

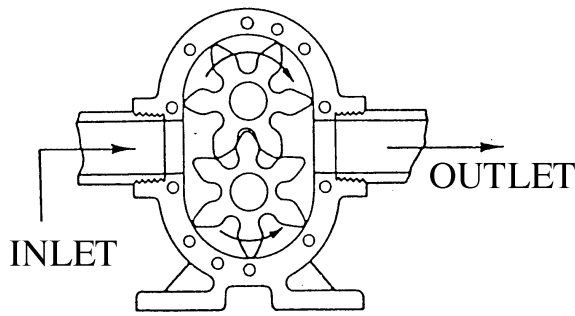
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# 5 Gear Pumps — Fundamentals

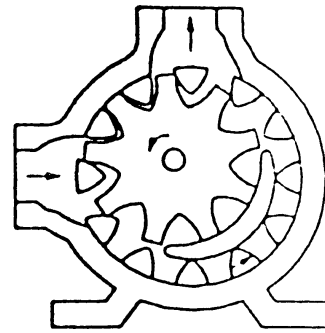
Gear pumps belong to a positive displacement rotary group, and are made by enclosing two or more gears in a close-fitting housing. A driver turns a shaft connected to one of the gears, causing it to rotate. This gear drives the other gear through the meshing of the teeth of the two gears, just as with power transmission gears.<sup>5</sup> As the gears rotate, on one side, the teeth are coming out of mesh with each other (see [Figure 28](#)). As a tooth is pulled out of the space between two teeth of the other gear, it creates a vacuum. Since the housing forms a seal all around the set of gears, the liquid that rushes into this space to fill this void has to come in through the pump's suction port. Once the spaces between gear teeth are filled with liquid, the liquid rides in these pockets, trapped in place by the housing, until it reaches the discharge side of the pump. The liquid stays in place between the teeth until it reaches the other side of the gear mesh, where the teeth are coming together. Then, when a tooth from the other gear comes into the space between the teeth, the liquid there is forced out. Since the housing still forms a seal around the gears, the only place for the displaced liquid to go is out the pump's discharge port. The pump thus operates like a conveyor belt, with the pockets of liquid between the gear teeth being picked up at the gear mesh, carried to the other side, and dropped off at the other side of the mesh.

There are two basic types of gear pumps: external and internal. External gear pumps usually have two gears with an equal number of teeth on the outside of each gear. Internal gear pumps have one larger gear with the teeth turned inward, meshing with a smaller gear with external teeth. If the larger gear has one tooth more than the inner gear, the two gears form a seal by themselves. If the larger gear has at least two teeth more than the smaller gear, then a crescent-shaped projection of the housing goes between the two gears to help form a seal. The operating principle is the same for all of these types of pumps, and they operate in similar fashion.

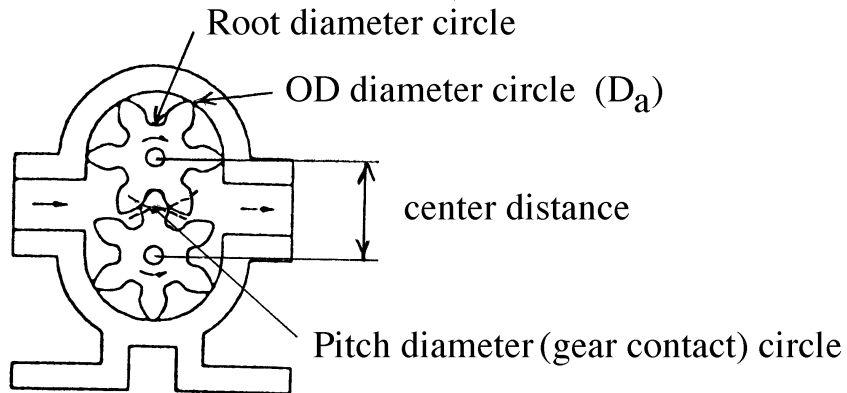
The displacement of a pump is the volume of liquid moved in those pockets between gear teeth. It is the theoretical output of the pump before any losses are subtracted. The instantaneous mode of displacement varies slightly as the teeth move through different positions in the mesh, so displacement per shaft revolution cannot be calculated exactly. However, there are some good approximations. For example, if the cavity area between the gear teeth is assumed to be approximately equal to the area of the teeth themselves (i.e., a cavity is an inverse of a tooth), then the



External gear



Internal gear



Addendum = radial distance from the pitch circle and OD circle  $\left( a = \frac{D_a - D_p}{4} \right)$

Dedendum = radial distance from the pitch circle to the root circle  $\left( b = \frac{D_p - D_r}{4} \right)$

**FIGURE 28** Different types of gear pumps, with geometry illustrations.

displacement per revolution would be equal to the volume occupied by half the space between the gear addendum (outside diameter) and a root diameter, multiplied by two (to account for two gears), times gear width:

$$q = \frac{\pi}{4} (D_a^2 - D_r^2) \times \frac{1}{2} \times 2 \times W (\text{in}^3/\text{rev}); \quad (36)$$

or, simplifying and dividing by 231, to convert in<sup>3</sup>/rev to gal/rev:

$$q = 0.0034 \times (D_a^2 - D_r^2) W, \quad (37)$$

where

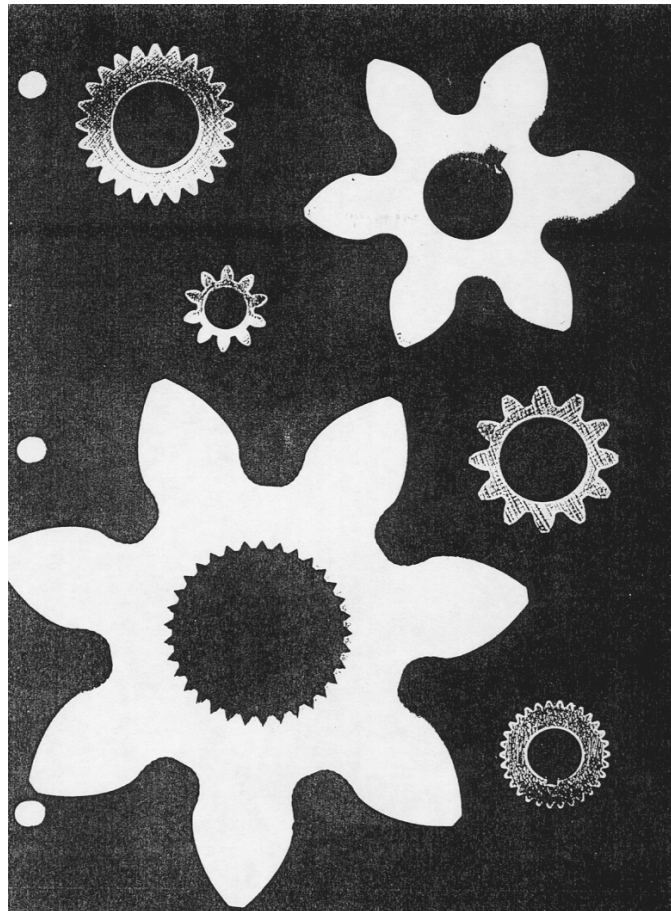
$q$  = displacement (gallons/revolution)

$D_a$  = gear outside diameter (inches)

$D_r$  = gear root diameter (inches)

$W$  = gear face width (inches).

This formula assumes that both gears have the same outside diameter and number of teeth. The addendum of gears for pumps is often extended when compared to power transmission gears. This is to increase the pump's displacement. Gears with smaller numbers of teeth have larger addendum for a given center distance. So, most gear pumps have 12 or less teeth on the gears. Examples of gears with various numbers of teeth, pitches, and sizes are shown in [Figure 29](#).



**FIGURE 29** Pumping gears with different number of teeth ( $Z$ ), pitch diameters ( $D_p$ ), and pitches ( $Z/D_p$ ).

Some pumps have as few as six teeth. This is about the minimum for relatively smooth power transmission between gears. Lobe pumps are similar to gear pumps with two or three teeth, but they use separate timing gears, outside of the liquid, to transmit power from the driving to the driven shaft.

## QUIZ #4 — GEAR PUMP CAPACITY

A plant mechanic has measured the pump gear at the repair shop:

$$\begin{aligned}D_a &= \text{Gear OD} = 3'' \\D_r &= \text{ID (root)} = 2'' \\ \text{Width} &= 4''\end{aligned}$$

Predict how much oil this gear pump will deliver at 1200 RPM.

### SOLUTION TO QUIZ #4

Using [Equation 37](#),

$$q = 0.0034 \times (D_a^2 - D_r^2) W = 0.0034(3^2 - 2^2) \times 4 = 0.07 \text{ gal/rev},$$

$$Q = q \times \text{RPM} = 0.07 \times 1200 = 80 \text{ gpm}.$$

Slip is the difference between the theoretical flow (displacement  $\times$  speed) and actual flow, assuming that there is no cavitation. Slip is the leakage of liquid from the high pressure side of the pump back to the low pressure side. There are a number of separate slip paths in any gear pump, including any liquid from the outlet of the pump that is bled off to flush a seal chamber or lubricate bearings. Three paths are common to all gear pumps: between the ends of the gears and the endplates (known as lateral clearance), between the tips of the gear teeth and the inside of the casing (known as radial clearance), and between the profiles of the meshing teeth. The slip through this last path is very small and is usually ignored.

Slip varies strongly with differential pressure and viscosity and, to some extent, with speed. Slip is directly proportional to differential pressure. It varies inversely, but not proportionally, with viscosity. Slip varies asymptotically with viscosity, approaching zero slip at high viscosities. This means that at low viscosities, small changes can mean large differences in slip. Slip varies inversely with speed to a small extent, but this is normally ignored, and predictions are made slightly conservatively at higher speeds. There is also a strong relationship between clearances and slip. Slip, through a particular clearance, varies directly with the cube of that clearance. This is similar to the oil flow in a hydrodynamic bearing,<sup>6</sup> and, indeed, the interaction between gear ends and the casing wall (or wearplate) is also similar, producing a like hydrodynamic bearing effect. This means that if you double the lateral clearance, you will get eight times as much slip through that clearance. The percentage of slip through each slip path varies with pump design, but in most gear

pumps, over half of the slip goes through the lateral clearance; this is because it is usually the largest clearance and it has the shortest distance from high to low pressure. This is why some high pressure pumps eliminate lateral clearance altogether by using discharge pressure to hold movable endplates against the gear faces while the pump is running.

## CAVITATION IN GEAR PUMPS

Cavitation is the formation of voids or bubbles in a liquid as the pressure drops below the vapor pressure of the liquid in the pump's inlet. These bubbles then collapse when they reach the high pressure side of the pump. This collapse can, over time, damage the pump and erode hard surfaces. Cavitation causes a drop in output flow that can sometimes be mistaken for slip, but cavitation can usually be identified by its distinctive sound. Significant cavitation will usually sound like gravel rattling around inside the pump. A rule of thumb is that the liquid velocity in the inlet port should be no more than 5 ft/sec for low-required net inlet pressure.

When pumping viscous fluids, the rotational speed of the pump must be such that the fluid has enough time to fill the voids between gear teeth at the inlet. In other words, the pump can only move the fluid out if there is sufficient suction pressure to push the liquid into the pump inlet. Otherwise, the voids are not filled completely, effectively reducing actual flow through the pump. Therefore, minimum allowable suction pressure depends on the rotating speed, size (pitch diameter), number of gear teeth, and viscosity of the fluid. An empirical approximate relationship, based on charts is<sup>7</sup>:

$$p_{\min} = \frac{V_p^{0.826} \times SSU^{0.09}}{61.4} \text{ (psia)} \quad (38)$$

where

$$V_p = \frac{D_p \times \text{RPM} \times 3.13}{Z} \text{ (in/min per tooth),}$$

and

$Z$  = number of gear teeth  
 $D_p$  = pitch diameter (inches)  
 $SSU$  = viscosity.

Therefore, pump suction pressure must be greater than the minimum allowable value. If this condition is not maintained, the pump flow will decrease, accompanied by noise, vibrations, and possible damage to the equipment. The cavitation damage in gear pumps, however, is not as severe as in centrifugal pumps. Typically, gear pumps are used for oil and similar liquids which have a significantly lower cavitation (boiling) intensity. The resulting bubbles implode less vigorously than in the case

of cold water, and their impact against the equipment's internal boundaries is, therefore, less severe.

## TRAPPING METHODS

As the teeth mesh, they can form closed spaces where one pair of teeth come together before the pair ahead of them has broken contact. This closed space decreases in volume as the teeth continue to move, and the liquid trapped inside can reach very high pressures and come out through the pump's lateral clearances at extremely high velocities. This damages the pump by eroding the endplates and gears; it also causes excessive noise and power consumption by the pump. Trapping problems are worse at high speeds and high pressures. Two methods are used to prevent trapping: helical gears and grooves.

Helical gears have the teeth twisted around the gear in a helix, so that any two teeth can only be in contact at one point. The trapped liquid can move axially along both teeth to escape the mesh.

Grooves in the gears or endplates are used to provide escape routes for trapped liquid. Grooves in endplates must be open to the trapped volume until it reaches its minimum size, and then another groove opens to the trapped space as it expands again. The two grooves must stay far enough apart so that a tooth is always in between them to ensure there is never an opening from inlet to discharge which would increase slip.

## LUBRICATION

Journal bearings are the simplest type of bearing used in pumps. They are often called sleeve bearings because they are basically a sleeve that the shaft fits into. However, they are the most critical part of applying a pump to a particular application because they do not depend on rigid, mechanical parts for operation, but on a self-forming hydrodynamic film of liquid that separates the moving and stationary parts.

A journal bearing can operate in three ways.<sup>8</sup> First, it can operate with the shaft rubbing the bearing; this is called boundary lubrication. Second, the shaft may form a liquid film that completely separates it from the shaft; this is called hydrodynamic film operation. And finally, the third and most common mode is mixed film lubrication; this is where parts of the bearing and shaft are separated by a liquid film while other parts are in rubbing contact.

Boundary lubrication occurs at low shaft speeds or low fluid viscosities where the strength of the liquid film is insufficient to support the load on the bearing. Since the parts are rubbing under load, they will wear. Limits have been established that attempt to keep this wear down to acceptable levels. The limits are based on the amount of heat that can be removed from the bearing surfaces actually in contact, and on surface chemistry interactions between the shaft, bearing, and liquid. Boundary lubrication is often called "PV-lubrication" because the bearing load per unit area ( $P$ ) and the relative velocity between the parts ( $V$ ) are the factors. Typically, the following values are used to estimate load capabilities of various bearing materials:



Material	PV-value (psi × ft/min)
carbon	120,000
bronze	60,000
iron	30,000
plastics	3,000

Hydrodynamic operation is different from boundary lubrication in that the bearing material is not important, and the viscosity instead of the chemistry of the liquid is important. Bearing clearance also becomes a very important factor.

Roller bearings are often used on gear pumps where journal bearings will not work because of high loads, low speeds, or low viscosities. The bearing manufacturer's recommendations should be followed<sup>8</sup> in applying these bearings, except that most bearing manufacturers do not have information on bearing performance with lubricants below 150 SSU. In the absence of any better information, use the following rules of thumb:

- Liquid viscosity above 5 cSt — use full bearing catalog rating
- Liquid viscosity 5 to 2.5 cSt — use 75% of catalog rating
- Liquid viscosity 2.5 to 1 cSt — use 25% of catalog rating

(Note: cSt = viscosity in centistokes)

It may seem surprising, but the ends of the gears usually operate with hydrodynamic lubrication. The loads here are generally low, and the teeth form an excellent type of thrust bearing called a *step thrust bearing*. Wearplates can be used between the ends of the gears and the housing when the combination of gear and housing material could cause wear or galling problems. Galling is wear by adhesion of material from one part onto the other and is characteristic of stainless steel sliding against a similar metal under load. Wearplates can also be used when there is no hydrodynamic film on the ends of the gears. The wearplates will then be made from a material with good boundary lubrication characteristics, such as carbon or bronze.

Wear seldom occurs to the teeth of steel or cast iron gears unless there are abrasives present in the liquid, or when the gear teeth are heavily loaded and the material that they are made from does not have the strength necessary to resist deterioration of the tooth surface. Even with very low viscosity liquids, the loads on the gear teeth are normally low, and the contact is intermittent, so boundary lubrication is adequate. However, stainless steel gears generally exhibit severe wear<sup>9</sup> unless a full liquid film separates the teeth. Any particular pump at a certain speed will have a liquid viscosity below which the gears will begin to gall.

The choice of materials greatly affects the point where galling begins. Some materials are restricted to use only under full film lubrication conditions, while others can operate down well into the mixed film region without problems. Hardened martensitic stainless steels, particularly 440C, have good resistance to galling. 440C can be run against itself and is no more likely to gall than carbon steel. The other

extreme is 18-8 austenitic stainless steels, like 304 or 316. These will gall when run against themselves or each other if there is any contact at all between the gears.

## **USER COMMENTS**

The following are some direct comments on various types of rotary pumps made by the users interviewed at the chemical plants, as they see it:

### **EXTERNAL GEAR PUMPS**

Workhorse of the industry, applied mostly for low capacity and high pressure. Range of viscosities is very wide: from lube oil to one million SSU. Application issues include close clearances between the gears and casing. Bearings are immersed in product and are therefore product lubricated, which makes them product sensitive. Both extremes of viscosity (very low and very high) may present lubrication problems. Seal chambers are restrictive, since gear pump manufacturers are only now beginning to come up with large sealing chambers — something centrifugal pump manufacturers have addressed 5 to 10 years ago. Due to these sealing chamber size restrictions, some standard mechanical seals may not fit in these pumps, without special design alterations. Gear pumps are often noisy in operation, and generate flow pulsations downstream.

Flow control of all positive displacement pumps is not as straightforward as for centrifugals. However, recent advances in variable frequency drives (VFD) make such method of flow control convenient, and relatively inexpensive. It also allows wiring the VFD signal to the operator control room, for remote control and monitoring.

Abrasive applications are an issue, just as for any other pump type. To combat abrasion, speed should be decreased, because wear is exponential with speed. Coatings include carburizing (low carbon steel), nitriding (alloy steel), or exotic materials (nickel alloys).

Cavitation is not a big issue for gear pumps, for many reasons. First of all, they typically operate at lower speeds. Second, the “positive filling” of the inlets makes them less sensitive to flow non-uniformity, separation, and backflow — which is a very serious factor for centrifugal pumps. Third, gear pumps typically pump oils, and similar fluids, the properties of which are such (e.g., latent heat of vaporization, characterizing the intensity of cavitation damage, is much lower) that even if cavitation does occur, the damage to the internals is less.<sup>4</sup>

The necessity to have the relief valve (internal in-built, or external) is a limitation. Without a relief valve, very high discharge pressures may result, damaging the pump or connecting piping, as well as cause safety issues. Therefore, a relief valve must always be present. The integral relief valve, which is a part of a pump, is not designed to regulate the flow, but only relieves occasional overpressure, for a limited time. If the relief valve opens, and the equipment is not shut-down relatively soon, or the problem is not corrected otherwise, fluid overheating could result in a matter of minutes or less. Attention to relief valve operation is very important.



## **INTERNAL GEAR PUMPS**

Designed for low pressure at low speed. Drive gear is cantilever, vs. between-bearings arrangement of external gear pumps. A cantilever design requires a bigger shaft, to minimize deflections. This may shorten seal life.

These pumps are simple to assemble and repair, with little training, and, when applied appropriately, can do the job well and inexpensively.

The issues are similar to the external gear pumps — close clearances, with possibility of contact, wear or galling, if stainless construction (in which case wearplates made from carbon or bronze are required). In general, issues, benefits, and limitations are similar to those for external gear pumps.

## **SLIDING VANE PUMPS**

These are mainly applied for low viscosity liquids. However, pumping lube oils and gasoline is not uncommon. Vanes slide (i.e., adjust) to compensate for wear and are easy to replace. If not replaced on time, however, vanes can wear out to the point of breakage, causing catastrophic failures. Preventative maintenance, therefore, should include vane replacement, and should be done at regular, established intervals. Vanes are available in softer or harder materials — as required for various liquids, for mildly abrasive and corrosive applications. However, very little development work seems to have been done in vane material, and manufacturers should be encouraged to do so. These pumps can be extremely noisy at speeds over 300 RPM.

## **LOBE PUMPS**

Similar to external gear pumps, but they require timing gears since the lobes are designed for no contact and do not transmit torque. Occasional contact can happen in reality, as differential pressure deflects the shaft, pushing gears to rub against the casing walls. Larger and stiffer shafts minimize such deflections, to prevent gear contact. Information about the rotors' deflection with differential pressure can be obtained from the manufacturer, or estimates can be done by the plant engineers. Lobe pumps are good for high displacements (flows) and low pressure applications, and are often used for blowers/vacuum applications, as well as food applications.