ELSEVIER

Journal of Food Engineering **28** (1996) 349–360

0260-8774/96/$15.00

0260-8774(95)00046-1

Residence Time Distribution of Particulate Foods at Aseptic Processing Temperatures

D. I. Chandarana & J. A. Unverferth

National Food Processors Association, 1401 New York Avenue, NW, Washington, DC 20005, USA

(Received 31 August 1994; revised version received 15 May 1995; accepted 6 July 1995)

ABSTRACT

Knowledge of experimental residence time distribution of foods containing particles being processed aseptically is crucial to designing safe thermal processes while simultaneously ensuring optimum product quality. Past attempts at designing high-temperature short-time process recommendations depended on conservative estimates for residence time in a holding tube while ignoring the effect of the scraped-surface heat exchangers. This resulted in excessive thermal treatment and a consequent loss of textural and nutritional quality attributes.

Experiments were conducted to determine residence time of particles in food being processed in a commercial scale aseptic processing system at 135–140°C. Residence time data, which included among others, the effect of particle–particle interaction in a viscous fluid product made up of a 6% starch solution containing 15% diced potatoes, were collected and treated statistically.

The data show that the methodology developed yields reproducible data, which when treated statistically, allows prediction of fastest particle residence time with a high level of confidence. In addition, data presented for the high-viscosity starch-based product, showed a marked absence of any channeling effects as the product passed through scraped-surface heat exchangers, a holding tube, and interconnecting piping of a commercial processing system. Copyright © 1996 Elsevier Science Limited.

INTRODUCTION

Thermal process design for low-acid foods is comprised of two main critical parameters: namely, process time and temperature history of the product. Ideally, during a process both parameters must be measured and controlled in order to assure proper delivery of the designed lethality.

For aseptically processed low-acid foods containing discrete particles, continuous monitoring of particle temperature is difficult, if not improbable, during the actual process. Several publications have dealt with this issue (Sastry, 1986; Chandarana & Gavin, 1989a; 1989b; Chandarana *et al.*, 1989). The process time, on the other hand, can be experimentally determined. In recent years, several researchers have concentrated efforts in this area (Taeymans *et al.*, 1985; McCoy *et al.*, 1987; Berry, 1989; Sastry, 1989; Segner *et al.*, 1989; Alkskog *et al.*, 1989; Lee & Singh, 1990; Dutta & Sastry, 1990a; 1990b; Yang & Swartzel, 1991; Tucker & Withers, 1992; Yang & Swartzel, 1992; Abdelrahim *et al.*, 1993a, 1993b; Scott & Holdsworth, 1994). The United States governmental agencies that regulate the production of low-acid shelf-stable foods have indicated that particle residence times must be 'known with a high level of confidence' in order to ensure safety of these foods (Dignan *et al.*, 1989; Berry, 1989; Pflug *et al.*, 1990). The food industry agrees that knowledge of particle residence time distribution is indeed critical to ensuring a high-quality, safe product (Heldman, 1989).

Berry (1989), Dignan *et al.* (1989) and Pflug *et al.* (1990) indicated that actual data on residence time distribution of particles determined in a commercial system under normal operating conditions should be used in process design. In the absence of necessary data, conservative assumptions must be made. In addition, they recommended against using one or more tracer particles in a flowing stream of fluid, since the data so obtained would not reflect the effect of particle–particle interaction. Indeed, particle–particle interaction plays an important role in the particle residence time distribution (Berry, 1989; Sastry, 1989; Dutta & Sastry, 1990a, 1990b).

An overwhelming majority of researchers that have studied residence time distributions have either concentrated on fluids alone (Chen & Zahradnik, 1967; Milton & Zahradnik, 1973), studied two-phase flow in holding tubes under atmospheric conditions (McCoy *et al.*, 1987; Berry, 1989; Sastry, 1989; Dutta & Sastry, 1990a, 1990b; Segner *et al.*, 1989; Alkskog *et al.*, 1989), or studied two-phase flow in scraped-surface heat exchangers (SSHE) under atmospheric pressure at low temperature (Lee & Singh, 1990).

Recently, some residence time distribution studies at aseptic processing temperatures have been reported (Taeymans *et al.*, 1985; Ramaswamy *et al.*, 1992; Abdelrahim *et al.*, 1993a, 1993b). However, each of these researchers determined residence time through the whole system. Residence times through individual components were not studied.

Currently available literature on two-phase, solid–liquid food flow indicates that residence time distribution of particles in two-phase flow can be affected by product flow rate, particle size, particle concentration, product viscosity, and rotational speed of the SSHE (Taeymans *et al.*, 1985; McCoy *et al.*, 1987; Alkskog *et al.*, 1989; Sastry, 1989; Dutta & Sastry, 1990a, 1990b; Lee & Singh, 1990). Therefore, data on actual product processes under commercial conditions is important for developing safe thermal process recommendations.

In none of the above works have particle velocities in excess of twice the mean product velocity been reported. There is general agreement among researchers and regulators that no data reported thus far can be directly applied to aseptic processing of any specific food-containing particles.

With the exception of the work done by Segner *et al.* (1989), Tucker and Withers (1992), and Scott and Holdsworth (1994), who measured particle residence time using an electromagnetic induction technique, virtually all of the research reported thus far is based on visual/optical observation. However, optical methods, applied successfully to measure particle residence time distributions in model food systems, are not always appropriate for foods that are generally opaque.

With the above factors and constraints in mind, a food industry consortium was formed under the auspices of the National Food Processors Association (NFPA) in order to (1) develop a reliable and economical method for conducting residence time distribution testing on actual foods containing particles processed aseptically in a commercial aseptic processing system and (2) to use the data to estimate fastest particle residence time.

MATERIALS AND METHODS

Aseptic processing system

The aseptic processing system used in this study was located at the Land O' Lakes, Inc. Proving Center, Clear Lake, WI. The system consists of horizontal SSHE heaters and coolers (Model 672, Cherry-Burrell Process Equipment Div., Louisville, KY) with barrels 152·4 mm (6 in) in diameter and 1828·8 mm (72 in) in length with 89 mm (3·5 in) mutators, each with two sets of straight plastic blades, and a 47·5 mm (1·87 in) internal diameter insulated 316 stainless steel holding tube sloped upwards at 20·8 mm/m (0·25 in/ft). A double piston, positive displacement pump (Model 670, Marlen Research, Overland Park, KS) was used for pumping the product, and a rotary lobe pump (Waukesha Div., Waukesha, WI) was used to maintain the necessary back pressure. A Metal Box Freshfill SL1 (FMC Corp., Madera, CA) aseptic packaging machine fitted with a Raque filler (Raque, Louisville, KY) was used for aseptically packaging the product.

Instrumentation

The instrumentation used for detecting tracer particles flowing through the system was similar to the one used by Segner *et al.* (1989). The instrumentation is described below.

The theory behind the method used is based on Faraday's law of electromotive induction, which states that if a magnet is moved towards or away from an electrical coil, an electric current is induced in the coil (Halliday & Resnick, 1970). This current induces an electromotive force (EMF). If a magnet moves relative to a coil (made of a number of turns), a current will be set up in every turn and the EMFs are additive. Thus, the electrical effect is a function of the number of turns of wire in the coil. In addition, the electrical effect is also a function of the magnitude of the relative motion between the magnet and the coil, as well as the orientation of the magnets as they pass through the coil and the magnetic strength of the magnet being used.

In order to use the above phenomena to detect food particles with embedded magnets in various sections of the aseptic processing system, coils of varnished 24 gauge copper wire were wrapped around 316 stainless steel tubing with 34·8 mm

(1·37 in) internal diameter and installed at the inlet of the heater, inlet and exit of the holding tube, and the exit of the cooler. The coils consisted of 800 turns. A 2·2 kΩ resistor was connected across each coil and the voltage drop across the coil was measured using a data acquisition system capable of reading analog voltage inputs. A shielded cable, grounded on both ends, was used to connect the coil to the data acquisition system. The data acquisition and control system used was a Keithley Series 500 (Keithley, Taunton, MA) controlled by LabTech Notebook software (Laboratory Technologies Corp., Willmington, MA) running on a CompuAdd Model 433 personal computer (CompuAdd, Austin, TX). Passage of a magnet through the coils result in a sudden change in EMF signal received by the data acquisition system.

Product temperature at the heater inlet, heater exit, holding tube exit, and cooler exit were monitored using copper-constantan (type T) thermocouples installed in the product stream using sanitary fittings. The data acquisition system used was the same as described above.

Product

The product used in the tests consisted of a 15% (w/w) mixture of dehydrofrozen diced potatoes with chicken/alginate cube test particles (12·7 mm × 12·7 mm × 12·7 mm) or dehydrofrozen test particles in a two-starch solution consisting of Thermtex (2% w/w) and Thermoflo (4% w/w) starches (National Starch Co., Bridgewater, NJ).

Chicken/alginate cubes or diced potatoes carrying small flexible magnets (Highforce, Magnet Sales and Mfg Co., Culver City, CA) were used as tracer particles for the residence time distribution tests. The chicken/alginate cubes (Table 1) were prepared by a slight modification of the formula used by Brown *et al.* (1984).

A Bohlin rheometer (Model CS, Bohlin Instruments, Cranbury, NJ) was used to determine the rheological characteristics of the carrier fluid just before the product was pumped into the aseptic system. For the test where dehydrofrozen potatoes were used as tracers, the carrier fluid had a consistency coefficient of 3·86 Pa.s^n and a flow behavior index of 0·45 at 120°C. The carrier fluid, when chicken/alginate particles were used as tracers, had a consistency coefficient of 3·1 Pa.s^n and a flow behavior index of 0·47 at 120°C. The fluid formulation was specifically selected to

TABLE 1
Chicken/Alginate Formulation used in the Residence Time Study

Ingredient	*Percent*
Strained chicken baby food	87·35
Distilled water	7·85
Alginic acid (sodium salt)	4·37
Calcium sulfate	0·36
Tri-sodium citrate	0·07
Total	100

result in such a high viscosity that the tracers, even with the magnet inserted, were suspended in the fluid and did not sink to the bottom.

The dehydrofrozen diced potatoes were defrosted at room temperature. The potatoes were then immersed in a 3·4% (w/w) calcium chloride solution for 30 min in order to firm the potatoes and minimize breakage during the biological tests. A small quantity of water was heated to 40°C and appropriate quantities of Thermflo and Thermtex starches were added and blended for 3 min (3) in a liquefier. The starch solution was then pumped into a large mixing vat containing water and blended for 10 min. The starch solution was heated to 50°C and held for aseptic processing.

Experimental methods

Small pieces (approximately 6 mm × 2 mm × 1 mm) of flexible magnets were inserted into diced potatoes, or chicken/alginate cubes. These particles were used as tracer particles in a food product.

The product was preheated to 120°C as it was pumped ($3{\cdot}8 \times 10^{-4}$ m^3/s) through SSHE preheaters operated at 2·5 rotations per second (Fig. 1). Tracer particles were introduced into the product stream using a special particle charging device just prior to the final SSHE heater. Tracers were introduced singly.

The product, along with the tracers, was heated to the aseptic processing temperature (140°C) in the SSHE heater, held in the holding tube, and finally cooled in the SSHE coolers. The passage of the magnet-containing tracers through

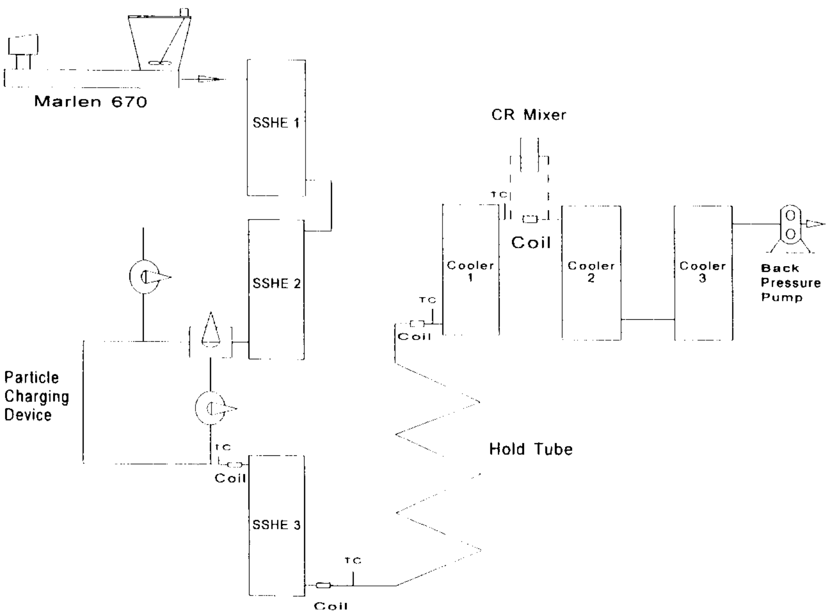

Fig. 1. Schematic diagram of the aseptic processing system at Land O'Lakes used for the residence time studies.

the coils generated EMFs which were recorded by the data acquisition system. The coils and the thermocouples were monitored at a rate of 10 Hz. Time, EMFs across the coil, and the temperatures were recorded on the hard disk of the computer for further analysis.

DATA ANALYSIS

The presence of a tracer particle passing through a coil detector was indicated by a spike (positive or negative) in the EMF recorded (Fig. 2). The number of parameters monitored and the frequency of data recording resulted in an enormous number of data points. A digital filter was designed to identify the time at which a spike in the EMF was recorded and to filter noise. The elapsed time between spikes in EMF at the beginning and end of a given section of the system (heater, hold tube or cooler) was the residence time of that particular tracer particle.

Experimental residence times of the tracer particles (potatoes or chicken/alginate cubes) for each of the system sections (heater, hold tube, and cooler) were separately fitted with Gamma and Lognormal probability distributions (Breiman, 1973). Normal distribution was not considered appropriate for this type of data; residence time data can only be positive numbers, however, it is theoretically possible to predict a negative residence time from a normal distribution. Preliminary review of data identified a small number of particles with residence times that far exceeded the residence time of the rest of the particles. These residence times represented particles that were stuck somewhere in the processing system and did

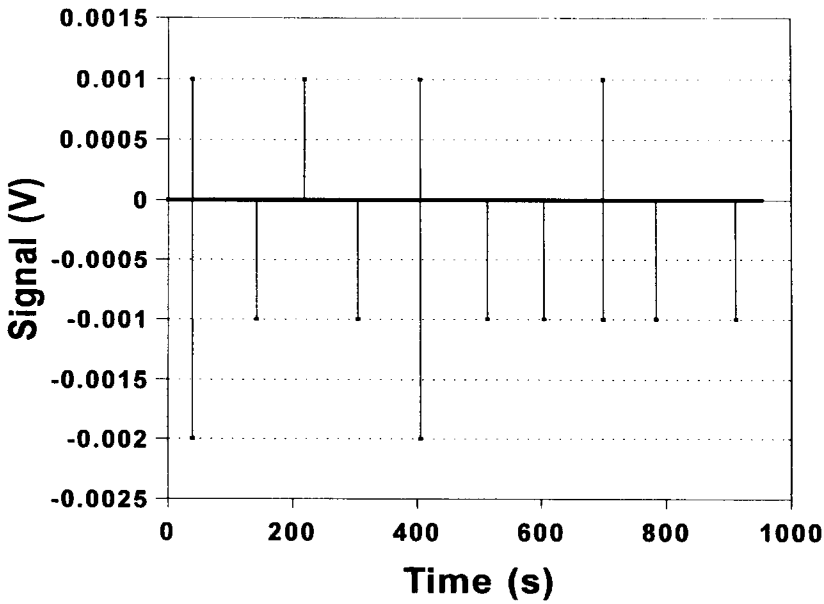

Fig. 2. Sample EMF signals detected by a coil as tracers passed through during the residence time research.

not represent continuously moving particles of interest. The residence time of these particles were excluded from further analyses. This is a conservative approach. The experimental and theoretical cumulative distribution functions were compared using a non-parametric Kolmogorov–Smirnov test for goodness of fit (Sokal & Rohlf, 1987). The distribution functions were then used to predict fastest particle residence time for both types of particles in each of the three system components. The criterion used for this prediction was that the prediction should cover 99·85% of the population. This criterion is equivalent to the well-known 'mean minus three standard deviations' limit used for normal distributions and was chosen in order to be conservative in thermal process design.

RESULTS AND DISCUSSION

The experimentally determined residence times of potato and chicken/alginate tracers are shown in Table 2. Also included in Table 2 are the mean product residence time determined from the product flow rate and the cross-section area of the system component.

Based on the criterion described earlier for predicting fastest particle residence time, 99·85% of the particles would have residence times greater than the predicted fastest particle. The residence times of such fastest particles are shown in Table 3. Also shown in Table 3 is the ratio of the fastest particle residence time to the mean product residence time from Table 2 and the Kolmogorov–Smirnov statistic and the critical Kolmogorov–Smirnov statistic. Both Gamma and Lognormal distributions describe and fit the experimental data as indicated by the Kolmogorov–Smirnov statistic. Following a general convention used by process authorities when developing thermal process recommendations, the fastest particle residence time predicted by the Gamma distribution would be used. This would be a conservative approach to process design. Figures 3–5 show the observed and predicted cumulative functions for the Gamma distribution of potato tracers in the heater, hold tube, and cooler. It is also apparent that the fastest particle residence time for potatoes was fractionally less than that of chicken/alginate cubes. Thus, for this product, using the potato data for process calculation is more conservative.

TABLE 2

Experimental Residence Time Data for Diced Potatoes and Chicken/Alginate Cubes

Section	*Tracer*	*Minimum time (s)*	*Maximum time (s)*	*Particle mean time (s)*	*Std. deviation (s)*	*Mean product residence time (s)*
Heater	Potato	22·5	81·20	56·43	8·70	58·15
	Ch./alg.	44·5	72·10	55·03	5·71	58·15
Hold tube	Potato	50·8	131·40	94·54	11·11	95·04
	Ch./alg.	49·1	107·50	93·53	7·40	95·04
Cooler	Potato	10·9	33·60	22·10	4·36	18·88
	Ch./alg.	14·7	27·90	20·01	2·97	18·88

TABLE 3
Fastest Particle Residence Time Predicted by Gamma and Lognormal Probability Distributions

Section	*Tracer*	*Distribution*	*Minimum predicted time (s)*	*FPRTR*[a]	*K–S Stat*[b]	*K–S Critical*[c]
Heater	Potato	Gamma	34·0	0·58	0·08	0·14
		Lognormal	35·5	0·61	0·08	0·14
	Ch./alg.	Gamma	39·5	0·68	0·06	0·16
		Lognormal	40·0	0·69	0·05	0·16
Hold tube	Potato	Gamma	65·0	0·68	0·17	0·14
		Lognormal	66·5	0·70	0·17	0·14
	Ch./alg.	Gamma	73·0	0·77	0·19	0·16
		Lognormal	73·5	0·77	0·19	0·16
Cooler	Potato	Gamma	11·5	0·61	0·06	0·15
		Lognormal	12·0	0·64	0·05	0·15
	Ch./alg.	Gamma	12·0	0·64	0·05	0·17
		Lognormal	12·5	0·66	0·03	0·17

[a] FPRTR=fastest particle residence time/average product residence time.
[b] K–S Stat=Kolmogorov–Smirnov Statistic.
[c] 0·01 Significance value.

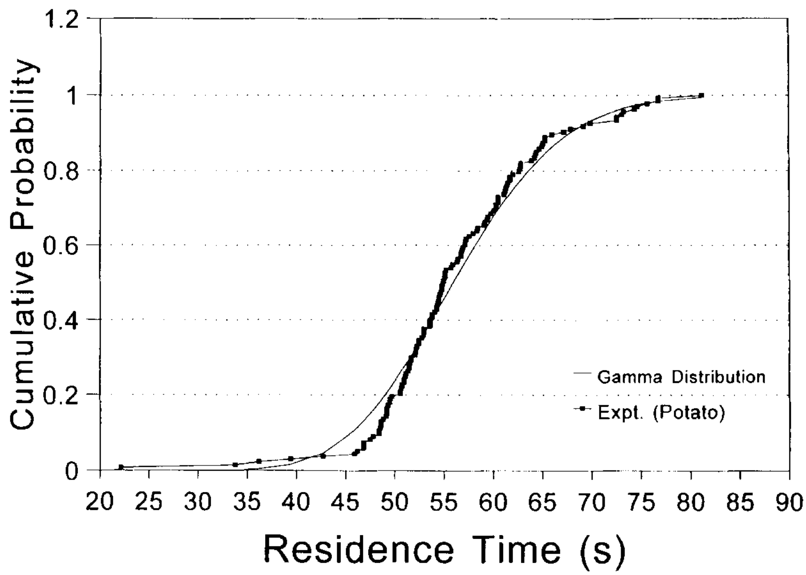

Fig. 3. Gamma distribution fit for residence time of potatoes in the heater.

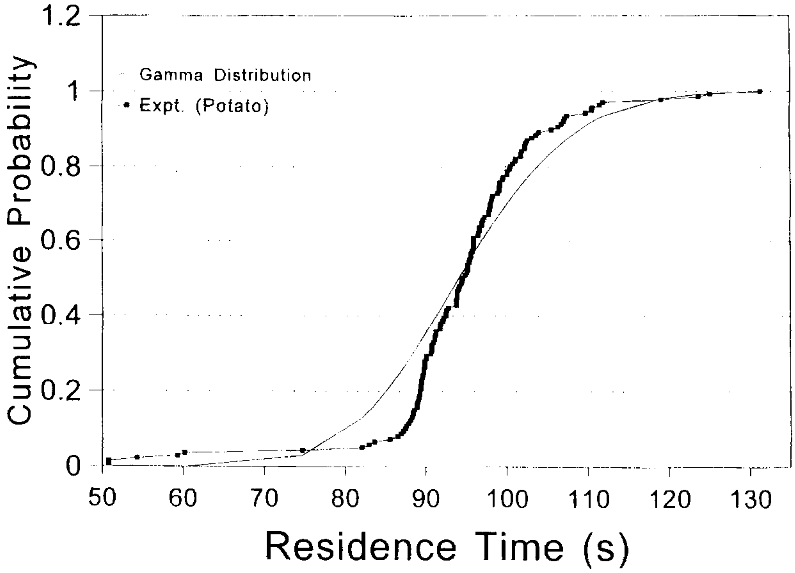

Fig. 4. Gamma distribution fit for residence time of potatoes in the hold tube.

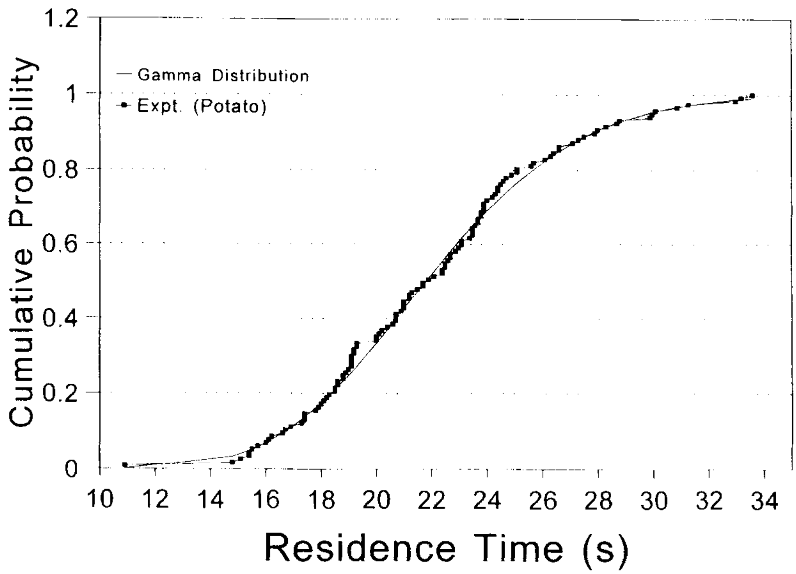

Fig. 5. Gamma distribution fit for residence time of potatoes in the cooler.

A direct comparison with data in the literature is somewhat difficult since our data is very unique. Data available in the literature is either at temperatures below 100°C (McCoy *et al.*, 1987; Berry, 1989; Sastry, 1989; Dutta & Sastry, 1990a, 1990b; Lee & Singh, 1990; Tucker & Withers, 1992; Scott & Holdsworth, 1994) or the experiments were designed to yield residence times for the whole system rather than each individual component (Abdelrahim *et al.*, 1993a, 1993b). Abdelrahim *et al.* (1993b) applied an autocatalytic growth model to residence time distribution data. However, the data were not analyzed to estimate the residence time of the fastest particle. The data of Abdelrahim *et al.* (1993b) indicates that the ratio of particle residence time to mean product residence time is approximately 1·0 when combining the heater, hold tube, and cooler as one unit. This is to be expected since no individual particle can be expected to be the one moving at the fastest speed throughout the system.

The data in Table 3 indicates that a laminar flow correction ($V_{avg}/V_{max}=0{\cdot}5$) is conservative for the holding tube. This assumption is not necessarily valid for flow of liquid/particle mixtures through a SSHE as demonstrated by the residence time of the fastest observed potato tracer in the SSHE heater (Table 2).

Results from earlier studies have indicated the possibility of 'frog-leap' (channeling) among particles (Dutta & Sastry, 1990a, 1990b). However, such an effect was not observed in the tests reported here.

CONCLUSION

It has been demonstrated that the EMF generated by magnets embedded in food particles flowing through an electrical coil could be reliably measured using simple, inexpensive instrumentation in a commercial system under commercial operating conditions. This EMF could be used to calculate residence time of particles in the heater, hold tube and cooler of an aseptic processing system at process temperature. The residence time data fit both Gamma and Lognormal probability distributions. These distributions were capable of predicting the residence time of the fastest moving particle. Using a laminar flow correction ($V_{avg}/V_{max}=0{\cdot}5$) for fastest particle residence time in the holding tube is conservative. This may not necessarily be valid for the SSHE.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial and facilities support of the members of the National Food Processors Association's Aseptic Processing Committee during all phases of this research. The authors also acknowledge the assistance of Robert Smith in preparation of the tracer particles.

REFERENCES

Abdelrahim, K. A., Ramaswamy, H. S., Marcotte, M. & Toupin, C. (1993). Residence time distribution of carrot cubes in starch solutions in a pilot scale aseptic processing system. *Food Res. Int.*, **26**, 431–41.

Abdelrahim, K. A., Ramaswamy, H. S., Marcotte, M. & Toupin, C. (1993). Mathematical characterization of residence time distribution curves of carrot cubes in a pilot scale aseptic processing system. *Lebensm. Wiss. u. Technol.*, **26**, 498–504.
Alkskog, L., Mejvik, L. & Karlsson, E. (1989). Recent experiences in the sterilization of particulate containing food. Presented at the National Food Processors Association Annual Convention, Anaheim, CA. January 26–February 1.
Berry, M. R. (1989). Predicting fastest particle residence time. Proceedings of the First International Congress on Aseptic Processing Technologies, Indianapolis, IN. March 19–21.
Breiman, L. (1973). *Statistics with a View Towards Applications*. H. Miffin Co., Boston, MA.
Brown, K. L., Ayers, C. A., Gaze, J. E. & Newman, M. E. (1984). Thermal destruction of bacterial spores immobilized in food/alginate particles. *Food Microbiol.*, **1** 187.
Chandarana, D. I. & Gavin, III, A. (1989a). Establishing thermal processes for heterogeneous foods to be processed aseptically; A theoretical comparison of process development methods. *J. Food Sci.*, **54**, 198.
Chandarana, D. I. & Gavin, III, A. (1989b). Modeling and heat transfer study of heterogeneous foods processed aseptically. Proceedings of the First International Congress on Aseptic Processing Technologies, Indianapolis, IN. March 19–21.
Chandarana, D. I., Gavin, III, A. & Wheaton, F. W. (1989). Simulation of parameters for modeling aseptic processing of foods containing particulates. *Food Technol.*, **43**(3), 137.
Chen, A. C. & Zahradnik, J. W. (1967). Residence-time distribution in a swept-surface heat exchanger. *Trans ASAE*, **10** 508.
Dignan, D. M., Berry, M. R., Pflug, I. J. & Gardine, T. D. (1989). Safety considerations in establishing aseptic processes for low-acid foods containing particulates, *Food Technol.*, **43** (3) 118.
Dutta, B. & Sastry, S. K. (1990). Velocity distributions of food particle suspensions in holding tube flow: Experimental and modeling studies on average particle velocities, *J. Food Sci.*, **55**(5) 1448.
Dutta, B. & Sastry, S. K. (1990). Velocity distributions of food particle suspensions in holding tube flow: Distribution characteristics and fastest particle velocities, *J. Food Sci.*, **55** 1703.
Halliday, D. & Resnick, R. (1970). *Physics Part II*. John Wiley and Sons, New York, NY.
Heldman, D. R. (1989). Establishing aseptic thermal processes for low-acid foods containing particles, *Food Technol.*, **43**(3) 122.
Lee, J. H. & Singh, R. K. (1990). Particle residence time distribution in a scraped surface heat exchanger, Paper 90-6522. American Society of Agricultural Engineers, St Joseph, MI.
McCoy, S. C., Zuritz, C. A. & Sastry, S. K. (1987). Residence time distribution of simulated food particles in a holding tube, Paper No. 87-6536. American Society of Agricultural Engineers, St Joseph, MI.
Milton, J. L. & Zahradnik, J. W. (1973). Residence time distribution of a votator pilot plant using a non-Newtonian fluid. *Trans ASAE*, **16** 1186.
Pflug, I. J., Berry, M. R. & Dignan, D. M. (1990). Establishing the heat preservation process for aseptically packaged low-acid food containing large particulates, sterilized in a continuous heat–hold–cool system. *J. Food Protection*, **53** (4) 312.
Ramaswamy, H. S., Pannu, K. S., Simpson, B. K. & Smith, J. P. (1992). Apparatus for evaluating particle/fluid flow at elevated temperatures. *Food Res. Int.*, **25** 277–284.
Sastry, S. K. (1986). Mathematical evaluation of process schedules for aseptic processing of low-acid foods containing discrete particulates. *J. Food Sci.*, **51** (1986) 1323.
Sastry, S. K. (1989). Aseptic technology for particulate foods: Issues, problems and some potential solutions. Proceedings of the First International Congress on Aseptic Processing Technologies, Indianapolis, IN. March 19–21.
Scott, G. M. & Holdsworth, M. D. (1994). Particle residence time distribution of particulate foods in viscous carrier fluids for continuous flow systems. Technical Memorandum No.

707, Campden Food and Drink Research Association, Campden, UK.

Segner, W. P., Ragusa, T. P., Marcus, C. L. & Soutter, E. A. (1989). Biological evaluation of a heat transfer simulation for sterilizing low-acid large particulate foods for aseptic packaging. *J. Food Process. Preserv.*, **13** 257–274.

Sokal & Rohlf, F. J. (1987). *Introduction to Biostatistics*, 2nd edn. W. H. Freeman and Co., New York, NY.

Taeymans, D., Roelans, E. & Lenges, J. (1985). Residence time distribution in a horizontal SSHE used for UHT processing of liquids containing solids. Presented at the Fourth International Congress on Engineering and Food, Edmonton, Alberta, Canada. July 7–10.

Tucker, G. S. & Withers, P. M. (1992). Determination of residence time distribution of food particles in viscous carrier fluids using Hall effect sensors. Technical Memorandum No. 667, Campden Food and Drink Research Association, Campden, UK.