R&D REPORT No. 87

Methods for studying the heating and cooling of mixtures of solids and liquids in heat exchangers

1999

Campden BRI

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SUMMARY

Experimental and modelling techniques are described that help explain the heat transfer and flow mechanisms occurring within heat exchangers used for continuous heating and cooling of solid and liquid mixtures. This was necessary in order that food processors could take account of the contributions made to the delivered thermal process during the heating and cooling stages, and thus estimate the level of safety margin. By virtue of being able to better define this contribution, it is possible to design processes that lead to products of optimal quality and thus avoid the unnecessary over-processing that can occur in a continuous heat process.

The residence times (RT) of particles were measured using Hall effect sensors in two tubular heat exchangers, an 8-pass 34 mm and a 9-pass 48 mm i.d. system. Mean RTs for carrots in the cooling passes were approximately 10% lower than those in the heating passes. Two explanations were proposed for this: (i) that the carrot particles cooled more slowly than the surrounding liquid, resulting in a localised reduction in viscosity and thus an increased particle slip velocity, and (ii) that the carrier liquid adjacent to the cooler tube walls had an increased viscosity, imposing a reduction in the flow area or a coring effect.

A novel process validation method was developed using a *Bacillus amyloliquefaciens* α -amylase time-temperature integrator injected into the centre of silicone particles. These particles were used to validate pasteurisation treatments for production of yogfruit batches of whole 10-12 mm strawberry, 10 mm pineapple and 17 mm apricot. The kinetic factor (z-value) for the amylase was 9.7 ± 0.3 C° between 70 and 90 °C, close to the values for microbial spore and cell destruction. For these high acid products the target pasteurisation (P-value) was equivalent to 5 minutes at 85 °C ($T_{ref} = 85$ °C, z = 10 C°).

In addition to particle residence time measurements and process validation, other experimental and modelling techniques were developed, described in the text. These were used by companies to design, optimise and validate continuous thermal processes for foods containing discrete particles, that resulted in commercially sterile foods of high quality.

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1. INTRODUCTION

Thermal processing of mixtures of solids and liquids is commonplace in the food industry; however, technology for in-container processing is more widely accepted than that for the continuous process. This is partly due to the lack of understanding of the heat transfer and flow mechanisms that occur within the heat exchanger sections of a heat-hold-cool process. Consequently, food processors have no option but to ignore any contributions to the thermal processing received by the product during heating and cooling, and thus establish the safety of a process based solely on the treatment occurring in the holding tube. This leads to products that are over-processed and of less than optimal quality.

A number of different types of continuous heat exchangers were studied, suitable for processing food particles up to 15 mm size, including scraped surface heat exchangers, tubular heat exchangers and direct steam injection systems (Tucker, 1998a,b). Experimental validation techniques and mathematical models provided the means to establish confidence to include lethality contributions from the heating and cooling sections in commercial pasteurisation and sterilisation processes. The benefits to food companies were shown to be the potential to reduce excessive processing times, compared with batch in-container processes, thus increasing plant throughputs and improving product quality (Tucker, 1996a; Tucker, 1997a).

The report describes the key findings from MAFF LINK project AFM 48, entitled 'Methodologies for studying the heating and cooling of mixtures of solids and liquids in heat exchangers'. The reference section lists publications that have arisen solely from this project. Acknowledgement of the research conducted outside of this project can be obtained from the appropriate references listed.

2. METHODS:

The overall project objectives were to develop experimental and modelling techniques which describe the heat transfer and flow mechanisms occurring within heat exchangers used for the continuous heating and cooling of mixtures of solids and liquids. These allow the degree of thermal process delivered within a heat exchanger (both heating and cooling) to be safely assessed, and thus to investigate the potential to improve product quality by optimising heat exchanger performance.

The project objectives were broken down into a number of technical areas. Further details of the experimental methods can be found in the references given.

2.1 Fluid Flow Measurements

- To develop experimental methods for measuring the particle residence time distribution (RTD) within each heat exchanger system (Tucker and Heydon, 1998).
- To measure the carrier liquid rheology at processing temperatures, and develop correlations which will allow liquid viscosity to be predicted as a function of starch concentration, temperature and wall shear rate (Tucker, 1998b).
- To develop experimental methods for measuring the liquid flow patterns and RTD which will be applicable to viscous liquid foods (Rodriguez, 1998).

2.2 Heat Transfer Considerations

• To measure the fluid/particle heat transfer coefficient within a number of heat exchangers, and develop correlations for its prediction as a function of process variables (Nixon and Fryer, 1998).

• To develop a method for measuring the wall heat transfer coefficient between the heated (or cooled) walls of a heat exchanger and the liquid (Nixon and Fryer, 1998).

2.3 Mathematical Modelling of Particle Temperatures

- To develop RTD models for both particles and liquids and incorporate these models into the finite difference models for temperature prediction (Tucker and Heydon, 1998).
- To validate the temperature prediction models using real processing equipment (Mankad at al, 1997).
- To use the models to demonstrate the potential reductions in process time which can be made if the contributions to particle cooking which occur within the heating and cooling stages of a thermal process are taken into account (Tucker, 1999b).

3. RESULTS

3.1 Fluid Flow Measurements

Experimental methods were developed for measuring the flow patterns of the solid and liquid phases within a heat exchanger.

3.1.1 Particle Residence Time Measurement in Heat Exchangers

Extensive work was conducted in tubular heat exchangers, in order to substantiate the previous data collected in isothermal holding tubes (Tucker, 1998b). The scope covered carrier liquids of varying viscosity, with particle concentrations up to 30 wt% of discrete particles, and at temperatures up to 85 °C.

Particle residence times (RT) were measured using Hall effect sensors in two Tetra Spiraflo tubular heat exchangers (Tetra Pak UK Ltd), an 8-pass 34 mm i.d. and a 9-pass 48 mm i.d. system (Tucker and Heydon, 1998). All of the trials were conducted in laminar conditions with tube Reynolds numbers ranging from 5 to 20. The fastest particles consistently travelled more slowly than the theoretical centreline velocity, calculated by assuming Newtonian flow behaviour, and gave similar velocities to those calculated by assuming power law behaviour.

The effect of increasing the carrier fluid viscosity using 4, 5 and 6 wt% Colflo 67 starch resulted in decreasing particle RTs as the viscosity increased. This effect was also observed with a low and high viscosity commercial fruit suspension containing 30 wt% of 9.0 mm peach and apricot pieces in a starch carrier fluid. Figure 1 shows the particle frequency distributions for the low viscosity peach product at a flowrate of 12 kg.min⁻¹.

The effect of increasing the concentration of 9 mm carrots from 7.5 to 22.5 wt% in 5 wt% Colflo 67, at constant flowrate of 8.0 L.min⁻¹, resulted in reduced

particle RTs for increasing carrot concentration and a narrower distribution. Figure 2 shows the schematic layout of the Tetra Spiraflo.

Figure 1: Particle frequency distributions for the low viscosity peach product at a flowrate of 12 kg.min⁻¹.

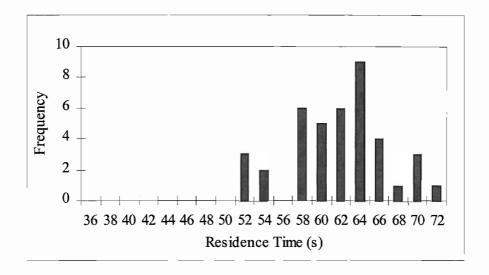
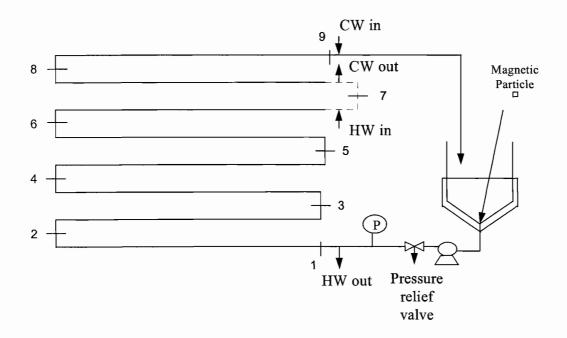


Figure 2: Schematic diagram of the Tetra Spiraflo at CCFRA with 6 heating and 2 cooling tubes, to show the points for RT readings (HW is hot water, CW is cold water)



It was observed that the mean carrot RTs in the two cooling passes were significantly lower than those in the six heating passes, for all four carrot concentrations. Two causes were proposed for the increased particle velocity:

- (i) The carrot particles cooled more slowly than the surrounding liquid, resulting in a localised reduction in viscosity and hence an increased particle slip velocity.
- (ii) The carrier liquid adjacent to the cooler walls increased in viscosity and so imposed a reduction in the flow area, giving rise to a coring effect.

Particle RT measurements were also made using Hall effect sensors to determine the distribution of RTs in the injection stages of a direct steam injection system. This is a process that may have applications to the thermal processing of solid/liquid suspensions but it is critical to understand the flow patterns within the steam injector. The results indicated that the injector was acting as a pipe section of increased diameter, and did not adversely affect the values or distribution of particle RTs.

3.1.2 Viscometry

The majority of products evaluated were of high viscosity, and displayed complex rheological and thermal properties that changed significantly within the heat exchanger (Bolmstedt, 1998). Relationships between shear stress and shear rate were correlated using the power law model (see equation 1) in order that apparent viscosities (equation 2) and pressure drops could be estimated for pipeline flow. The flow conditions in these trials were exclusively laminar (Re < 2,100), as calculated according to tube Reynolds numbers from equation (3), with most Reynolds numbers ranging from 5 to 50.

$$\sigma = k.\dot{\gamma}^n \tag{1}$$

$$\eta = k \dot{\mathcal{Y}}^{n-1} \tag{2}$$

$$\operatorname{Re} = \frac{\rho \cdot v^{2-n} D^n}{k} \left[\frac{6n+2}{n} \right]^{1-n} \tag{3}$$

where, σ is the wall shear stress (Pa)

 $\dot{\gamma}$ is the wall shear rate (s⁻¹)

k is the consistency coefficient (Pa.sⁿ)

n is the flow behaviour index

 η is the apparent viscosity (Pa.s)

Re is the tube Reynolds number

ρ is the product density (kg.m⁻³)

v is the mean flow velocity (m.s⁻¹)

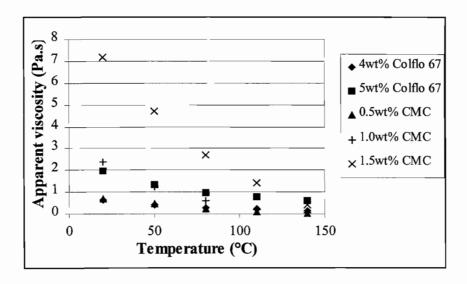
D is the tube diameter (m)

All of the starch-based foods studied in this project had flow behaviour indices (n) less than unity; that is they were shear thinning. For these foods, the viscosity should be referred to as apparent viscosity (η) because of its dependence on the shear rate. Thus, these foods reduced in viscosity as they were sheared, in addition to the reduction in viscosity with increased temperature. Table 1 summarises the flow behaviour indices and consistency coefficients for Colflo 67 starch and carboxymethylcellulose (CMC) solutions, at temperatures ranging from 20 to 140 °C. Colflo 67 was used as the carrier liquid for most of the thermal experiments at CCFRA, and CMC for the flow experiments at the University of Birmingham. Figure 3 presents the apparent viscosities of each liquid at a shear rate of 10 s⁻¹, calculated using the power law constants and equation 2.

Table 1: Flow behaviour indices (n) and consistency coefficients (k) for Colflo 67 starch and carboxymethylcellulose (CMC) solutions at temperatures ranging from 20 to 140 °C.

Carrier liquid		20 °C	50 °C	80 °C	110 °C	140 °C
4 wt% Colflo 67	n	0.70	0.70	0.70	0.70	0.70
-	k (Pa.s ⁿ)	1.30	0.80	0.56	0.43	0.29
5 wt% Colflo 67	n	0.54	0.54	0.54	0.54	0.54
	k (Pa.s ⁿ)	5.66	3.85	2.80	2.24	1.68
0.5 wt% CMC	n	0.39	0.43	0.53	0.73	0.93
-	k (Pa.s ⁿ)	2.75	1.62	0.98	0.14	0.01
1.0 wt% CMC	n	0.31	0.40	0.49	0.60	0.72
	k (Pa.s ⁿ)	11.67	4.91	1.93	0.48	0.07
1.5 wt% CMC	n	0.26	0.32	0.41	0.50	0.55
	k (Pa.s ⁿ)	39.38	22.47	10.42	4.54	1.12

Figure 3: Apparent viscosities of each carrier liquid, at a shear rate of 10 s⁻¹, calculated using the power law constants and equation 2.



The relative stability of the rheological parameters at elevated temperatures showed Colflo 67 to be a more suitable carrier liquid for the thermal experiments than CMC. The minimal change in apparent viscosity with temperature ensured that Colfo 67 solutions retained their particle suspending properties during a heat treatment. One complication in the rheological behaviour of gelatinised starch-based foods was shown with high starch concentrations (> 4 wt%), in that the foods also exhibited elastic behaviour. This property may have a benefit for suspending small particles, such as spices, where the normal forces associated with viscoelastic behaviour may assist in keeping the small particles separated and in suspension.

Comparisons were made of different rheometry methods, such as tube viscometry, a cylinder rotating in a large sample volume and cone & plate viscometry on the carrier fluid only. In one set of trials, a tomato and lentil soup was used as the food product, containing 29.11 wt% particulates (lentils, 9 mm carrots, 9 mm potatoes and dried onions) and 3.74 wt% thickeners (flour, Colflo 67 and pea fibre). Comparisons of apparent viscosity values at a shear rate of 50 s⁻¹ were satisfactory between the tube viscometer and the cylinder rotating in a large volume, whereas the cone & plate tests on the carrier liquid gave lower values. Table 2 gives a summary of the rheological data that was modelled from pressured drop and flowrate data using the power law for the three replicate trials conducted.

Table 2: Summary of the rheological data for tomato and lentil soup, modelled from pressure drop and flowrate data using the power law. Code: CP (cone & plate on the carrier liquid) at 40 °C, CiLV (cylinder rotating in a large volume) at 40 °C, T (tube) at 40, 55 and 70 °C. k, consistency coefficient, n, flow behaviour index, η_a , apparent viscosity at a shear rate of 50 s⁻¹.

Trial 1	k, (Pa.s ⁿ)	n	η _a , (Pa.s)
СР	12.4	0.38	1.11
CiLV	24.0	0.37	2.06
T, 40	17.5	0.44	1.94
T, 55	16.3	0.44	1.85
T, 70	21.8	0.40	2.11

Trial 2	k, (Pa.s ⁿ)	n	η _a , (Pa.s)
СР	10.9	0.39	1.02
CiLV	22.4	0.38	1.97
T, 40	13.3	0.49	1.79
T, 55	12.1	0.49	1.62
T, 70	17.2	0.39	1.60

Trial 3	k, (Pa.s ⁿ)	n	η _a , (Pa.s)
СР	7.5	0.39	0.70
CiLV	17.3	0.33	1.25
T, 40	13.3	0.49	1.79
T, 55	11.5	0.45	1.33
T, 70	8.3	0.53	1.34

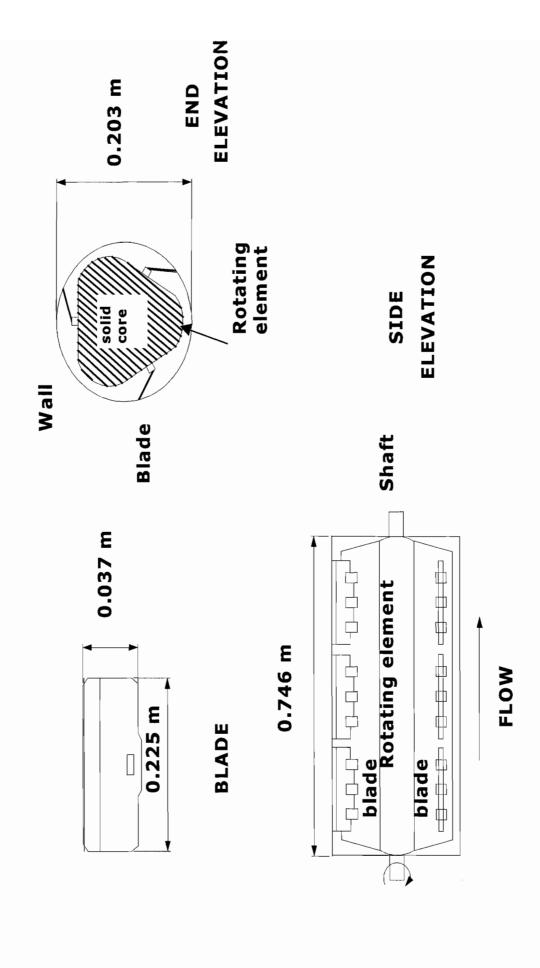
The breakdown of the particulates during continuous pumping was a factor that was likely to have affected the rheological measurements. This would result in starch release from the potatoes and lentils over the duration of each trial (ca. 60 minutes) and a breakdown in particle definition. The batches were prepared at 85 °C, then gradually cooled while pressure drop and flowrates were taken. Tube viscometry data taken at 70 °C represented product with the best particle definition. Temperature control was estimated as \pm 5 °C over the entire tube viscometer equipment.

For process design purposes, the tube viscometry trials showed that a cylinder rotating in a large sample volume was a satisfactory method for this product type. This method requires substantially less product than the tube viscometer.

3.1.3 Laser Doppler Anemometry (LDA) and Positron Emission Particle Tracking (PEPT)

Towards the end of the project, the advanced techniques of Laser Doppler Anemometry (LDA) and Positron Emission Particle Tracking (PEPT) became available at the University of Birmingham (Seville and Fryer, 1997) which provided data of high quality. A scraped surface heat exchanger was modified with a transparent barrel that allowed LDA to be carried out (see figures 4 and 5), and data handling software written to deduce liquid velocities as a function of time. This illuminated the liquid flow patterns inside the exchanger.

Minimal modifications were required to use PEPT on the exchanger. The effect of changing blade pattern on the particle flow patterns was demonstrated using PEPT (Rodriguez, 1998; Rodriguez et al., 1998), and the results compared with particle RT data and with computational models. Figure 6 shows an example of the particle traces achieved in the scraped surface heat exchanger. Much of the LDA and PEPT work was to develop the method to obtain the flow visualisation data.



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Figure 5: Experimental set-up for the LDA trials on the scraped surface heat exchanger

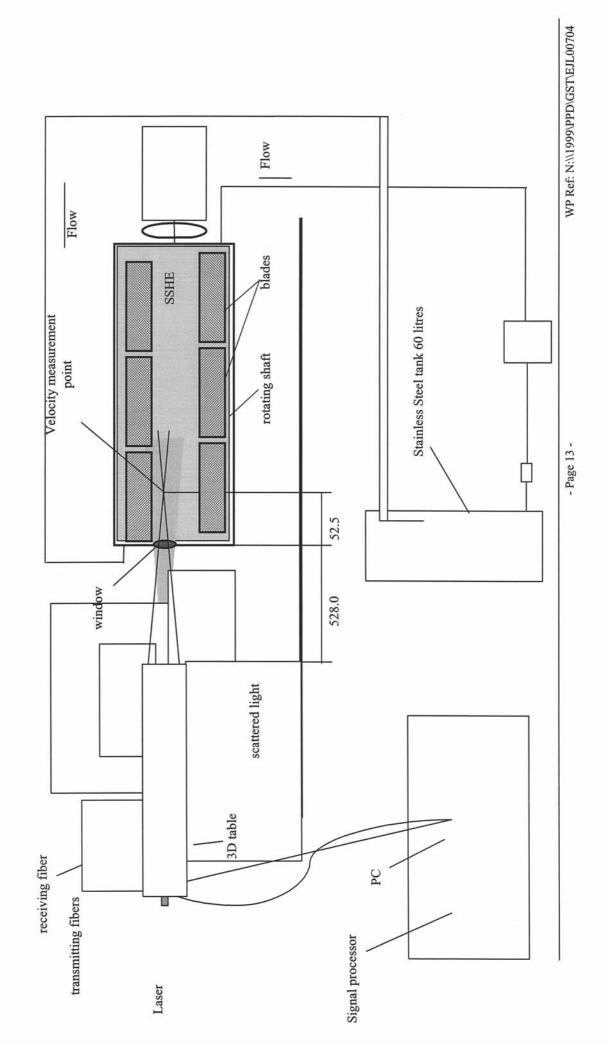
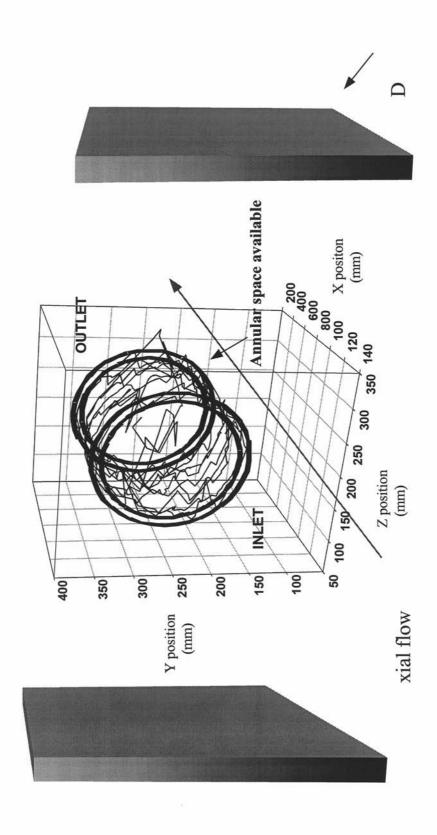


Figure 6: An example of the particle traces achieved in the scraped surface heat exchanger from PEPT data.



3.2 Heat Transfer Considerations

Methods were developed for measuring the wall and fluid/particle heat transfer coefficients, as key input for the particle temperature models.

3.2.1 Process Validation using Time and Temperature Integrator Systems (TTIs)

Chemical time-temperature integrators (TTIs) were investigated as markers for validating the pasteurisation achieved during particle heating processes and an alternative method to spore encapsulation in alginate beads.

This validation method was developed using a novel process **Bacillus** amyloliquefaciens α-amylase time-temperature integrator injected into the centre of silicone particles (Tucker, 1998c,d). These amylase particles were used to validate pasteurisation processes for production scale yogfruit batches of whole 10-12 mm strawberry, 10 mm pineapple and 17 mm apricot. The kinetic factor (z-value) for the amylase was 9.7 ± 0.3 C° over the temperature range 70-90 °C, which was within the range of values common to many pasteurisation treatments. Amylase activity before and after processing was converted to pasteurisation values (P-values) using the appropriate decimal reduction time (D_T value). For most of these high acid products the target P-value was equivalent to 5 minutes at 85 °C ($T_{ref} = 85$ °C, z = 10 C°). This compared with minimum P-values measured using the α-amylase of 8.3, 6.0 and 9.7 minutes respectively, thus demonstrating the microbiological safety of these processes (Tucker, 1998e).

Figures 7 and 8 present the distributions of P-values for a 430 kg batch of 10 mm pineapple and passion yogfruit and a 325 kg batch of 20 mm apricot fool. The P-values were calculated from the measured reduction in amylase activity using equation 4, with a $D_{85} = 6.95$ minutes.

$$P = D_{T} \cdot [\log (A_{initial}) - \log (A_{final})]$$
(4)

where, A_{final} is the final activity after a specific time-temperature history (min⁻¹) $A_{\text{initial}} \text{ is the initial activity (min}^{-1})$

Figure 7: Distribution of pasteurisation values for the 430 kg batch of 10 mm pineapple yogfruit, calculated with $D_{85} = 6.95$ minutes. Sample size was 44.

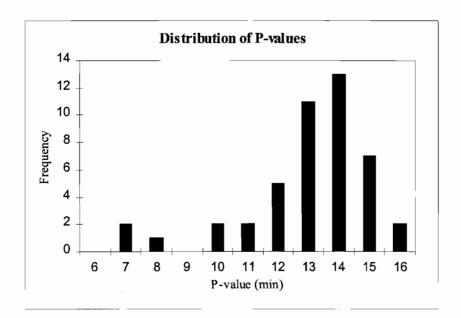
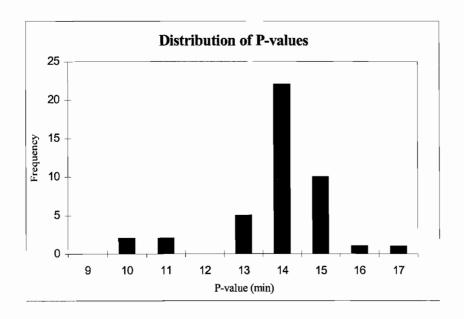


Figure 8: Distribution of pasteurisation values for the 325 kg batch of 20 mm apricot fool yogfruit, calculated with $D_{85} = 6.95$ minutes. Sample size was 45.



A TTI feasibility study was also conducted on an industrial ohmic plant using 10-12 mm whole strawberries as the yogfruit product. Amylase, encapsulated in 5 mm silicone bubbles, was sealed into the centres of 15 strawberries, added to the feed batch and allowed to pass through the ohmic process unhindered. On retrieval, the amylase activities were assayed and a minimum P-value calculated of 160 s at 90 °C ($T_{\text{ref}} = 90 \text{ °C}$, z = 10 C°); this compared with the target of 90 s.

The encapsulation of TTIs into silicone particles, which were made to have similar thermal properties to the target food pieces, was demonstrated as a process validation method with considerable potential. A batch-continuous process and an ohmic process were used as case studies because they were examples of processes that had previously required microbiological methods for their validation. Both of these yogfruit processes were successfully validated with the TTIs. The key step in making this method applicable as a validation tool was in the TTI encapsulation, ensuring that the enzyme was isolated from the surrounding food but could be injected and extracted with a hypodermic syringe.

3.2.2 Measurement of the variation in heat transfer within scraped surface heat exchangers

To evaluate the efficiency of heat transfer within a heat exchanger, 10 mm amylase particles were processed in a Contherm scraped surface heat exchanger (Tetra Pak UK Ltd). The aim was to model the centre particle P-values using the PCTemp program, and by matching the measured and predicted P-values for a particle with known thermal properties it was hoped that approximate values for the fluid/particle heat transfer coefficient (h_{fb}) could be estimated.

Single particle trials were the first conducted, using 6 wt% Colflo 67 starch as the carrier fluid and an outlet Contherm temperature of 85 °C. The reduction in amylase activities was converted to P-values and compared with the theoretical carrier fluid P-values, assuming a linear ramp in fluid temperature up the exchanger. This showed that the amylase particles had experienced higher temperature regimes than estimated. It

was thought this was due to the centrifugal forces acting on the particles, causing them to travel up the Contherm near to the steam heated walls where the fluid temperature was highest.

The next trials used 30 wt% of 9 mm carrots in a 4 wt% Colflo 67 carrier fluid. The distribution of particle P-values was large, which was thought to be caused by fluid temperature gradients in the radial direction. Within a high viscosity fluid of high particle concentration, the degree of radial mixing was likely to be poor. This was supported by LDA and PEPT results at the University of Birmingham that showed the liquid and particle tracks following closely the circular motion of the high speed blades (see figure 6).

The amylase technique had proved useful for measuring the particle pasteurisation treatment, but evaluation of the fluid-particle heat transfer coefficients was not attempted from these data because of the lack of information on the radial temperature distribution.

3.2.3 Measurement of the wall heat transfer efficiency within tubular heat exchangers

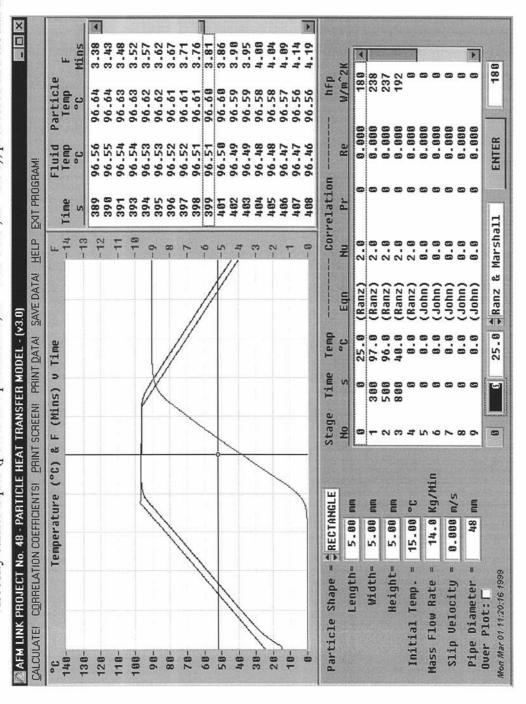
A method was developed at the University of Birmingham for using heat flux sensors to measure wall heat transfer coefficients (h_w). Extensive h_w data were obtained for tube-in-tube systems and correlations were derived (Mankad et al., 1997; Nixon and Fryer, 1998). Significant heat transfer enhancement effects were found with laminar flows in the presence of particles. As an approximation, the increase in h_w was directly proportional to the concentration of particulates, up to 30 wt% solids.

3.3 Mathematical Modelling of Particle Temperatures

The CCFRA PCTemp model, for predicting temperatures in food particles as they undergo a continuous thermal process, was re-coded (DACAM Systems, Windsor). These were finite difference models, for the 1D sphere, 2D cylinder and 3D rectangle, with a series of complex energy balances at the particle surfaces that allowed heat transfer coefficients to be used. The program user was given the choice of selecting a fluid/particle heat transfer coefficient correlation from a list that included the one developed within this project (referred to as Mankad and Fryer).

This model was used to estimate particle temperatures for particles in tubular heat exchange processes. An example of a heat-hold-cool process for a product containing 5 mm diced carrots in a non-Newtonian (power law) carrier liquid is given in figure 9. The product was pasteurised, with reference temperature 93.3 °C and z-value 8.3 C°, and needed to exceed 5 minutes equivalent at 93.3 °C for microbiological safety. Particle slip velocity was assumed to be zero, and the Ranz-Marshall heat transfer correlation was used to determine the fluid/particle heat transfer coefficient. The particle P-value contributions were 0.2, 7.5 and 1.3 minutes for the heating, holding and cooling stages, respectively.

A finite volume model was written at the University of Birmingham for the calculation of energy balances between the heating media and product, between the particles and liquid, and within the particles. This was used for thermal process design, with examples given of optimal processes that demonstrated the thermal contributions from the heating, holding and cooling stages. Percentage reductions in holding tube time were calculated based on the heat transfer and flow data gathered in this project.



4. CONCLUSIONS

Expertise developed during this project has been successfully applied to process and product development trials on numerous commercial food products. In most continuous processing trials using commercial food products, there were significant product quality improvements over those achieved in the existing in-container or in-vessel processes. By utilising the high rates of heat transfer in a heat exchange system it was possible to attain the existing levels of pasteurisation (or sterilisation) but with a reduced cook value (Tucker, 1996b). Real and quantifiable improvements were obtained in the essential areas such as a firmer particle, reduced overcooking of heat sensitive ingredients, greater retention of flavours and volatile components, and improved textural properties of sauces. The interest from food companies in adopting continuous processing has been encouraging.

Future research projects are planned in several areas:

- In the use of heat recovery systems with foods of medium to high viscosity, for counter current tubular heat exchangers. This project will investigate the operational limits on heat transfer and pressure drop, and explore the potential energy savings that can be realised.
- In understanding the factors that affect the operational efficiency of tubular heat exchangers, including the effects of particles on heat transfer efficiency and the use of computational fluid dynamics for hygienic design.
- In the use of TTIs to validate thermal processes, by developing the TTI concept from a single TTI particle to one that contains three separate TTIs. These TTI particles will be used to validate the microbiological safety of various process types, gather information on process variability, and provide the data for deducing the time-temperature history experienced by one of the multiple TTI particles.

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ACKNOWLEDGEMENT

This project was funded by the MAFF Advanced and Hygienic Food Manufacturing LINK scheme (February 1995 - January 1999), in collaboration with the University of Birmingham, DACAM, G.R. Spinks & Co. Ltd. H.J. Heinz Co. Ltd., Tetra Pak UK Ltd and Unilever Research Colworth Laboratory.