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# DESIGN FOR FOOD QUALITY

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## 1 Introduction

When designing food production systems there are two main issues which are in conflict and which need to be considered carefully. These are: the simplicity and efficiency of the production itself, and the quality of the product that is produced. The latter is assessed in terms of consumer perception of such factors as taste and appearance. This paper reports some of the findings of a recent research project looking at the particular case of yoghurt production. This is a singularly complex foodstuff as its properties vary with processing and the ways in which this happens are not fully understood. What emerges however is that simplistic, empirical models of these properties are sufficient to provide bounds which can be used for design work. In particular, they can be incorporated within a constraint-based approach to design of food systems.

## 2 Background

In the area of food and pharmaceutical production there are inevitably trade-offs between the cost of the production process and the quality of the final product [1]. The production cost depends upon a variety of factors including: the availability of the raw ingredients, the required transportation to the production plant, the processing required to produce the food product, the packaging of the product, and its transportation to a point of sale. The quality of the final product is essentially its perception by the consumer. Frequently sensory factors come into play including: colour, smell, texture and taste. In addition, the consumer is increasingly concerned about the dietary and environmental implications of the ingredients used. There are thus a large number of factors to be considered when a new food product is designed and when its production facilities are configured.

Some of these issues have been considered in a recent research project concerned with the design of production systems for yoghurt. The purpose of the paper is to discuss these issues and to illustrate how some of the design conflicts can be handled. Yoghurt is a difficult food stuff to produce as its properties are adversely affected by any production process. It tends to "shear thin" resulting in a less viscous final product. As one of the normal consumer requirements is for yoghurt to be reasonably thick (viscous) there is an immediate conflict.

In addition to this, yoghurt is typically produced in a number of forms, effectively with different degrees of thickness (viscosity) and this requires a number of different yoghurt "bases" to be created. To these are added additional ingredients such as fruit, colouring and preservatives. These can themselves affect the thickness. For these reasons it is highly desirable to be able to understand (and model) the effects of these interactions and investigate the possibility for reducing the number of underlying bases and of moving some of the "customisation" to later in the production process.

Of particular importance in the design process for food systems is the need to understand how the product behaves during production and what the effect is upon the perceived final quality. The main challenge here is often the lack of understanding of such behaviour. This leads to a requirement at least to bound the problem and establish what the "worst case" possibilities are. For food products where understanding is established, it is possible to model some of the processing effects [2]. In the case of yoghurt, there is little general understanding of its behaviour. Furthermore those models that have been published tend to be consider only specific situations or depend upon experimental intervention [3, 4].

As a consequence, the main method used has been to rely upon the results of experimental investigation into the properties of specific yoghurt types taken from the range of those in current production. Models have been fitted to these data to allow qualitative predictions to be made about the effects of shearing during processing and of changes in temperature on the apparent viscosity of the product. Similar empirical studies have been undertaken with consumer panels to assess what features of the final product are important - particularly those which are related to viscosity. This has allowed the creation of a design model of the changes in properties during production. As this is based upon a constraint approach it is possible to investigate the effects of changes in the production system with a view to creating a product that is more acceptable to the general consumer.

The main general result is that it is important to be able to establish simple relations between the design parameters and find bounds upon what happens during production. This is similar to the idea of using heuristics, based on previous design experience, to simplify initial design work [5]. For the specific case of yoghurt production this has been achieved by modelling of physical behaviour based upon empirical results and, in particular, a new relation between the flow parameters and temperature has been proposed and validated. This then allows the production process to be modelled and simulated with a view to identifying key stages in the process and the optimal choice of the associated parameters.

In the next section, the use of constraint-based techniques is discussed with reference to the modelling of flow and to design optimisation. To apply this approach to food stuffs such as yoghurt, some model of their behaviour is required, and in section 4 use is made of the Herschel-Bulkley relation and empirical fitting to obtain a simulation of three stages in a production process. Working in a constraint modelling environment allows the effects of such design parameters as mixing time to be investigated and related to the viscosity of the final product. The underlying models assume constant temperature. In section 5, a model is proposed which introduces temperature dependence and simplifies the influence of the other parameters. Although this is simplistic, it is sufficiently good to provide bounds for design work and this is illustrated by the ability to predict the results of measurements taken after flow of the material along a pipe.

# 3 Modelling

Modelling of food material and the effects of processing it is a complicated issue since the governing equations are only partially understood and tend to be non-linear. With materials such as yoghurt, the properties vary with processing: prolonged shearing produces thinning. There are a number of conflicting constraints that come in to play. The constraint modelling approach [6, 7] is being used as a means for trying to find viable solutions to the processing and consumer requirements.

The ideas of constraint modelling arose from investigations into the mechanical design process. In the early conceptual stages of a new design task, the precise rules by which the design is to operate are largely unknown. What are more apparent are the constraints which dictate what the limitations are. For example, a part may need to be less than a particular size but still be sufficiently strong. As the design progresses more and more constraints emerge, partly from a better understanding of the area. The aim of the designer is to find a design solution which meets all the imposed constraints. Often this is not possible since the constraints are in conflict and the skill of the designer is in deciding which constraints can be relaxed without jeopardising the overall design.

The purpose of the work described here is to investigate the use of the constraint approach in the design of food processing systems. There are constraints here in terms of how the food product is processed and how it is perceived by the consumer. Modelling of the properties of food material often involves the use of non-linear algebraic equations and the solution of these seems to be a natural application of the resolution techniques within the modeller.

## 3.1 Pipe flow

As an initial example, consider the modelling of a Newtonian fluid through a simple pipe network shown in figure 1. There are six nodes and six pipes involved. The model for the flow can be created in terms of constraint rules. Some of these rules relate to conservation of mass flow at each of the nodes. Others encapsulate Bernoulli's equation for the pipes. For the example shown, there are four constraints of the first type and six of the second. Applying these and allowing the system to vary the nodal pressures and edge velocities gives the solution shown in the figure.

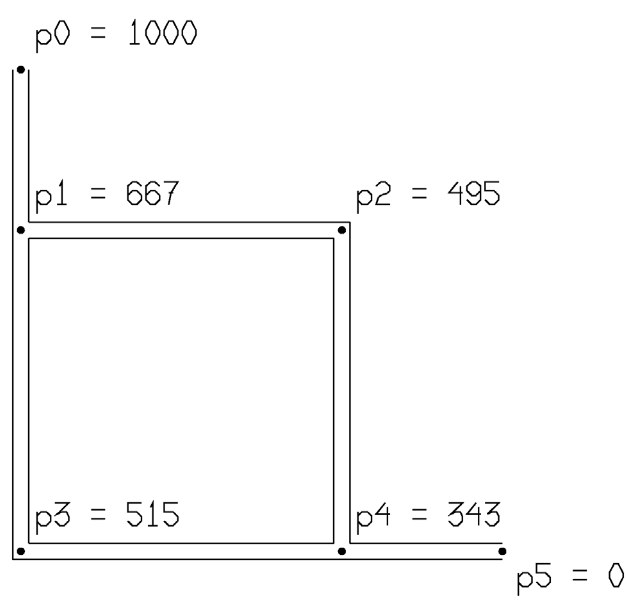


Figure 1 Simple pipe flow solved using constraints

The constraint modelling approach for flow along pipes can be generalised to deal with a non-Newtonian fluid. The example here illustrates the use of the tool in selecting appropriate pipe sizes. The fluid is yoghurt and a commonly used description of its behaviour [4,8] is the Herschel-Bulkley model

$$\tau = \tau_0 + K(\mathrm{d}\gamma/\mathrm{d}t)^n \qquad (1)$$

where $\tau$ is the shear stress in the material, $\tau_0$ is the yield stress, $K$ is the consistency factor, $\mathrm{d}\gamma/\mathrm{d}t$ is the shear rate, and $n$ is the flow behaviour index.

The flow along a horizontal circular pipe is considered. For a given pressure gradient, the volume flow rate can be expressed [4, 8] as relations between that gradient, the fluid parameters and the radius and length of the pipe. This is a highly non-linear expression. It allows the flow rate to be determined for a given pressure gradient. Often however there is a need to determine the pressure gradient to provide a specified flow rate. In such a case this non-linear equation needs to be solved to determine the pressure to be applied to create the given flow.

When the fluid is yoghurt, there is a further complication. Excessive processing can damage the material properties and result in product which is not acceptable to the consumer in terms of its texture. Such detriment occurs if the shear rate becomes too large. This imposes a limit on the value of the shear stress and strain, and in particular on the shear stress at the pipe wall which represents the largest value of shear stress across the cross-section of the pipe.

The constraint modelling system can be used to find the best pipe radius to achieve a given flow rate without making the shear strain excessive. The constraint rules encapsulate the relation between the flow rate, and the pressure gradient, and the limit on the value of strain rate. The basic strategy is to let the system vary the pressure gradient and the radius, and search for values which allow the constraint rules to be satisfied. What is found is that the sensitivities of the constraints to changes in the two parameters are markedly different and care is required in introducing “dummy” variables which are multiples of the true ones but have roughly equal magnitudes. In this case, a change in the dummy radius variable has significantly less effect than the same change in the dummy pressure gradient variable.

The value of the target for the shear rate can of course be varied. This changes the corresponding values of the pipe radius and the pressure gradient. Figure 2 shows graphs of these changes. The higher the target, the smaller the pipe needs to be (to prevent the shear stress building up over the cross-section) and hence the greater the pressure gradient needs to be to maintain the prescribed flow rate.

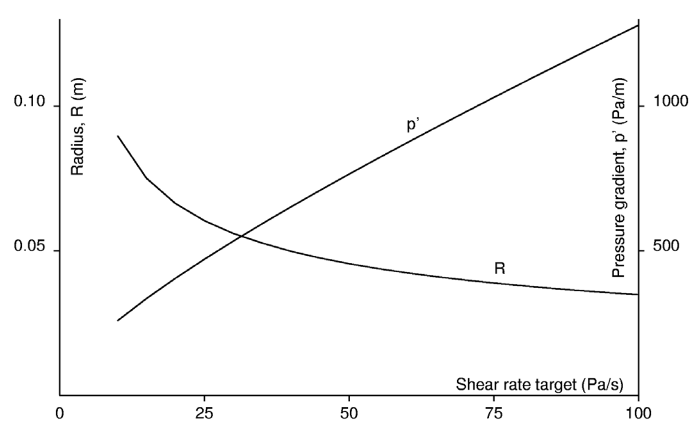


Figure 2 Pipe radius and pressure gradient for prescribed shear rate constraint

## 3.2 Optimisation of pipe size

Another example of the use of constraints is now given. This is based on a method [2] for finding the optimum pipe size for pumping a fluid which is assumed to obey the Herschel-Bulkley model. The fluid given as an example is tomato ketchup.

There are a number of considerations taken into account regarding the flow itself. In particular this is assumed to be laminar and the (generalised) Reynolds number is required. The flow is in the form of the plug and the dimensionless unsheared plug radius appears in the equations. This needs to be found from these equations and as these are non-linear, an iterative scheme is required.

Once the flow properties are established (for an assumed pipe diameter) the cost of the system is dealt with. Three aspects are considered [2]. The first is the total annual cost per unit length of installed pipe. The second is the cost of the pump, its installation, and maintenance. The third is the annual charge for electrical consumption.

Starting with an assumed pipe diameter, the cost can be found. In [2], a test for this being minimal is developed based on the derivative of the cost being zero. This is rearranged to give the pipe diameter in terms of the (optimal) cost. An iterative scheme is then introduced. This revised value given by this formula is used to update the assumed pipe diameter and the cost recalculated. This process is found to converge.

Numerical techniques are required due to the highly non-linear nature of the equations used to model the system. The constraint modeller has been used successfully to handle the same problem. As this is set up to handle non-linear equations, it is a suitable tool for the pipe problem. What is found is that it can handle the task but care is needed in adjusting the sensitivity of the variable to be changed.

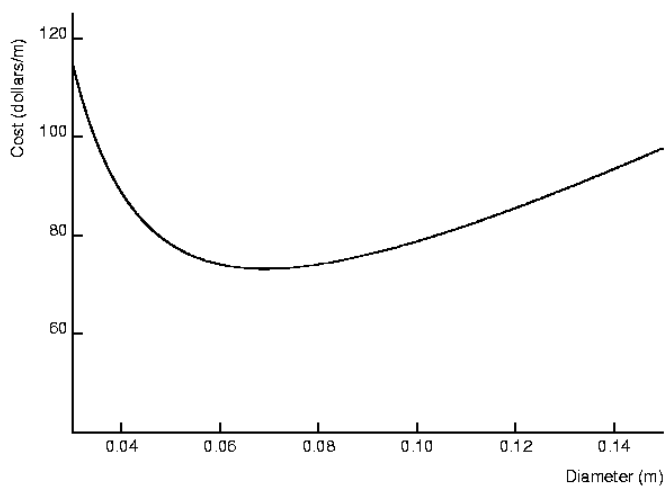


Figure 3 Cost as a function of pipe diameter

The use of the constraint approach has the advantage of only dealing with the original equations from the pipe model and there is no need to adapt any by differentiation or other means. Effectively use is being made of the iterative schemes within the constraint modelling software.

There are essentially two degrees of freedom. One is based around the selection of the plug diameter. The other is the selection of the diameter itself. The various design and fluid parameters are used as global variables. Constraint rules are imposed to ensure that the two expressions for the Reynolds's number are the same. A further rule simply has the cost value so that this is minimised. When the rules are invoked, the values of the two variable parameters are adjusted and the constraint modeller successfully finds an optimal configuration.

Figure 3 shows a graph of cost against pipe diameter for typical values of the parameters. This confirms the fact that the optimal configuration is well defined and hence both methods are able to find it.

# 4 Effect of flow upon yoghurt viscosity

This section discusses a means for assessing the effect that processing has upon yoghurt viscosity. The viscosity controls the final appearance of the food to the consumer and is a large determinant in the acceptability of the product. Three key parts of the production process are considered. The first represents flow of yoghurt along a pipe. This has the effect of reducing the viscosity by a small amount. The second is a mixing stage where consistency is achieved and fruit may be added. Here the viscosity is deliberately reduced so that mixing can take place more effectively. The final stage is a cooling and recovery phase in which the temperature is allowed to reduce thus raising the viscosity. The overall aim is to reach a prescribed target viscosity.

The Herschel-Bulkley model, equation (1), is assumed to hold for yoghurt. Figure 4 shows the graph of shear stress $\tau$ against strain rate $d\gamma/dt$ in the case when $\tau_0$ = 10 Pa, $K$ = 10 Pa.s$^n$ and $n$ = 0.3. The apparent viscosity $\eta$ is defined as the quotient of the shear stress and the strain rate, and so this reduces as the strain rate increases.

As in the previous section, the Herschel-Bulkley model can be used to investigate the flow of material along a circular pipe by finding the relation between the volume flow rate and the imposed pressure gradient.

It is well-known that as rheological tests are repeated on materials such as yoghurt the graphs of shear stress against strain rate show a hysteresis effect. In addition the values of the stress reduce as the work done on the material increases. Such results are shown in figure 5. Here the hysteresis loops have been averaged out to show the effect of the reduction in stress. As such, each one is effectively a graph of the Herschel-Bulkley relationship.

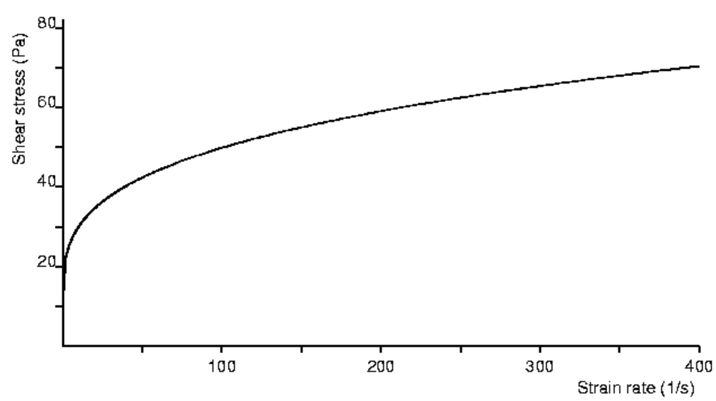


Figure 4 Graph of the Herschel-Bulkley relation

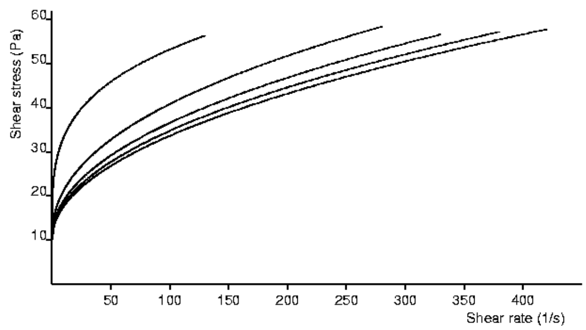


Figure 5 Decrease of shear stress with experimental repetition

For the purposes here, the hysteresis effect in the results is ignored. Values have been taken from the graphs and the constraint modeller used to fit values of the three parameters $\tau_0$, $K$ and $n$. From the graphs it appears that $\tau_0$ is (roughly) the same on each repeat and a value of 10 Pa has been taken. Table 1 gives the values of the parameters associated with each of the repeat curves in the figure.

Table 1 Values of Herschel-Bulkley parameters for curves in figure 5

| Curve | $\tau_0$ (Pa) | $K$ (Pa $s^n$) | $n$ |
|---|---|---|---|
| 1 | 10 | 12.59 | 0.268 |
| 5 | 10 | 4.11 | 0.437 |
| 10 | 10 | 2.97 | 0.476 |
| 15 | 10 | 2.71 | 0.482 |
| 21 | 10 | 2.45 | 0.491 |

Let the curve number be $m$. The above data can be interpolated with respect to $m$. The following formulae for the three parameters have been obtained.

$$\tau_0 = 10$$

$$K = 1.944 + 10.791/(m + 0.1036)$$

$$n = 0.5103 - 0.4094/(m + 0.6891)$$

In the production process, the temperature of the material changes and it is known that this has an effect upon the Herschel-Bulkley parameters and upon the apparent viscosity. Figure 6 shows the relation between viscosity and temperature obtained experimentally after different processing times; the longer the time the lower the graph. The viscosity decreases exponentially as the temperature rises. Such graphs can be interpreted as recovery curves for the viscosity as the yoghurt is allowed to rest and to cool after being processed (for the given time). Again a formula has been fitted to the data presented in these graphs. If the processing time is $t$ (in minutes) and $\theta$ is the temperature in degrees centigrade, the viscosity $\eta$ is given by

$$\eta = (14.9 + 45.5e^{-0.178t})\, e^{-0.282\theta} \qquad (2)$$

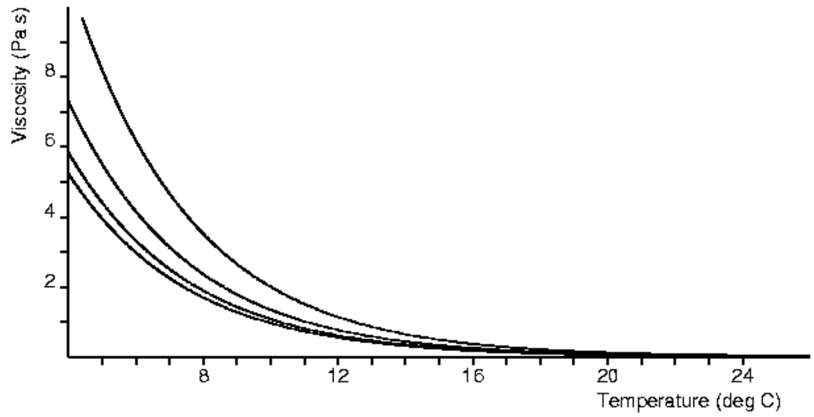


Figure 6 Variation of viscosity with temperature and with processing

## 4.1 Three stage simulation

There are three stages in the production process that are represented. The first is a flow along a pipe. This has the effect of reducing the viscosity. The second stage is a mixing stage. Here the yoghurt is mixed with the effect of reducing the viscosity considerably. The final stage is a cooling and recovery stage. Here the yoghurt is allowed to rest and cool.

For the pipe flow, as in the previous section, there are two issues to address. The first is to find the pressure gradient. This is done by applying a single constraint rule which is derived from the expression for flow rate. This specifies that the flow rate should be the given desired value. To resolve the constraint, the modeller is allowed to vary the value of the pressure gradient. Thus this is a one degree of freedom problem and the solution is found quickly.

The other calculation performed with the pipe flow is to find the reduction in the viscosity. This is done by using the imposed flow rate to determine an average flow velocity in the pipe and hence an average time. Then the viscosity is determined by equation (2).

The mixing time is effectively determined by the required final viscosity. If this time is increased then the final viscosity is reduced. The mixing time is found by applying a single constraint rule to ensure that the final viscosity is the required value. To resolve the constraint, the time for the second stage is allowed to vary. Thus this is again a single degree of freedom problem and a solution is found quickly. Once the value of the mixing time is known, the other parameters of the yoghurt can be determined.

Figure 7 shows graphs of viscosity against time for three different modelling episodes. In each case, the pipe flow takes place over the first 20s. The main difference between the three cases is that the mixing time changes: the mixing regime starts at 20s in all cases and lasts until 50s, 124s and 225s. This has the effect of reducing the final viscosity after recovery (over a further 125s). It is clear that, in this case, the effect of the pipe flow in the initial parts of the graphs is small compared to effects of the mixing and recovery stages.

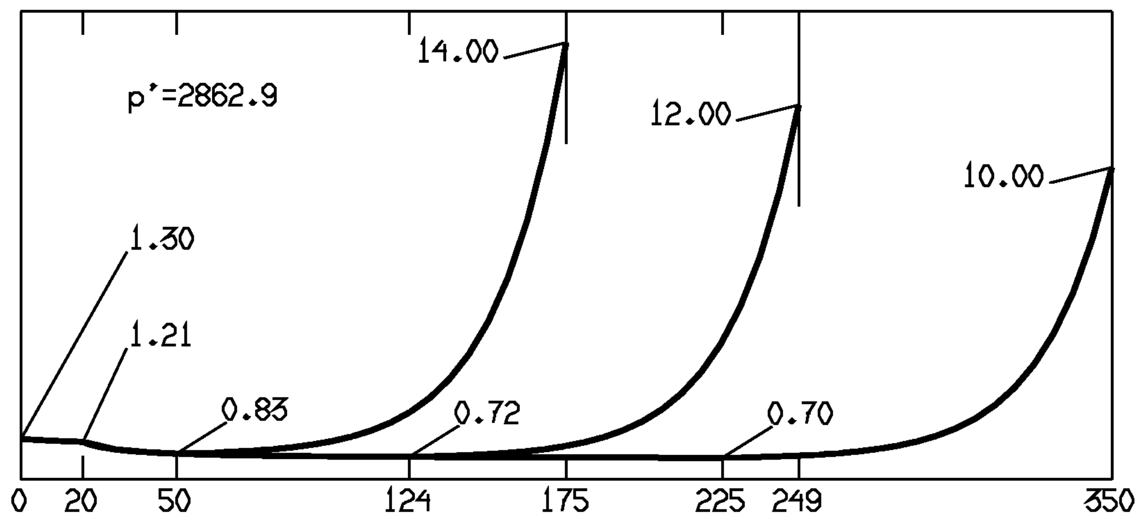


Figure 7 Graphs of viscosity against time over three modelling episodes

## 5 Simpler constraints and bounding

One of the challenges of design in the food area is in deciding which model of the material properties to use. In the case of the yoghurt examples above, the Herschel-Bulkley model (equation (1)) has been used. This model has been used extensively for representing yoghurt and other dairy products [4, 8, 9, 10, 11]. It also has application to other food stuffs such as those based upon tomato concentrates [2, 12, 13].

However there are other models. One is the simpler "power law" model

$$\tau = K(d\gamma/dt)^{n} \qquad (3)$$

which is the same as Herschel-Bulkley except that the yield stress is omitted. This has also been used successfully for a number of products [8, 9, 14]. There is an argument [15] that the idea of yield stress was only introduced for some materials because of a lack of ability to measure (and hence model) what happened for small values of strain rate. In a similar way, there is some doubt about the confidence to be placed in estimates for the other Herschel-Bulkley parameters. The typical rheological measurement is to subject a sample to a constant shear stress and produce graphs of strain rate against time. Working across such graphs for a given time, pairs of values of shear stress and strain rate are obtained and used to fit the Herschel-Bulkley relation. As the time for any single rheological measure is considerable, the number of points used for the final fit is small and hence the potential errors in the estimates of the parameters high. It is shown [16] that the correlation between the Herschel-Bulkley and the power models is often as good as that between either model and the experimental results for this final fit. This suggests that one might as well opt for the simplicity of the latter model.

In [17], the hysteresis effect is discussed in the shear stress against strain rate curves for yoghurt. It is noted that on the upward rise there is a good fit to the Herschel-Bulkley model while the downward return is more linear.

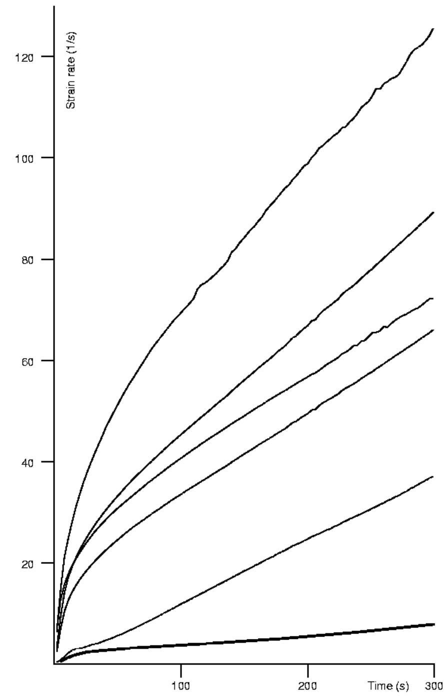


Figure 8 Rheograms for yoghurt samples from various processing stages

## 5.1 Revised model

All the above models are essentially ones in which the temperature is constant. In food processing the temperature naturally varies and so for design analysis it is important to incorporate such effects. When temperature is incorporated into models it is usually done using the assumption of Arrhenius (see [8, 17]) that the effect is exponential in the temperature. So, for example, the consistency factor $K$ in the Herschel-Bulkley relation (equation (1)) might be assumed to have the form

$$K = K_0 \exp( E_0/R\theta)$$

where θ is temperature. However, as noted above, there is a lack of confidence in the Herschel-Bulkley parameters for a single temperature and this may be compounded when the additional terms have to be determined as well. In [17], there is a proposed fit to the Herschel-Bulkley and linear models for varying temperatures. However, this is only for a limited range of temperatures. Using the model outside this range results in the prediction of negative shear stresses.

For these reasons, it is proposed that a better strategy for obtaining basic relations is to return to the results of the original rheological measurements. These are graphs of strain rate against time for fixed values of shear stress. Such graphs are shown in figure 8 for samples of yoghurt taken from different stages in a production plant; the initial sharp rise in some cases reflects that the material has not recovered fully from previous processing.

It has been found [18] that (for yoghurt) these can be well approximated by an expression of the form

$$d\gamma/dt = A\, \tau^m\, b^\theta\, t \qquad (4)$$

where $A$, $m$ and $b$ are constants.

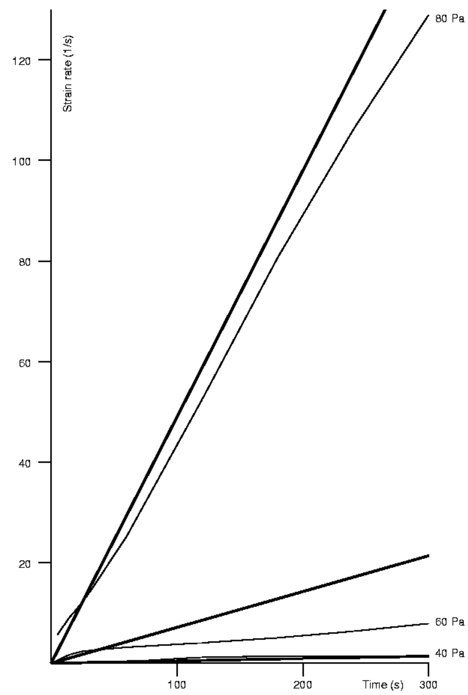


Figure 9 Comparison of theoretical and experimental results

Figure 9 shows example fits (thick lines) to results (thin curves) for a single yoghurt at three different shear stresses. The yoghurt was fully recovered from previous processing and so the experimental results are linear in the initial stages.

If equation (4) is rearranged to give the shear stress, then it is similar to the power law (equation (3)) which as noted above is not very different in practice to the Herschel-Bulkley model. There are a number of advantages in using equation (4). Firstly it is reasonably simple to use and fits the original data reasonably well. This means that it can be used to bound the problem at the early stages of design. It gives the dependency on time and temperature explicitly and does not make simplifying approximations to remove them. The effects of time and temperature are often key in designing good plant and processes.

As an example, consider the case of modelling flow along a pipe. The residence times for different parts of the fluid vary and the above expression can be used (together with results for flow velocity) to take account of the differing thinning effects that take place. This enables the properties of the fluid as it emerges from the pipe to be determined. In particular, the graphs obtained when measuring the material after processing can be predicted using an assumption based on deformation energy stored [18]. Figure 10 shows the predictions (thick lines) of the experimental results (thin curves) for yoghurt after processing by pipe flow.

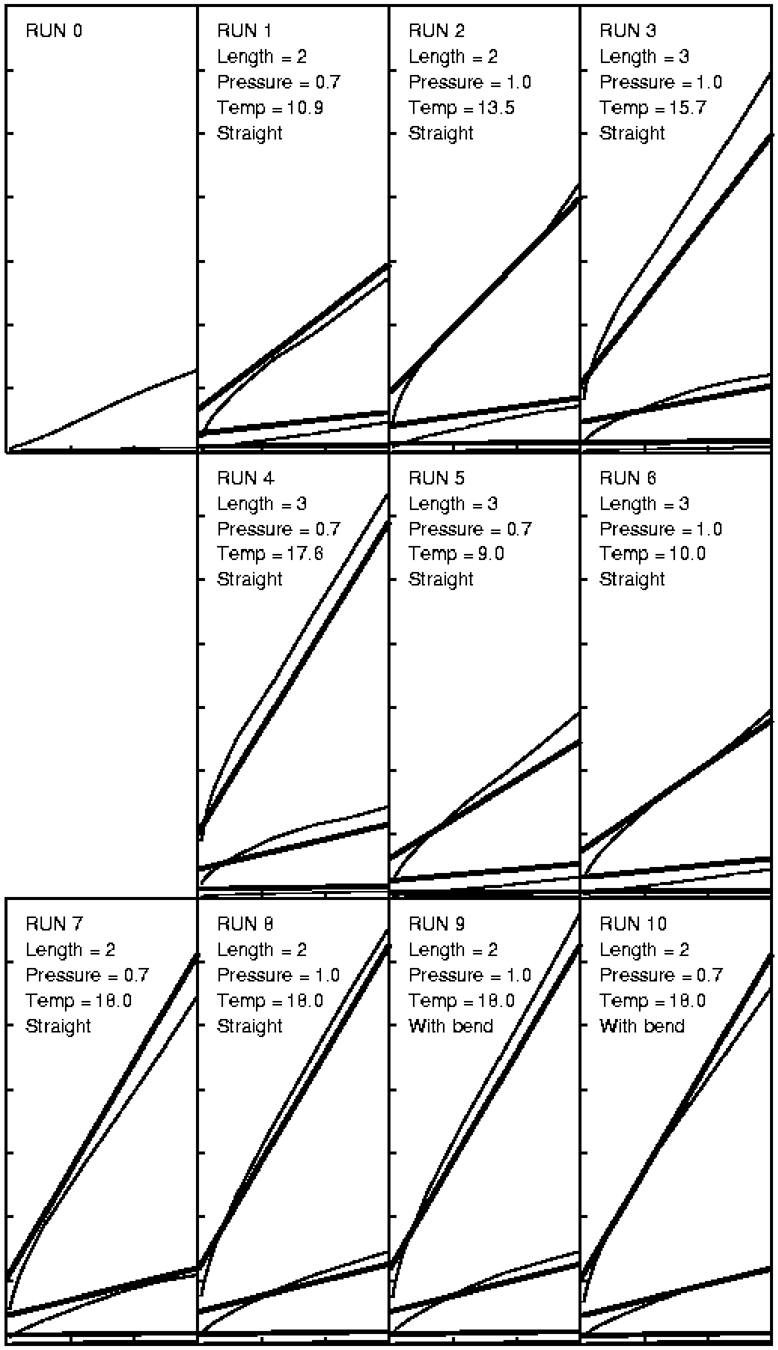


Figure 10 Agreement between experiment and theoretical predictions after pipe flow processing

# 6 Conclusions

Design of food production systems is a complex task driven by the conflicting requirements of the production processes themselves and of the final consumer's perceived view of quality. To meet these, it is important to be able to model the effects of processing upon the key attributes of the food material. These attributes also need to be related to the sensory qualities of the product for the consumer. Often such models are incomplete due a lack of a full understanding of how the material behaves. However, it can be sufficient to have simplistic models to bound what can occur. This then helps to provide some understanding of how the production processes affect the final quality and from this the key design parameters of the process can be identified and optimised.

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