in the open air there is a flash fire but little hazardous pressure develops. If the dust cloud is in a confined situation, however, such as a conveyor or storage vessel, then ignition of the cloud will lead to a build-up of pressure. The magnitude of this pressure depends upon the volume of the suspension, the nature of the material, and the rate of relief to atmosphere. Research has shown that the particle size must be below about 200 μm for a hazard to exist.

At some point in a pneumatic conveying system, or time in the conveying cycle, whether dilute or dense phase, positive or negative pressure, the material will be dispersed as a suspension. A typical point is at discharge into a receiving vessel and a common time is during a transient operation such as start-up or shut-down. Consideration, therefore, must be given to the possibility of an explosion and its effects on the plant should a source of ignition be present.

Due to legal and Health and Safety Executive requirements it is advisable for specialist advice to be sought on dust explosion risks. Authoritative literature on the subject is widely available and there are many tests that can be carried out to determine the seriousness of the problem. It is strongly recommended that a specialist in this field is consulted if there is any doubt about the potential explosion risk connected with pneumatically conveying any material.

26.2.2.1 Ignition sources

For an explosion to occur two conditions must be satisfied. Firstly, a sufficiently energetic source of ignition must be provided and secondly the concentration of the material in the air must be favourable. Two sources of ignition frequently met in industrial plant are a hot surface and a spark. Consequently, the minimum ignition temperature and the minimum ignition energy are the ignition characteristics commonly measured in routine testing for explosibility.

Ignition temperature, however, is not constant for a given dust cloud, for it depends upon the size and shape of the apparatus used to measure it. Minimum ignition temperatures, therefore, are determined in a standardized form of apparatus, which enables meaningful comparisons between materials to be made. Typical values of minimum ignition temperature for sugar, coffee and cocoa are 350, 410 and 420°C, respectively [8].

The minimum energy relates to ignition by sparks, whether produced be electricity, friction or hot cutting. A characteristic of any form of spark is that a small particle or a small volume of gas at high temperature is produced for a short period of time. Since it is much easier for experimental purposes to measure the energy delivered by an electric spark than by friction or thermal processes, the routine test for determining this characteristic uses an electric spark ignition source. Typical values of minimum ignition energy for titanium, polystyrene and coal are 10, 15 and 60 mJ, respectively [7].

26.2.2.2 Explosibility limits

For a flame to propagate through a dust cloud the concentration of the material in air must fall within a range which is defined by the lower and upper explosibility limits. The lower explosibility limit, or minimum explosible concentration, may be defined as the minimum concentration of material in a cloud or suspension necessary for sustained flame propagation. This is a fairly well defined quantity and can be determined reliably in small scale tests. Values are usually expressed in terms of the mass of material per unit volume of air. Typical values for wood flour and grain dust are 40 and 55 g/m^3, respectively [7].

As the concentration of the material is increased above the lower explosibility limit the vigour of the explosion increases. When the dust concentration is increased beyond the stoichiometric value, the dust has a quenching effect. Eventually a concentration is reached at which flame propagation no longer occurs. This concentration is the upper explosion limit. This limit is not as easy to determine because of the difficulty of achieving a uniform dispersion of the material. From values that have been determined it would appear that for most common materials the upper limit is probably in the range of 2–10 kg/m^3. This is equivalent to solids loading ratios of about 1.5–8, which covers the major part of the dilute phase conveying range.

It is reasonable to conclude from this that should a favourable source of ignition be present in a pneumatic conveying system, then dilute phase systems are more of a problem than dense phase systems with respect to explosions. With truly dense phase systems, concentrations are well above the minimum explosibility limit and so it is highly unlikely that an explosion will occur in the pipeline of such a system. Care should still be exercised with such installations, however, since it is possible for an explosive concentration to exist at entry to a cyclone or receiver. Consideration should also be given to the start-up and shut-down transients associated with dense phase systems, for with certain modes of operation dilute phase situations may exist.

26.2.2.3 Pressure generation

When a dust explosion occurs in industrial plant spectacular destruction can result if it is initially confined in a system that is ultimately too weak to stand the full force of the explosion. Two other important characteristics of a dust explosion therefore are also derived by means of tests. One is the maximum explosion pressure generated, which would be required if it was desired to contain the explosion within the system. The other characteristic is the maximum rate of pressure rise, which would be relevant to the needs of suppressing an explosion within the system. Typical explosion characteristics of some well known materials are presented below in Table 26.2 [7].

The data in the last two columns serves to illustrate the magnitude and rapidity of the sequence of events that follows such an explosion. Explosion pressures may be as

Table 26.2 Explosion characteristics of some well known materials

Material	Minimum ignition temperature (°C)	Minimum explosible concentration (kg/m^3)	Minimum ignition energy (mJ)	Maximum explosion pressure (bar)	Maximum rate of pressure rise (bar/s)
Metal powders					
Aluminium	640	0.045	15	6.2	1360
Magnesium	520	0.02	40	6.6	1020
Zinc	600	0.48	650	3.4	120
Plastics					
Nylon	500	0.03	20	6.5	270
Polyethylene	390	0.02	10	5.4	510
Polystyrene	490	0.015	15	6.2	480
Agricultural					
Coffee	410	0.085	85	3.4	17
Grain dust	430	0.055	55	6.6	190
Sugar	350	0.035	35	6.1	340
Wheat flour	380	0.05	50	6.4	250
Miscellaneous					
Coal	610	0.055	55	5.9	150
Wood flour	430	0.04	40	7.6	380

high as 10 bar and the maximum rate of pressure rise may be in excess of 1000 bar/s, which means that it may only take 0.01 s to reach maximum pressure.

If ignition occurs within a pipeline, the pipeline may be capable of withstanding the full explosion pressure. If this is so, the resulting pressure wave would pass along the pipeline and be relieved at the weakest point, which is usually the collection hopper or cyclone. Because of their size these are generally only capable of withstanding pressures of 0.15–0.3 bar gauge and, if exposed to higher internal pressures, may burst or disintegrate. Consequently, the collection unit is likely to be the most vulnerable part of the system.

26.2.2.4 Expansion effects

The combustion of a dust cloud will result in either a rapid build-up of pressure or in an uncontrolled expansion. It is the expansion effect, or the pressure rise if the expansion is restricted, that presents one of the main hazards in dust explosions. The expansion effects arise principally because of the heat developed in the combustion and, in some cases, to gases being evolved from the dust because of the high temperature to which it has been exposed.

The pressure wave resulting from an uncontrolled dust explosion in a building usually shakes down more dust that has settled over a period of time onto pipe-work, roof beams and supports, ledges, etc. This makes an ideal condition for the secondary explosion that almost always follows. It is this secondary explosion that can demolish a factory and kill the operatives. It is essential, therefore, that an explosion occurring in a pneumatic conveying system is not allowed to be discharged into a building, and that good housekeeping procedures are adopted to minimize the build up of potentially explosive dusts on surfaces in such buildings.

26.2.2.5 Oxygen concentration

Another characteristic of dust explosions, that can also be measured, is the percentage of oxygen in the conveying gas at which an explosion will occur for a given material. If the oxygen level in air is reduced, a point will be reached at which a flame cannot be supported. If a material is considered to be highly explosive it would generally be conveyed with an inert gas such as nitrogen, instead of air.

For many materials, however, such an extreme measure is not necessary. The use of nitrogen will add significantly to the operating costs, particularly with an open system. If the oxygen content needs to be reduced by only a small amount, a proportion of nitrogen can be added to the air to keep the oxygen level below the required concentration.

26.3 Conveying systems

A wide range of pneumatic conveying systems are available to cater for an equally wide range of conveying applications. The majority of systems are generally conventional, continuously operating, open systems in a fixed location. To suit the material being conveyed or the process, however, innovatory, batch operating and closed systems are

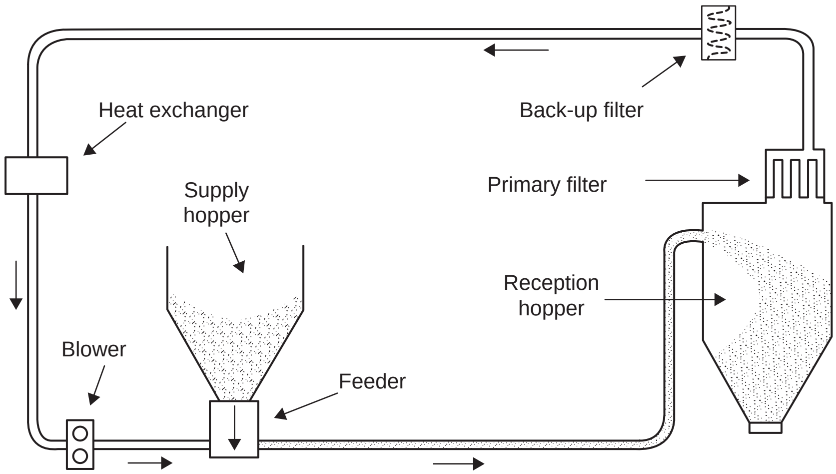


Figure 26.2 Closed loop pneumatic conveying system.

commonly used, as well as mobile systems. To add to the complexity of selection, systems can be either positive or negative pressure in operation, or a combination of the two.

26.3.1 Closed systems

For the conveying of toxic or radioactive materials, where the air coming into contact with the material must not be released into the atmosphere, or must be very closely regulated, a closed system would be essential. A sketch of a typical system was given in Figure 2.10 and is reproduced here as Figure 26.2 for reference. A closed system may also be chosen to convey a potentially explosive material, typically with an inert gas. In a closed system the gas can be re-circulated and so the operating costs, in terms of inert gas, are significantly reduced.

A null point needs to be established in the gas only part of the system, where the pressure is effectively atmospheric, and provision for make up or control of the conveying gas can be established here. If this null point is positioned after the blower the conveying system can operate entirely under vacuum. If the null point is located before the blower it will operate as a positive pressure system.

26.3.2 Open systems

Where strict environmental control is not necessary an open system is generally preferred, since the capital cost of the plant will be less, the operational complexity will be reduced, and a much wider range of systems will be available. Most pneumatic conveying pipeline and channel systems can ensure totally enclosed material conveying, and so with suitable gas–solid separation and venting, the vast majority of materials can be handled quite safely in an open system. Many potentially combustible materials are conveyed in open systems by incorporating necessary safety features.

26.3.2.1 Positive pressure systems

Although positive pressure conveying systems discharging to a reception point at atmospheric pressure are probably the most common of all pneumatic conveying systems, the feeding of a material into a pipeline in which there is air at a high pressure does present a number of problems. A wide range of feeding devices is available that can be used, as considered in Chapters 3 and 4. With each type of feeder, however, there is the potential of air leaking from the system, and carrying dust with it, as a result of the adverse pressure gradient.

With the use of diverter valves, multiple delivery to a number of reception points can be arranged very easily with positive pressure systems. Although multiple point feeding into a common line can also be arranged, care must be taken with regard to the potential for air leaking across a number of feeding points when not in use, as a result of the high pressure air in the pipeline.

26.3.2.2 Negative pressure (vacuum) systems

Negative pressure systems are commonly used for drawing materials from multiple sources to a single point. There is no adverse pressure difference across the feeding device in a negative pressure system and so multiple point feeding into a common line presents few problems. In comparison with a positive pressure system, however, the filtration plant has to be much larger, as a higher volume of air has to be filtered under vacuum conditions.

A particular advantage of negative pressure systems, whether open or closed, in terms of potentially hazardous materials, is that should a pipeline coupling be inadvertently left un-tightened, or a bend in the pipeline fail, air will be drawn into a system maintained under vacuum. With a positive pressure system a considerable amount of dust could be released into the atmosphere before the plant could be shut down safely. The author has personal experience here, for while conveying cement at 50 tonne/h a flexible hose connecting the blow tank with the pipeline came adrift when the pressure in the line was three bar gauge. It can happen. If it had been a food product, chemical or metal powder, that was being conveyed, the consequences could have been very serious.

Vacuum systems are also widely used for clearing dust released into the atmosphere from many other bulk solids handling operations. This is generally achieved by the use of ventilated hoods. This may be at a material transfer point in a mechanical conveying system, or at a gravity loading station for sack filling from storage hoppers. Mobile conveying systems such as road and rail vehicles require similar ventilation systems when being loaded with bulk particulate materials.

26.4 System components

The selection of components for a pneumatic conveying system is as important as the selection of the type of conveying system for a given duty. Air movers, pipeline feeding devices and gas–solid separation systems, all have to be carefully considered and there are multiple choices for each.

26.4.1 Blowers and compressors

With air movers a positive displacement machine is generally required. If a blower or compressor is incorrectly specified, in terms of either pressure or volumetric flow rate, the pipeline is likely to block, and with a toxic material this will create its own hazards since the pipeline will have to be unblocked by some means. A minimum gas velocity must be maintained throughout the pipeline system to ensure satisfactory conveying, and it must be remembered that all gases are compressible with respect to both pressure and temperature when it comes to evaluating flow rates from specified velocities.

The compression process in most air movers is adiabatic and it is far from being reversible. As a result, the temperature of the air leaving a compressor can be very high. If, for example, air at 20°C is compressed to 1 bar gauge in a positive displacement blower, the minimum temperature after compression, for a reversible process, would be about 84°C, and with an isentropic efficiency of 80 per cent it would be 100°C. If the same air is compressed to 3 bar gauge in a screw compressor it will be delivered at a temperature of about 200°C.

26.4.1.1 Oil free air

Oil free air is generally recommended for most pneumatic conveying systems and not just those where the material must not be contaminated, such as food products, pharmaceuticals and chemicals. Lubricating oil, if used in an air compressor, can be carried over with the air and can be trapped at bends in the pipeline or obstructions. Most lubricating oils eventually break down into more carbonaceous matter which is prone to spontaneous combustion, particularly in an oxygen rich environment, and where frictional heating may be generated by moving particulate matter.

Although conventional coalescing after-filters can be fitted, which are highly efficient at removing aerosol oil drops, oil in the super-heated phase will pass straight through them. Super-heated oil vapour will turn back to liquid further down the pipeline if the air cools. Ultimately precipitation may occur, followed by oil breakdown, and eventually a compressed air fire. The only safe solution, where oil injected compressors are used, is to use chemical after-filters such as the carbon absorber type which are capable of removing oil in both liquid droplet and super-heated phases. The solution, however, is expensive and requires continuous maintenance, and replacement of carbon filter cells.

26.4.2 Pipeline feeding

There have been numerous developments in pipeline feeders to meet the demands of different material characteristics, and ever increasing pressure capabilities for long distance and dense phase conveying. Although the majority of systems probably operate with positive displacement blowers at a pressure below one bar gauge, discharging to atmospheric pressure, there is an increasing demand for conveying systems to feed materials into chemical reactors and combustion systems which operate at a pressure of 20 bar or more.

With positive pressure systems the main problem is feeding the material into a pipeline which contains air at pressure. Due to adverse pressure it is almost impossible to prevent air from leaking across the feeding device. This air will almost certainly carry dust with it, and so if this air or dust must be controlled, some means of containment must be incorporated into the conveying system.

26.4.2.1 Rotary valves

The rotary valve is probably the most commonly used device for feeding conveying pipelines. By virtue of the moving parts and a need to maintain clearances between the rotor blades and the casing, air will leak across the feeder when there is a pressure difference. Rotary valves are ideally suited to both positive pressure and vacuum conveying. The rotary valve is a positive displacement device and so feed rate can be controlled fairly precisely by varying the speed of rotation. The situation with regard to screw feeders is very similar, as these are also positive displacement devices. In positive pressure systems air leakage can be minimized by reducing blade tip clearances, increasing the number of rotor blades, and providing seals on the rotor end plates, but it cannot be eliminated.

Air at pressure will always return with the empty pockets, apart from leaking past blade tip clearances. The air leaking across a rotary valve will often restrict the flow of material into a rotary valve from the supply hopper above. To minimize this influence it is usual to vent a rotary valve in some way. A common device is to provide a vent on the return side of the valve as shown earlier in Figure 22.3. Since the vented air will contain some fine material, this is either directed back to the supply hopper, ducted to a separate filter unit, or re-introduced back into the conveying pipeline.

As there will be a carry-over of material any filter used must be regularly cleaned, otherwise it will rapidly block and cease to be effective. If the air is vented into the supply hopper above, or to a separate filter, the pipe connecting the vent to the filter unit must be designed and sized as if it were a miniature pneumatic conveying system, in order to prevent it from getting blocked. With low pressure conveying systems a venturi can be used to feed the dusty gas from the vent directly back into the pipeline.

If the material to be conveyed is potentially explosive, the use of rotary valves will have to be questioned. With metal blades and a metal housing, a shower of sparks would result if the two were to meet, and a single spark would provide an adequate source of ignition for many materials. With positive pressure conveying systems rotary valve blade tip clearances need to be very small and so differential expansion, resulting from the handling of hot material, or bearing wear, could cause the two to meet. Bearing failure on a rotary valve could well result in a surface at a sufficiently high temperature to provide a necessary ignition source, both within and external to the conveying system. In a fault situation dust can leak from a pressurized conveying system and so bearings external to the system are vulnerable.

26.4.2.2 Blow tanks

The use of blow tanks has increased considerably in recent years and there have been many developments with regard to type and configuration. A particular advantage with these systems is that the blow tank also serves as the feeding device, and so many of the problems associated with pressure differentials across the feeder are largely eliminated. Blow tanks vary in size from a few cubic litres to 30 m^3 or more, generally depending upon the material flow rate required and the need to maintain a reasonable rate of blow tank cycling.

With single blow tanks, conveying is by way of batches, but with a large blow tank it may take many minutes to convey the batch, and so the material is likely to be conveyed on a semi-continuous basis. Although continuous air leakage does not occur with blow tanks, as it does with rotary valves, consideration does have to be given to the venting of the blow tank at the end of the conveying cycle, as well as on filling. A similar situation exists with regard to gate valve feeders. Blow tanks generally form the basis of mobile conveying systems, such as road and rail vehicles, and so special provision must be made for venting these during filling operations.

If a discharge valve is not employed on a blow tank there will be a considerable surge at the end of the conveying cycle as the pressurized air in the empty blow tank has to be vented through the pipeline. This will represent a considerable loading on the filtration plant and so it must be sized to take this transient situation into account. With a discharge valve the blow tank can be isolated, once the blow tank is empty, and as a consequence the cycling frequency can be increased quite considerably. In this case, however, the pressurized air in the blow tank will have to be vented before the blow tank can be re-filled and this will create a similar surge loading on the filter through which this air passes.

26.5 Conveying operations

Consideration must be given to some conveying operations and the conveying of certain materials with regard to safety provisions. Mention has already been made of start-up and shut-down transients, for example. In most dense phase conveying situations, the concentration of the material will be well above the value at which an explosion would be possible. During transient operation, however, and plant shut-down in particular, the concentration of the material in the air cannot be guaranteed to be above the required value while the system is being purged. Regardless of the conveying system and the mode of conveying, however, the material will generally be discharged into a receiving vessel, where there is every possibility of the material being dispersed in a low concentration cloud.

Pneumatic conveying is an extremely aggressive means of conveying materials, and particularly so in dilute phase conveying where high gas velocities are required. As a result abrasive particles can cause severe wear of the conveying plant and friable particles can suffer considerable degradation. The consequences of these influences must be given every consideration.

26.5.1 Tramp materials

High conveying air velocities also mean that tramp materials can be conveyed through the pipeline with the material being conveyed. It is possible for nuts, bolts and washers to find their way into the conveyed material, somewhere in the system, and these will be conveyed quite successfully through the pipeline, with the potential of generating showers of sparks, as they will inevitably make numerous contacts with the bends and pipeline walls in their passage through the pipeline.

26.5.2 Static electricity

Whenever two dissimilar materials come into contact, a charge is transferred between them. The amount of charge transfer depends upon the type of contact made, as well as on the nature of the materials. Almost all bulk solids acquire an electrostatic charge in conveying and handling operations. In a large number of cases the amount of charge generated is too small to have any noticeable effect, but in many cases appreciable charge generation can occur, resulting in high electric fields. Very often these are just a nuisance, but occasionally they can attain hazardous levels. In all cases where dust clouds are present the build-up of an electrostatic charge should be prevented.

Pneumatic conveying systems are prolific generators of static electricity. Frictional charging of the particles moving along the walls of a pipeline can lead to a carry-over of net charge into the receiving hopper. In the case of non-conducting materials a build-up of charge might occur in the receiving vessel, because of the difficulties of leakage through an insulating medium. In the case of conducting solids, electrostatic problems can still arise when the particles are suspended in air. In such a case the air prevents the electric charge on each individual particle from leaking away.

It is possible, therefore, for high electric fields to exist in receiving hoppers. In many cases the charge may reach the breakdown level for air and produce a spark. Such a spark may have sufficient energy to provide the necessary source of ignition for the dust cloud in the vessel, and hence cause an explosion. A 'rule of thumb' value of 25 mJ is often taken, and materials with ignition energies less than this may be regarded as being particularly prone to ignition by static electricity (see Table 26.2). In these cases special precautions should be taken.

26.5.2.1 Earthing

From an electrostatic point of view, pneumatic conveying lines should be constructed of metal and be securely bonded to earth. All flanged joints in the pipe-work should maintain electrical continuity across them, to reduce the chance of arc-over within the pipe. Particular attention should be given to areas where rubber or plastic is inserted for anti-vibration purposes, and where sight glasses are positioned in pipelines. Regular routine checks of the integrity of the earthing of all metal parts of the system should be carried out. The use of well grounded facilities can help to reduce these potential hazards.

Although certainly safer than systems that have plastic sections, where charge can build up, earthed metal systems will not ensure that the system is safe. Metal pipes provide a very effective source of charge for particles conveyed through them. The charge created on the pipe will flow instantly to earth, but that on the particles may remain for long periods. The storage potential is particularly important with regard to operations subsequent to conveying, for it is quite possible for such a charge on a material to be transferred to operatives.

If this occurred in the presence of an appropriate concentration of the material, the spark could provide the necessary ignition energy to cause an explosion. In this case special precautions should be taken, including the use of anti-static clothing and conducting footwear by all people in direct contact with a dust cloud. These, however, would be quite useless if they were to be used on a highly insulated floor, such as is often found in modern buildings. The operatives should stand on an earthed metal grid or plate at the point of operation.

26.5.2.2 Humidity control

Static generation on a material increases as the relative humidity of the surrounding air decreases and since it is more difficult to generate and store charges under more humid conditions, increasing the relative humidity of the conveying air to 60–75 per cent may also be used as a means of controlling the problem. The use of humidity for charge control is obviously not suitable for hygroscopic materials, and must be considered in relation to the possibility of condensation and freezing in any application.

26.5.3 Particle attrition

Of those materials that are explosible, research has shown that it is only the fraction with a particle size less than about 200 μm that poses the problem. If a size analysis of a material to be conveyed shows that there is no significant amount of material below this size, the possibility of an explosion occurring during its conveying should not be dismissed. Degradation caused by pneumatic conveying can result in the generation of a considerable number of fines, particularly if the material is friable. This point was illustrated earlier in Figure 24.2 which shows the possible fractional size distribution of a material both before and after conveying.

Initially the material had a mean particle size of about 350 μm, with a typically Gaussian distribution, and contained essentially no material below 200 μm in size. After conveying the mean particle size of the material was about 280 μm. The really significant effect, however, is shown in the fractional size plot in Figure 24.2. A considerable number of fines can be produced and even on a percentage mass basis these can cause a significant secondary peak in the particle size distribution. This is likely to occur with a very friable material, such as granulated sugar, when conveyed at high velocity over a long distance in a pipeline with a large number of bends. In terms of explosion risks the material after conveying could be a serious contender.

26.5.4 Erosive wear

Many materials that require conveying are abrasive. These include some of the larger bulk commodities such as cement, alumina, fly ash and silica sand. With a conveying air velocity of only 20 m/s silica sand is capable of wearing a hole in a conventional steel bend in a pipeline in less than 2 h. Erosive wear can be reduced with wear resistant materials and special bends, but it cannot be eliminated. Even straight pipeline is prone to wear under some circumstances.

If an abrasive material has to be conveyed, therefore, consideration must be given to the possibility of a bend or some other component in the system failing, with the consequent release of dust, particularly with a positive pressure conveying system.

Bends are available that have detectors embedded into them so that notice can be given in advance of an impending failure.

26.5.5 Material deposition

In long straight horizontal pipe runs, and large diameter pipelines, there is the possibility of material coming out of suspension in dilute phase conveying and depositing on the bottom of the pipeline. Accumulations of material such as pulverized coal in a pipeline could result in a fire, through spontaneous combustion, and possibly an explosion. An increase in conveying air velocity will generally help to reduce the problem but this is not an ideal solution. A disturbance to the flow with a turbulence generator usually cures the problem.

Food products, of course, will deteriorate if left in pipelines, and contamination of subsequent product could result. Since it is unlikely to be known whether such deposition occurs or not, it is necessary to physically clean all lines periodically. For food and pharmaceutical products, pipelines and all valves and components that could possibly come into contact with the material being conveyed are likely to be made of stainless steel. A particular problem with carbon steel is that it is liable to rust, as a result of condensation in the pipeline, and so contaminate the material.

26.5.5.1 Pipeline purging

If a pipeline is to be purged with the conveying air, in order to clear it of material, radiused bends should be used rather than blind tees. Blind tees are used in pipelines because they will trap the conveyed material and so provide protection to a bend from abrasive particles, since the particles will impact against each other rather than the bend wall. Material will require a much longer purging time to be completely cleared from blind tees. If additional air is available for purging, the process will be more effective. Air stored in a receiver will help here, particularly if it is at pressure, but care must be taken not to overload the filtration plant during this operation.

In dense phase conveying, air velocities employed are very much lower than those required for dilute phase conveying. Pipeline purging can be a major problem if additional air is not available. If high pressure air is used for conveying a material it is common for the pipeline to be stepped to a larger bore along its length once or twice in order to allow the air to expand and so prevent excessive velocities from occurring towards the end of the pipeline. This does, however, create problems if such a pipeline needs to be purged clear, for the purging velocity will decrease at each step to a larger bore and so considerably more air would be needed for the purpose (see Figure 9.16).

26.5.6 Power failure

The consequences of a power failure on system operation need to be considered at the design stage so that back-up systems and preventative measures can be incorporated at the time of installation. With a pneumatic conveying system the plant will generally shut itself down safely on loss of power, but whether it can be started up again will depend upon the type of conveying system, pipeline routing, mode of conveying and material properties.

In many cases the pipeline will block and the only method of restarting the system will be to physically remove the material from where the pipeline is blocked, usually at the bottom of a vertical lift. If this is not an option then a stand-by power system must be available to take over. Alternatively an air receiver can be built into the air supply system, and this will provide air to purge the lines sufficiently clear of material so that the system can be restarted when power is reinstated (see Figure 20.9).

If the possibility of the pipeline becoming blocked from any eventuality must be avoided, consideration should be given to the use of an innovatory system. In 'conventional systems' the material is simply blown or sucked through the pipeline. In 'innovatory systems' the material is either conditioned as it is fed into the pipeline, or along the length of the pipeline. There is no difference in any of the basic system components employed.

Air pulsing or trace air lines are generally employed. Parallel lines are used either to inject air into the pipeline, to give the material artificial air retention, or to allow the air within the pipeline to by-pass short sections of material, to give the material artificial permeability. Depending upon the properties of the material to be conveyed, one or other of these innovatory systems will generally guarantee that the pipeline can be restarted on full load.

26.6 Explosion protection

Despite the fact that the potential for an explosion in a pneumatic conveying system is high, the demand for such systems also remains high. This is partly due to the fact that the system totally encloses the material, such that dust generation external to the system is virtually eliminated, and with a pipeline total flexibility in the conveying route is possible without material transfer or staging. There are also a number of different means by which a pneumatic conveying system can quite easily be protected.

Since the dispersion of powdered and granular materials in air is fundamental to pneumatic conveying, it is evident that if a material is known or shown to be explosible, then consideration should be given to the hazard that this presents at the design stage of a system, or when re-commissioning an existing system to convey a different material. While it is equally obvious that the generation of sources of ignition should be minimized, unforeseen mechanical, electrical or human failures mean that the complete elimination of ignition sources cannot be relied upon, particularly where powered machinery is involved.

To avoid the potentially catastrophic effects of an explosion, therefore, reliance is normally placed on the adequate functioning of a means of protection for the system. Such protection is normally based on one or more of the following approaches:

1. Minimizing sources of ignition and prevention of ignition.
2. Allowing the explosion to take its full course but ensuring that it does so safely by either containment or explosion relief venting.
3. Detection and suppression.

The method of protection selected will depend upon a number of factors. These include the design of any associated plant or process, the running costs, the economics of alternative protection methods, the explosibility of the material, and the extent to which an explosion and its consequences can be foreseen, together with the requirements of any local regulatory authorities concerned.

26.6.1 Minimizing sources and prevention of ignition

The first step in any explosion protection programme is to minimize or eliminate, as far as possible, all potential sources of ignition. The minimum ignition temperature is relevant to ignition by hot surfaces. Rotary valve bearings have already been mentioned in this context, as an example, and welding operations on any part of the system should be prohibited while the system is operating. The possibility of sparks must also be reviewed, with due consideration given to valve operations, friction with conveyed materials, and electrostatic generation.

26.6.1.1 Inerting

Prevention of ignition can be guaranteed by using an inert gas such as nitrogen for conveying the material. Alternatively, nitrogen can be added to the air in order to reduce the percentage of oxygen present in the conveying air to a level at which a flame cannot be supported. The maximum oxygen concentration is one of the many standard tests that can be carried out with a material, as mentioned earlier. Since inert gases are rather expensive, these methods are generally used with closed loop systems (see Figure 26.2).

26.6.2 Containment

The combustion of a dust cloud will result in either a rapid build up of pressure or in an uncontrolled expansion. It is the expansion effect, or the pressure rise if the expansion is restricted, that presents one of the main hazards in dust explosions. The expansion effects arise principally because of the heat generated in the combustion and, in some cases, to gases being evolved from the dust because of the high temperature to which it has been exposed.

If the presence of evolved gases is neglected, the situation can be modelled very approximately with the thermodynamic relationship (see Section 9.2.3):

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$$

If the explosion is confined, V_1 will equal V_2 and so the resulting pressure, p_2, will be given by:

$$p_2 = p_1 \times \frac{T_2}{T_1}$$

Flame temperatures are typically a couple of thousand degrees and so it can be seen that explosion pressures can reach 7 or 8 bar. The critical information from Table 26.2, however, is that this pressure can be reached in milliseconds.

When a dust explosion occurs in industrial plant spectacular destruction can result if it is initially confined in a system that is ultimately too weak to withstand the full force of the explosion. Blow tanks and rotary valves, however, can be obtained that will withstand these pressures and in a positive pressure system the compressor or blower can be protected by means of a non-return valve in the air supply line. Most pipelines are also capable of withstanding this order of pressure.

If this is so, the resulting pressure wave would pass along the pipeline and be relieved at the weakest point, which is usually the reception vessel. Due to their size these are generally only capable of withstanding very low pressures, as mentioned earlier, and so if exposed to a higher internal pressure they would probably rupture or burst. Consequently the collection unit is likely to be the most vulnerable part of the system. It is unlikely to be an economic proposition to design the reception vessel to withstand the explosion pressure. There are, however, alternative means of protecting the receiving vessel.

26.6.3 Explosion relief venting

The usual solution to the problem in situations where the risk of an explosion is only very slight is to allow an explosion to take its full course, while employing suitable precautions to ensure that it does so in a safe manner. As an alternative to containment, the reception vessel can be fitted with appropriate relief venting. This may take the form of bursting panels, displacement panels or hinged doors that operate once a predetermined pressure has been reached.

In venting explosions to atmosphere strict attention must be paid to the safe dissipation of the explosion products. It is a characteristic that the volume of flame discharged from vents can be very large, and obviously must be directed to a safe place away from operatives and neighbouring plant. If this is necessary it is normally achieved by attaching a length of ducting to the vent, or by installing deflector plates. The duct attached to the vent should be short, free from bends (if at all possible) and other restrictions to flow, and be kept clear of dust at all times.

The size of duct, in terms of flow cross-section area, for explosion venting is particularly important. This is related to the maximum rate of pressure rise and the more vigorously explosible materials require larger areas of venting. The size of vent is also dependent upon the volume of the receiving hopper or silo. This situation can also be modelled very approximately from the above thermodynamic relationship. If the explosion is to be vented to prevent a pressure rise, p_1 will now be approximately equal to p_2, but V_1 will no longer equal V_2. Thus:

$$V_2 = V_1 \times \frac{T_2}{T_1}$$

and hence the volumetric flow rate of the gases now leaving the reception vessel will be about seven times higher than normal, and this does not take account of gases generated as a result of the explosion. There will be no possibility of the existing filter plant being able to cope with this increased flow rate and so venting is essential.

To keep the pressure drop in the explosion relief ducting to as low a value as possible, the duct will have to be of a large section area. Since pressure drop varies approximately with the square of velocity, the velocity of the gases in the ducting will have to be very much lower than that of the incoming conveying air. Combined with the sevenfold increase in steady state flow rate, and the fact that this is a transient situation, duct sizing is a complex task and should only be assessed by an expert.

26.6.4 Detection and suppression

If a system is inconveniently sited to allow for venting; a vent of the required size cannot be fitted onto the existing hopper; or if the material is toxic, so that it cannot be freely discharged to atmosphere, the protection may be achieved by a detection and suppression approach. Although there may be only a few tens of milliseconds between the ignition of the material to the build up of pressure to destructive proportions, this is sufficient for an automatic suppression system to operate effectively, as illustrated in Figure 26.3.

Commercial equipment is available that is capable of both detecting the onset of an explosion and of suppressing the explosion before it is able to develop. The sensing device, on detecting a rise in pressure, can send signals to switch off the air supply and stop the feeding device in order to prevent the conveying of any further material. A signal can also be sent to operate the automatic opening of a venting system. An automated opening has the advantage that vents are opened extremely rapidly and for very explosible materials this helps to reduce the maximum explosion pressure. Alternatively a suppressant system can be triggered. Such equipment operates as illustrated in Figure 26.4.

Suppression involves the discharge of a suitable agent into the system within which the explosion is developing. The composition of the agent depends upon the material being conveyed, and is typically a halogenated hydrocarbon, or an inert gas or powder. The suppressant is contained in a sealed receptacle attached to the plant and is rapidly discharged into the system by means of an electrically fired detonator or a controlled explosive charge. Thus, as soon as the existence of an explosion is detected, the control mechanism fires the suppressant into the plant and the flame is extinguished.

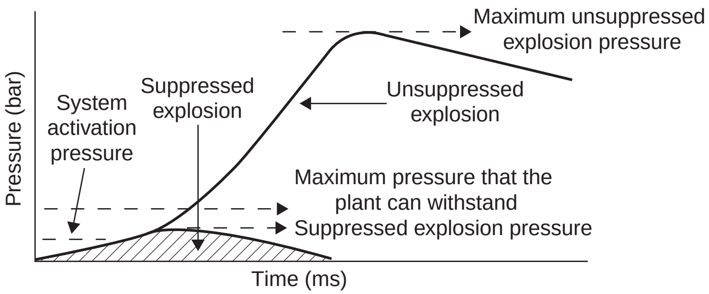


Figure 26.3 Comparison of pressure–time histories of unsuppressed and suppressed explosions.

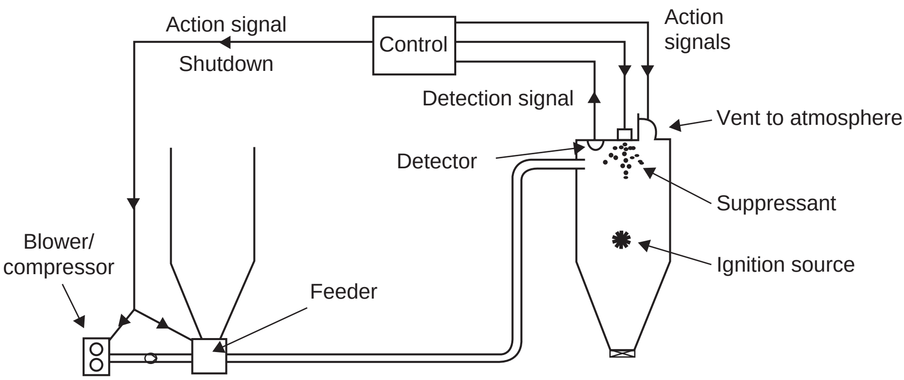


Figure 26.4 Basic scheme for detection and suppression.

Alternatively the explosion can be automatically vented. When the explosion is detected a vent closure is ruptured automatically, thus providing a rapid opening of the vent. The vented explosion then proceeds as for cases in which the vents are opened by the pressure of the explosion. Since it is obvious that once an explosion has been initiated, no more material should be fed into the system, plant shut-down can also be rapidly achieved with the detector approach.

26.6.5 Secondary explosions

With positive pressure conveying systems there is always the possibility of a failure or defect in the system resulting in the discharge of a dust cloud into the atmosphere. Abrasive materials wearing holes in pipeline bends and neglecting to tighten pipeline couplings have already been mentioned. Filters can also represent a weak link. A pressure surge from a blow tank, or supplementary air from an air receiver on purging a pipeline, may result in the release of dust, or even the failure of a filter element. A flammable dust cloud can be produced quite accidentally in many different circumstances.

There must, therefore, be no possible sources of ignition external to the system. One of the major sources of ignition in this situation comes from electrical equipment. If the material being conveyed is potentially explosive, therefore, it is essential that all the lighting, switches and switchgear, contacts and fuses, and electrical equipment in the vicinity, or within the same building, should be of a standard or class that would not be able to provide a source of ignition, whether a spark or hot surface. It is equally important that good housekeeping is maintained at all times within the same area, such that any dust release is not allowed to accumulate on any surfaces anywhere, and on lighting and electrical equipment in particular.

The release of a dust explosion from a conveying system into a building, or the explosion of a dust cloud released from a conveying system inside a building, are both clearly very serious situations. Little hazardous pressure is likely to develop from either of these sources of explosion within a large building, if short-lived, but the pressure wave generated usually shakes down more dust which has settled over a period of time onto pipe-work, roof beams and supports, ledges, lighting, etc. This then makes

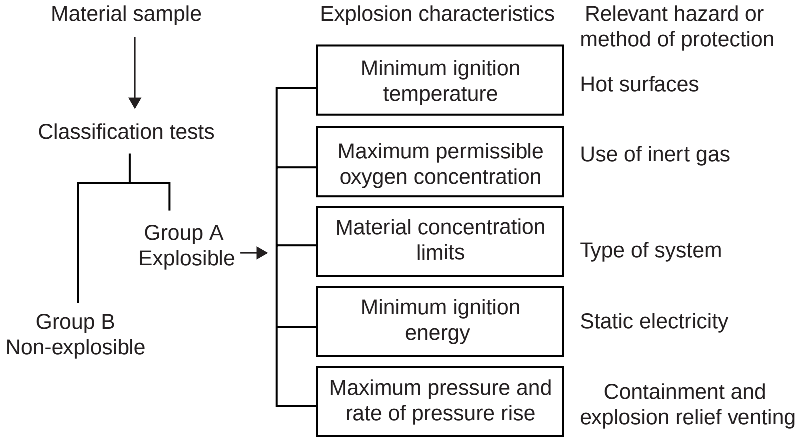


Figure 26.5 Basic scheme of explosion tests.

Table 26.3 Classification of test apparatus

Apparatus	Direction of dispersion of material	Ignition source	Application
Vertical tube	Vertically upwards	Electric spark or electrically heated wire coil	All types of dust
Horizontal tube	Horizontal	Electrically heated coil at 1300°C	Carbonaceous materials, especially of small particle size
Inflammator	Vertically downwards	Electrically heated wire coil or electric spark	Carbonaceous and metal dusts, especially large or fluffy particles

an ideal condition for the secondary explosion that almost always follows. It is this secondary explosion that can demolish a factory and kill the operatives.

26.6.6 Determination of explosion parameters

In the UK all tests concerned with assessing the explosibility or measurement of explosion characteristics of materials in suspension are methods agreed with HM Factory Inspectorate, and are carried out in the sequence shown in Figure 26.5.

As a result of this established procedure, data regarding the explosion characteristics of many materials already exists [1, 7–9]. With a material that has not been previously tested, the first step should be to determine whether it is potentially explosive. The outcome of such a test will then indicate the necessity of incorporating precautionary measures into the system design. In the UK, explosibility tests were conducted on an official basis by the Fire Research Station, with apparatus of the type summarized in Table 26.3.

26.6.6.1 Test apparatus

In the vertical tube apparatus the dust is placed in a cup and dispersed upwards over the ignition source by a controlled air blast. Observation of the flame propagation can then be made. A modification of the electrodes will allow this device to be used for the determination of minimum ignition energy. The Hartmann bomb is a more substantial version of this apparatus that can also be used for the measurement of explosion pressure and rate of pressure rise [10].

The horizontal tube apparatus also involves the dispersion by air of a dust sample over an ignition source. Since the residence time of a dust near the coil is short, any material that is observed to propagate a flame must be regarded as presenting a serious explosion hazard. The inflammator is essentially a vertically mounted glass tube. A sample of dust, held in a horizontal tube, is blown by air and is directed downwards by a deflector plate.

Although convenient for the testing of explosion characteristics, the Hartmann bomb has been criticized on the grounds that test results do not reliably scale up to correspond to industrial plant. This has led to the development of the so-called 20-l sphere apparatus. This consists of a spherical stainless steel vessel fitted with a water jacket. A dust cloud is formed in the vessel as the dust enters from a pressurized chamber through a perforated dispersion ring. Sixty milliseconds after the dust is released into the sphere the detonator is fired and the resulting pressure rise is monitored [10].

26.6.6.2 Material classification

Depending on the outcome of such tests the material is simply classified with respect to explosibility as follows:

- Group A – materials which ignited and propagated a flame in the test apparatus.
- Group B – materials which did not propagate a flame in the test apparatus.

Group A materials clearly represent a direct explosion risk and, as such, it would be a wise precaution, or even a legal requirement, to incorporate protection measures into the system. The range of materials that fall into this group is wide, as indicated earlier. Sand, alumina and certain paint pigments are examples of Group B materials. Some Group B materials, although not explosible, may nevertheless present a fire risk. Further details regarding materials that have been categorized with respect to this A and B classification may be obtained from [11].

If a material is shown to be of the Group A type, further information on the extent of the explosion hazard may be required when considering suitable precautions for its safe handling. The following parameters can be determined by use of the test methods described above:

1. minimum ignition temperature,
2. maximum permissible oxygen concentration to prevent ignition,
3. minimum explosible concentration,
4. minimum ignition energy,
5. maximum explosion pressure and rate of pressure rise.

Since the explosion characteristics, in terms of these parameters, of many materials are well documented elsewhere [7–9], it is not appropriate to include this information here. In order to illustrate the magnitude of the quantities involved, however, details regarding a few well known materials are given in Table 26.2 [7]. A summary of the applications of the results of these various tests to practical conditions is included in Figure 26.5.

References

1. P Field. Dust Explosions. Handbook of Powder Technology. Vol 4. Elsevier. 1982.
2. J Cross and D Farrer. Dust Explosions. Plenum Press. 1982.
3. HM (UK) Factory Inspectorate Technical Data Note 14. Health: Dust in Industry. London: HMSO. 1970.
4. C Schofield. Dust: The problems and approaches to solutions. Proc Solidex '82 Conf. Harrogate. March/April 1982.
5. Health and Safety Executive. Guidance Note EH 15/80. Threshold Limit Values. London: HMSO. 1980.
6. Corn Starch Dust Explosion at General Foods Ltd, Banbury, 18 November 1981. Health and Safety Executive Report. London: HMSO. 1983.
7. HM (UK) Factory Inspectorate. Dust Explosions in Factories. Health and Safety at Work Booklet No 22. London: HMSO. 1976.
8. M N Raferty. Explosibility tests for industrial dusts. Fire Research Technical Paper No 21. Ministry of Technology and Fire Offices Committee. London: HMSO. 1962.
9. C R Woodcock and J S Mason. Bulk Solids Handling: An Introduction to the Practice and Technology. Chapman and Hall. 1987.
10. K N Palmer. Dust Explosions and Fires. Chapman and Hall. London. 1973.
11. Dust Explosions in Factories. Classified list of dusts that have been tested for explosibility in the form of a dust cloud. Department of Employment. HM Factory Inspectorate SHW 830. London: HMSO. 1974.

Appendix 1

Determination of relevant material properties

A1.1 Introduction

For the purpose of characterizing and defining materials, for which conveying data has been obtained, it would always be recommended that various bench scale tests should be carried out on each material to obtain a number of measurable properties for reference. Such properties will allow comparison between the conveying capability of different materials to be made, and can enable correlations between material properties and pneumatic conveying characteristics to be determined, as illustrated in Section 13.3.2.

Details of a number of such tests that can be carried out to provide bulk and particle properties are presented in this appendix. Some property values are required for material identification purposes, such as mean particle size, size distribution and bulk and particle density. Some material properties will be required in system design, such as particle hardness, friability, moisture content and particle shape. Some of the bulk properties in which air and material interact are particularly useful in identifying conveying capability, such as air retention and permeability.

Such data was recorded for many of the materials tested in the various pneumatic conveying programmes that are reported in this Design Guide. Data obtained is presented in Appendix 2, along with additional conveying characteristics for a variety of materials and pipelines.

A1.1.1 The need for characterization

For the efficient transport and storage of bulk solids, descriptive parameters are required in a similar way to those used for single phase fluids such as liquids and gases. For these, property values such as density, viscosity and specific heat are used, and the influence of temperature and pressure can be readily taken into account. For bulk solids, however, few of these properties are appropriate and very few of the relationships that apply to single phase fluids and flow can be applied. By virtue of the nature of bulk solids it is found that very many more property values are required. The problem is even more complex than conventional two phase flow in which liquid and vapour exist together, for example, such as boiling and condensation, for they are both fluids and the different phases are of the same fluid.

A1.1.2 Particle and bulk properties

By virtue of the nature of bulk solids it is clear that some properties will relate specifically to the individual particles, and some to the material in its bulk form. The ambient fluid will also have to be taken into account. Two of the most common properties are density and size. Neither of these, however, is as straightforward as might at first appear. For density there are bulk and particle values, but for the bulk, in air, this can vary significantly with the degree of compaction of the material. Size, of course, relates only to the particles, but a bulk solid will generally contain a vast number of individual particles and in most cases the particles encompass a wide size range.

There is, therefore, a particular need for property values that specifically relate to bulk solids in the design of systems required to handle, store and transport bulk solid products. It is also important that any descriptive terms or parameters that are used for bulk solids are convenient, consistent and easily understood.

A1.2 Particle size and shape

Particle size is a property that can relate to both individual particles and to the bulk. Shape is principally a particle property. Most bulk solids consist of many particles of different sizes, randomly grouped together to form a bulk. For some purposes a single linear dimension, as a representative value of particle size, may be all that is required to specify a material. In other cases some form of distribution may also be necessary in order to give some indication of the size range of the particles constituting the bulk material.

A1.2.1 Particle size

A spherical particle is clearly defined by its diameter and this is a meaningful parameter. The general definition of particle size, however, is neither straightforward nor unique. Irregular particles may have a diameter defined in terms of a three-dimensional equivalence, such as:

- the diameter of a sphere having the same surface area,
- the diameter of a sphere having the same volume or mass,
- the size of a hole (circular or square) through which the particle will just pass.

Alternatively the equivalent diameter could be defined in terms of a two-dimensional equivalence, such as:

- the diameter of an inscribed circle,
- the diameter of a circumscribed circle,
- the diameter of a circle with the same perimeter.

There are also statistical diameters, such as:

- Feret's diameter, which is the distance between the tangents to extremities of the particle, measured in a fixed direction;
- Martin's diameter, which is the length of the line, in a fixed direction, that divides the particle seen in three dimensions into two equal areas.

The measurement of the sizes of individual particles is mainly of value in research work. In industry the use of size distributions is generally of greater value.

A1.2.2 Particle size distribution

A size distribution can be obtained by submitting a representative sample of a bulk solid to a particle size analysis. This relates the distribution of the particle size fractions that comprise the bulk. Two methods of presenting the data are commonly used. One is a cumulative plot and the other is a fractional plot. Both linear and logarithmic plots are used for the particle size axis.

A1.2.2.1 Cumulative representation

A typical cumulative percentage frequency curve is shown in Figure A1.1. This is generally represented on a percentage mass basis and can either be in terms of the percentage greater than a given particle size, or the percentage below the size. This can be used to determine the percentage of the material less than or greater than a specified size. In Figure A1.1, for example, Y per cent of the material is small than X micron.

The particle size corresponding to the 50 per cent value is generally referred to as the median value or mean particle size. The importance of representing the particle size distribution is clearly shown in Figure A1.2.

Both materials represented on Figure A1.2 have exactly the same median value but the size distributions are totally different. As a result the flow and storage characteristics of the two materials are likely to be very different. Size distribution and the mean particle size, therefore, are both very important properties.

A1.2.2.2 Fractional representation

A typical fractional percentage frequency curve is shown in Figure 24.2. This is often represented in the form of a histogram. It is particularly useful for comparative purposes as it has the effect of magnifying the results for individual particle size bands. In Figure 24.2 two plots are presented and these represent the potential size distributions for a very friable material before and after conveying. It can be seen that very

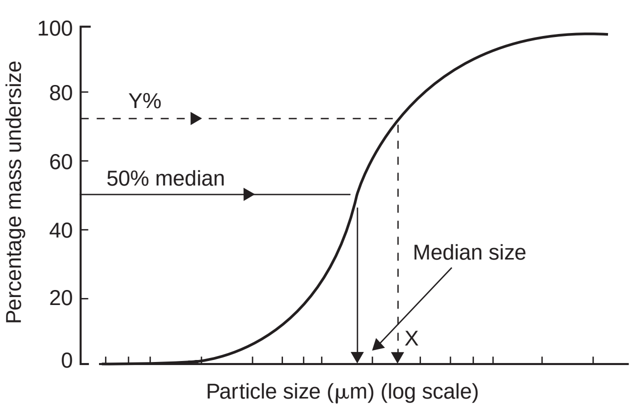


Figure A1.1 Typical cumulative particle size distribution curve.

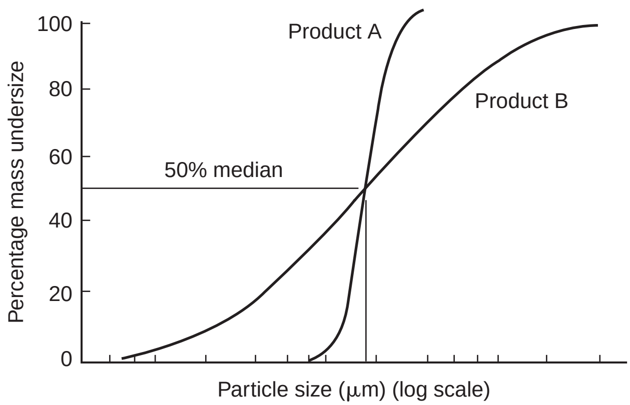


Figure A1.2 Typical cumulative particle size distribution curves for two materials with different size distributions but the same median.

significant degradation has occurred, resulting in the generation of a large percentage of fines, which can be clearly identified with this plot. It will be recalled that the plot is on a gravimetric basis and so the number of particles that this represents will be extremely large.

A1.2.2.3 Methods of determining size

There are many methods of determining the particle size distribution of bulk solids. The approximate useful range of a number of methods is indicated below:

Method	Range (micron)
Dry sieving	100 000–45
Wet sieving	100 000–10
Sedimentation and elutriation	75–2
Electrical sensing zone	800–1
Microscopy (light)	150–1
Microscopy (electron)	1–0.01
Laser diffraction	3500–0.001

This is an area where there have been many major developments and changes over recent years, as well as needs in terms of the sizing of an increasing number of materials in the sub-micron and nano-size ranges.

A1.2.2.3.1 Sieving

Sieving is probably the most common way of obtaining a particle size distribution. They are easy to use, produce reasonably consistent and reliable results, and sieves can be found that will cover the size range of a large proportion of the bulk solids of industrial importance. Sieving relies on the use of a series of sieves, each consisting of a woven wire mesh or perforated plate rigidly mounted in a shallow frame. Such sieves are specially manufactured so that the apertures in the wire mesh or perforated plate are of a certain size.

The measuring technique involves placing a pre-determined mass of the material to be sized on the top surface of a series of sieves stacked together. The stack is then agitated, generally by a mechanical shaker for a given time. The sieves are graduated from the largest at the top to the smallest at the bottom, with a similar pan beneath to collect the ‘fines’. The range of sizes is selected to suit the material being examined. Collecting and weighing the material retained on each sieve and in the pan then allows the size distribution to be analysed.

Sieving may be carried out either wet or dry. In wet sieving the bulk solid is washed with water, usually by means of a water spray, during the sieving operation. Wet sieving is used where there are problems of fine particles adhering to coarser particles. This is particularly a problem with materials subject to the influence of electrostatic charge. It is also possible to sieve to a smaller particle size with wet sieving.

A1.2.2.3.2 Sedimentation

The sedimentation method is based on the rate of settling of particles. This process is carried out by dispersing the sample in a liquid. If the bulk solid dissolves in water a suitable non-reactive liquid has to be used. With this method it is the ‘Stokes’ diameter that is determined. This is the diameter of a sphere that has the same density and free-falling velocity as the irregular particles under test.

A1.2.2.3.3 Elutriation

The elutriation method is based on the vertical lift of particles from a porous surface by an upward flow of air at a known velocity. It is the ‘Stokes’ diameter that is determined by this method, as with the sedimentation method described above. The proportion of the sample that is removed at a given air velocity is measured. The air velocity is then increased and the process is repeated. It is clearly a slow process as only one size can be measured at a time, but it is ideal for materials that are very friable and susceptible to damage on sieves and forced flow through laser diffraction devices.

A1.2.2.3.4 Electrical sensing zone

The electrical sensing method (the Coulter principle) enables both size and number of particles to be determined. The material sample is mixed in an electrically conductive liquid and the suspension is made to flow through a small orifice. On either side of the orifice is an electrode. Any particle that passes through the orifice increases the resistance between the electrodes.

This generates a voltage pulse, the magnitude of which is a function of the volume of the particle. The results, therefore, are given in terms of the diameter of a sphere of equivalent volume. These pulses are electronically scaled and counted and from the resulting data the size distribution of the sample can be determined, either in gravimetric of particle number terms.

A1.2.2.3.5 Microscopy

With the optical microscope method a sample of material is dispersed on a glass slide and the individual particles are observed and measured. Areas of the magnified images are compared with areas of reference circles of known sizes on a graticule. From this the diameter of the particles corresponding to their equivalent projected area are deduced. By using a transmission electron microscope, particles finer than one micron can be sized by similar means.

The principle disadvantage of sizing by microscopy is that it can be both tedious and time consuming. With the use of sophisticated electronic image analysing and counting techniques, however, the time element can be reduced considerably. A particular advantage of viewing the material through a microscope, however, is that, unlike all other sizing techniques, it also gives the opportunity to learn something of the shape and structure of the particles. These are also important characteristics, which relate to the nature of the bulk solid and how it may handle. It influences the packing arrangement of the particles and their interaction with fluids, and hence affects the flowability and conveyability of the bulk.

A1.2.2.3.6 Laser diffraction

During the early 1970s techniques were developed for determining the size distribution of a sample of fine particulate material by measuring the diffraction that occurs as a beam of light passes through a suspension of the sample. Within a few years the technique was improved to a point where a reliable size analysis could be made by a semi-skilled operative in just a few minutes. In recent years laser diffraction devices have taken most of the market share of both electrical sensing zone and sedimentation devices. The range of particle sizes has also increased, to both larger and smaller particles, with continuing development.

A1.2.3 Particle shape

The term particle shape is clearly self explanatory. The most established approach is to describe shape by quantitative terms that give an indication as to the shape of the particles as observed with the naked eye or through a microscope. In some cases it might be necessary to ascribe a numerical value to particle shape. For this purpose a sphere is generally taken as the reference shape.

A1.2.3.1 Descriptive terms

Shape is clearly difficult to define with one meaningful parameter, the significance of which can be understood universally. For this reason quantitative terms are used to give some indication of the general nature of shape, and standards exist that attempt to define the terms. A British Standard [1] defines the terminology of particle shape for powders, defined as particles with a maximum dimension of less than 1000 micron, as follows:

Term	Definition
Acicular	Needle-shaped
Angular	Sharp-edged or having roughly polyhedral shape
Crystalline	Of geometric shape, freely developed in a fluid medium
Dendritic	Having a branched crystalline shape
Fibrous	Regularly or irregularly thread-like
Flaky	Plate-like
Granular	Having an approximately equidimensional but irregular shape
Irregular	Lacking any symmetry
Nodular	Having a rounded irregular shape
Spherical	Globule shaped

A1.2.3.2 Shape factors

The problem with descriptive terms is that they are relative and, despite attempts to define the terminology, everyone has their own ideas regarding the meaning of the terms such as angular, irregular, nodular, and so on. Efforts have been made by researchers, therefore, to define shape on a more quantitative basis and many shape factors have been proposed. These are generally based on different measured characteristics of the particles.

One characteristic that has a physical significance is sphericity, ϕ, which is defined as the ratio of (the surface area of a sphere having the same volume as the particle) to (the surface area of the particle). In mathematical terms this is given by:

$$\phi = \frac{\pi\left(\dfrac{6V}{\pi}\right)^{2/3}}{S} \tag{A1.1}$$

where V is the particle volume (m^3) and S, the particle surface area (m^2).

The significance of this is that it gives an indication of the departure of the particle shape from that of a sphere of the same volume. Thus, for a sphere $\phi = 1$, but for any other shape ϕ will have a value less than unity (for example for a cube $\phi = 0.8$). Unfortunately the problem with using this apparently useful parameter is purely a practical one, in that is it not easy to measure the volume V and surface area A of a single irregular particle. There is then the additional problem of specifying a single representative value for the bulk that could contain particles of varying shape.

The general shape and structure of the particles is of particular importance to system designers. If the structure appears to be fragile it could indicate that they may be susceptible to degradation during conveying. A fibrous, thread-like shape will indicate that the particles may lock together and this may lead to problems in supply hoppers. The sharp edges of hard crystalline materials will indicate the possibility of erosion and abrasion of system components. Such information, therefore, enables the system to be selected and designed to minimize the risk of operational problems.

A1.2.3.3 Specific surface

Specific surface area is an important material property, especially when the material is used as a catalyst or an absorber, or is an active agent in a pharmaceutical product. Most particles are irregular and even with a single size range an accurate total surface for all the particles cannot usually be determined from a mean particle diameter. In some circumstances, however, the surface area can be calculated from particle size data [2]. The specific surface may also be calculated by air permeability and nitrogen adsorption (BET) methods. This is considered further in Section A1.5.6 on Aeration Properties A1.

A1.3 Particle and bulk density

Particle density relates, as the name implies, to the individual particles in a bulk solid. Only if the material is a mixture or blend of different materials, or if it is significantly influenced by contaminants, will there be any problem here. Bulk density is clearly a bulk property and material composition need not be considered. The condition or state of the bulk, however, is important, for different values will be obtained with aeration and compaction. The dimensions used for both particle and bulk density are kg/m^3.

A1.3.1 Particle density

Particle density is the mass of an individual particle of a bulk solid, divided by the volume of the particle.

A1.3.1.1 Reference values

The volume may be measured inclusive or exclusive of any open and closed pores that may exist. Closed pores are defined as being cavities not communicating with the surface of the particle. As a result, particle density can be expressed in a number of different ways:

- *True particle density*: This is the mass of the particle divided by the volume of the particle, excluding open and closed pores.
- *Apparent particle density*: This is the mass of the particle divided by the volume of the particle, excluding open pores but including closed pores.
- *Effective particle density*: This is the mass of the particle divided by the volume of the particle, including both open and closed pores.

A.1.3.1.2 Methods of determination

One of two devices is generally used for determining particle density. In both methods the displacement volume of a given mass of a small sample of material is measured.

A1.3.1.2.1 Relative density method

The classical method of determining the particle density of a material is to use a relative density technique. Relative density in this case is the ratio of the density of the particles tested to that of the known density of the comparing liquid used. The particle density, ρ_p, is then given by:

$$\rho_p = \text{relative density of particles} \times \text{density of comparing liquid} \tag{A1.2}$$

A more convenient device, however, is the air comparison pycnometer.

A1.3.1.2.2 Air comparison pycnometer

The air comparison pycnometer is particularly suitable for fine powders and for materials that are soluble or friable. The device consists of two small identical cylinders with pistons, one for measuring and one for reference. The cylinders are connected through a valve and a differential pressure indicator. The measuring piston is also connected to a scale, reading volume in cubic centimeters.

A1.3.2 Bulk density

This is the mass of material divided by the volume occupied by the material. If it is required to quote the bulk density exclusive of moisture, the term dry bulk density should be used. The normal procedure is to fill a container of known size and determine the volume occupied by the measured mass of the sample used. The container should be of regular geometric shape with smooth inner surfaces. As a general guideline the smallest dimension of the container should be at least 10 times the maximum particle size of the sample.

A1.3.2.1 Reference values

Bulk density values are difficult to determine with any degree of precision, and are very dependent on the sample and the method of filling the container. It is often more appropriate to quote a range of bulk densities rather than one specific value. In any bulk density measurement the test conditions should simulate or represent the actual conditions under which the bulk density needs to be known as closely as possible. In practice the value will vary depending on circumstances. Three main conditions are generally recognized for which bulk density values are specified.

A1.3.2.1.1 As poured bulk density

This is the bulk density that results from pouring the material into a heap or container in the absence of any applied compacting force. The bulk density, ρ_b, is then:

$$\rho_b = \frac{\text{mass of particles}}{\text{enclosed volume}}\ \mathrm{kg/m^3} \tag{A1.3}$$

A1.3.2.1.2 Compacted (tapped) bulk density

This is the bulk density created by the application of compacting forces, for example by tapping, impact or vibration. Compaction of the bulk solid can be accomplished by tamping the material, layer by layer, with some form of rod, according to a prescribed procedure. In the case of powders the container can be relatively small, and a glass measuring cylinder is generally used. Compaction of the powder can be achieved by bumping the cylinder against a flat surface according to a prescribed procedure.

A1.3.2.1.3 Aerated bulk density

This is the bulk density created when the material is fluidized and the particles are separated from each other by an air film. This only applies to fine, dry powders, for with large particles the air will simply pass through the interstices and not separate the particles, and wet and cohesive materials will not aerate/fluidize. The aerated bulk density can be measured very simply by inverting a glass measuring cylinder, partly filled with a known mass of the material, and reading off the inverted level as quickly as possible. For a more precise value a special apparatus should be used in which a column of powder is expanded by air via a porous base. Aeration should be according to a prescribed procedure.

A1.3.2.2 Application

A knowledge of the bulk density is essential for the determination of several important factors in the design of a conveying system. These include:

- The approximate mass of material discharged per unit time by a feeder of known volumetric capacity.
- The approximate mass of material in a hopper or receiver of known volume, and
- The approximate volume of a hopper or receiver that is required to store a specified mass of material.

Unfortunately, unlike particle density that has a unique value, bulk density depends upon the condition of the material. If, for example, a material has just been pneumatically conveyed to a receiving vessel, the aeration can have the effect of ‘fluffing up’ the material such that it will have a low bulk density. After a period of time, however, a combination of this air percolating out of the bulk, together with a reorientation of the particles due to extraneous vibrations that occur in almost every plant, the volume occupied by a given mass will gradually reduce and therefore increase its bulk density.

Obviously, the bulk density used to size a specific item of equipment should approximate, as closely as possible, to the condition of the material at that point in the system at any given time. This is difficult to determine, however, and experience has shown that a knowledge of the ‘as poured’ and ‘tapped’ values enables the designer to estimate, with a reasonable degree of accuracy, the volume or mass of material in or delivered by the component in question.

A1.3.3 Voidage

There will clearly be a difference between the particle and bulk density values for any given bulk solid. In general the particle density will be about double that of the 'as poured' value. Obviously, this bulk density value depends upon the particle density, particle shape and how the constituent particles are packed or positioned with respect to each other. The normal method of relating these factors is by the expression:

$$\rho_b = \rho_p(1 - \varepsilon) \text{ kg/m}^3 \tag{A1.4}$$

where ρ_b is the bulk density (kg/m^3); ρ_p, the particle density (kg/m^3) and ε, the voidage. The voidage, therefore, represents the proportion of space not occupied by the particles within the bulk.

A1.4 Flow properties

Bulk solids range from very free flowing to very cohesive. The position of a particular material relative to these two extremes provides an indication of its 'flowability'. It is essential that a designer has an indication of this at an early stage, since it influences the type of system and components that are required to handle the material. Flowability is significantly influenced by the inter-particulate forces that exist within a bulk solid.

With free-flowing materials the forces of attraction between the constituent particles are negligible, so that the bulk can be very easily induced to flow under the action of gravity, even if it has been subject to prior consolidation. When such materials flow they do so as individual, discrete particles; dry sand and granulated sugar are examples. With cohesive materials the inter-particulate forces are high enough to prevent this from occurring and when such materials flow they do so in a 'lumpy' or 'batch-wise' manner. Starch and cocoa powder are typical examples.

In general free-flowing materials present few problems with respect to the design of a system. However, great care must be exercised with systems to handle cohesive materials since their reluctance to flow can lead to numerous difficulties. Unfortunately the transition from free flowing to cohesive behaviour is ill defined, and there are many materials which, by a slight change in operating conditions, can effectively change their flow characteristics. It is clearly important, therefore, to have a thorough understanding of the nature of the material at the design stage of a system.

A1.4.1 Factors influencing flowability

The principal factors influencing the flowability of bulk solids are particle size, particle shape, electrostatic charge and moisture. It is quite possible that a combination of these, rather than any single factor, would be responsible for the poor flow characteristics of a material.

A1.4.1.1 Particle size

With respect to particle size, there is a natural force of attraction between particles that increases with decreasing size. This factor alone is sufficient to render a material that is identical in every other respect, less free flowing over a finer size range. From experience it would appear that 50–100 μm is the approximate range where dry, regularly shaped materials exhibit a noticeable change in flow characteristics. A knowledge of particle size distribution is therefore clearly essential.

A1.4.1.2 Particle shape

The influence of particle shape is easier to understand. Regular shaped particles cannot pack together to form a mechanical bond and so cannot impede the free movement of a particle with respect to its neighbours. Highly irregular shaped and fibrous particles, however, can interlock and thereby render the bulk less free flowing than a more regular shaped material.

A1.4.1.3 Electrostatic charge

As a result of handling the material it is possible for the particles to acquire an electrostatic charge. Experience has shown that such a charge can change even the most free-flowing material into one that exhibits cohesive characteristics. Certain polymers, such as PVC resins, are particularly susceptible to flow problems of this kind.

A1.4.1.4 Moisture

Moisture can affect flowability in several ways. Deliquescent materials such as sugar may form a hydrate of the surface of the particles. These may cause them to bind together to form a cake and prevent them from flowing. With materials such as sand, where the particles are impervious, any moisture will adhere to the surface of the particles. This moisture can be sufficient to form water bonds, thereby causing the particles to cohere. Moisture in this form is referred to as 'free moisture'. The general trend is for added moisture to increase the cohesiveness of a bulk solid until a peak is reached, after which further moisture addition has the opposite effect until ultimately the bulk solid will behave like a slurry.

With materials that have particles that are pervious to water, any moisture will be preferentially absorbed into the particles until a point is reached where they become saturated. Unless the material is also deliquescent, moisture in this form does not contribute to its cohesion. It is the excess water that contributes to cohesion since this then manifests itself as surface moisture. With some pervious materials there may be a certain amount of water that, under normal atmospheric conditions, always remains within the particles, such as with 'wheat flour'. This is commonly referred to as 'inherent moisture'.

A1.4.2 Tests for flowability

Tests for characterizing the flowability of bulk solids range from very simple tests to highly sophisticated techniques. A very simple approach is to take a handful of the material and to see if it can be consolidated into a ball by squeezing it. Alternatively a shear tester can be used to quantify this characteristic, but a high level of expertise is required to use the equipment. The approach that is commonly adopted is to undertake a quick comparative test and to place the outcome in context with experience from handling and testing similar types of material. To this end the angle of repose is a useful indicator of a material's flowability.

A1.4.2.1 Angle of repose

The angle of repose is the angle between the horizontal and the natural slope of a heap of the material. In general, the lower the angle the more flowable is the material. In general, the lower the angle the more flowable is the material. Unfortunately, different angles can be obtained from the same material, depending on the method adopted.

A1.4.2.1.1 Poured angle of repose

The most commonly used method is to pour a sample of material from a known elevation onto a plate and measure the resulting angle. This is known as the poured angle of repose. For a poured angle of repose the pour point can be fixed or raised. If it is raised as the same rate as the growth rate of the mound it may discourage collapse of the pile. Pouring from a fixed height above the base, however, is likely to more closely simulate the filling of a hopper or loading of a stockpile. The flowability may be assessed in terms of this poured angle of repose as follows:

Rating	Angle to horizontal (degrees)
Very free flowing	25–30
Free flowing	30–38
Fairly free flowing	38–45
Cohesive	45–55
Very cohesive	>55

A1.4.2.1.2 Drained angle of repose

Alternatively the angle of slope of the inverted cone that forms when a mass of bulk solid is allowed to discharge through an orifice in the base of a flat bottomed container can be measured. This is known as the drained angle of repose. This drained angle of repose can additionally be obtained by allowing material to drain past a small circular table positioned within a cylinder. The device is filled with material and the angle of the material on the table is measured after the material has either been drained from the cylinder via a hole in the base, or by carefully removing the cylinder from the material.

A1.4.2.1.3 Fluidized angle of repose

It is clear that the flow characteristics of a given material are likely to be improved if its angle of repose can be reduced. Two common methods of achieving this are by the application of vibration and by the introduction of air to the material. With many materials either of these methods can be used to induce a 'fluidized' condition in which the angle of repose tends towards zero and the material takes on the characteristics of a liquid.

A1.4.2.2 Application

It should be emphasized that, although the angle of repose is not the most definitive property of a bulk solid with respect to its flowability, it often serves to characterize the material in this respect to a level that is sufficient for system design. The angle of repose, of course, is particularly useful for calculating the volume of a stored mass of bulk solid, such as that in a stockpile or silo.

A1.5 Aeration properties

Aeration is a rather loose term to describe the condition that exists when, through some form of agitation, the constituent particles of a bulk solid are separated from one another by an air film. In practice the term is only relevant to powders and fine granular materials, but bulk solids consisting of coarse particles can be aerated if the particle density is low enough. A simple visual test that can be used to assess the aeration potential of a bulk solid is to place a sample of it in a glass jar. If it is shaken and inverted for a short period, the resulting volume increase in the space occupied by the material is an indication of the degree of aeration.

A1.5.1 Fluidization

A special case of aeration is fluidization. This occurs when the aeration is sufficient to cause the material to assume liquid-like properties. The onset of fluidization roughly coincides with the situation when the air flow percolating through a column of material is just sufficient to support the column in a fluidized state. Increasing the air flow still further can result in considerable expansion of the material with bubbling of the air as it breaks through the surface.

A particulate material in this fluidized state exhibits a number of fluid-like characteristics. It will, for example, flow through a hole in a vessel in which the material is fluidized, light objects will 'float' on its surface, and in a large vessel the surface will remain effectively horizontal if the vessel is tilted. A development of this characteristic is the continuous aeration of a bulk solid in an inclined channel which allows the material to flow steadily along the channel even when its slope is as little as two or three degrees.

A1.5.1.1 Fluidized angle of repose

Most free-flowing materials display a natural angle of repose of around 30–38°. In order to get such a material to flow continuously, under gravity alone, or on an inclined surface it would normally be necessary for the slope of the surface to be greater than this angle of repose. Materials exhibiting some degree of cohesiveness have much larger angles of repose and often will not flow, even on steeply inclined surfaces, without some form of assistance.

The introduction of air to a bulk solid, by supporting the material on a plate made of a suitable porous substance, for example, and allowing the air to flow upwards through it into the material, can significantly reduce the angle of repose. The material will then flow continuously from the plate when it is inclined at a very shallow angle. This needs only to be greater than the fluidized angle of repose of the material. For most free-flowing materials this is about 2–6°.

A1.5.1.2 Applications

The tendency for a bulk solid to flow in the manner of a fluid when aerated has resulted in the widespread use of aeration as a 'flow aid'. A particular example of this is for the assisting of 'difficult' materials to discharge from hoppers. If a bulk solid is fluidized easily the system for handling it will have to incorporate positive means of control. Shut-off valves will have to be provided at hopper outlets, for example, otherwise flood feeding may occur. Conversely, if the material does not fluidized, or requires too much air, it is unlikely to be unsuitable for transport by air-assisted gravity conveyor.

The fluidization technique has also found widespread acceptance in industry as a means of ensuring continuous contacting between the particles of a bulk solid and a gas or liquid for chemical process purposes. One of the first applications was the gasification of powdered coal. Many other processes have since been developed that make use of the properties of fluidized beds, including drying, mixing, plastic coating and fluidized combustion.

A1.5.2 The permeameter

A number of bulk solids properties associated with aeration can be determined by means of a permeameter. This consists of a vessel of uniform section area, which is usually circular, having a porous membrane at the base. An air supply that is capable of being varied over a wide range is provided. A means of measuring the pressure drop across the bulk solid is also required. A sketch of such a device is shown in Figure A1.3.

A1.5.2.1 Superficial air velocity

Although the volumetric flow rate of air is measured and controlled, it is the superficial air velocity that is the important parameter. This is the volumetric flow rate of the air divided by the cross-sectional area of the fluidizing vessel when empty. A programme of tests with a material entails the determination of the variation of the pressure drop, across a bed of material of given depth, with superficial air velocity. A typical relationship

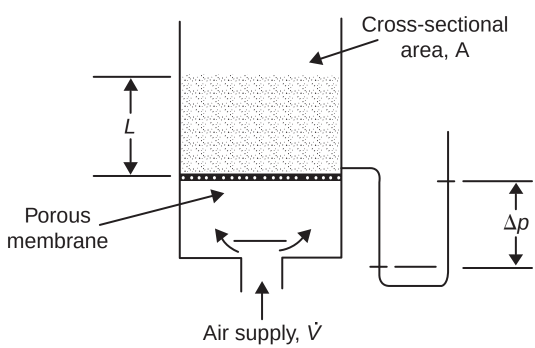


Figure A1.3 Sketch of a typical permeameter.

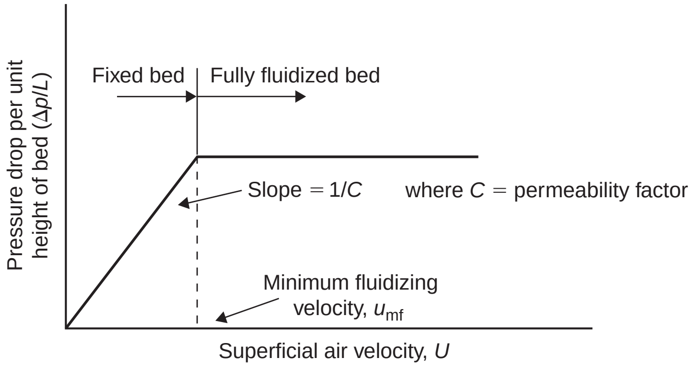


Figure A1.4 Typical relationship between pressure gradient and air velocity for flow through a bed of material.

between pressure gradient and air velocity for flow through a bed of material is shown in Figure A1.4.

A1.5.2.2 Permeability factor

When air percolates through a material, a pressure drop will result, in the direction of flow. The relationship between air flow rate and the pressure drop, for the fixed bed region, as shown in Figure A1.4, is called the permeability. Referring to Figure A1.4:

$$U = \frac{C\Delta p}{L} \text{ m/s} \tag{A1.5}$$

where U is the superficial air velocity through bed (m/s) $= \dot{V}/A$; $\dot{V}$, the volumetric air flow rate (m^3/s); A, the cross-sectional area of bed (m^2); Δp, the pressure drop across bed (N/m^2); L, the bed height (m) and C, the permeability factor ($m^3 s/kg$ or $m^4/N{\cdot}s$).

The permeability factor, C, can be measured by use of the permeameter, as shown in Figure A1.3, which in turn enables the graph shown in Figure A1.4 to be drawn and the permeability factor to be measured. It is normally expressed in units of $m^3 s/kg$ or $m^4/N{\cdot}s$.

A1.5.3 The fluidization process

The permeameter, if provided with a glass or Perspex container, can be used to illustrate the influence of superficial air velocity on fluidization behaviour. At low flow rates the air will merely filter through the interstitial voids without disturbing the packing arrangement of the bed. If the air flow rate is gradually increased, the pressure drop across the bed will increase, as shown in Figure A1.4. For a given bed the pressure drop across it depends only on the flow rate of the air, and in most cases the relationship is approximately proportional. This phase is termed a ‘fixed’ or ‘packed’ bed.

A1.5.3.1 Minimum fluidizing velocity

If the air flow rate is increased further, a stage is reached when the pressure drop approaches the magnitude of the downward gravity force per unit cross-sectional area of the bed of particles. The pressure drop across the bed at this point can be readily calculated from fluid mechanics with the expression:

$$\Delta p = \rho g L \, \mathrm{N/m^2} \tag{A1.6}$$

where ρ is the bulk density of fluidized material (kg/m^3); g, the gravitational acceleration (m/s^2) and L, the bed height (m).

If the bed is not restrained on its upper surface there will be a slight expansion of the bed accompanied by a re-arrangement of the particles as each one tends to 'float' separately in the upward flow of air. This re-arrangement brings the particles towards a state corresponding to the loosest possible packing in the bed, which is now on the point of becoming 'fluidized'. The 'minimum fluidizing velocity', U_{mf}, is defined as the point at which the bed of particles becomes fully supported from this loosest packing arrangement.

A1.5.3.2 Pneumatic transport

Further increase in the superficial velocity will cause little, if any, change in the pressure drop across the bed. It will, however, cause the bed to expand, thus allowing additional spaces between the particles through which the air can pass. At still higher velocities the excess air tends to pass through the bed as a series of bubbles. Eventually a stage is reached where the interstitial velocity of the upward flowing air approaches the terminal velocity of individual solid particles. These particles then become entrained in the air flow, being carried upwards from the surface of the bed, and the system approaches a condition to that of pneumatic transport.

A1.5.4 The influence of particle size and density

The behaviour of a bulk solid in these flow situations is strongly dependent upon the characteristics of the material. The quality of fluidization, or whether a fluidized state can be achieved, is influenced by particle size, particle density and cohesiveness.

A1.5.4.1 The Geldart classification

Probably the most useful work dealing with fluidization characteristics of different types of particulate bulk solids has been that of Geldart [3]. He showed that the behaviour of a material fluidized by a gas can generally be classified into one of four recognizable groups. These groups are characterized by the difference in density of the solid and fluidizing medium, and by the mean particle size. The classification for fluidization with ambient air was presented in Figure 2.17 and is reproduced here in Figure A1.5 for reference. For fluidization with air the density of the air can be neglected and so the vertical axis is simply in terms of the particle density.

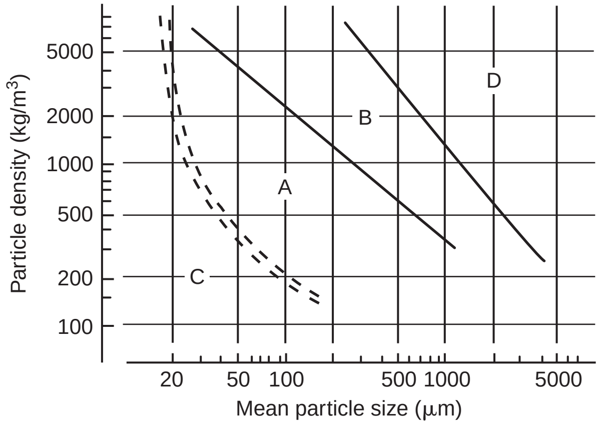


Figure A1.5 Geldart's classification of fluidization behaviour for fluidization with ambient air.

The salient features of the four groups identified may be summarized as follows:

- *Group A*: Materials in this group show considerable expansion of the bed when fluidized. They also have good air retention properties, for when the air supply is cut off relatively slow settling of the bed results.
- *Group B*: Materials in this group fluidize very well and would typify the generally accepted model of fluidized bed behaviour. At air velocities above the minimum fluidizing velocity the expansion of the bed is small, and bubbling occurs at or just above this value. Collapse of the bed is rapid when the gas flow is shut off.
- *Group C*: This covers the cohesive materials. These are difficult to fluidize satisfactorily because of the high inter-particulate forces resulting from the very small particle size. Attempts to fluidize such materials usually results in the formation of stable channels or in the whole bed rising as a plug. Some success may be achieved, however, with the aid of mechanical vibrators or stirrers.
- *Group D*: This group includes materials having a large particle size and/or a high particle density. Fluidization behaviour is generally similar to Group B materials, but the quantity of air required trends to become rather high.

A1.5.5 Air retention

Some bulk solids, when fluidized or agitated in some way, have a tendency to retain air for a period, as mentioned in relation to Group A materials in Geldart's classification mentioned above. A measure of the air retention capability of a material can also be obtained by use of the permeameter (Figure A1.3).

A1.5.5.1 De-aeration constant

The air retention capability of a material is assessed in terms of the time it takes a fluidized bed of material to return to a specified bulk density, or level in the permeameter, after quickly shutting off the air supply. The starting, or reference, point for such a determination, is that the fluidizing should be at the point that provides a maximum volume increase of the material without severe bubbling at the material surface.

For convenience a scale should be provided on the permeameter. With some bulk solids the level of the material falls very rapidly, particularly in the early stages, and so this is not a constant that can conveniently be recorded manually at the time it is carried out.

A1.5.5.1.1 Analysis

One method of obtaining the necessary data is to use high speed photography. Another method is to use a video tape recording of the fall. Sutton and Richmond [4] analysed this transient fall by extending Fick's Law of Diffusion to the situation. They obtained:

$$\frac{\mathrm{d}\rho}{\mathrm{d}\tau} = k'' \frac{\Delta p}{L} \tag{A1.7}$$

where ρ is the material bulk density (kg/m^3); ρ, the time (s); k'', the de-aeration constant (m/s); Δp, the pressure drop across bed (N/m^2) and L, the bed height (m).

Integration of this expression between suitable experimentally derived limits will yield the de-aeration constant. High values of this constant indicate a high settling rate and, therefore, poor air retention capability.

A further method of monitoring rapid transients is to use an electronic differential pressure transducer. If this is connected across the pressure tappings on the column of material on the permeameter, it will provide a suitable trace of the pressure decay following the shut off of the air, for evaluation of the constant.

The value of the de-aeration constant obtained will give some indication of the capability of a material for dense phase pneumatic conveying, without the need for air addition along the length of the pipeline. It will also give an indication of the effect that aeration might have on the material, for aiding its discharge from hoppers.

A1.5.5.1.2 Vibrated de-aeration constant

If the bed of material in the de-aerated condition is vibrated, the height will fall in a similar manner to that described above, in which the fluidized bed height falls when the air supply is cut off. A comparison of the two de-aeration plots of bed height versus time is illustrated in Figure A1.6 [5].

It is possible, therefore, that this vibration test could generally be of more value than the permeameter method. For materials that exhibit poor air retention characteristics, and hence de-aerate rapidly, the rate of change can be slow enough to observe visually. On the other hand, for some very air retentive powders, the settling time can run into hours and even days and vibration can speed up the process considerably.

It is also very much easier to apply to cohesive and other materials that are difficult to aerate. Vibration is applied in the vertical plane, but only a narrow band of frequencies have a settling effect on materials. If the frequency is too low it has little

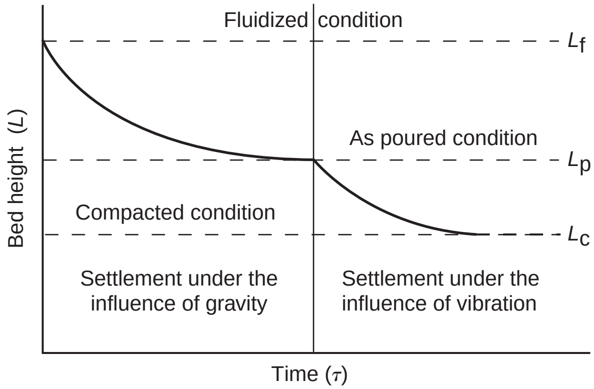


Figure A1.6 Comparison of de-aeration curves.

effect and if it is too high dilation will occur instead of compaction. It is also the case that the higher the frequency the lower the penetration of vibration into the material.

A1.5.5.1.3 Analysis

An idealized graph showing the change in bed height with respect to time was shown above in Figure A1.6. This compares settlement under the influence of gravity and vibration. It can be seen that the relationship in each case is similar and, therefore, it is not unreasonable to apply the analysis proposed by Sutton and Richmond for the settlement of powders under the influence of gravity to the settlement of powders under the influence of vibration. The application of the analysis of Sutton and Richmond to this case yields:

$$\frac{\mathrm{d}\rho}{\mathrm{d}\tau} = k_v'' \frac{\Delta\rho}{L} \tag{A1.8}$$

where k_v'' is the vibrated de-aeration constant (m/s) and $\Delta\rho = \rho_\infty - \rho$ (kg/m^3).

This expression can be put into a form where it can be integrated and the following boundary conditions applied:

at $\tau = 0,\ L = L_1 \quad \tau = \infty,\ L = L_\infty$

The result is:

$$L_\infty \ln\left[\frac{\dfrac{1}{L}\left(\dfrac{1}{L_\infty} - \dfrac{1}{L_1}\right)}{\dfrac{1}{L_1}\left(\dfrac{1}{L_\infty} - \dfrac{1}{L}\right)}\right] = k_v''\tau \tag{A1.9}$$

where L_1 is the initial bed height (m) and L_∞, the final bed height (m).

This equation can be written in the form of a straight line graph, the slope of which is the vibrated de-aeration constant.

Thus

$$H = k_{\mathrm{v}}''\tau \tag{A1.10}$$

where

$$H = L_\infty \ln\left[\frac{\dfrac{1}{L}\left(\dfrac{1}{L_\infty} - \dfrac{1}{L_1}\right)}{\dfrac{1}{L_1}\left(\dfrac{1}{L_\infty} - \dfrac{1}{L}\right)}\right] \tag{A1.11}$$

A detailed test procedure is given in Ref. [5]. These tests are relatively easy to undertake and take little time to carry out. A small sample of the material is all that is required and the equipment needed to carry out the tests manually is relatively simple and inexpensive.

A1.5.6 Specific surface

The specific surface of a material is expressed in terms of the total surface area per unit mass, m^2/kg, or per unit volume, m^2/m^3, of the material. Specific surface is often used as a measure of the 'fineness' of a material. Several different methods for determining a value of specific surface have been developed.

A1.5.6.1 British Standard procedure

A British Standard [2] sets out a procedure and provides a theory and equations from which an estimated value of specific surface can be obtained by using an air permeameter. The theory is based on an equation derived by Carmen and Arnell. This relies on the fact that the rate of flow of a moving fluid, under the influence of a constant pressure difference through a compacted bed of uniform cross-sectional area, is a function of the surface area that the walls of the channels through the bed present to the moving fluid. As there is normally a great variation in, and a lack of precise knowledge of, the shape and dimensions of such channels, rigorous mathematical treatment is impracticable. By making a number of assumptions, however, the specific surface of many powders can be estimated from air permeability data.

A1.5.6.2 Lea and Nurse method

A permeability cell, similar to the permeameter, is used, except that the air flow is in the opposite direction. It consists of two metal cylinders, 25.40 mm diameter, connected by flanges with a recess for a perforated plate [6]. Filter paper is placed on the perforated plate and a given mass of material is introduced. A plunger is provided to form the sample into a cylindrical bed 10.00 mm deep. The sample, in the case of cement, must have a porosity of 0.475. The cell is connected to a bed manometer and a flow meter manometer. Specific surface, for a specified air flow rate, is determined from the manometer reading and the density of the material.

A1.5.6.3 The Blaine method

The cell of this permeability apparatus is 12.70 mm diameter with a perforated plate at the base. A plunger is provided to form a bed of material 15 mm high. This method is usually associated with cement, for which the porosity must be 0.500. Air is evacuated until the manometer liquid reaches the top mark. The valve is shut tight and a clock is started when the liquid reaches the second marked level. The time is recorded for the liquid to drop to the third level. Prior calibration of the instrument to a set procedure is necessary, and Ref. [7] provides equations for the evaluation of specific surface.

References

1. BS 2955. Glossary of terms relating to powders. 1958.
2. BS 4359. Methods for determination of specific surface of powders. Part 2: Air permeability method. 1971.
3. D Geldart. Types of gas fluidisation. Powder Technology. Vol 7, pp 285–292. 1973.
4. H M Sutton and R A Richmond. Improving the storage conditions of fine powders by aeration. Transactions of the Institution of Chemical Engineers. Vol 51. 1973.
5. M G Jones and D Mills. Product classification for pneumatic conveying. Powder Handling and Processing. Vol 2. No 2. pp 117–122. June 1990.
6. BS 4550. Part 3, Section 3.3. Methods of testing cement. 1978.
7. ASTM Standard test method for fineness of Portland cement by air permeability apparatus. C204. pp 211–218. 1984.

Appendix 2

Additional conveying data

A2.1 Introduction

Conveying data on a wide variety of materials has been used to illustrate the influence of material properties on conveying capability and performance. The importance of material grade has been highlighted, as well as the potential influence of material degradation as a result of pneumatic conveying. Conveying data has also been used to show how scaling parameters for pipeline bends, pipeline orientation and pipeline material can be evaluated.

The main point with regard to conveying data, however, is its importance in system design. Since different materials, conveyed under identical conditions of air flow rate and pressure drop, can exhibit widely varying material flow rates, conveying data and scaling is widely used for system design. The determination and specification of the minimum conveying air velocity is equally important.

To this end actual conveying data in the form of complete performance maps has been used throughout. For most applications just one or two data points will be required, but this will allow a wide range of pressure drop options to be considered and a choice between dilute and dense phase conveying, where this is a possibility. Full details of each pipeline used are also provided.

A2.2 Materials and pipelines listings

The different materials for which conveying characteristics are presented in this Design Guide are listed in Table A2.1. The figure number for the appropriate data is given, together with the pipeline reference number. Pipeline information can be obtained from Table A2.1.

Details of the pipelines used for conveying the various materials are presented in Table A2.2. The number of the figure in the text is given for each so that a sketch can be viewed, and basic details are listed in Table A2.2.

From the sketches of the pipelines it will be seen that many of the routings follow a prescribed pattern. This was to a design of the author for the benefit of the original Design Guide and for the specific purpose of generating a wide range of conveying data. A dimensioned plan view of the laboratory in which they were installed is given in Figure A2.1.

Table A2.1 Reference list of materials for which conveying characteristics are presented

Material	Type or condition	Figure no.	Pipeline no.	Material
Alumina	Floury	13.21b	9	
	Sandy	12.14a	3	
		13.21a	9	
			6	
Alumina	Calcined	12.6a	2	
Alumina	Hydrate	12.6b	2	
		A2.9b	18	
Aluminium fluoride		A2.9a	18	
Ammonium chloride		A2.2a	2	
Barytes		12.7b	2	
		12.13b	3	
		14.14a	7	
		14.14b	12	
		14.28a	14	Steel
		14.28b	14	Rubber
		A2.7a	17	
Bentonite		12.21a	5	
Cement	Ordinary Portland	12.23a	6	
		13.3	3	
		13.6	7	
		22.5	16	
		A2.7b	17	
	Oil well	14.29a	14	Steel
		14.29b	14	Rubber
Coal	Pearls	12.1a	1	
	Minus 25 mm	12.8	2	
		12.21c	5	
		A2.5a	6	
	Granular			
	As supplied	13.28a	3	
	Degraded	13.28b	3	
	Pulverized	A2.4	3	
Coke	Fines	12.16b	3	
Copper concentrate		12.16a	3	
Cryolite		11.8a	6	
		A2.3a	13	
Dicalcium phosphate	48%	11.8b	6	
	52%	13.26b	6	
Fluidized bed combustor ash		12.9	2	
		A2.3b	5	
Fluorspar		12.21b	5	

(*Continued*)

Table A2.1 (*continued*)

Material	Type or condition	Figure no.	Pipeline no.	Material
Fly ash	Coarse	13.25a	10	
	Fine	12.3a	1	
		12.10	2	
		12.18	3	
		13.25b	10	
		14.21	13	
		14.33a	15a	
		14.33b	15b	
		14.35	15c	
Iron powder		12.3b	1	
		12.13a	3	
Magnesium sulphate		12.13d	3	
		12.23d	6	
		17.2	16	
Nylon	Pellets	13.10	8	
Pearlite		12.1d	1	
		12.13c	3	
Polyethylene	Pellets	13.7	3	
Potassium chloride		11.5b	6	
		A2.6b	16	
Potassium sulphate		12.23b	6	
		A2.6a	16	
PVC	Powder	12.7a	2	
	Resin	12.19a	4	
Silica sand		12.21d	5	
		A2.2b	1	
Sodium carbonate	*Soda ash*			
	Heavy	12.1c	1	
	Light			
	Fresh	13.31a	11	
	Degraded	13.31b	11	
Sodium chloride	Salt	12.1b	1	
Sodium sulphate	Fresh	13.2	6	
	Degraded	13.27b	6	
Sugar	*Granulated*			
	Fresh	13.2	3	
	Degraded	13.27b	3	
Terephthalic acid	PTA	12.19b	4	
Water flour		12.11a	3	
Zircon sand		12.14b	3	

Table A2.2 Reference list of pipelines used for conveying trials with materials

Pipeline reference number	Figure number in text	Pipeline details			
		Bore (mm)	Length (m)	Number of bends	Bend geometry (*D*/*d*)
1	12.2	53	35	8	5
2	12.5	53	34	7	5
3	12.12	53	50	9	24
4	12.20	53	50	7	–
5	12.22	53	70	9	various
6	12.24	81	95	9	16
7	13.4	53	101	17	24
8	13.8	81	49	6	5
9	13.20	53	47	6	8
10	13.24	63	133	10	–
11	13.30	53	37	5	8
12	14.13	53	104	9	24
13	14.20	53	50	11	6
14	14.27	53	40	5	–
15a	14.31	53	115	10	–
15b		53–68			
15c		53–68–81			
16	17.1	105	95	9	12
17	28.8	53	163	17	24
18	28.10	53	98	13	–

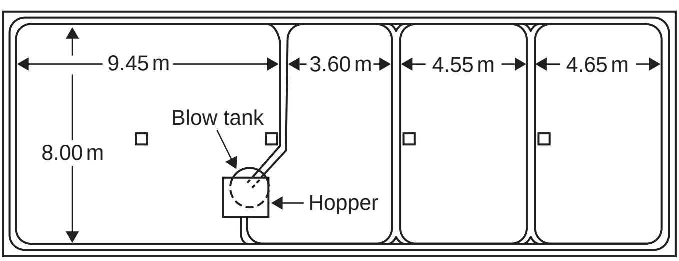


Figure A2.1 Plan of test loops for pipelines 3, 6, 7, 12, 16 and 17.

Pipeline lengths were varied from 50 m with no. 3 to 163 m with no. 17 so that scaling parameters for conveying distance could be determined. Pipelines could also be built having a similar conveying distance but a different number of bends, such as nos 7 and 12 so that the influence of the bends could be investigated. Provision was made for seven rows of pipe-work, with three levels of 53 mm bore pipeline and two rows each of 81 and 105 mm bore pipeline. By this means identical pipelines could be constructed with pipe bore being the only variable so that scaling parameters for this could also be established.

A2.3 Material properties listings

Much emphasis has been given to the various property values of the materials conveyed, partly because of their influence on the mode of conveying that can be achieved

Table A2.3 Basic property values of materials tested

Material	Mean particle size (μm)	Bulk density (kg/m^3)	Particle density (kg/m^3)
Alumina			
Sandy	79	1040	3600
Calcined	66	750	3920
Hydrate	60	1110	2420
Aluminium fluoride	–	1420	–
Ammonium chloride	–	900	1500
Barytes	12	1590	4250
Bentonite	24	760	2300
Cement – Ordinary Portland	14	1070	3060
Coal			
Pearls	10 000	690	1320
Minus 25 mm	5 600	750	1400
Granular			
As supplied	778	870	1550
Degraded	146	700	1550
Pulverized	84	393	1550
Coke – Fines	800	–	–
Copper concentrate	55	1660	3950
Fluidized bed combustor ash	1 200	1270	2500
Fluorspar	66	1580	3700
Fly ash			
Coarse	110	–	–
Fine	25	700	1700
Iron powder	64	2380	5710
Magnesium sulphate	370	1380	2355
Pearlite	200	100	800
Polyethylene – pellets	4 000	540	910
Potassium chloride	580	1180	1990
Potassium sulphate	170	1240	2625
PVC			
Powder	90	615	990
Resin	120	490	1400
Silica sand	70	1250	2630
Sodium carbonate – soda ash			
Heavy	340	1160	2500
Light	115		
Sodium chloride – salt	390	1220	2630
Sugar – granulated			
Fresh	460	890	1580
Degraded	170	655	1580
Terephthalic acid – PTA	–	930	–
Wheat flour	90	510	1470
Zircon sand	120	2600	4600

with a material. These are particularly important in contractual agreements and should be noted for reference by all parties involved. The basic properties of size and density, where available, are listed in Table A2.3.

In the programme of work undertaken to determine the classification for pneumatic conveying, presented in Figure 13.16, bulk material properties based on air-to-material interactions were determined. These values are presented, for the materials included in the investigation, in Table A2.4.

Table A2.4 Additional property values for some of the materials tested

Material	Compaction (%)	Permeability ($m^3s/kg \times 10^{-6}$)	Vibrated de-aeration rate ($m/s \times 10^{-3}$)
Alumina – sandy	17	0.42	19
Barytes	43	0.48	3.9
Cement – Ordinary Portland	40	0.71	3.0
Coal – granular			
As supplied	14	42	24
Degraded	36	1.0	2.9
Pulverized	31	0.53	4.3
Copper concentrate	30	0.33	9.8
Fly ash – fine	49	0.6	2.0
Iron powder	34	0.34	7.0
Magnesium sulphate	29	6.3	17
Pearlite	30	5.7	8.8
Polyethylene – pellets	5	420	60
Potassium chloride	16	11	26
Potassium sulphate	17	0.99	18
PVC – powder	22	1.2	8
Silica sand	12	3.9	34
Sugar – granulated			
Fresh	10	20	13
Degraded	43	1.4	8.3
Wheat flour	37	1.3	6.2
Zircon sand	15	1.3	10

A2.4 Additional conveying data

Further conveying data is included here for a few additional materials and for the conveying of some materials in additional pipelines. The first two are for the low pressure, dilute phase conveying of materials (Figure A2.2).

The next two sets of conveying data are for high pressure conveying, although neither material was capable of being conveyed in dense phase. Cryolite conveyed through the 53 mm bore 50 m long pipeline no. 13 (Figure 14.20) is presented in Figure A2.3a and fluidized bed combustor ash conveyed through the 53 mm bore 70 m long pipeline no. 5 (Figure 12.22) is presented in Figure A2.3b.

The minimum conveying air velocity for the bed ash was about 11 m/s and as a consequence solids loading ratios of up to about 35 were achieved with the high conveying pressures. Although the mean particle size of the material was about 1.2 mm, it contained a high percentage of fines and so conveying with an inlet air velocity of only 11 m/s was quite possible. The minimum conveying air velocity for the Cryolite was about 14 m/s and so solids loading ratios were much lower. The mean particle size was in the region of 3 mm, with a top size of about 8 mm, and a large proportion of fines.

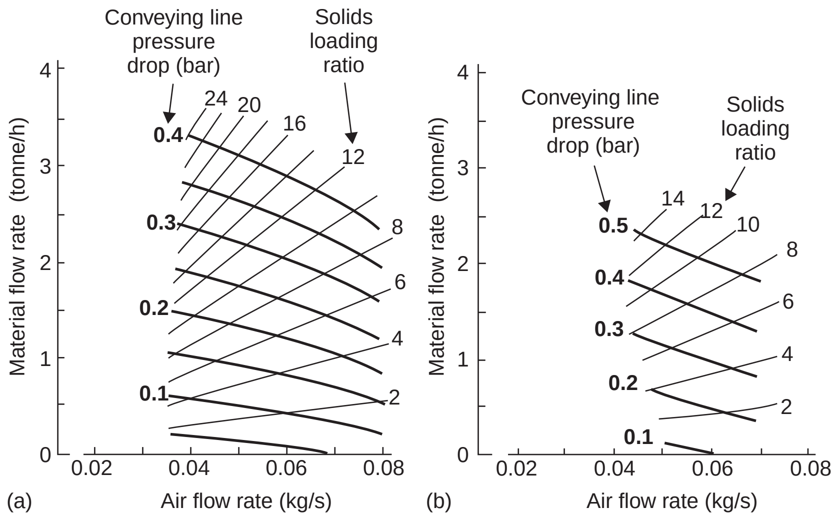


Figure A2.2 Conveying characteristics for low pressure, dilute phase conveying: (a) ammonium chloride in pipeline no. 1 and (b) silica sand in pipeline no. 2.

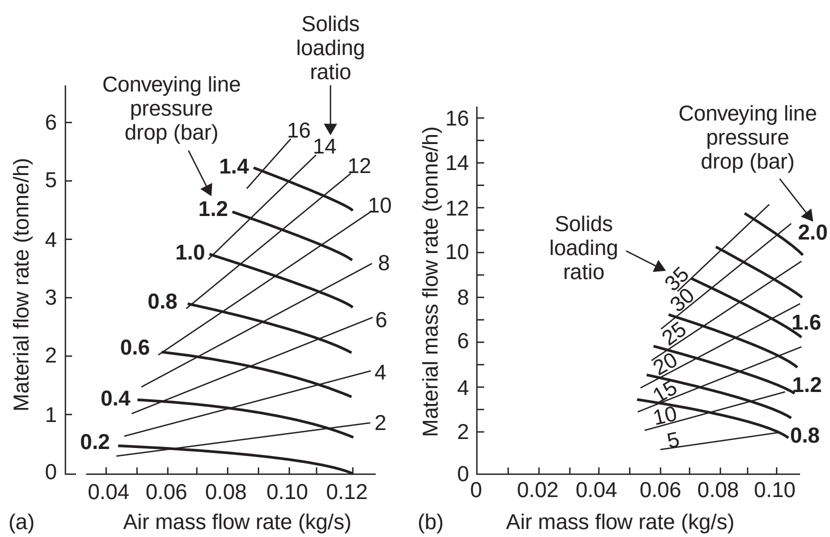


Figure A2.3 Conveying characteristics for high pressure, dilute phase conveying: (a) cryolite in pipeline no. 13 and (b) fluidized bed ash in pipeline no. 5.

Both of these materials are extremely abrasive and so it would be essential to reinforce all bends in any pipeline conveying either of these materials. In an erosive wear conveying programme the bed ash wore through a Booth bend (Figure 5.1b) in a relatively short period of time. It is suspected that the impact energy of the large particles was sufficient to displace the protective cushion of particles retained in the recessed pocket of the bend. Due to the large particles in these materials, particularly with the cryolite, it would also be recommended that all straight pipeline sections should be suitably reinforced. An alloy cast iron pipeline, or a steel pipe lined with basalt would be appropriate.

Conveying characteristics for pulverized coal conveyed through the 53 mm bore 50 m long pipeline no. 3 (Figure 12.12) are presented in Figure A2.4. This is another material that could only be conveyed in dilute phase. The mean particle size of the coal was about 84 μm which is too granular to give the material the necessary air retention. As a consequence the minimum conveying air velocity for the material was about 10 m/s, which explains why solids loading ratio values up to 40 were achieved.

The conveying characteristics for two further materials that were conveyed through the 81 mm bore 95 m long pipeline no. 6 (Figure 12.24) are presented in Figure A2.5. One material is −25 mm coal and the other is sandy alumina. Neither material could be conveyed in dense phase despite the availability of high pressure air. The minimum conveying air velocity for the coal was about 12 m/s and that for the alumina was about 14 m/s and hence the maximum values of solids loading ratios were about 12 and 20, respectively.

With a conveying line pressure drop of 1.6 bar a maximum of about 14½ tonne/h could be achieved with the coal but only 9½ tonne/h could be achieved with the alumina. These figures compare with only 6 tonne/h for potassium sulphate (Figure 11.5b) and 21 tonne/h for dicalcium phosphate (Figure 11.8b) conveyed through exactly the same pipeline with a pressure drop of 1.6 bar.

The conveying characteristics for two further materials that were conveyed through the 105 mm bore 95 m long pipeline no. 16 (Figure 17.1) are presented in Figure A2.6. These are potassium sulphate and potassium chloride, neither of which could be conveyed in dense phase, and with a relatively low pressure gradient the maximum value

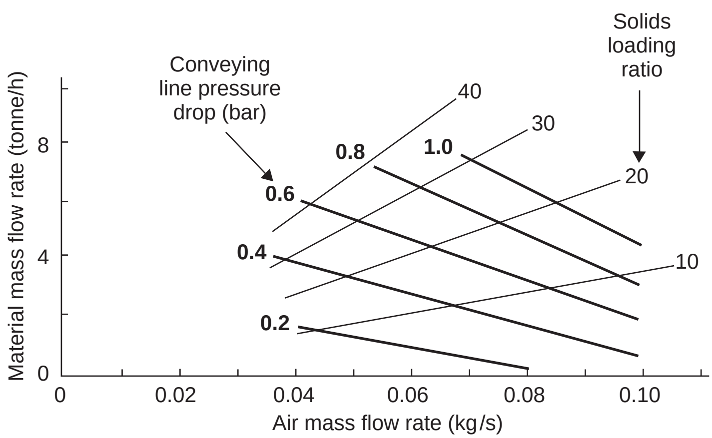


Figure A2.4 Conveying characteristics for pulverized coal in pipeline no. 3.

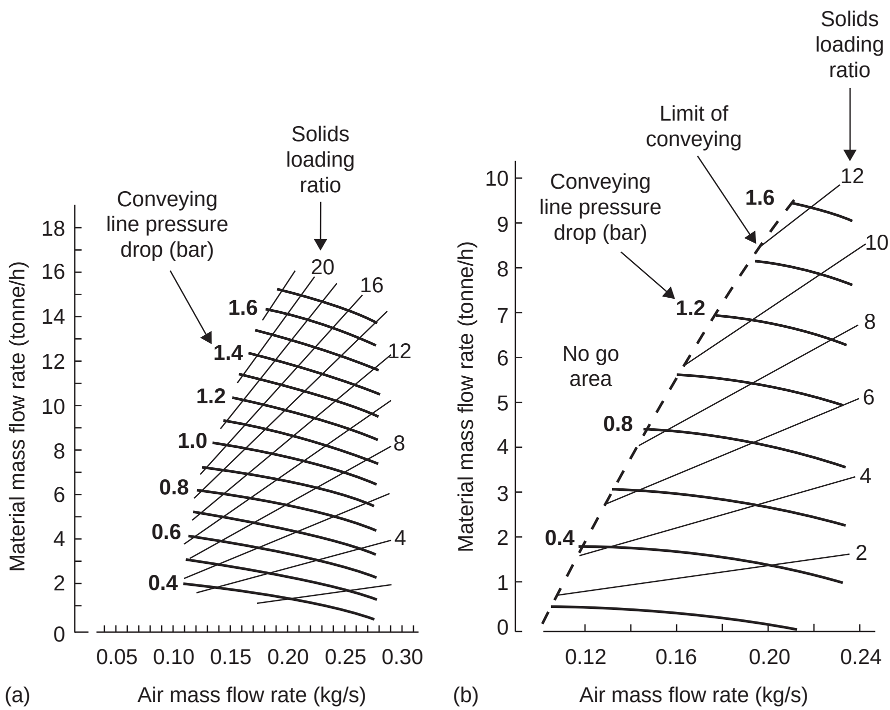


Figure A2.5 Conveying characteristics for materials conveyed through pipeline no. 6: (a) minus 25 mm coal and (b) sandy alumina.

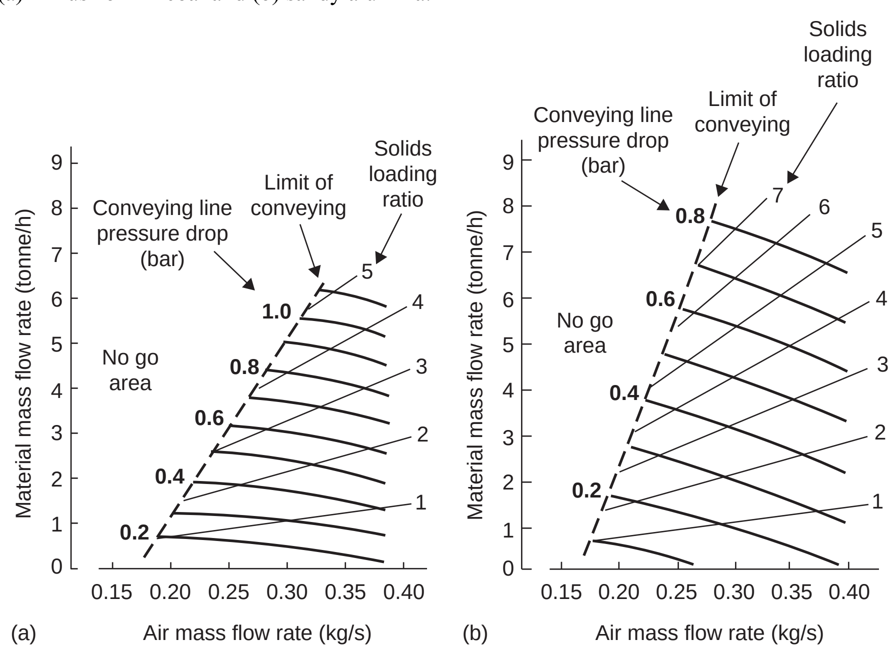


Figure A2.6 Conveying characteristics for materials conveyed through pipeline no. 16: (a) potassium sulphate and (b) potassium chloride.

of solids loading ratio for the potassium sulphate was only about five. The minimum conveying air velocity for these two materials was about 15–16 m/s. With a conveying line pressure drop of 0.8 bar only 4.4 tonne/h of potassium sulphate could be conveyed. This compares with about 10 tonne/h for cement in this pipeline (Figure 22.5), but for exactly the same air flow rate 49 tonne/h was conveyed with a pressure drop of 2.8 bar. To increase the flow rate for both of the Figure A2.6 materials a larger bore pipeline would be recommended rather than an increase in air supply pressure.

The influence of conveying distance on the value of solids loading ratio that can be achieved with dilute phase conveying was shown in Figure A2.6. Conveying distance has a similar influence with regard to materials that have dense phase conveying potential. Conveying data for barytes and cement in a longer pipeline is presented in Figure A2.7.

The pipeline used was 53 mm bore and 163 m long. A sketch of the pipeline is given in Figure A2.8. This is shown in relation to the additional elements of 53 mm bore pipeline that were available for alternative pipeline routings with this particular bore of pipeline in the laboratory shown in Figure A2.1.

Solids loading ratios for the materials in Figure A2.7 are now below 100 despite the fact that air supply pressures above 4 bar gauge were employed. With these two materials capable of being conveyed in dense phase, the potential of using high air supply

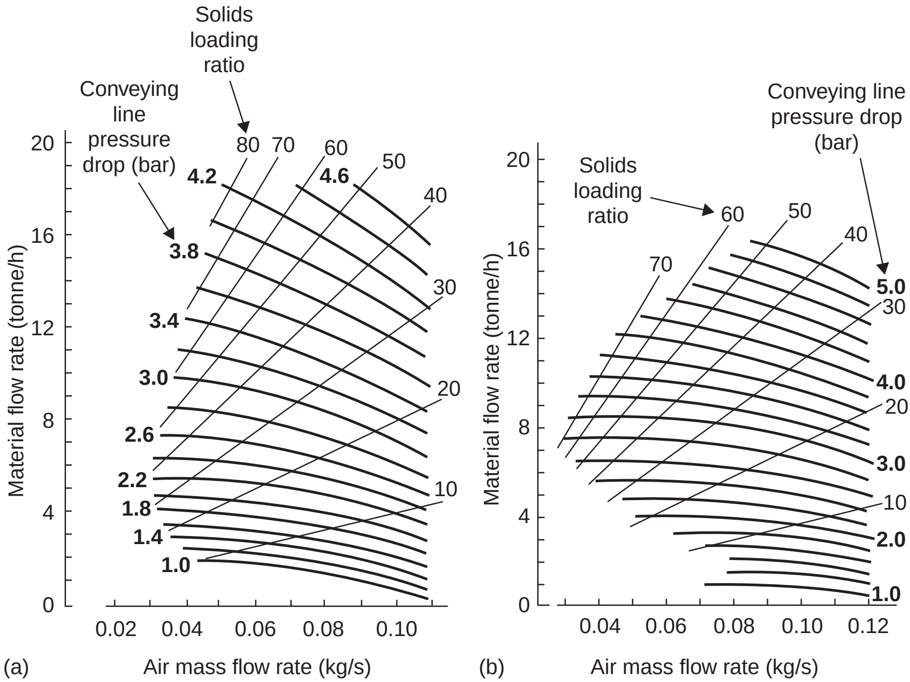


Figure A2.7 Conveying characteristics for materials conveyed through pipeline no. 17: (a) barytes and (b) cement.

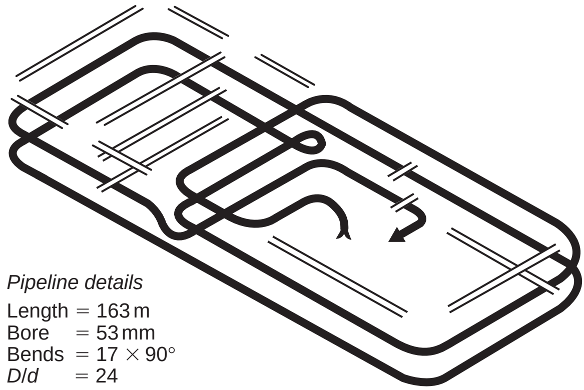


Figure A2.8 Sketch of pipeline no. 17.

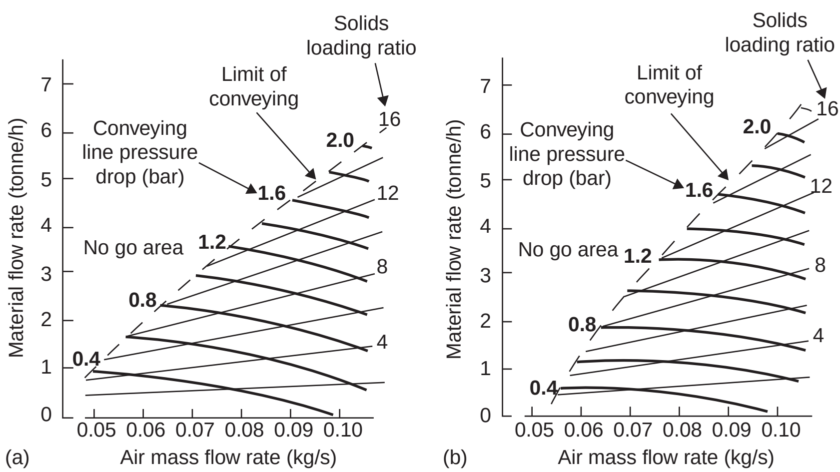


Figure A2.9 Conveying characteristics for materials conveyed through pipeline no. 18: (a) aluminium fluoride and (b) aluminium hydrate.

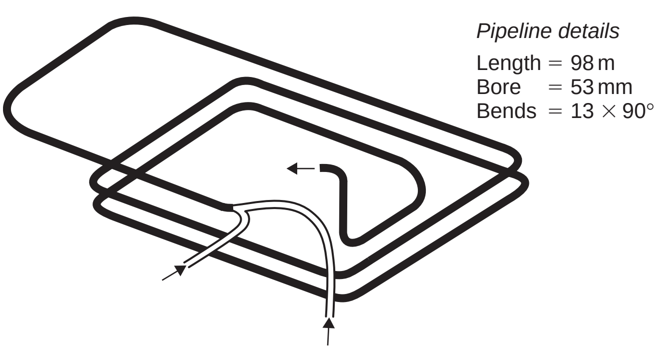


Figure A2.10 Sketch of pipeline no. 18.

pressures can be clearly seen. Compared with the materials conveyed through the larger bore and shorter length pipeline presented in Figure A2.6, material flow rates are very much higher and air flow rates required are much lower.

Conveying characteristics for two further fine granular materials with no natural dense phase conveying capability are shown in Figure A2.9. A sketch of the pipeline used for conveying these materials is shown in Figure A2.10. The minimum conveying air velocity for the aluminium fluoride was about 14 m/s and that for the aluminium hydrate was about 13 m/s.

Index