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Heat transfer in food processing: ensuring product quality and safety

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Abstract

Heat transfer to foods is commonplace but critical; heating develops flavour and texture and ensures product safety. The food industry must ensure that all parts of the product have all been processed sufficiently, without unacceptable loss of quality. Conventionally, food is significantly over-processed to ensure safety. This paper reviews some problems which heat-transfer engineers face in the food industry, and recent progress in understanding them. Examples are taken in (i) safety: the problems of predicting and validating food processes, using a combination of modelling, visualisation and enzyme temperature–time indicators which pass through a process and show how much cooking they have received, (ii) quality: the combination of reaction engineering and heat transfer in the generation of flavours and colours for ales, and (iii) process operation: how to clean food process plant.

1. Introduction

1.1. Types of thermal process in the food industry

Thermal processing is ubiquitous in food processing. Many of the commonest food-processing operations, such as canning, baking and pasteurisation, rely on heating:

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- For preservation, i.e. to kill bacteria and inactivate enzymes, such as the pasteurisation of milk and the sterilisation of canned food. Here the aim is to deliver the required microbial kill with as little damage as possible.
- To develop taste and flavour, such as when cooking meats and vegetables, where in addition to sterilisation heat is required to carry out physical changes to the food.
- To develop the structure of the material, such as in baking of bread or biscuits, where heating acts both to change the starch structure and function and also to develop the bubble structure within the material (for examples, see [11]).

There are also processes, such as drying and frying, where heat and mass transfer are coupled. Many processes were developed empirically, and only after many years have attempts been made to develop an engineering understanding. The consumer desires minimally processed products that retain nutrition and flavour, display an acceptable shelf life and are convenient to prepare.

1.2. Heat transfer and reactions in foods

Foods are physically complex fluids and soft solids, with rheological and material properties that are time- and process-dependent and which have a natural variation. It is thus difficult to specify the physics in such a way as to allow accurate prediction of the process. Some safety margin is added to ensure that every part of the material is safe. Modelling methods have been developed to help in process design or as part of a control specification; purely empirical correlations or graphical solutions were followed by models based around very simple approximations, such as simple geometries (spheres or cylinders) and uniform physical properties.

In food processing, the effect of thermal processing, where T is a function of time t, is commonly described through the 'integrated lethality' calculated using

$$F = \int_0^t 10\left(\frac{T(t) - T_{\text{ref}}}{z}\right) \mathrm{d}t \tag{1}$$

where z is the increase in temperature that increases the rate by a factor of 10, and T_{ref} is a reference temperature. F has units of time; it is the length of time that food has to be held at the reference temperature to obtain the same effect as the actual process. Estimates of F values were first proposed by Ball [5], where for canned low-acid foods (pH < 4.5), the proposed reference temperature (T_{ref}) was 121.1 °C (250 F) and z = 10 °C was used, based on estimates of the death of *Clostridium botulinum*. A process was then considered safe if the slowest heating point of a can reached an F value of 3 min.

Eq. (1) is an experimental fit, a local approximation to the Arrhenius expression: although only accurate over a narrow temperature range, it fits microbial behaviour in the narrow range of temperature appropriate to cooking. The equation assumes that microbial death, which is not strictly true. More accurate models for microbial growth and death are available and can be used in predicting the results of processes, for example Bellara et al., [6] modelled the growth of pathogenic bacterial species after thermal treatment within agar cylinders. Investigations modelled the inactivation of the bacteria and explored the notion that slow heating rates ($\leqslant$2 °C/min) may increase thermotolerance in potentially pathogenic bacteria [21].

Any type of model requires accurate data, often lacking in the food industry. This paper reviews some of the recent attempts that have been made to understand heat transfer and its consequences in food processing, using examples from recent work at Birmingham.

2. Prediction of food safety: models and validation

2.1. Models for food processes

Before personal computers became common, calculating integrated lethality from Eq. (1) was complex and time consuming even for simple products. In place of repetitive manual calculations "simpler" methods were used, for example, F could be estimated by measuring temperature, calculating lethality and using graphical solutions (see [20]). Real products are rarely regular, have thermal properties which vary with temperature and have different heat resistances along the boundary. For example, in retorts, condensing steam is used and condensation will affect the uniformity of heat transfer to the product surface [37]. Complex thermal effects in conduction can result from the polymorphic nature of food components; for example Tewkesbury et al. [32] used a FE model to predict the cooling of chocolate (a complex mixture of triglycerides with six polymorphic forms) within a polycarbonate mould. Both conduction cooling of chocolate, and the change in the effective specific heat capacity of chocolate were modelled as a function of temperature and cooling rate.

For most commercially processed products heating is rarely by pure conduction. In canning, for example, heat transfer occurs by a combination of conduction and natural convection within the can. CFD can solve for the flow field within the can. Kumar et al. [18] describe the heating of canned viscous liquids that have temperature-dependant viscosity. In their model an initial conductive heat-transfer phase reduces the viscosity of the liquid at the periphery of the can. This less viscous and more buoyant hot liquid rises and then re-circulates to the centre of the can. Abdhul Ghani et al. [1,2] provided estimates of the axial velocity of the fluid in cans and modelled bacterial inactivation.

In recent work, Cox et al. [15] and Bakalis et al. [4] used positron emission particle tracking (PEPT) to examine the three-dimensional flow of liquids within rotating cans (including cans under heat-transfer conditions). The method can measure flow velocities of tracers even through several centimetres of stainless steel. Fig. 1 shows the flow pattern inside a can with a 10% headspace (volume of air in the can). The flow pattern is three-dimensional, as fluid elements travel from the centre of the can to the walls and back. These flow patterns be followed by PEPT thanks to its temporal and spatial resolution through metal, and the isokinetic nature of the flow followers. PEPT thus allows the mixing patterns within the material to be quantified, leading to new ways of validating model predictions.

The next stage is to model the system in which cooking takes place. Varga et al. [36] used FE methods to model horizontal cascading water retorts, and verified their model with industrial scale measurements. It was stated that a reliable mathematical solution required a model combined with an appropriate statistical method to estimate real world variability, as well as an understanding of the quantitative implications of the variance upon the system. Similarly, Verboven et al. [38] used CFD to examine temperature deviations within an industrial scale forced convection oven.

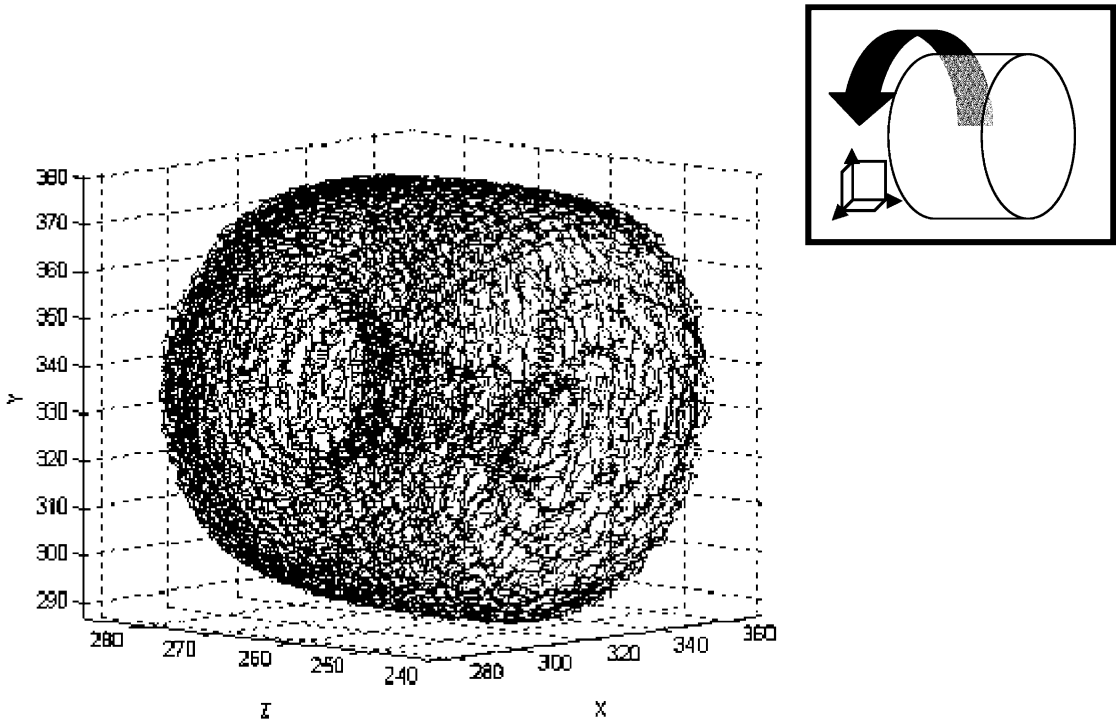

Fig. 1. The three-dimensional flow of viscous liquids (14.9 Pa s sucrose solution) within a metal can with a 10% headspace at ambient temperature. The trace follows the trajectory of a single isokinetic particle within half the can. The axis labels (x, y and z) refer to the PEPT camera coordinates and are in millimetres. The inset figure shows the orientation of the can and the direction of rotation.

The limitations of conduction heat transfer in processing large solids are obvious: by the time the centre is cooked the outside is overcooked. Alternative processes, such as microwave or electrical resistance ('ohmic') cooking heat volumetrically. The problem is in ensuring uniform heating and in validation. Excellent discussions of the problems inherent in modelling microwave processes, and in validating them for commercial production, are given by Bows [7] and Bows et al. [8]. The interaction between the applied field and the food material is key. Multimode resonant applicators, used in all domestic ovens and almost all industrial applications produce one resultant heating pattern from the complex interaction of the field, material and applicator. Strategies to minimise temperature differences (rotating turntables, mode stirrers or moving the product) are not always sufficient to overcome undesirable effects. For electrical heating, complex temperature distributions can be found, such as by Kemp et al. [17]. Local heating and cooling effects have been shown by thermocouple measurements and in elegant MRI experiments by Ruan et al. (1999) [40].

2.2. Time–temperature indicators

One technology that allows for the verification of processes is the use of time–temperature indicators (TTIs). Taoukis [31] reviewed the use of TTIs for product safety assurance and shelf life

during transportation, storage and sale. The other aspect of TTIs use is as thermal process indicators to define the efficiency of pasteurisation and sterilisation processes. A successful system allows the thermal history of processed food to be evaluated without temperature loggers, whilst mimicking the thermal characteristics of any given target attribute (e.g. microbiological load or vitamin retention).

Biochemical TTIs offer such a technology. The most familiar and widely used are encapsulated spores. Non-pathogenic analogues of important food contaminating organisms (e.g. *Bacillus stearothermophilus* in place of *Clostridium botulinum*) are encapsulated into alginate spheres, which are placed at the centre of the foodstuff, and the product processed. Comparison of pre- and post-process numbers of spores allow determination of the overall kill for the process (as with Eq. (3)). The preparation and analysis is non-trivial [34]. More recently spores are being replaced with chemical or biochemical indicators, such as purified bacterial enzymes. TTI particles are placed in the food and after heating the proportion of denatured enzyme can be assayed and applied to Eq. (2), which is equivalent to Eq. (1).

$$F = D_T \log\left(\frac{A_{\text{initial}}}{A_{\text{final}}}\right) \tag{2}$$

where F is the integrated lethality for the process (in minutes), D_T is the decimal reduction time, the process time which reduces the value by a factor of 10, A_{final} is the concentration of enzyme that has not been denatured and A_{initial} is the activity of unprocessed enzyme.

Tucker [34] describes one such example (*Bacillus amyloliquifaciens* α-amylase) whose thermal characteristics ($D_T = 18.7$ min and $z = 9.7$) closely match those of *Clostridium botulinum*. It is of great for examining pasteurisation treatment, as it ensures a sufficient cook to kill most aerobic pathogens (e.g. *Listeria* and *Salmonella*) as well as the psychrotrophic *Clostridia*. Maesmans et al. [22] and Loey et al. [35] describe other potential measurement systems. For conduction-cooked products bacterial enzyme based TTIs have provided a rapid method of process validation [34]. In continuous processing such an approach can be difficult, although considerable efforts have been made to determine temperature–time distributions in convective and flowing food systems. For TTIs to be truly useful in such processes the trajectories of the TTI particles through the equipment (in relation to the heating surfaces) needs to be known, perhaps by using methods such as PEPT. Combination of model and validation is needed to be able to demonstrate product safety to the food industry.

3. Models for quality

Quality is more difficult to specify than safety; nevertheless, it is important to be able to include quality parameters in any heat-transfer model. One example of the link between heat transfer and quality is given by Robbins and Fryer [28,29] who describe how the roasting of barley can be modelled. Brewing has been in existence for millennia. It is in essence fairly simple, using a malted cereal and water (and more recently hops) to produce a medium which is then fermented using brewers yeast. Speciality malts are highly coloured and flavoured products that are added in small quantities (3–10%) to adjust the colour and flavour of the beer being produced. They come in numerous varieties [9] and are typically made or finished in roasting drums with heated walls.

Batch sizes of around 3 tonnes are common in industry. Speciality malts can be divided into two main categories, dry roasted (e.g. roast barley, roast malt) and wet roasted (e.g. crystal malt). Crystal Malt is used in premium lagers and most real ales, roast barley and other dry roasted products are used in some ales and in stouts and porters. Production of speciality malts, as with many food-processing operations, is currently an artisan operation in which operators adjust the temperature and length of run by observing product changes in colour by eye. During roasting the moisture content falls, and colour and flavour are developed: what is needed is some way of predicting the moisture and temperature profiles in the system and how colour and flavour develop as a result.

To enable a sample of grain to be processed uniformly a spouted bed roaster was designed and built. This system is easier to characterise than the commercial system and allows a mathematical model of the roast process to be developed and tested under well-defined conditions. Work by Bruce [10] and Sokhansanj and Bruce [30] gave a good starting point for simulating barley drying. A similar model was developed by Jumah et al. [16] specifically for the spouted bed drying of corn. The model assumptions include that moisture loss is controlled by internal diffusion; water diffuses to the surface of the grain where it is evaporated into the air stream. Values for the required physical properties were either found in the literature or measured independently of the experiments. The kinetics of colour change for crystal malt were found by Trauth [33], and for roast barley by Robbins [26]. They take a similar form:

$$\frac{\mathrm{d}C}{\mathrm{d}t} = -k \qquad k = A\exp\left(\frac{-B}{T_g}\right) \tag{3}$$

i.e. that over some range the behaviour is essentially zero order.

Fig. 2 shows a typical result for the production of roast barley. Good agreement is seen between the modelled and measured moisture and temperature of the grains using data from the literature. This is a good basis on which to superimpose the model for the reactions within the grains. Fig. 3

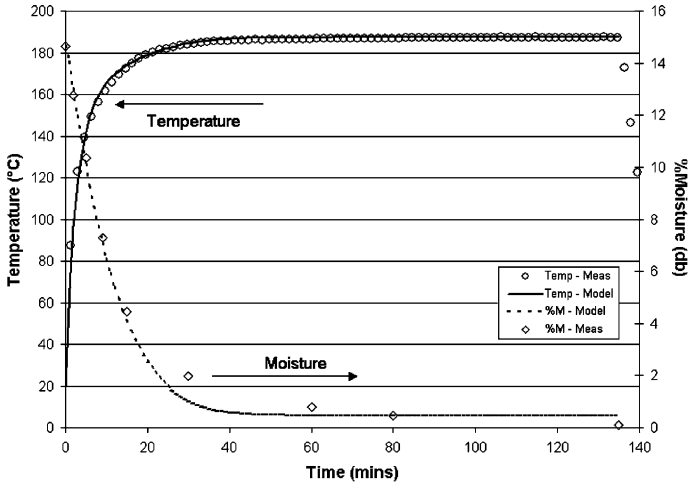

Fig. 2. Measured and modelled response for a roast barley [28]. Final grain temperature of 188 °C.

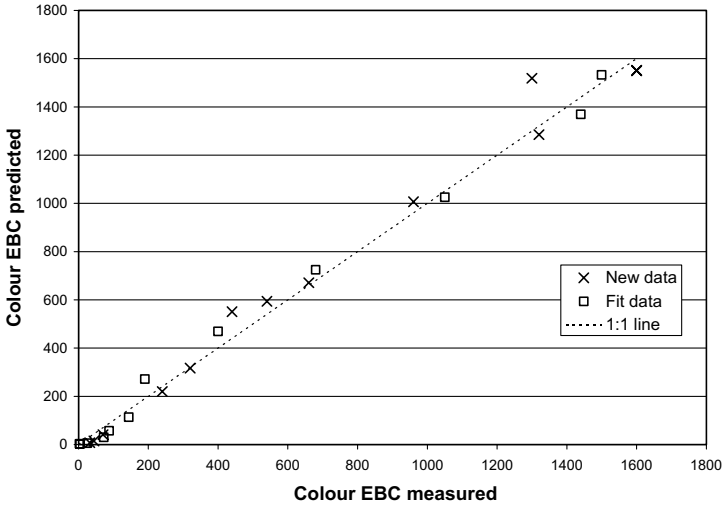

Fig. 3. Comparison of the measured and predicted EBC colour for a number of roast barley experiments [28]. The data used to fit the model is given a square symbol, whereas new data is given the cross symbol. There is good agreement between the model and experimental data across the whole range of colours. EBC colour is a brewing colour unit, with 0 EBC being a no colour (e.g. water) and 1600 EBC being a very dark colour (e.g. a very dark stout). A standard lager is about 10 EBC.

shows the comparison of the final predicted and measured colour (from the spouted bed) for a number of roast barley experiments. Once more good agreement is seen between the predicted and measured results.

These types of model are relatively simple; to predict the generation of flavour, for example, would be much more complex because of the very complex chemistry involved in the formation of flavours. There is evidence that in some cases potentially toxic compounds can be formed during cooking (see, for example, [23]). The development of models for these sorts of processes is thus critical in food safety as well.

4. Fouling and cleaning problems in food processing

4.1. The fouling problem

Fouling devices by foods is a severe problem, in which a range of components, both organic and mineral are deposited. Fouling deposits from a range of materials, including tomato juice, grape juice and milk, have been studied; the composition of deposits is different from the fluid (for example, see [27]). Fouling profiles can be significantly affected by small changes in fluid composition: for example, the addition of calcium phosphate to whey protein concentrate changes the rate, extent and composition of the deposit [14]. The microscopic appearance of tomato soil was that of clotted tomato with unclotted juice adhering to the denser, sticky soiling film [12]. Fouling deposits form as a result of adhesion of species to the surface and cohesion between elements of the material. The aim of most cleaning research is to devise ways of optimising removal; i.e. to

minimise the cleaning time in terms of the effect of flow velocity, cleaning agent chemical concentration and other variables.

Extensive development work has been carried out to produce cleaning-in-place (CIP) equipment and protocols which meets these requirements, but it is not known in practice how optimal these protocols are. One key parameter, the force required to remove deposit, is not known directly. On a smaller scale, atomic force microscopy (AFM) has been used to characterise surface and fouling (such as [25]). Low-adhesion coatings [24] have been shown to reduce fouling in some situations such as mineral scales. Zhao et al. [39] demonstrate that biofouling can be reduced by changing surface energy, and link this to adhesive energy between surface and deposits. An understanding of the interaction between deposits and surfaces is clearly critical in cleaning.

Micromanipulation equipment has been developed at Birmingham to study biofilm adhesion and removal of deposits [13,19]; we have used both tomato paste and whey protein deposits as model fluids, as starch and dairy product fouling is widespread in the food industry.

4.2. Quantification of removal

4.2.1. Tomato starches

Experiments were carried out in which discs were placed in a pre-heated laboratory oven set at 100 °C and baked for times between zero to 240 min. The apparent adhesive strength was then measured after the sample was hydrated for 30 min. Fig. 4(a) shows the plot of adhesive strength versus baking time. Results are the mean of four samples, and show that the experimental procedure was highly repeatable. The apparent adhesive strength increases with longer baking time but the change becomes less significant after heating for 3 h. The baking makes the sample dry and dark in colour. The longer the baking time, the dryer and darker the sample, however there is little change noticeable in the surface of the deposit after baking for 200 min. The dried sample was hydrated for different lengths of time and the resulting apparent adhesive strength then measured. Fig. 4(b) plots adhesive strength versus hydration time. The error bars in all figures represent the standard error of the mean. The apparent adhesive strength decreases with hydration time by a factor of about three: it then remains essentially constant.

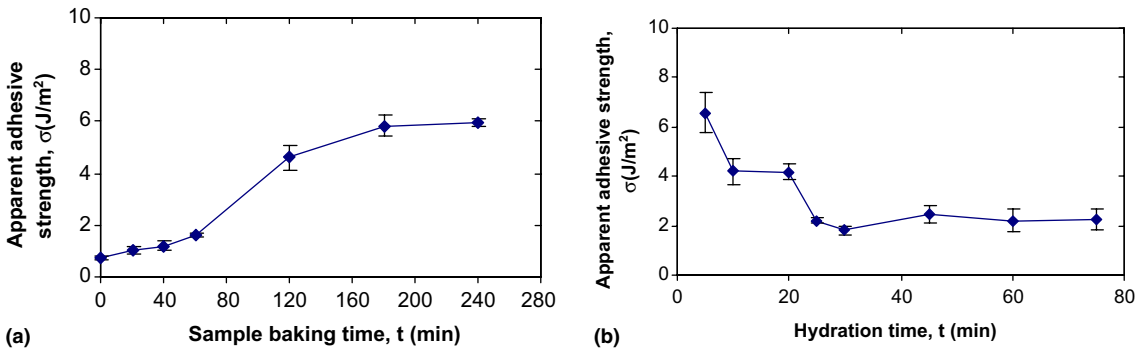

Fig. 4. Adhesion strength of tomato versus (a) sample baking time, hydration time = 30 min and (b) hydration time, baking time 60 min. Error bars in figures represent the standard error of the mean [19].

4.2.2. Milk protein

Unlike tomato paste, milk deposit cannot be removed by water alone. The force required to disrupt and remove the milk protein deposit has been measured without chemical being used and with cleaning chemical containing 0.5 wt% NaOH, used. The effect of chemical was observed by submerging the deposit into the 0.5 wt% NaOH solution for different lengths of time and at different temperatures before the force measurement was carried out. It was found difficult to remove all the deposits from the substrate when no chemicals were used, however the whole deposit could be removed from the surface with chemicals added. The force needed for removal reduced with time: the minimum value is reached after 50 min at 20 °C and 5 min at 70 °C, demonstrating the effect that temperature has on the cleaning rate. Both the minimum force and the rate at which the force reduces varied with temperature. The diffusion of chemical agent into the deposit will be a function of temperature as the diffusion coefficient is thermally activated; any chemical reaction will also be thermally activated.

4.2.3. Cohesive and adhesive structures

It is possible, by setting the micromanipulation probe to pass above the disc, to leave deposit on the surface. In this case the force measured by the probe will corresponds to that required to break the cohesive forces between parts of the deposit. This has been done for both types of deposit. Fig. 5 compares the results for full and partial removal.

For tomato, the force required for partial removal of the deposit exceeds that for the total removal, showing clearly that cohesive forces are greater than those for adhesion to the surface. For milk, the initial thickness of the deposit layer was around 1300 μm. Force measurements were taken after leaving the gap between the probe and substrate to 900, 600, 100 and 20 μm respectively. Here, the cohesive forces between elements of deposit are weaker than those of adhesion between surface and protein deposits, opposite to the behaviour of tomato starch, in which it is easier to remove the whole of the deposit than a surface layer.

This type of measurement makes it possible to explain cleaning measurements. It is reasonable to suppose that the removal of deposit from a surface will occur when the forces required to break

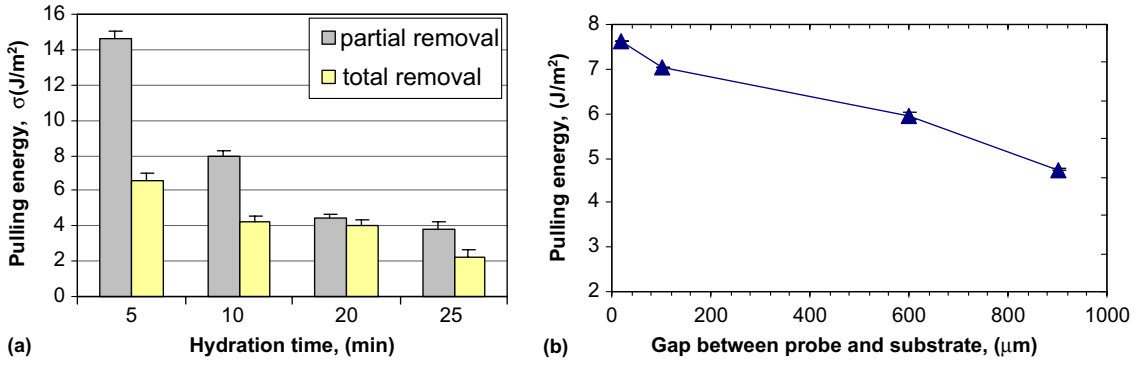

Fig. 5. Pulling energy for partial removal and total removal of fouling samples (a) for tomato deposit, at different hydration time, showing that the cohesive forces are greater than those of adhesion, and (b) for milk, showing that adhesion exceeds cohesion.

either the deposit–surface or the deposit–deposit bonds are exceeded by the forces provided by fluid shear. The cleaning behaviour of deposits was studied visually, and in terms of heat-transfer recovery. For tomato, fouling deposit is removed in large chunks; in the limit, the surface becomes clean in one go, and all of the tomato is removed from the surface in a couple of seconds. This reflects the data shown in Fig. 5a; the forces holding the deposit together exceed those that which bind it to the surface. When the diffusion of water to the interface has lowered the adhesive force sufficiently, all of the deposit is removed. In contrast, the removal of milk protein deposits are more commonly removed in patches and gradually in small chunks from the surface, or by removal of very small particles from the deposit. Here the energetics is different; the most difficult step is removal of the final layer from the surface, whilst deposit–deposit bonds are easier to break. Modifying the surface to make it lower energy might be effective in this case as an antifouling or easy-cleaning strategy, as the surface–deposit bonds are the strongest, whilst for tomato they are already the weakest.

5. Heat transfer in food processing

This paper has concentrated on the heating of foods. The problems of predicting the rate of heating and the resulting changes in product quality and sterility are significant, in part because of the complexity of food materials and their imperfectly known physical properties. Other areas have not been described; for example, refrigeration and freezing are significant industrial processes which are of particular importance in the safe storage of foods, see, for example, [3].

The industry is a very conservative one. Developing new processes, or using the results of models to change processing schedules, is very difficult to do, and requires a lot of data for safety before any process can be approved. As the margins in the industry are very low, few food manufacturers can afford to do the sort of modelling that would be commonplace in, for example, the chemical industry.

The problems of the food industry are similar to those of other industries that deal with complex fluids. The above does not claim to be comprehensive. The interested reader should try some of the journals in the area, such as the *Journal of Food Engineering*, *Innovative Food Science and Emerging Technologies*, and *Transactions Part C of the Institution of Chemical Engineers* for papers which go into more detail.

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References

[1] A.G. Abdul Ghani, M.M. Farid, X.D. Chen, P. Richards, Numerical simulation of natural convection heating of canned food by computational dynamics, J. Food Eng. 41 (1999) 55–64.
[2] A.G. Abdul Ghani, M.M. Farid, X.D. Chen, P. Richards, An investigation of deactivation of bacteria in a canned liquid food during sterilization using computational fluid dynamics, J. Food. Eng. 42 (1999) 207–214.
[3] D.L. Archer, Freezing: an underutilized food safety technology? Int. J. Food Microbiol. 90 (2004) 127–138.
[4] S. Bakalis, P.W. Cox, W. Wang-Nolan, D.J. Parker, P.J. Fryer, Use of Positron Emission Particle Tracking (PEPT) technique for velocity measurements in model food fluids, J. Food Sci. 68 (2003) 2684–2692.
[5] C.O. Ball, Thermal process time for canned foods, Bull. Nat. Resour. Council 7 (1923) 1.
[6] S.R. Bellara, P.J. Fryer, C.M. McFarlane, C.R. Thomas, P.M. Hocking, B.M. Mackey, Visualization and modelling of the thermal inactivation of bacteria in a model food, Appl. Env. Microbiol. 65 (1999) 3095–3099.
[7] J.R. Bows, A classification system for microwave heating of food, Int. J. Food Sci. Technol. 35 (2000) 417–430.
[8] J.R. Bows, M.L. Patrick, R. Janes, D.C. Dibben, Microwave phase control heating, Int. J. Food Sci. Technol. 34 (1999) 295–304.
[9] R.C. Breiss, Speciality malts and applications in brewing, Brewers Digest 61 (10) (1986) 20–21.
[10] D. Bruce, Exposed-layer Barley drying: three models fitted to new data up to 150 °C, J. Agric. Eng. Res. 32 (4) (1985) 337–347.
[11] G.M. Campbell, C. Webb, S.S. Pandiella, K. Niranjan, Bubbles in Food, Eagan Press, 1999.
[12] C.S. Cheow, A.T. Jackson, Circulation cleaning of a plate heat exchanger fouled by tomato juice, I. Cleaning with water, J. Food Technol. 17 (1982) 417–430.
[13] M.J. Chen, Z. Zhang, T.R. Bott, Direct measurement of the adhesive strength of biofilms in pipes by micromanipulation, Biotechnol. Tech. 12 (1998) 875–880.
[14] G.K. Christian, S.D. Changani, P.J. Fryer, The effect of adding minerals on fouling from whey protein concentrate: development of a model fouling fluid for a plate heat exchanger, Trans. IChemE C 80 (2002) 231–239.
[15] P.W. Cox, S. Bakalis, H. Ismail, R. Forster, D.J. Parker, P.J. Fryer, Visualisation of three-dimensional flows in rotating cans using Positron Emission Particle Tracking (PEPT), J. Food Eng. 60 (2003) 229–240.
[16] R.Y. Jumah, A.S. Mujumdar, G.S.V. Raghavan, A mathematical model for constant and intermittent batch drying of grains in a novel rotating jet spouted bed, Drying Technol. 14 (3 and 4) (1996) 765–802.
[17] M. Kemp, L. Davies, P.J. Fryer, The geometry of shadows: effects of inhomogeneities in electrical field processing, J. Food Eng. 40 (1999) 245–258.
[18] A. Kumar, M. Bhattacharya, J. Blaylock, Numerical simulation of natural convection heating of canned thick viscous food products, J. Food Sci. 55 (1990) 1403–1411, 1420.
[19] W. Liu, G.K. Christian, Z. Zhang, P.J. Fryer, Development and use of a novel method for measuring the force required to disrupt and remove fouling deposits, Trans IChemE C 80 (2002) 286–291.
[20] A. Lopez, Heat process determinationsA Complete Course in Canning and Related Processes, vol. 2, The Canning Trade Inc., Baltimore, 1987, pp. 21–30.
[21] B.M. Mackey, C.M. Derrick, Changes in the heat resistance of *Salmonella typhimurium* during heating at rising temperatures, Lett. Appl. Microbiol. 4 (1987) 13–16.
[22] G. Maesmans, M. Hendrickx, S. De Cordt, P. Tobback, Theoretical considerations on design of multicomponent time temperature integrators in evaluation of thermal processes, J. Food Process Preserv. 17 (1993) 369–389.
[23] D.S. Mottram, B.L. Wedzicha, A.C. Dodson, Acrylamide is formed in the Maillard reaction, Nature 448 (2002) 418–419.
[24] A. Nejim, C. Jeynes, Q. Zhao, H. Muller-Steinhagen, Ion implantation of stainless steel heater alloys for anti-fouling applications, in: J. Matsuo, G. Takaoka, I. Yamada (Eds.), Proceedings of the 1998 International Conference on Ion Implantation Technology, IEEE, Piscataway, USA, 1999, pp. 869–872.
[25] A.N. Parbhu, A.N. Lee, S.J. Thomsen, D.C.W. Siew, Atomic force microscopy applied to monitoring initial stages of milk fouling on stainless steel, in: D.I. Wilson, P.J. Fryer, A.P.M. Hasting (Eds.), Fouling, Cleaning and Disinfection in Food Processing, Department of Chemical Engineering, University of Cambridge, UK, 2002, pp. 33–40.
[26] P.T. Robbins, The roasting of speciality malts, PhD Thesis, University of Birmingham, 2004.

[27] P.T. Robbins, M.T. Belmar, B.L. Elliott, P.J. Fryer, A comparison of milk and whey fouling in a pilot scale plate heat exchanger: implications for modelling and mechanistic studies, Trans. IChemE C 77 (1999) 97–106.
[28] P.T. Robbins, P.J. Fryer, The spouted-bed roasting of barley: development of a predictive model for moisture and temperature, J. Food Eng. 59 (2003) 199–208.
[29] P.T. Robbins, P.J. Fryer, Modelling the small scale production of speciality malts, paper presented at ICEF 9, Montpellier, March 2004.
[30] S. Sokhansanj, D.M. Bruce, A conduction model to predict grain temperatures in grain drying simulation, Trans. ASAE 30 (4) (1987) 1181–1184.
[31] P.S. Taoukis, Modelling the use of time-temperature indicators in distribution and stock rotation, in: L.M.M. Tijskens, M. Hertog, B. Nicolai (Eds.), Food Process Modelling, Woodhead, 2001.
[32] H. Tewkesbury, A.G.F. Stapley, P.J. Fryer, Modelling temperature distributions in cooling chocolate moulds, Chem. Eng. Sci. 55 (2000) 3123–3132.
[33] E. Trauth, Modelling of the Maillard reaction during the roasting of malt, MSc Thesis, University of Leeds, 2000.
[34] G.S. Tucker, Validation of Heat processes, in: P. Richardson (Ed.), Thermal Technologies in Food Processing, Woodhead Publishing, 2001.
[35] A. Van Loey, L. Ludikhuyze, M. Hendrickx, S. De Cordt, P. Tobback, Theoretical consideration on the influence of the *z*-value of a single component time/temperature integrator on thermal process impact evaluation, J. Food Protect. 58 (1995) 39–48.
[36] S. Varga, J.C. Oliveria, Smout, C. Chantal, M.E. Hendrickx, Modelling temperature variability in batch retorts and its impact on lethality distribution, J. Food. Eng. 44 (2000) 163–174.
[37] P. Verboven, B.M. Nicolaï, N. Scheerlinck, J. De Baerdemaeker, The local surface heat transfer coefficient in thermal food process calculations: A CFD approach, J. Food Eng. 33 (1997) 15–35.
[38] P. Verboven, N. Scheerlinck, J. De Baerdemaeker, B.M. Nicolaï, Computational fluid dynamics modelling and validation of the temperature distribution in a forced convection oven, J. Food Eng. 43 (2000) 61–73.
[39] Q. Zhao, Y. Liu, H. Muller-Steinhagen, in: D.I. Wilson, P.J. Fryer, A.P.M. Hasting (Eds.), Fouling, Cleaning and Disinfection in Food Processing, Department of Chemical Engineering, University of Cambridge, UK, 2002, pp. 41–48.
[40] R.R. Ruan, P. Chen, K. Chang, H.J. Kim, I.A. Taub, Rapid food particle temperature mapping during ohmic heating using FLASH MRI, J. Food Sci. 64 (1999) 1024–1026.