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Aseptic Processing: A Study of Liquid/Solid Interactions and their Influence on the Rheological Behaviour of Products and Sterilisation Efficiency

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SUMMARY

This report addresses the continuous flow processing of food products containing liquids and solids (e.g. soups and meat products) and focuses on the mechanisms within holding tube flows. Experimental validation of both model predictions and novel measuring techniques were central to the methodologies adopted.

Tube viscometry proved successful for characterising the flow behaviour of gelatinised Colflo 67 between 80 and 135°C. Flow behaviour indices between 0.3 and 0.5 were obtained with the power law model, and the introduction of particles (5 - 25mm) resulted in the flow tending towards plug flow as the particle fraction increased.

Particle residence time studies using Hall effect sensors and visual systems showed that the assumption of a Newtonian fluid in laminar flow led to a large safety factor. Trials were conducted using diced vegetables (15-25mm) in gelatinised Colflo 67 (4 to 6 wt%) at temperatures between 70 and 140°C. Slip velocity between the particles and fluid was proven to be a significant factor in estimating the fluid/particle heat transfer coefficient.

Application of the results to the food industry can contribute significantly to improving the efficiency of sterilisation processes through, for example, the ability to measure particle residence times in holding tubes. This may lead to reductions in requirements for holding tube lengths and in the production of higher quality food products.

Future research is planned to develop methodologies for investigating the flow and heat transfer mechanisms which occur for particles within the heating and cooling sections of a thermal process. This area is poorly understood and hinders the progress of continuous processing of particulate foods as a genuine competitor to in pack sterilised or pasteurised foods.

CONTENTS

EXECUTIVE SUMMARY

CCFRA has for many years been at the forefront of the application and validation of heat processing technology to the production of commercially sterile foods. This necessitates an understanding of the key issues influencing the safety and quality of such products and the development of appropriate validation procedures for use in the assessment of process schedules for traditional and emerging processing techniques.

This project had as its objective the assimilation of data which could provide an insight into the mechanism of the flow of mixtures of solids and liquids in UHT food processing systems. This was met through the development of predictive models for the estimation of the relative velocities of the solid and liquid phases (residence times). The rheological properties of the liquids and of the mixtures have an important effect on the relative velocities and it has therefore been necessary to develop methods for measuring and predicting rheology. Rheological measurements can also be used as an on-line QA tool to confirm the consistency of materials flowing in a wide range of food plants - not only in UHT systems.

In order to address these key issues a number of approaches were adopted and these are summarised below together with key conclusions from each stage of the work.

The system variables to be investigated were flowrate (1.5 to 5 $l.min^{-1}$), flow pattern, solids fraction (0 to 0.45), ratio of particle to fluid density (0.9 to 1.1), ratio of particle to tube diameter (0.2 to 0.5), carrier fluid rheology and a comparison of vertical vs horizontal flow.

1. Tube Viscometry

The pressure drop of mixtures of solids and liquids flowing in pipe systems was measured and the data were used in several simple rheological models including the power law to characterise the flow behaviour. This portable system was based on the use of differential pressure cells. It was found to be capable of monitoring day to day variations in batches when used in a commercial production plant.

2. Residence Time Measurement

The two research teams at the University of Cambridge and CCFRA constructed systems to facilitate the measurement of particle residence times as a function of particle and fluid properties. At CCFRA a residence time measurement system was developed based on the Hall effect which permitted the measurement of particle residence times of magnetised particles passing through stainless steel pipes; this system was used successfully in large pilot plant trials. With further development it could form the basis of a process validation technique for UHT processing of particles and provide corroborative results for use in conjunction with other techniques such as microbiological tracers.

3. Heat Transfer Modelling

The flow characteristics of mixtures and the relative velocities of particles to liquids are important factors influencing the heat transfer between fluids and in UHT systems are central to the assurance of commercial sterility. Research at the University of Cambridge has led to an improved understanding of the convection occurring at the surface of particles in UHT processing following the development of correlations for the prediction of heat transfer coefficients. These were found to fit in well with other approximations and correlations used for heat transfer in other industrial sectors.

4. Flow and Heat Transfer Maps

Whilst the generation of the research data is of key importance in this project, mechanisms are necessary to aid its application of the new data to process validation and design. To that end the flow and heat transfer data have been correlated to form the basis of flow and heat transfer maps which can be used to assess the regimes likely to exist in specific production plants.

At the outset, the likelihood of success for this project was estimated as being high - about 70%. The objectives have been achieved with the added bonus of the development of a new and innovative residence time measurement technique based on the Hall effect which can form the basis of a commercial process validation tool for UHT processes.

The application of pressure drop measurement to the assurance of product consistency has the potential to reduce the level of rejected product and the levels of rework undertaken in many production processes through monitoring of product consistency and provides a control mechanism for up stream and down stream operations.

The traditional approach to the estimation of thermal processes delivered in UHT systems has involved the assumption that the flow is laminar and the liquid has Newtonian flow characteristics on which basis the minimum residence time of any part of the product is half that of the residence time calculated for the average flow velocity. The results obtained in this work, from the residence time, heat transfer studies and rheological studies, would suggest that this may be an excessively safe approach leading to over processing of food products. This will limit the realisation of the full potential for quality improvements claimed to be attainable with UHT processing.

1. INTRODUCTION

The focus of this project was to investigate UHT processing of foods comprising mixtures of solids and liquids in which the liquids were typically of high viscosity, and the density differences between solids and liquids were minimal. The flow behaviour within the holding section was chosen to be the subject of the study, because it is currently assumed (for microbiological safety purposes) that all sterilisation occurs in this section (Pflug, Berry and Dignan, 1990). Although horizontal holding tubes are typical for UHT processes, vertical holding tubes were also considered, since there may be advantages in using this arrangement.

The function of using a holding section in a thermal process is to ensure that all parts of the product are subjected to the desired thermal process. Therefore, the food particles must stay in the holding section for a sufficient time to allow heat transfer to and within the particles. This process is greatly influenced by the magnitude of the heat transfer coefficient between the liquid and the particles, and as such is dependent on the relative speeds of each.

Knowledge of the viscosity is central to understanding both the particle residence time distribution and heat transfer characteristics, and is therefore an essential parameter to be measured. Bench viscometers can be used to measure the rheological behaviour of non-Newtonian homogeneous food products, but in order to study the effects of the introduction of particles to viscous carrier fluids it is necessary to consider other measuring techniques.

Tube viscometry was the method selected to provide basic flow data for plant design and analysis, with comparisons of rheological data with a bench viscometer where appropriate. Particle residence times in the holding tube were measured using Hall effect sensors, which detected simulated food particles containing a magnet. Parallel work studied flows optically to measure velocity profiles and flow patterns. Heat transfer to/from the particles was measured experimentally and then incorporated into a model for process flows. Flow maps and correlations were developed to indicate typical operating regions of continuous flow processing plant incorporating data generated during the project.

The objectives of this project were broadly divided into the areas of rheology, particle residence time and heat transfer. Data generated within each area would be correlated by means of flow maps and design equations, for use by companies involved in the production of food products containing particulates. These research areas are summarised as follows:

(a) To construct a tube viscometer system at CCFRA for the measurement of apparent viscosity of flowing particulate food (i.e. products comprising particles in the range 5 to 25mm) by measuring pressure drop as a function of volumetric flowrate. The experimental trials would investigate the influence of particle size and concentration on the rheological behaviour, as indicated by the viscous parameters to be measured. The equipment would be designed to be portable and would be used in food production environments to generate data for real food products. The bulk of this work would be conducted at room temperature, but the measurement system should be tested at elevated temperatures and pressures similar to those experienced in a UHT process. Simple rheological models, such as the power law, were envisaged as providing the most likely means of analysing the data in such a way that the technology could be transferred easily to a food production environment.

(b) To construct two similar systems (at CCFRA and Cambridge) for the measurement of particle residence time in holding tubes. It was envisaged that the flow systems would involve a transparent pipe to allow the observation and video recording of particle flow behaviour. Experimental trials would investigate the effects of flow velocity, flow pattern, particle velocity and pressure drop as functions of solids fraction, particle/fluid density ratio, particle/pipe diameter ratio, carrier fluid viscosity, and overall flowrate. The experiments conducted at Cambridge would be undertaken at ambient temperatures and would include both horizontal and vertical holding tubes.

(c) To construct a flow cell at Cambridge in which simulated particles could be suspended in a flowing liquid, and their temperature history measured as a function of the liquid properties and the flow velocity. Models would be developed to relate particle/fluid slip velocity to the rate of heat transfer, and hence values of the fluid/particle heat transfer coefficients would be deduced. Values for slip velocities would arise from the experiments described in objective (b), and be used to obtain heat transfer coefficients for comparison with those predicted by the much used Ranz-Marshall correlation (1948).

(d) To collate all of the data on rheology, particle residence times and heat transfer into flow maps or design equations to allow a thermal process to be designed. This would involve the prediction of heat transfer coefficient, particle residence time distribution and pressure drop, for a given mixture of solids and liquids. The parameters for the flow map would be empirical and chosen largely by trial and error, such as the particle Froude number. The flow maps would allow rapid estimation of the probable flow regime in a particular case and would thus assist designers to avoid unsuitable formulations.

Within the areas covered by each objective, considerable innovative research was necessary. No satisfactory system existed for the accurate measurement of the bulk flow behaviour of a mixture of solids and liquids. Tube viscometry would be tested under conditions hitherto untried, in both pilot scale and production equipment. The published methods for measuring particle residence times in continuous processes required considerable improvement before they could be adopted by industry. Therefore, residence time models derived from these published data were unreliable. Models would be developed from the data generated using improved experimental techniques, so giving industry the confidence to use these models. Heat transfer predictions relied on the Ranz-Marshall correlation (derived for steady state evaporation from a spherical drop of water) for obtaining the fluid/particle heat transfer coefficient. New models, which would be developed based on heat transfer correlations tested with food-based fluids, would then be applied with greater confidence by the food industry. Finally, no flow maps or comprehensive design equations were available for mixtures of solids and liquids, and these would be developed towards the end of the project.

Details of the research carried out in each organisation involved with research for the project are given in later sections of this report. The technical achievements of the project were published at appropriate times, using a wide variety of sources to increase the level of information dissemination. This report describes the work conducted at Campden & Chorleywood Food Research Association, at the University of Cambridge, and within the industrial consortium of companies supporting this project.

2. TUBE VISCOMETRY AND RESIDENCE TIME STUDIES (CCFRA)

2.1 Tube Viscometry

Conventional methods for the measurement of food viscosity measure the torque required to counteract the resistance caused by a fluid in a viscometer cell; these are either shear stress controlled or shear rate controlled. The torque is related to the shear stress and is a function of the fluid viscosity as well as the geometry of the viscometer measuring cell.

Unfortunately, there are two main limitations restricting the use of bench viscometers throughout all sectors of the food industry, and in particular with respect to mixtures of solids and liquids (Tucker, 1993a).

The first problem is that solid food particles entrained within a fluid will cause irregularities in the measured torque, so giving rise to variable values of viscosity. As the size of the particles increases there will also be a tendency for the particles to physically block the measuring gap of the viscometer. The other restriction is that few rotational viscometers are designed to operate at the high temperatures and pressures associated with UHT processing.

One method of measuring viscosity which is not limited by these two criteria is the tube viscometer (Tucker, 1993b). This relies on a basic engineering principle in that the pressure drop along a straight length of pipe is related to the wall shear stress, and the volumetric flowrate is related to the wall shear rate. Therefore, by measuring pressure drop and volumetric flowrate it is possible to characterise the overall flow properties of the food in terms of a simple model.

Tube viscometry was used to characterise the flow behaviour of various starches over temperatures between 80 and 135°C (Tucker, 1992; Tucker, 1993c; Tucker and Fryer, 1994; Scott, 1994; Heydon, Scott and Tucker, 1995). These trials used a scraped surface heat exchanger to raise the fluid temperature from ambient to elevated temperatures, with back pressure maintained through a valve (figure 1). The use of the power law model proved satisfactory for correlating these data over a limited range of wall shear rates, with flow behaviour indices generally lying between 0.3 and 0.5 (table 1).

FIGURE 1: SCHEMATIC DIAGRAM OF THE TUBE VISCOMETER

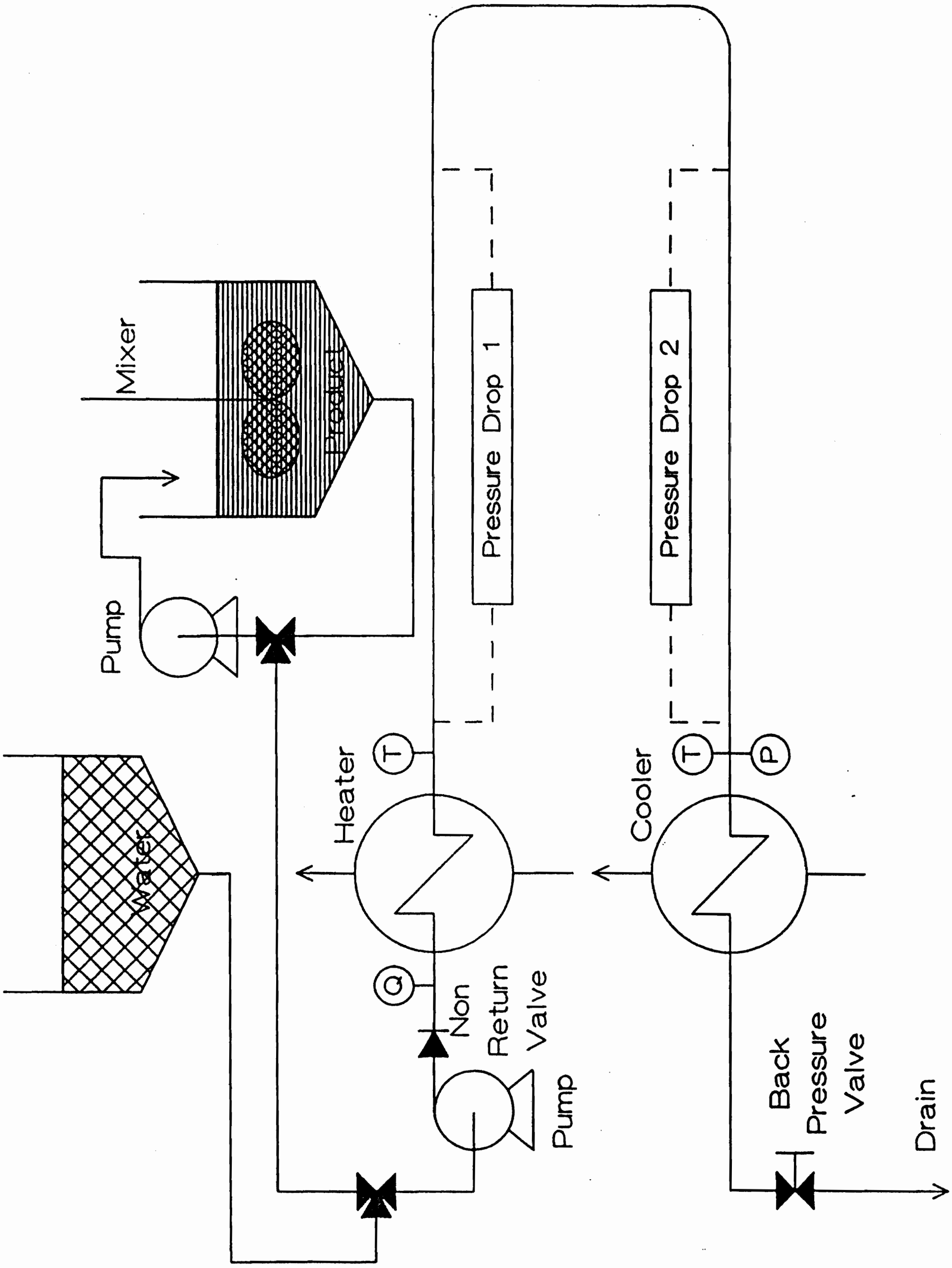


TABLE 1: SUMMARY OF POWER LAW CONSTANTS FOR COLFLO 67 STARCH PROCESSED UNDER UHT CONDITIONS.

Temperature (°C)	Concentration (wt%)	n (dimensionless)	k ($N.s^n.m^{-2}$)
100	4	0.22	2.84
	5	0.31	5.71
	6	0.43	11.81
	7	0.26	19.10
110	4	0.48	1.20
	5	0.20	7.02
	6	0.50	8.65
	7	0.25	17.01
120	4	0.34	1.81
	5	0.41	3.16
	6	0.42	8.05
	7	0.28	16.21
130	4	0.48	1.42
	5	0.46	2.85
	6	0.49	8.76
	7	0.20	18.02
135	4	0.86	0.55
	5	0.36	2.86
	6	0.50	8.02
	7	0.25	12.10

For gelatinised Colflo 67 the following generalised relationship was proposed (Scott, 1994; Scott, Holdsworth and Tucker, 1995) for the prediction of apparent viscosity at the pipe wall $(\mu_a)_w$ as a function of shear rate ($\dot{\gamma}$), processing temperature (T, in Kelvin) and starch concentration (C).

$$(\mu_a)_w = 0.00452.\exp(514/T).\dot{\gamma}^{-0.617}.C^{3.44} \quad (1)$$

This was an expression derived from experimental measurements; therefore its applicability was limited to the conditions observed during the experimental trials. The following limits were imposed on the variables in the expression.

Temperature (T):	100-135°C. [NB. Temperature in equation (1) must be expressed in Kelvin, 273-408K]
Shear Rate ($\dot{\gamma}$):	$0\text{-}60s^{-1}$.
Starch Concentration (C):	4-7wt%.

Tube viscometry results for mixtures of solids and liquids of up to 45 wt% diced vegetables in gelatinised Colflo 67, showed the consistency coefficient (k) to be the more sensitive variable, with the flow behaviour index (n) being between 0.3 and 0.5 for most mixtures (Tucker and Richardson, 1993; Tucker, 1994a; Scott and Holdsworth, 1994).

The power law constants k and n are summarised in table 2 for various combinations of particle size, fraction and temperature (Tucker, 1994a). Table 2 presents apparent viscosity for pipe flow $(\mu_a)_p$ at three different wall shear rates (10, 30, 50s^{-1}).

TABLE 2; POWER LAW DATA FOR 2^3 FACTORIAL DESIGN FOR MIXTURES OF DICED SWEDE AND GELATINISED COLFLO 67

FACTORS

A : Swede dice size; low = 7.5mm, high = 20.0mm
B : Swede fraction; low = 0.04, high = 0.22
C : Bulk temperature; low = 30°C, high = 72°C

Factor Combinations			Power Law Constants		Pipe Flow Apparent Viscosity (Pa.s)		
A	B	C	n	k (Pa.s^n)	$\dot{\gamma} = 10s^{-1}$	$\dot{\gamma} = 30s^{-1}$	$\dot{\gamma} = 50s^{-1}$
L	L	L	0.38	3.8	1.29	0.65	0.48
L	L	H	0.36	3.1	1.01	0.50	0.36
L	H	L	0.26	7.4	2.30	1.02	0.70
L	H	H	0.35	2.5	0.84	0.41	0.29
H	L	L	0.45	3.0	1.11	0.61	0.46
H	L	H	0.34	2.4	0.79	0.38	0.27
H	H	L	0.30	3.4	1.07	0.50	0.35
H	H	H	0.38	1.9	0.64	0.32	0.23

2.2 Particle Residence Time Measurement

A method for the measurement of particle residence times was designed to detect a particle containing a small magnet and travelling in a stainless steel pipe (Tucker, 1994b,c; Tucker and Scott, 1994). The sensors were based on the Hall effect and were proven to reliably operate through a pipe wall (2-3mm) at a range of up to 40mm. To measure the particle residence times, two sensor arrays were required, each consisting of 4 individual sensor devices, mounted on the pipe a fixed distance apart (figure 2). The time taken for the magnetic particle to reach the second sensor array, having passed the first, allowed the particle residence time to be calculated.

An example of a measured residence time distribution is given in figure 3, for 45wt% of 10mm diced rutabaga in 4.0wt% Colflo 67, and flowing at 6.44 $l.min^{-1}$ (Scott and Holdsworth, 1994). Efficiency factors (defined as the minimum particle residence time divided by the mean bulk fluid residence time, and expressed as a percentage) were calculated from these data. Efficiency factors were all in excess of 50%, which results from laminar flow of a Newtonian fluid and which is currently taken as the design criterion for aseptic processes.

The Hall effect sensors were designed to measure particle residence times in holding tubes of industrial processes. Results were validated using holding tubes connected to a scraped-surface heat exchanger and to an ohmic heating system. For most mixtures, the measured particle residence times were greater than those of the bulk mixture (Tucker and Withers, 1992; Tucker and Withers, 1994). The trials on APV's pilot ohmic heating system indicated that particle residence times were nearer to those expected for plug flow than for a Newtonian fluid.

Development of the Hall sensor methodology allowed particle residence times to be measured for pipe flow, around heat exchangers, and through valves, pumps and other process equipment. The sensors were portable and operated at high temperatures (to 140°C), high pressures (to 5 bar), in opaque liquids, and through stainless steel pipes (Tucker, 1994c).

FIGURE 2: SCHEMATIC DIAGRAM OF THE HALL EFFECT SENSOR ARRAYS

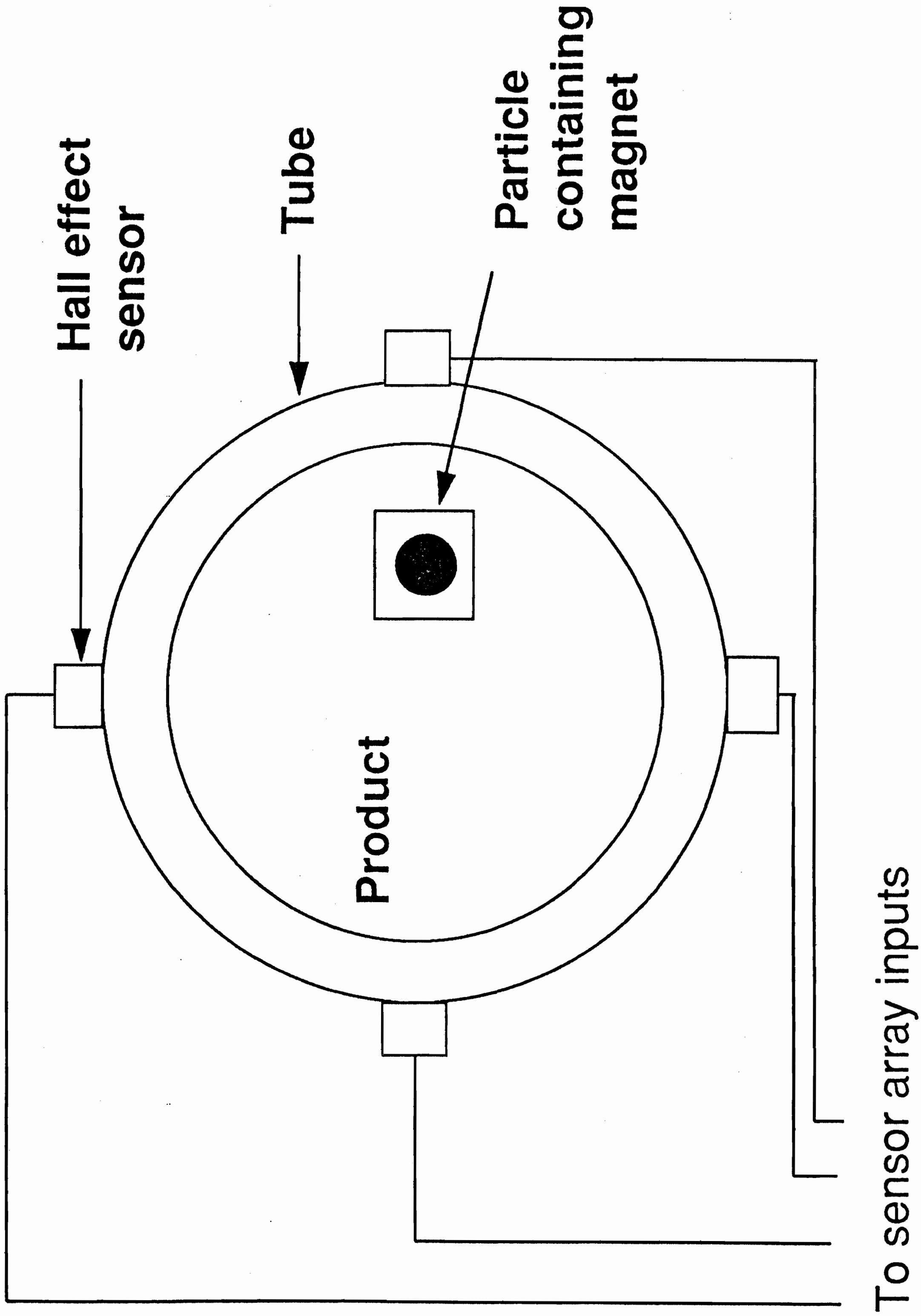
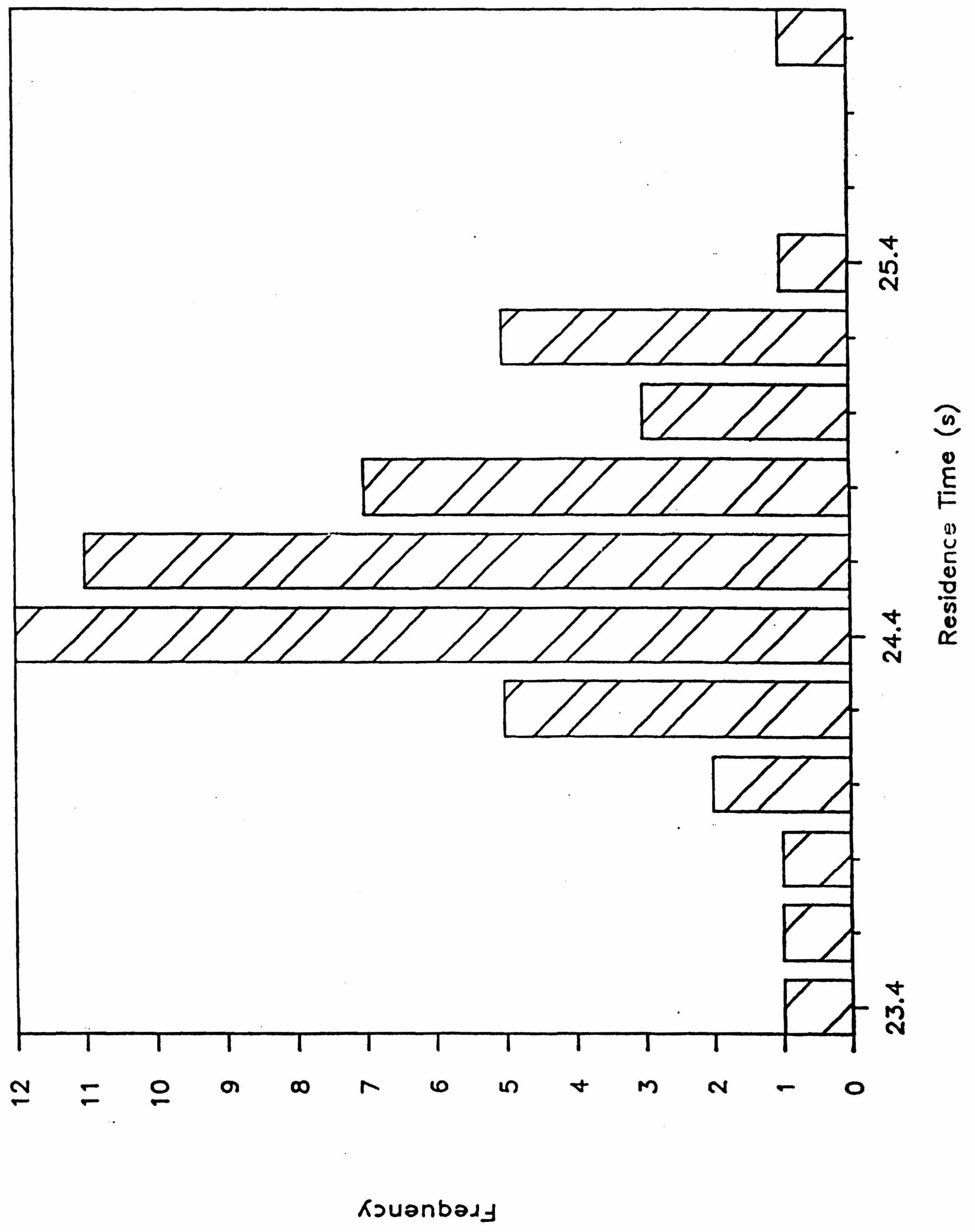


FIGURE 3: RESIDENCE TIME DISTRIBUTION FOR 45wt% OF 10.0mm DICED RUTABAGA IN 4.0wt% COLFLO 67 FLOWING AT 6.44 $l.min^{-1}$



3. HEAT TRANSFER AND RESIDENCE TIME STUDIES (UNIVERSITY OF CAMBRIDGE)

3.1 Fluid flow

In parallel with the work on industrial systems at CCFRA, work at Cambridge was carried out to develop an understanding of the dynamics of two-phase food flows (Lareo, 1993).

Similar types of carrier fluids and particles to those described in the CCFRA section were used in the Cambridge work. Transparent plastic apparatus was constructed and the experiments were conducted at room temperature and pressure. In addition to electronic detection of metallised tracer particles, the use of transparent tubes enabled the fluid flow patterns and particle behaviour to be observed directly (figure 4). This represented a vital complement to the indirect measurements of particle velocity and pressure drop at CCFRA.

A number of areas of work were studied:

(i) a systematic study of the flow patterns and particle residence time distribution in vertical up and down flows was made, for solids fractions between 0 and 0.40 by weight (Lareo, Fryer and Branch, 1994; Lareo et al., 1995a). It was shown that the relative velocities of the two phases were strong functions of particle size, fluid viscosity and particle density. In some cases bimodal residence time distributions were seen; particles appeared to travel at two speeds. This has significant implications for the processing of mixtures (Lareo et al., 1995b).

The difference between the mean fluid velocity and mean particle velocity was substantial in some cases; this was a function of both the slip velocity between individual particles and the surrounding fluid, and of the velocity profile of the liquid. Slip velocities for individual particles were measured up to 1.0 $cm.s^{-1}$ in water, but were more commonly 1.0 $mm.s^{-1}$ or less with fluids of greater viscosity. Work on the measurement of fluid-particle heat transfer coefficient has shown the importance of accurately measuring slip velocities.

(ii) the flow patterns and radial velocity distributions of particles were studied using video recordings to image the particle tracks (Lareo, 1994). This was done for particle fractions up to 0.15 by weight; beyond this point it was impossible to resolve individual particles by this optical method. At low solids fractions, two types of particle behaviour were seen. Particles either followed the fluid flow pattern closely, giving an approximate parabolic flow profile, or showed a radial profile which was not a function of the fluid profile. These data suggest an explanation for the bimodal flows observed in the RTD measurements (Lareo et al., 1995c). This behaviour was correlated on a flow map, which related the Froude or Archimedes numbers of the flow to the Reynolds number of the particles.

(iii) models for pressure drop in fluid flows were developed on two bases, using alternative constitutive equations (for example the Ellis model) to those of CCFRA so that an improved match of velocity profile was obtained, and assuming the limiting case of a packed bed of particles moving as a plug in the centre of the flow with a narrow shear layer at the wall (Lareo et al., 1995d).

(iv) a provisional design of a flow map for single particles was proposed, which plotted the particle Reynolds number (Re_p) against the Froude number (Fr). Observations on the effect on particle movement, caused by the "wall" and the "flow", were made using the visual system of figure 4. This was combined with observed fluid viscosity profiles, to define the regions of the flow map (figure 5).

3.2 Heat Transfer

Experimental results for fluid flow showed that the difference between the particle and fluid velocities (particle slip) could be of the order of mm/s in real food flows (Mankad, 1992). Two types of effect were found due to velocity distributions in food flows:

(i) **slip velocity** effects governed the particle-fluid heat transfer coefficient between the two phases. Estimates showed that for slips in the range of mm/s the particle-fluid heat transfer coefficient was so low that it had a significant effect on the thermal response of the system.

(ii) **flow velocity** effects controlled the residence time of the fluid and particles within the system, and thus had an important effect on the thermal response of the system.

Two approaches were made to study these effects; experimental work was carried out to characterise the heat transfer coefficient between the fluid and the particles, and a computational model was written to study the effects of slip and flow velocity.

FIGURE 4: SCHEMATIC DIAGRAM OF VISUAL SYSTEM FOR OBTAINING POSITIONAL DATA OF FOOD PARTICLES

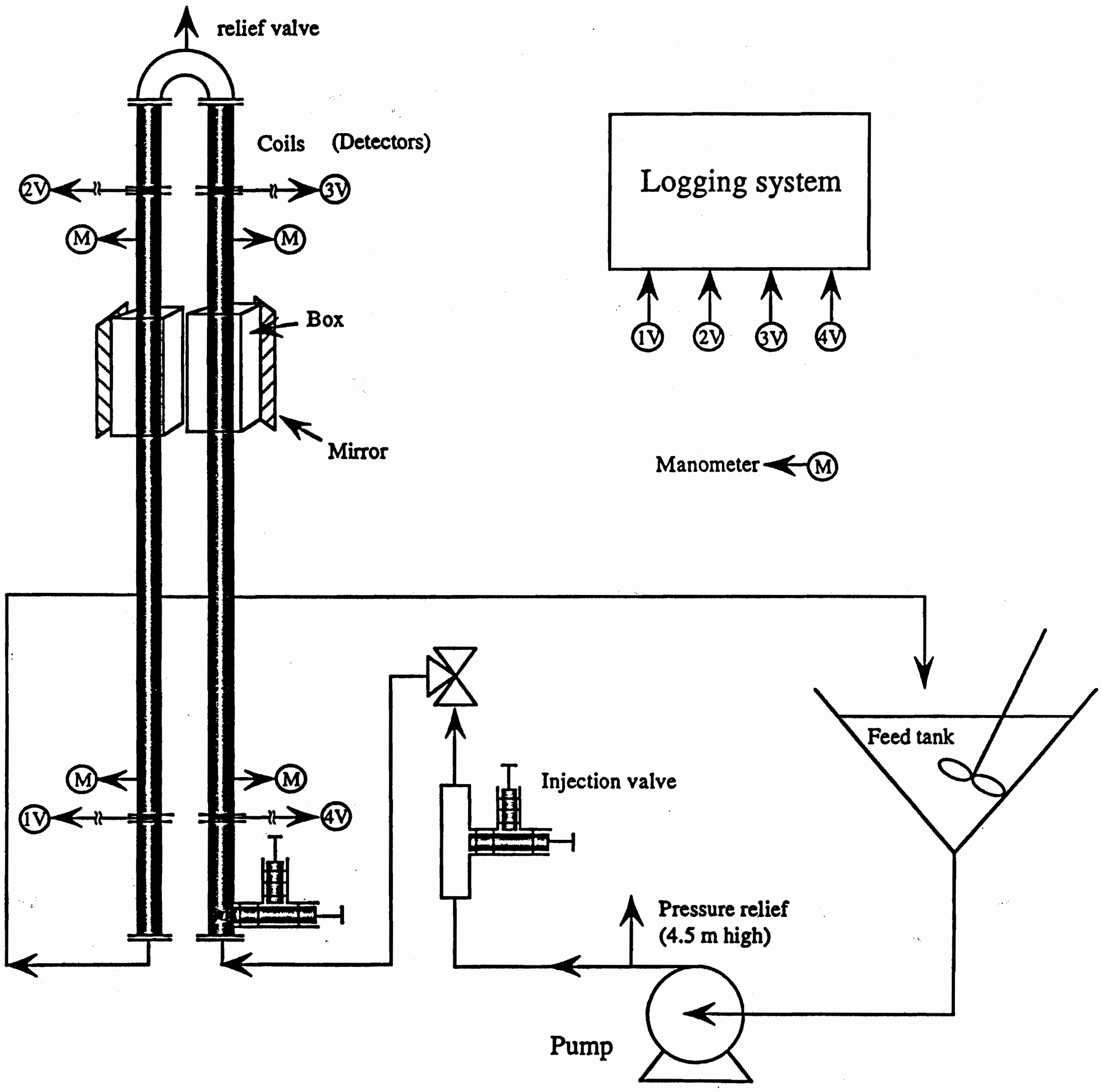
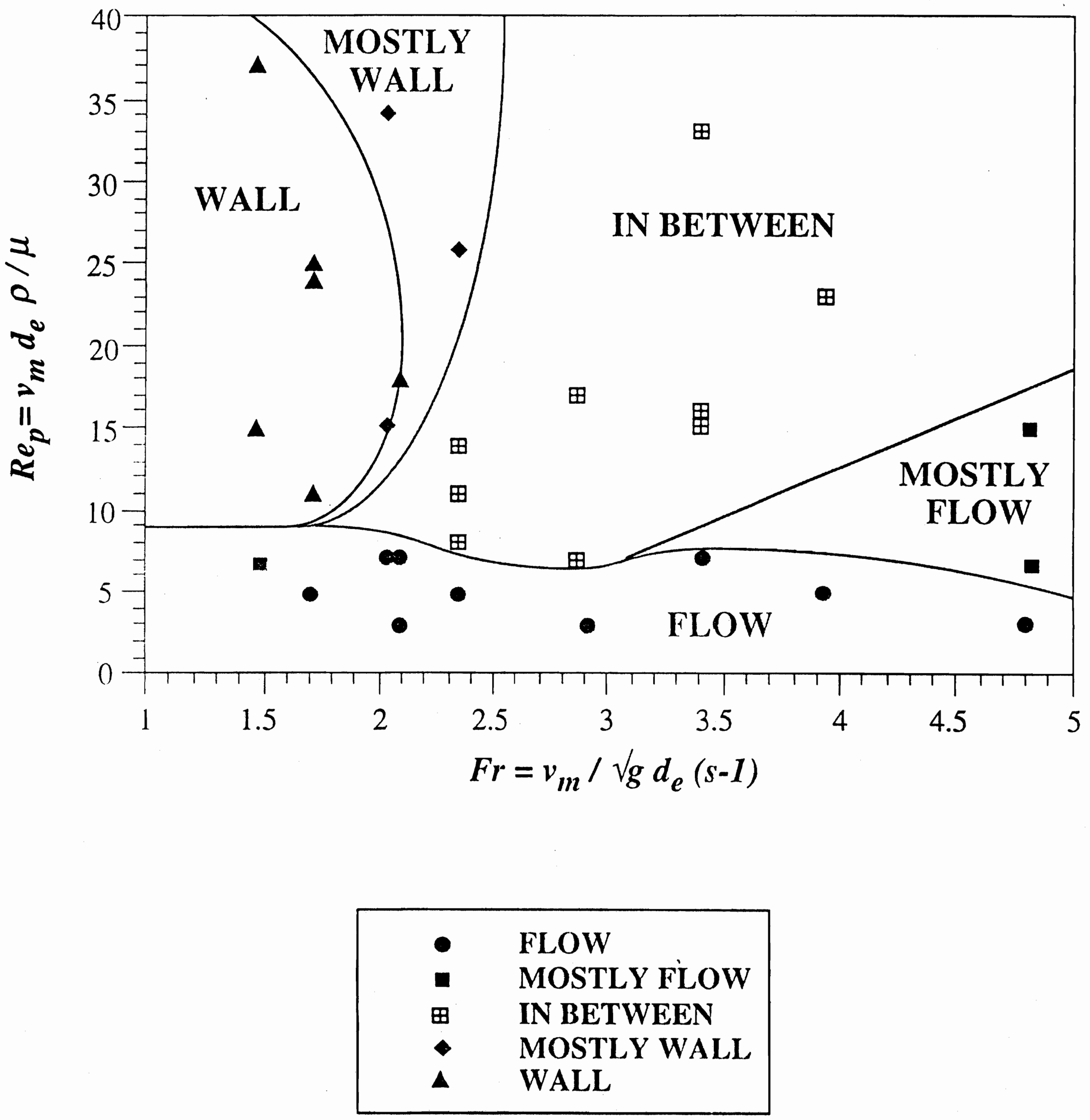


FIGURE 5: FLOW MAP FOR SINGLE PARTICLES SHOWING REGIONS IN WHICH THE PARTICLE IS AFFECTED BY THE TUBE WALLS OR THE VISCOUS FLOW



Experimental work in which a copper sphere was held stationary in a flowing liquid was used (figure 6) to determine heat transfer coefficients for four geometries, for slip Reynolds numbers between 5 and 2000 (Mankad et al., 1995):

(i) **Single particle experiments** were carried out to confirm the applicability of the standard Ranz-Marshall correlation to food systems:

$$Nu = 2.0 + 0.6Pr^{0.33}\, Re_{slip}^{0.50}$$

A good agreement (+/- 10%) was achieved between the experimental results and this correlation, over the entire slip Reynolds number range.

(ii) **Two particle experiments** were carried out to investigate the effect of one particle on another. Nusselt numbers were found to be up to a maximum of 25% greater, for slip Reynolds numbers of the order of 1000, than the equivalent experimental values for single particle experiments; however the average difference was consistently ca. +/- 10%.

(iii) **Packed bed experiments** represent the limiting value of heat transfer coefficient, at solids fractions of the order of 0.6. Experimental results showed that the Ranz-Marshall correlation was only suitable for prediction of Nusselt numbers in packed beds where the slip Reynolds number was less than 100. The following correlation was found to fit these data:

$$Nu = 0.5Re_{slip}^{0.60}\, Pr^{0.28}$$

(iv) **Variable voidage** (e) experiments were carried out for solids fractions in the range 0.10 to 0.30, and the Ranz-Marshall correlation was found only to apply for slip Reynolds numbers less than 100. Outside this range, the following correlation was found to fit these data:

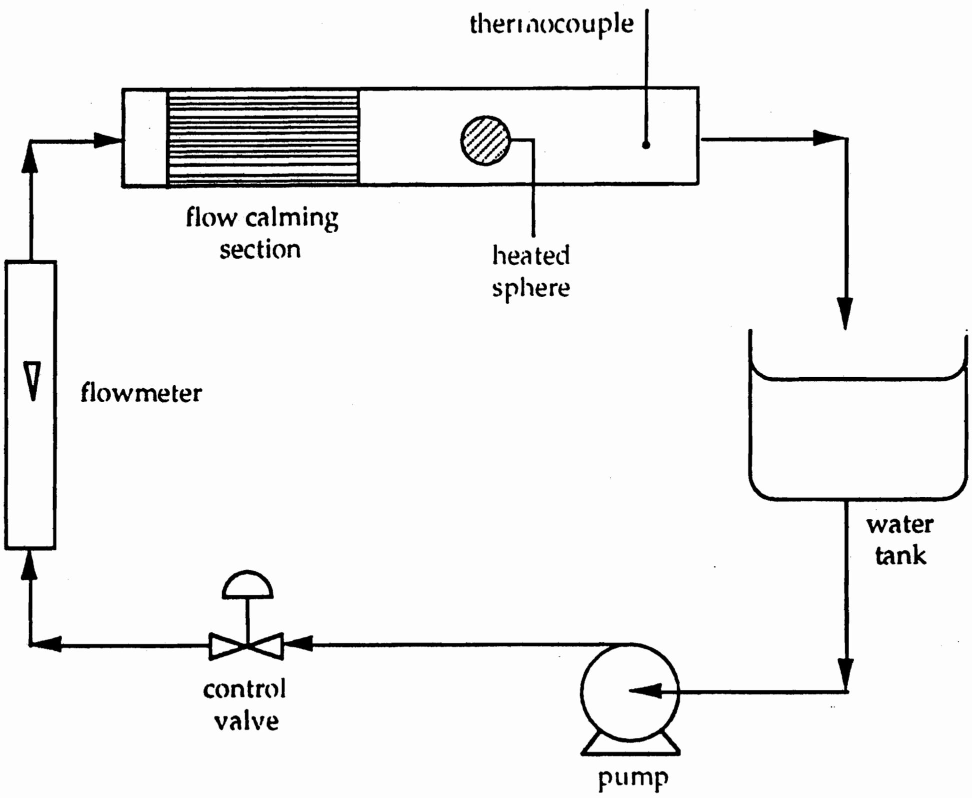
$$Nu = 2.7 + 1.1e^{-1.1}\, Re_{slip}^{0.46}\, Pr^{0.23}$$

The data indicates that some of the assumptions previously used to estimate heat transfer coefficients, especially in high solids fractions, are in error.

Modelling work involved writing a computational model of a food flow to investigate the effects of velocity on the thermal response of the system (Mankad, Branch and Fryer, 1994; Mankad et al., 1995). Initially, modelling concentrated on the effects of slip. Depending on the thermal conductivity of a food particle, the fluid-particle heat transfer coefficient may affect its heating rate; for the food flows under study, where particle-fluid relative velocities were very slow, the thermal response was very sensitive to slip. Models were written for homogeneous flows (Mankad, 1994; Mankad and Fryer, 1994), and showed that up to 30% reduction in process times (i.e. heating or holding tube lengths) resulted if slip effects were taken into account. These results have significant implications for the improved design of equipment.

A second area of study was the effect of flow velocity variations in food flows. A heterogeneous model was developed from the homogeneous version, and used to study the case of segregated flows, where there were two streams in the flow travelling at different velocities (Mankad and Fryer, 1995). This situation is more complex than the homogeneous flow case, and as a result of flow velocity variations within the fluid there were a range of temperatures in the particles and fluids passing a given point. Different parts of the flow thus become sterile at different distances through the process plant; models have been used to illustrate these effects on the design of heat/hold systems (Mankad, 1995). The optimal results for the whole system, in terms of the minimum overall process length, occur for uniform phase velocities, but individual sections of the flow do not show the same minima as the whole system, demonstrating the need to model the whole.

FIGURE 6: SCHEMATIC DIAGRAM OF THE APPARATUS USED TO MEASURE PARTICLE-FLUID HEAT TRANSFER COEFFICIENTS



4. THE INDUSTRIAL CONSORTIUM

Six companies involved in material handling and aseptic processing provided support for this project, and guided the progress of the research through a consortium which met quarterly. The activities of each company are summarised in this section.

4.1 APV Baker Ltd

APV supported the research at CCFRA and Cambridge through the provision of equipment for assembly into the experimental rigs needed by both organisations. In addition, six one-day trials were conducted on their pilot ohmic heating system to measure particle residence times, using the Hall effect sensors developed during the project. These data proved that the flow profiles were nearer to those for plug than for laminar flow, for the food products used here; this had hitherto been suspected but had not been demonstrated until now.

4.2 Alfa Laval Pumps Ltd

Alfa Laval Pumps provided two positive displacement lobe pumps suitable for pumping mixtures of solids and liquids. These were a 2" bi-lobe and a 3" circumferential piston pump.

4.3 H.J. Heinz Company Ltd

Heinz were particularly interested in the research activities concerning the rheology of mixtures of solids and liquids and food particle residence time measurement. At Kitt Green they installed a tube viscometer similar to that at CCFRA together with a modified version of the Hall effect sensing apparatus. Results for rheology and particle residence times have supported the findings at CCFRA and Cambridge, and generated data for use in models.

4.4 Master Foods

Master Foods' interest was primarily in the materials handling aspects of the research, and their main objective was to find an on-line method for determining changes in the viscosity of a product batch. They constructed a tube viscometer in their pilot plant to correlate pressure drop readings with different product formulations for a single canned product. Towards the end of the project they installed their system into one of the can filling lines, to obtain on-line data on the variability of the flow characteristics of the product. Data were generated for six different commercial products, using a ten metre length of 4" pipe over which the pressure drop was measured. Despite a number of practical operational problems it was successfully demonstrated that a system based on the principle of a tube viscometer could be employed satisfactorily.

4.5 Nestlé UK Ltd

Nestlé supplied CCFRA with most of the food materials (such as starches, glucose and diced vegetables) for the tube viscometer and particle residence time trials.

4.6 Unilever UK Central Resources

Unilever were interested in all aspects of the research programme, and in particular the use of the project data to build up their databases. They acted in a consultancy role during the early development of the various mathematical models, to ensure that the models would be of practical use to food companies. Unilever regularly supplied Cambridge with diced vegetables and carrier fluid materials.

5. DISCUSSION OF RESEARCH

The achievements in each objective are summarised below:

(a) The research at CCFRA in tube viscometry proved a highly successful means of evaluating the bulk flow characteristics of flowing mixtures. The rheology of Colflo 67 and C*Flo starches were characterised both with and without particles (0 to 40 wt.%) for temperatures of 80 to 135°C. This work resulted in a number of food companies incorporating pressure drop measurements into their existing pipelines. These applications covered both off- and on-line systems, encompassing a wide variety of food products.

(b) Particle residence time measurement was achieved using a system which was proven to operate through stainless steel pipes and at temperatures in excess of 140°C. The Hall effect sensors were proven to operate on an ohmic heating system with 15 and 25mm cubed particles and a 6wt% Colflo 67 carrier fluid. This method is more widely applicable to industry equipment than visual systems and has already found specific uses by two companies in the consortium. The visual system developed at Cambridge was coupled with a video camera to provide excellent images of the disruption to the velocity profiles caused by the introduction of food particles to a transparent carrier fluid. This work also provided visual evidence for the findings at CCFRA using stainless steel pipe systems.

(c) The experiments at Cambridge to measure heat transfer coefficient resulted in a number of correlations for its prediction. Heat transfer coefficient correlations for single spheres, in multi-particle flows and in packed beds were developed. For single particles the widely accepted Ranz-Marshall correlation was proven to be acceptable. The complex finite difference model for a sphere was coded for both homogeneous and heterogeneous flow, and the importance of accurately measuring slip velocity was demonstrated.

(d) The flow maps were developed towards the end of the project in order that the rheology, particle residence time and heat transfer research were incorporated. These indicated whether the dominating mechanism was controlled by the wall or the bulk flow. Further development of flow maps would be of benefit, in order that an estimate of the thermal process received by a particle could be made, before accurate measurements are required.

6. CONCLUSIONS

Considerable innovative research was conducted in this research project, and this will contribute towards underpinning the safe production of complex UHT processed foods. The heat transfer and flow properties of mixtures of solids and liquids are thus better understood for straight pipe systems in both horizontal and vertical orientation. The following paragraphs summarise some of the achievements of the project:

- Tube viscometry on an industrial scale was demonstrated as being a method for evaluating flow behaviour of mixtures of solids and liquids, with the potential for on-line viscosity monitoring and control.

- Hall effect sensors were developed for taking residence time measurements with magnetic particles. This methodology was demonstrated to be suitable with high temperatures and pressures, opaque materials, high concentrations of particles and through stainless steel pipes.

- Correlations were developed experimentally for predicting heat transfer coefficients in packed beds, for single particles, for two particles and for variable voidage between 0.1 and 0.3.

- A heat transfer model for spheres was written to include the heat transfer coefficient correlations. This was used to demonstrate the reduction in holding tube length which slip velocity can have; this can be up to 30%.

- slip velocities between particles and fluids were measured, and found to be of the order of $1.0mm.s^{-1}$.

These advances in technology will provide a basis by which food companies can progress into the thermal processing of mixtures of solids and liquids. The measurement techniques such as tube viscometry, Hall effect sensors and heat transfer coefficient correlations will enable the thermal process delivered in a holding tube to be more accurately assessed.

7. FUTURE RESEARCH WORK

The focus of this research project was the flow and heat transfer behaviour of food products in holding tubes, since it had always been assumed, for safety purposes, that all of the sterilisation occurred within this section. However, this can lead to an overkill situation resulting in excessive heat treatment of the food products because the sterilising effects occurring within the heating and cooling sections are ignored. Although this assumption will result in the food being more than adequately sterilised, this is likely to lead to a significant amount of overcooking which may impair the product quality.

Very little data are publicly available concerning the mechanisms by which food particles are heated and cooled in heat exchange equipment. Without this information it is not possible to optimise a continuous flow process to produce a commercially sterile but properly cooked food. Experimental and modelling techniques which build on those from this project need to be developed, in order to understand the heat transfer and flow mechanisms operating within common heat exchange equipment. The degree of sterilisation (or pasteurisation) and cooking within these exchangers can then be predicted, and better design procedures developed for thermal processes.

By ignoring the heating and cooling contributions to a thermal process it is not possible to properly optimise the process. Use of the results will permit the prediction of optimal processing conditions for achieving high quality thermally processed products at minimal cost. In a market dominated by cook-chill processes with short shelf-lives, there is a real opportunity to compete on food quality, but with the immense advantage of extended shelf-lives.

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