EFFECT OF PRODUCT AND PROCESS VARIABLES IN THE FLOW OF SPHERICAL PARTICLES IN A CARRIER FLUID THROUGH STRAIGHT TUBES

PAULO N. BAPTISTA, FERNANDA A.R. OLIVEIRA[1], SUSANA M. CALDAS and JORGE C. OLIVEIRA

Escola Superior de Biotecnologia
Universidade Católica Portuguesa
Rua Dr. António Bernardino de Almeida
4200 Porto
Portugal

AND

SUDHIR K. SASTRY

Ohio State University
Agricultural Engineering Department
590 Woody Hayes Dr.
Columbus, OH 43210

Accepted for Publication July 31, 1996

ABSTRACT

Residence time of particles and fluid-to-particle heat transfer coefficient, two of the major unknowns in the aseptic processing of particulate fluid foods, are intimately related with the linear and rotational velocities of the solid particles. These two velocities were measured by videotaping the flow of individual spherical particles in transparent straight tubes. The effect of fluid velocity and viscosity, particle diameter and density and tube diameter and upward inclination was statistically evaluated using a replicated full factorial design at two levels. Particle linear velocities between around one third of the average fluid velocity and 15% higher were obtained. Rotational velocities were usually lower, but of the same order of magnitude. Particle density and particle diameter had a significant effect on the two particle velocities analysed. The effect of fluid velocity was

[1]Corresponding author, fax: 351-2-590351.

Journal of Food Processing and Preservation **20** (1996) 467–486.

just noticeable for the linear velocity, with the particle velocity approaching or even exceeding the fluid velocity for the higher flow rates. The fluid viscosity influence was mainly evident on the rotational velocity, with the more viscous solutions slowing down the rotation.

INTRODUCTION

In the aspectic processing of particulate fluid foods the knowledge of the residence time distribution (RTD) linked to heat transfer considerations is most important to ensure the safety of the product. Dignan *et al.* (1989) related this safety basic requirement with the necessity of ensuring sterility at the center of the fastest particle travelling in the system, and Berry (1989) statistically predicted the fastest particle residence time. Although this approach is adequate when the food product is composed of particles with the same shape, dimension and density, real food products often do not present these characteristics. As a result, different particles will have different flow behaviors within the tube, and different residence time distribution might have to be considered to each type of particle. This effect should not be neglected in particulate foods and has to be related to the heat transfer coefficient between fluid and particle that is also dependent on the flow (relative velocity between fluid and particle) and particles characteristics (shape and dimension).

Dutta and Sastry (1990a,b) carried out studies of velocity distributions of food particle suspensions in holding tubes. In those studies fastest and average particle velocities were considered as function of flow rate, fluid viscosity and particle concentration. It was concluded that fluid viscosity was the variable that affected more significantly velocity distributions.

Few other studies specific to food particle velocities are described in literature (Salengke 1993). However, other phenomenological studies of solid/liquid mixtures applicable to the aseptic processing of particulate foods are available. Sastry and Zuritz (1987) developed a model for particles suspensions flowing in a tube and more recently Subramaniam and Zuritz (1990) presented a study where drag forces on solid spherical particles flowing in carboxymethylcellulose solutions were related with the flow rate, the fluid viscosity and the dimension of particles.

As a result of the difficulty in understanding the phenomenological behavior of the flow of solid/liquid mixtures, very conservative approaches were considered in order to establish the safety in the aseptic processing of particulate foods. Consequently a substantial part of the product will be overprocessed resulting in lower quality of the processed food. In order to gain a more clear understanding of the basic flow of particles, a factorial design at two levels was used in this work to analyze individual and interactive effects of selected variables on the linear and rotational velocity of particles and the ratio between these two velocities, for particles flowing close to the tube wall. The variables studied were those considered important in the flow of solid/liquid suspensions: flow rate, fluid viscosity, diameter and density of particles and diameter and upward inclination of the tube.

MATERIALS AND METHODS

Flow Visualization System — Test Rig

The experimental system (Fig. 1) was basically composed of a transparent straight tube (1) with a total length of 2.0 m. Tubes with different diameters (d_t) could be easily assembled and in this study two different sizes were used, 2.2 and 5.1 cm internal diameter. To introduce individual particles a T-tube (2) with 30 cm total length and internal diameter equal to the tube being used was placed just before the straight tube. At the end of the tube particles were recovered in a metallic net in an intermediate tank (3) of 30 cm diameter. The liquid phase was recirculated using a rotary lobe pump (4) (on line model OL1/0004/15, Johnson Pump Ltd., UK). A graduated transparent grid of 5 mm (squares) was placed over the tube for determination of particle linear velocity and to easily determine the flow position of the particle a large mirror with 45° inclination was placed above the transparent tube. The liquid flow rate was measured online by an electromagnetic flow meter (Model 8712 CR12M4, Rosemount, eden Prairie, MN, USA), with accuracy of ± 5L/h.

Particles and Fluid

The simulated food particles were spheres made of polystyrene or acetal (Hoover Precision Products, Inc., USA) with a density of 1.05–1.08 g/cm^3 and 1.42–1.43

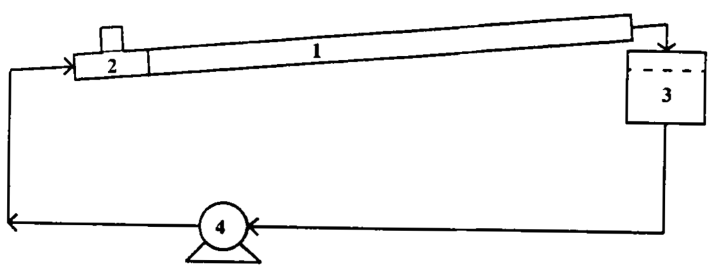


FIG. 1. SCHEME OF THE FLOW VISUALIZATION SYSTEM — TEST RIG

g/cm³, respectively. Particles with diameters of 0.635, 0.952, 1.59 and 2.54 cm were used, to yield different ratios of particle to tube diameter. Sodium Carboxymethylcellulose (CMC 70-G, Aqualon Co., Wilmington, DE, USA) solutions were used as the liquid phase. These solutions were prepared by adding, slowly, the CMC powder to water at 60C, with continuous stirring, maintained for 24 h, at least. The density of CMC solutions was 1.00 ± 0.01 g/cm³, being independent of CMC concentration in the range used. Table 1 shows the rheological properties for the two concentrations of CMC used, determined experimentally with a coaxial cylinder viscometer (Contraves RHEOMAT Model 115, Contraves AG, Zurich, Switzerland). The narrow gap approach was valid and shear rate and shear stress at the rotating bob wall was therefore read directly from the equipment. A logarithmic plot was made to check the validity of the power law model in the full range of shear rates in question (which was 6.65 to 1008 s^{-1}). Linear regression yielded the power law parameters in Table 1. It can be seen that the fluid consistency increases with the increase of the concentration of CMC, with a Newtonian behaviour for the low concentration, changing to pseudo-plastic for the higher concentration.

The Experiments

For each experiment, a single particle was introduced at the upstream end of the test rig using the T-tube. The particle flow along the bottom of the transparent tube was videotaped. Linear velocity of the particle (v_p) was determined by playing the visualization in slow motion and measuring the time necessary for the particle to travel a certain length of the transparent section. In the same length and time interval the rotational velocity of the particle (ω) was measured by coun-

TABLE 1.

RHEOLOGICAL CHARACTERISTICS OF THE CMC SOLUTIONS*

% CMC	Behaviour	Fluid Consistency Coefficient (K) ($Pa.s^n$)	Flow behaviour index (n)
0.1	Newtonian	0.0021 ± 0.0003	1.02 ± 0.02
0.3	Pseudoplastic	0.064 ± 0.004	0.75 ± 0.01

*At room temperature (approximately 22C) and shear rate range 6.65 to 1008 s^{-1}. Parameters were obtained from linear fitting of the Ostwald-de Waele equation ($\ln\tau = \ln K + (n - 1)\ln\gamma$), with the shear stress (τ) being calculated from torque readings and the shear rate (γ) from the rotational velocity.

ting the number of rotations of a line drawn circumferentially around the particle. For each experiment, six replicates were performed, to allow for the calculation of the standard deviation. To ensure the constant velocity of the particle, velocities were measured, for the same experiment, in at least two different sections of the transparent tube.

The Experimental Design

A factorial design at two levels, as described by Box *et al.* (1978) was used to evaluate the effect of all variables and combinations of variables. The variables selected for this study were the fluid velocity (v_f), the fluid viscosity (μ), the particle diameter (d_p), the particle density (ρ_p) and the tube upward inclination (I). The lower inclination corresponds to the minimum specifications of the U.S. Code of Federal Regulations (21CFR 113.40 g: 1/4 in. per foot, which is approximately 1.19°). The range of densities covers the reasonable limits of interest, from a typical value of lower density food particles, such as vegetables fully immersed in solutions up to higher density food particles such as cereal grains and some meat pieces. The limits of fluid viscosity do not include very viscous behaviour (the upper limit is of the order of magnitude of the consistency of fruit purees with 15–20% solids). For the 2.2 cm i.d. tube, a 2^5 factorial design was applied, corresponding to 32 experiments performed randomly with all the possible combinations of minimum and maximum levels for all the variables (Table 2). It should be noted that maximum and minimum viscosity levels are referred to in terms of CMC concentration, due to the different rheological behaviours observed for the two different CMC concentrations. To analyze the effect of tube diameter, some other experiments were performed with a 5.1 cm i.d. tube. The

TABLE 2.

LEVEL OF VARIABLES USED IN THE 2^5 FACTORIAL DESIGN ANALYSIS*

Level	Variable				
	Flow rate/ Average fluid velocity (L/h; cm/s)	**Fluid viscosity** (% CMC)	**Particle diameter/ Ratio d_p/d_t** (cm;-)	**Particle density** (g/cm³)	**Upward inclination** (°)
low (-)	180/13.1	0.10	0.635/0.29	1.065	1.19
high (+)	360/26.3	0.30	0.952/0.43	1.425	8.21

* tube i.d. = 2.2 cm

TABLE 3.

LEVEL OF VARIABLES USED IN THE 2^4 FACTORIAL DESIGN ANALYSIS: EFFECT OF PARTICLE DENSITY*

Level	Variable			
	Flow rate/ Average fluid velocity (L/h; cm/s)	Fluid viscosity (% CMC)	Particle density (g/cm^3)	Upward inclination (°)
low (-)	960/13.1	0.10	1.065	1.19
high (+)	1360/18.6	0.30	1.425	8.21

* tube i.d. = 5.1 cm

TABLE 4.

LEVEL OF VARIABLES USED IN THE 2^4 FACTORIAL DESIGN ANALYSIS: EFFECT OF PARTICLE DIAMETER*

Level	Variable			
	Flow rate/ Average fluid velocity (L/h; cm/s)	Fluid viscosity (% CMC)	Particle diameter/ Ratio d_p/d_t (cm; -)	Upward inclination (°)
low (-)	960/13.1	0.10	1.59/0.31	1.19
high (+)	1360/18.6	0.30	2.54/0.50	8.21

* tube i.d. = 5.1 cm

particle dimensions were chosen so that the ratio between particle and tube diameter would be approximately the same. However, for the 5.1 cm i.d. tube it was not possible to obtain particles with the exact levels of diameter and density and the experiments were divided into two 2^4 factorial design sets: one including the variables fluid velocity, fluid viscosity, particle diameter and tube upward inclinatioin (Table 3) and the other where the factor particle diameter was replaced by particle density (Table 4). As a result, eventual interactive effects involving simultaneously particle diameter and density could not be detected in the larger tube.

RESULTS AND DISCUSSION

The experiments were performed in laminar and transient flow regime, with Reynolds number between 112 and 2756 for the 2.2 cm i.d. tube and between 208 and 4491 for the 5.1 cm i.d. tube. Results are shown in Tables 5, 6 and 7.

Three responses were considered to analyze the particle flow: the normalized linear velocity ($v_{pn} = v_p/v_f$); the normalized rotational velocity ($\omega_n = \omega/v_f$) and the ratio between these two velocities ($\omega_n/v_{pn} = \omega/v_p$). Figures 2, 3 and 4 show the Pareto charts for each response. The vertical lines in each plot represent the 90% and 95% significance levels, with bars crossing these lines representing relevant effects at the defined level of significance. This analysis was performed with the Statgraphics 5.0 Statistics Software (Statgraphics 5.0, Statistical Graphics Corp. 1991).

Ultimately, this method of analysis is based on the analysis of variance. The response is considered to be given by a linear combination of all first order factors and interactions (which was verified by the high correlation coefficient of the models and overall residual of the order of magnitude of the standard error, $\approx$ 0.01). For each factor, or combination, the software analyses the statistical significance of the term in question by determining the probability of the model results with and without the term being statistically equal (test for the null hypothesis). The decision on whether they are equal or not depends on the level of confidence specified; the higher the level of confidence, the more demanding is the requirement for the null hypothesis to be verified. Pareto charts allow for a simple visualization of the relevance of the different effects. A bar that crosses the line corresponding to the standardized limit of confidence means a magnitude of the probability of the term being negligible which is not acceptable, hence the terms is relevant. The longer the bar, the more the factor, or combination, affects the response. Positive values mean that an increase in the factor increases the response while negative values indicate a reverse effect.

In the cases where an interactive effect was clearly significant, the analysis of the nature of the interaction is represented by a simple plot of the response, with the average values linked for simple visualization of whether a reverse response was found or not. This is a standard method of visualizing interactive effects, that does not intend to suggest linear variations. Factorial designs at two levels do not identify the type of variation that occurs within the limits of the factors.

TABLE 5.
EXPERIMENTAL DATA IN THE NARROWER TUBE (2.2 cm I.D.)

d_p (mm)	ρ_p (g/cm^3)	Q (L/h)	I (°)	μ (%CMC)	v_{pn}	ω_n	ω_n/v_{pn}
9.52	1.425	360	8.21	0.3	0.826 ± 0.008	0.351 ± 0.006	0.439
6.35	1.425	360	8.21	0.3	0.649 ± 0.006	0.236 ± 0.009	0.391
9.52	1.065	360	8.21	0.3	1.179 ± 0.010	0.259 ± 0.005	0.220
6.35	1.065	360	8.21	0.3	1.020 ± 0.012	0.234 ± 0.007	0.241
9.52	1.425	180	8.21	0.3	0.574 ± 0.019	0.507 ± 0.015	0.902
6.35	1.425	180	8.21	0.3	0.464 ± 0.013	0.507 ± 0.015	0.645
9.52	1.065	180	8.21	0.3	0.863 ± 0.019	0.223 ± 0.012	0.260
6.35	1.065	180	8.21	0.3	0.696 ± 0.013	0.216 ± 0.007	0.323
9.52	1.425	360	1.19	0.3	0.783 ± 0.010	0.337 ± 0.005	0.434
6.35	1.425	360	1.19	0.3	0.641 ± 0.008	0.226 ± 0.006	0.357
9.52	1.065	360	1.19	0.3	1.140 ± 0.009	0.258 ± 0.003	0.224
6.35	1.065	360	1.19	0.3	0.966 ± 0.012	0.233 ± 0.005	0.246
9.52	1.425	180	1.19	0.3	0.354 ± 0.018	0.319 ± 0.028	0.956
6.35	1.425	180	1.19	0.3	0.420 ± 0.016	0.278 ± 0.025	0.681
9.52	1.065	180	1.19	0.3	0.650 ± 0.028	0.192 ± 0.014	0.303
6.35	1.065	180	1.19	0.3	0.436 ± 0.033	0.154 ± 0.008	0.356
9.52	1.425	360	8.21	0.1	0.835 ± 0.008	0.716 ± 0.025	0.858
6.35	1.425	360	8.21	0.1	0.750 ± 0.013	0.093 ± 0.006	0.126
9.52	1.065	360	8.21	0.1	1.144 ± 0.025	1.158 ± 0.071	1.012
6.35	1.065	360	8.21	0.1	0.869 ± 0.028	0.191 ± 0.007	0.194
9.52	1.425	180	8.21	0.1	0.601 ± 0.014	0.599 ± 0.003	0.997
6.35	1.425	180	8.21	0.1	0.538 ± 0.009	0.515 ± 0.011	0.972
9.52	1.065	180	8.21	0.1	0.981 ± 0.019	0.293 ± 0.015	0.299
6.35	1.065	180	8.21	0.1	0.832 ± 0.018	0.245 ± 0.009	0.299
9.52	1.425	360	1.19	0.1	0.734 ± 0.007	0.670 ± 0.022	0.929
6.35	1.425	360	1.19	0.1	0.615 ± 0.010	0.497 ± 0.009	0.834
9.52	1.065	360	1.19	0.1	0.999 ± 0.007	0.173 ± 0.004	0.176
6.35	1.065	360	1.19	0.1	0.807 ± 0.012	0.176 ± 0.003	0.223
9.52	1.425	180	1.19	0.1	0.682 ± 0.036	0.601 ± 0.020	0.968
6.35	1.425	180	1.19	0.1	0.509 ± 0.013	0.443 ± 0.011	0.962
9.52	1.065	180	1.19	0.1	0.939 ± 0.015	0.302 ± 0.018	0.321
6.35	1.065	180	1.19	0.1	0.721 ± 0.013	0.242 ± 0.006	0.342

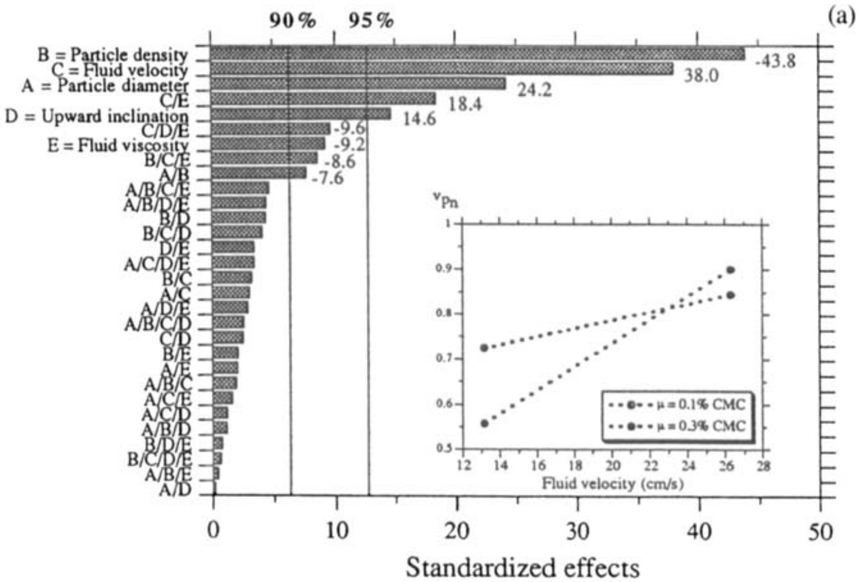
TABLE 6.
EXPERIMENTAL DATA FOR PARTICLES OF 1.59 cm DIAMETER IN THE WIDER TUBE (5.1 cm I.D.)

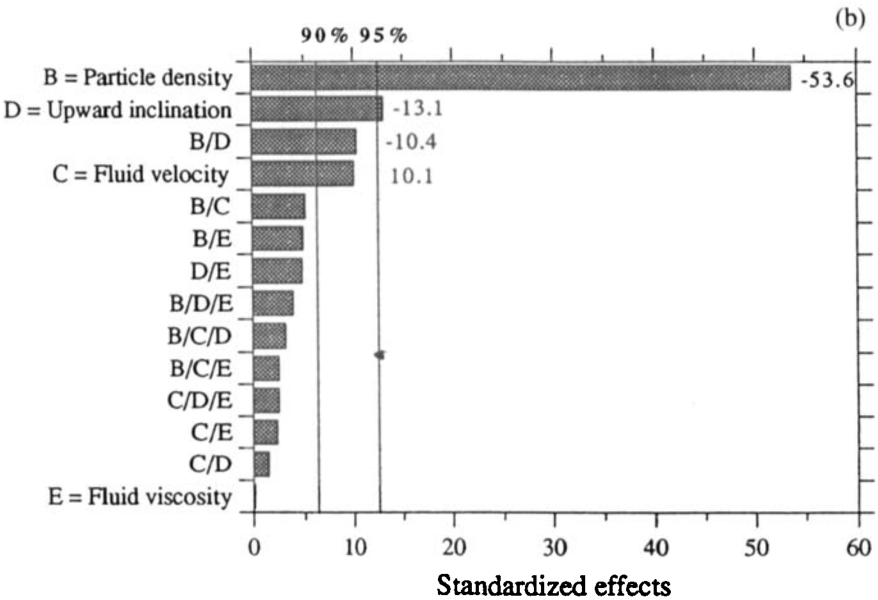
ρ_p (g/cm^3)	Q (L/h)	I (°)	μ (%CMC)	v_{pn}	ω_n	ω_n/v_{pn}
1.065	960	1.19	0.1	1.032 ± 0.049	0.063 ± 0.023	0.061
1.425	960	1.19	0.1	0.593 ± 0.029	0.585 ± 0.032	0.987
1.065	1360	1.19	0.1	1.089 ± 0.034	0.076 ± 0.013	0.070
1.425	1360	1.19	0.1	0.729 ± 0.025	0.717 ± 0.015	0.984
1.065	960	8.21	0.1	0.991 ± 0.052	0.050 ± 0.014	0.050
1.425	960	8.21	0.1	0.123 ± 0.023	0.136 ± 0.022	1.101
1.065	1360	8.21	0.1	1.044 ± 0.038	0.071 ± 0.019	0.068
1.425	1360	8.21	0.1	0.454 ± 0.008	0.438 ± 0.015	0.965
1.065	960	1.19	0.3	1.060 ± 0.055	0.199 ± 0.022	0.188
1.425	960	1.19	0.3	0.452 ± 0.008	0.443 ± 0.004	0.980
1.065	1360	1.19	0.3	1.157 ± 0.095	0.181 ± 0.015	0.157
1.425	1360	1.19	0.3	0.556 ± 0.008	0.542 ± 0.019	0.975
1.065	960	8.21	0.3	1.077 ± 0.076	0.180 ± 0.014	0.167
1.425	960	8.21	0.3	0.265 ± 0.006	0.246 ± 0.012	0.927
1.065	1360	8.21	0.3	1.099 ± 0.075	0.179 ± 0.012	0.163
1.425	1360	8.21	0.3	0.401 ± 0.007	0.393 ± 0.013	0.980

Analysis of the Normalized Linear Velocity (v_{pn})

It was observed that in most situations the particles would lag the fluid, with velocity values as low as 35% the average fluid velocity. However, in some cases, particularly for the larger low density particles flowing at the higher flow rate, the opposite was observed, with particles moving up to 18% faster than the average fluid velocity. The coefficient of variation was determined for all the experiments and values between 0.8 and 7.5% were obtained. Dutta and Sastry (1990a) also observed that in some situations (low viscosities and flow rates) the particles lag the fluid, although most works show that particles often have velocities higher than the fluid average velocity (Dutta and Sastry 1990a; Palmieri *et al.* 1992; Yang and Swartzel 1992; Sandeep and Zuritz 1994). It should be stressed that the particle velocity may be expected to depend on the radial position within the tube, decreasing from the tube center towards the tube wall, as a result of the fluid velocity profile.

Analysing Fig. 2a, it can be seen that particle density and fluid velocity are the variables that affect v_{pn} the most in the smaller tube, with particle diameter


(a)
90% 95%
B = Particle density
C = Fluid velocity
A = Particle diameter
C/E
D = Upward inclination
C/D/E
E = Fluid viscosity
B/C/E
A/B
A/B/C/E
A/B/D/E
B/D
B/C/D
D/E
A/C/D/E
B/C
A/C
A/D/E
A/B/C/D
C/D
B/E
A/E
A/B/C
A/C/E
A/C/D
A/B/D
B/D/E
B/C/D/E
A/B/E
A/D
-43.8
38.0
24.2
18.4
14.6
-9.6
-9.2
-8.6
-7.6
0
10
20
30
40
50
Standardized effects
vPn
Fluid velocity (cm/s)
μ = 0.1% CMC
μ = 0.3% CMC


(b)
90% 95%
B = Particle density
D = Upward inclination
B/D
C = Fluid velocity
B/C
B/E
D/E
B/D/E
B/C/D
B/C/E
C/D/E
C/E
C/D
E = Fluid viscosity
-53.6
-13.1
-10.4
10.1
0
10
20
30
40
50
60
Standardized effects

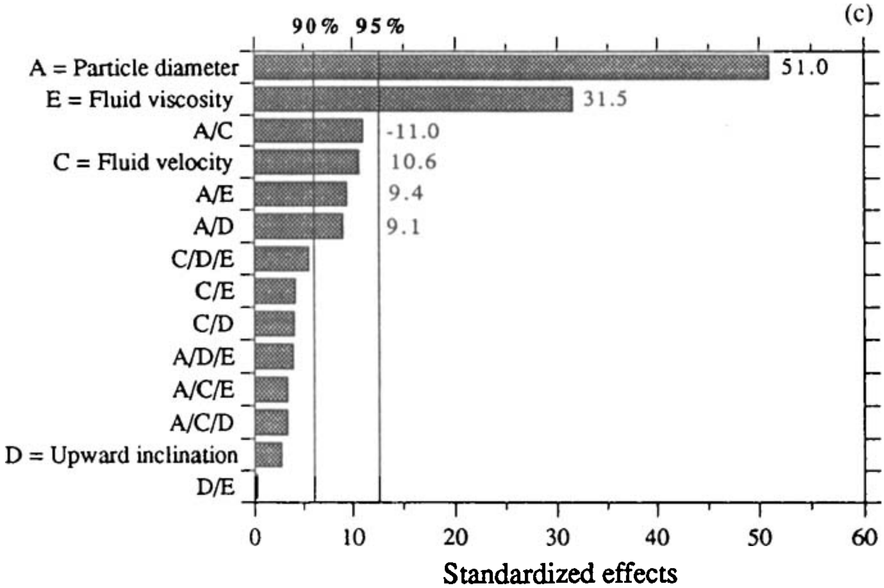


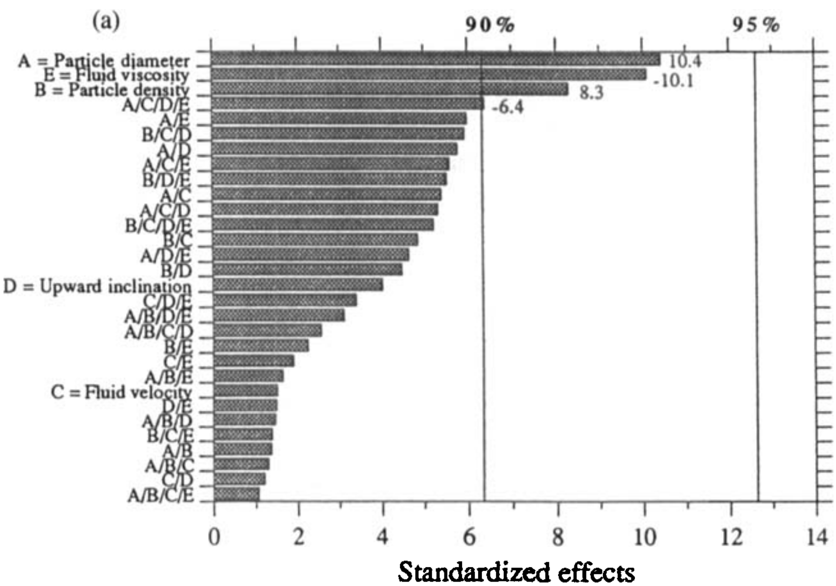
FIG. 2. PARETO CHARTS OF THE NORMALIZED LINEAR VELOCITY (v_{pn}): a) 2^5 FACTORIAL DESIGN (d_t = 2.2 cm) — THE SMALL PLOT SHOWS THE INTERACTIVE EFFECTS BETWEEN FLUID VELOCITY AND FLUID VISCOSITY; b) 2^4 FACTORIAL DESIGN (d_t = 5.1 cm, d_p = 1.59 cm); c) 2^4 FACTORIAL DESIGN (d_t = 5.1 cm, ρ_p = 1.065 g/cm^3) The two lines show the 95% and the 90% significance level, respectively.

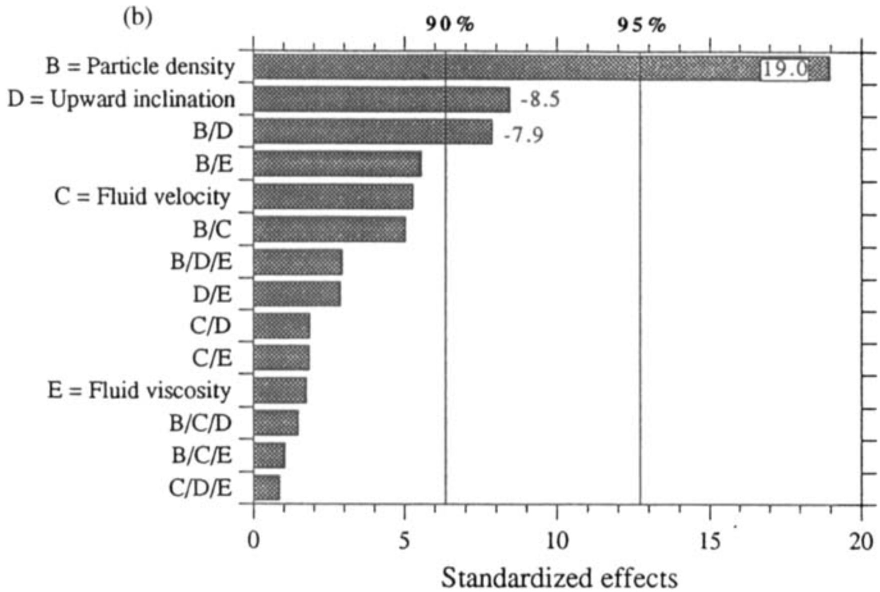
and tube inclination also significant to a 95% significance level. Higher density particles show a lower velocity. This effect was also evident in the larger tube (Fig. 2b). Similar results were reported by Yang and Swartzel (1992) when the particles were heavier than the carrier fluid, this behaviour being explained by the settling effect: the more dense particles would move nearer to the tube wall, where the fluid velocity is lower. In the present work the particles were always flowing in the same position, at the bottom of the tube, therefore showing that particle density itself has a direct effect on its velocity.

The fluid velocity has a positive effect. This effect is also visible in the larger tube (Fig. 2b and 2c), although to a lower significance level (90%), which is due to the lower range of fluid velocities tested in this case (Tables 3 and 4). Similar results were also reported by some authors (Yang and Swartzel 1992) and this effect was explained as an indirect effect of the radial position: as the fluid velocity increased the fluid lifted the particles, moving them towards the tube center. However, the present results show that the fluid velocity itself has a very important effect, since the particles position was always the same. In the smaller tube a double effect between fluid velocity and viscosity is also clear. The small plot in Fig. 2a, representing the average values of v_{pn} for all the ex-

TABLE 7.
EXPERIMENTAL DATA FOR PARTICLES OF 1.065 g/cm^3 DENSITY IN THE WIDER TUBE (5.1 cm I.D.)

d_p (mm)	Q (L/h)	I (°)	μ (%CMC)	v_{pn}	ω_n	ω_n/v_{pn}
15.9	960	1.19	0.1	1.032 ± 0.049	0.063 ± 0.023	0.061
25.4	960	1.19	0.1	1.152 ± 0.056	0.000 ± 0.000	0.000
15.9	1360	1.19	0.1	1.089 ± 0.034	0.076 ± 0.013	0.070
25.4	1360	1.19	0.1	1.121 ± 0.017	0.008 ± 0.022	0.007
15.9	960	8.21	0.1	0.991 ± 0.052	0.050 ± 0.014	0.050
25.4	960	8.21	0.1	1.169 ± 0.103	0.049 ± 0.028	0.042
15.9	1360	8.21	0.1	1.044 ± 0.038	0.071 ± 0.019	0.068
25.4	1360	8.21	0.1	1.158 ± 0.069	0.062 ± 0.038	0.054
15.9	960	1.19	0.3	1.060 ± 0.055	0.199 ± 0.022	0.188
25.4	960	1.19	0.3	1.239 ± 0.032	0.206 ± 0.033	0.166
15.9	1360	1.19	0.3	1.157 ± 0.095	0.181 ± 0.015	0.157
25.4	1360	1.19	0.3	1.272 ± 0.054	0.174 ± 0.023	0.137
15.9	960	8.21	0.3	1.077 ± 0.076	0.180 ± 0.014	0.167
25.4	960	8.21	0.3	1.260 ± 0.072	0.113 ± 0.052	0.090
15.9	1360	8.21	0.3	1.099 ± 0.075	0.179 ± 0.012	0.163
25.4	1360	8.21	0.3	1.265 ± 0.064	0.097 ± 0.009	0.077





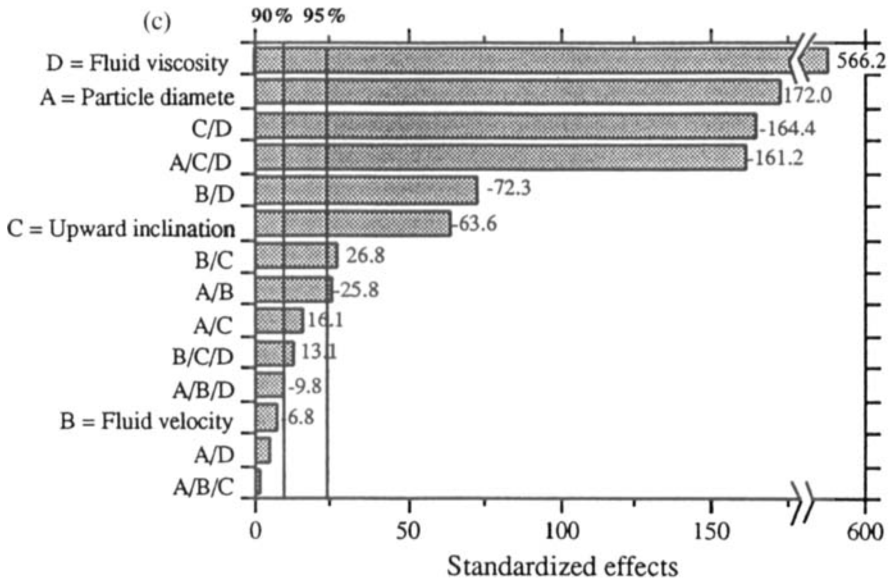


FIG. 3. PARETO CHARTS OF THE NORMALIZED ROTATIONAL VELOCITY (ω_n): a) 2^5 FACTORIAL DESIGN (d_t = 2.2 cm); b) 2^4 FACTORIAL DESIGN (d_t = 5.1 cm, d_p = 1.59 cm); c) 2^4 FACTORIAL DESIGN (d_t = 5.1 cm, ρ_p = 1.065 g/cm^3)
The two lines show the 95% and the 90% significance level, respectively.

periments at each set of conditions, shows that the fluid velocity effect is particularly important when the carrier fluid is more viscous, which may be explained by the increased steepness of the velocity gradient adjacent to the wall as the flow behavior decreases.

Larger particles show a higher v_{pn}, in both tubes. The smaller particles have a diameter approximately equal to one third of the tube diameter, while the larger particles have a diameter almost equal to half the tube diameter (Tables 2, 3 and 4). This implies that, considering the fluid velocity profile, the larger particles will be subjected to a higher drag force.

The effect of viscosity was particularly important for the low density particles flowing in the large tube. In this situation, the particles would move faster in the more viscous carrier fluid. This effect was also noticeable in the smaller tube (Fig. 2a), although mainly for the lower fluid velocity and with a lower significance level (90%). Dutta and Sastry (1990a) obtained similar results for the fastest moving spherical particles flowing in CMC suspensions. Again, this may be explained by the influence of the fluid viscosity on the velocity profile near the wall, as well as by the increased drag force the particle is subjected to.

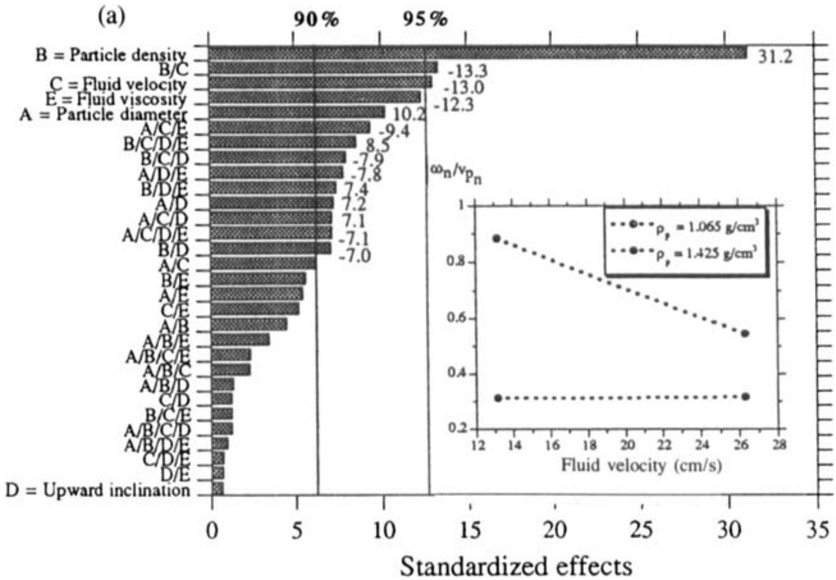
The tube inclination also showed effects significant to a 95% significance level, although opposite for the small and large tubes: the tube inclination produced a delay of the particles in the large tube, as might be expected due to the component of the particle weight force on the flow direction, but an acceleration of the particles in the small tube was observed. The reason for this can only be speculated. Tables 5, 6, 7 and 8 show that the normalized rotational velocity is usually lower than 1, which is the value it would have if the rotation would be due to rolling on the tube wall, and therefore it is evident that the particles slide, which must imply the existence of a layer, though eventually small, of fluid that flows between the particle and the wall (like a lubricating layer). As a particle falls due to gravity towards the bottom of the tube, it squeezes the layer of fluid underneath until the pressure thus created counteracts the weight of the particle and could even prevent the collision with the wall — this is basically the principle of lubrication of roller bearings. A higher inclination will increase the localized pressure in that lubricating layer because the force in the direction between particle and wall is not only the gravitational component, but adds the component of the drag force in that direction. The relevance of this depends on the magnitude of these forces, as the gravitational component decreases with the inclination of the tube, and therefore this effect would be more relevant in the smaller tube than in the larger, because the fluid velocity profile is more pronounced the smaller the tube. This could induce more turbulence which can accelerate the particle. As particles are always smaller than the tube radius, if there is more turbulence they move more often away from the wall and back and as they move away from the wall the maximum drag velocity that they are subjected to is higher. This effect would again be more significant in the small tube, where the velocity profile is more pronounced.

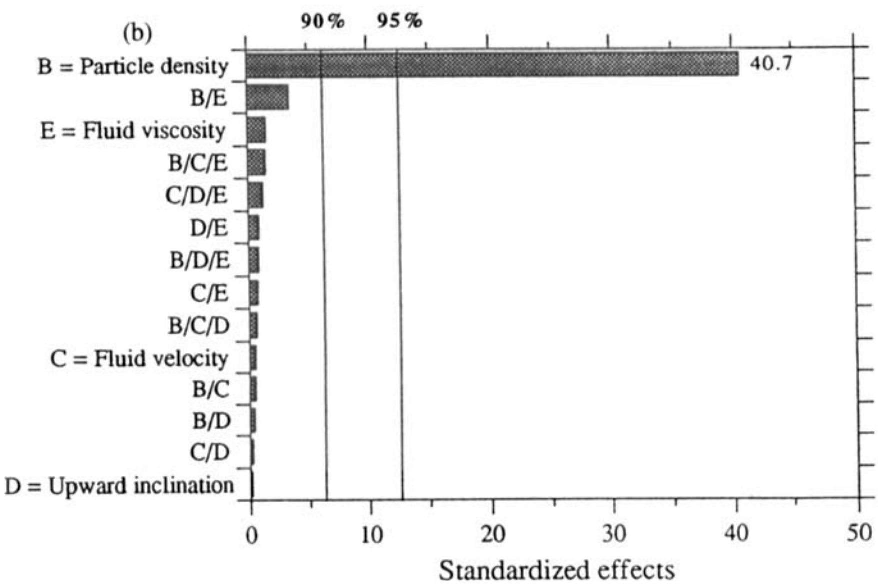
It is curious to note that these results agree well in general with the ones reported in an earlier work (Baptista *et al.* 1994), for the residence time distribution of suspensions of spherical particles flowing in a continuous tubular processing system, with heating, holding and cooling sections. In this work flow rate and particle diameter had a negative effect on the average residence time, while particle density had a positive effect. Fluid viscosity showed interactive effects with the other variables, presenting either positive or negative effects, depending on the other variables and therefore the comparison is not so straightforward. Nevertheless this indicates that the results obtained in the present work provide a good insight in the flow conditions in a more complex system, with elbows and flow restrictions.

Analysis of the Normalized Rotational Velocity (ω_n)

In terms of the normalized rotational velocity, values between 0.05 and 0.72, with coefficient of variation between 0.5 and 14.2% were obtained. Figure 3 shows that the variables that affect the particle rotational velocity more significantly are particle diameter, fluid viscosity and particle density, although in terms of particle diameter and fluid viscosity different results were observed for the two tubes. Tube inclination also had significant effects in the larger tube.

Higher density particles show higher rotational velocity. This may be related with the results previously discussed in terms of the linear velocity: heavier particles will move slower and therefore with a higher relative velocity in relation to the fluid, which may increase the torque that promote rotation. Increasing the particle diameter might also be expected to increase this torque adn thus the particle rotation. This was observed for the small tube but not for the larger one, where larger particles had a lower rotational velocity. This may be due to the high positive effect of the particle diameter on its linear velocity, which decreases the relative fluid-to-particle velocity, because in the large tube, when particle diameter was tested, only low density particles were used and their linear velocity was in general higher than the fluid average velocity. In terms of fluid viscosity different results were also obtained for the two tubes: for the small tube the particle rotational velocity was lower for the more viscous fluid, and the opposite was observed for the larger tube. These results show that there are two opposite effects regarding viscosity and tube width. One obvious effect is that the higher viscosity corresponds to a pseudo-plastic behavior, that is, to a lower behavior index which means a flatter velocity profile. A wider tube also implies a less pronounced velocity profile. The particle rotates as it is subjected to a torque resulting from different velocities on the top and on the bottom: the larger the


(a)
90%
95%
B = Particle density
B/C
C = Fluid velocity
E = Fluid viscosity
A = Particle diameter
A/C/E
B/C/D/E
B/C/D
A/D/E
B/D/E
A/D
A/C/D
A/C/D/E
B/D
A/C
B/E
A/E
C/E
A/B
A/B/E
A/B/C/E
A/B/C
A/B/D
C/D
B/C/E
A/B/C/D
A/B/D/E
C/D/E
D/E
D = Upward inclination
31.2
-13.3
-13.0
-12.3
10.2
-9.4
8.5
-7.9
-7.8
7.4
7.2
7.1
-7.1
-7.0
ωn/vpn
ρp = 1.065 g/cm³
ρp = 1.425 g/cm³
Fluid velocity (cm/s)
Standardized effects


(b)
90%
95%
B = Particle density
B/E
E = Fluid viscosity
B/C/E
C/D/E
D/E
B/D/E
C/E
B/C/D
C = Fluid velocity
B/C
B/D
C/D
D = Upward inclination
40.7
Standardized effects

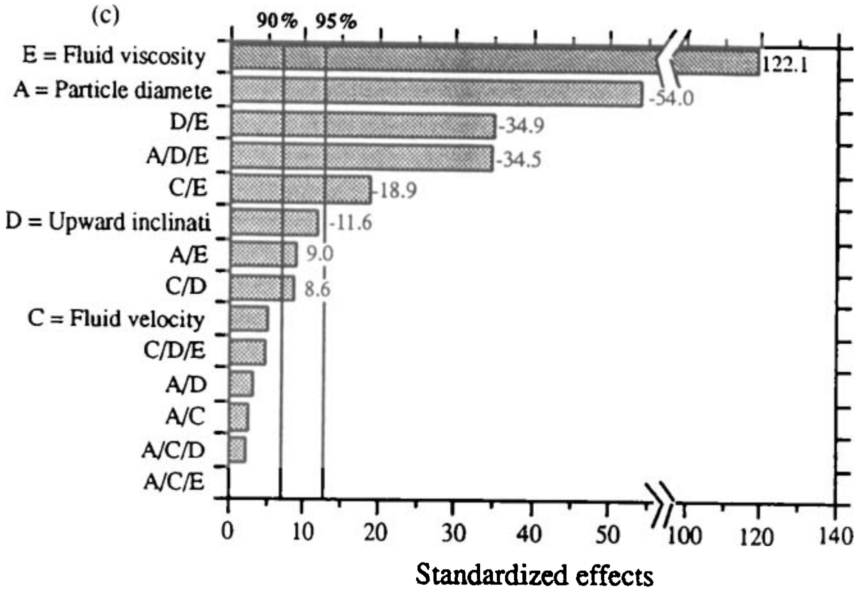


FIG. 4. PARETO CHART OF THE RATIO BETWEEN ROTATIONAL AND LINEAR VELOCITY (ω/v_p): a) 2^5 FACTORIAL DESIGN (d_t = 2.2 cm) — THE SMALL PLOT SHOWS THE INTERACTIVE EFFECTS BETWEEN PARTICLE DENSITY AND FLUID VELOCITY; b) 2^4 FACTORIAL DESIGN (d_t = 5.1 cm, d_p = 1.59 cm); c) 2^4 FACTORIAL DESIGN (d_t = 5.1 cm, ρ_p = 1.065 g/cm^3)

The two lines show the 95% and the 90% significance level, respectively.

velocity gradient in the region where the particle is located, the larger the torque and the faster the rotational velocity. This would imply a faster rotational velocity for the lower viscosity and narrower tube, as found experimentally for this tube. Another possible effect of viscosity has to do with consistency rather than with the behavior (and hence the velocity profile). The existence of a lubricating layer underneath the particle has been mentioned previously. The lubricating layer is more relevant the higher the viscosity (consistency) of the fluid and therefore the particle should roll more perfectly the higher the viscosity, sliding more for lower viscosity. This increasing rotational velocity with viscosity was found for the larger tube and therefore one could speculate that in these conditions the variation of the velocity gradient and consequent torque was too small to overcome this effect of a more consistent lubricating layer. Whatever the reason for the observations, it is evident that the fluid velocity profile in the region of the particle plays a major role on the particle rotation.

Tube inclination was also significant, as it can be seen that the rotational velocity decreased when the tube inclination was increased.

Analysis of the Ratio Between Normalized Rotational Velocity (ω_n) and Normalized Linear Velocity (v_{pn})

Figure 4 shows the results in terms of ratio between rotational and linear velocity, which gives an idea of the type of flow the particle presents. When the ratio equals 1, the particle is in perfect contact with the wall, rolling perfectly over it. If this ratio is lower than 1 the particle will slide somewhat, zero would correspond to perfect sliding and no rotation. However, this value can also be higher than 1 and in this case the particle will be spinning in the tube wall (like a car wheel stuck in snow). Values between 0.007 and 1.10 were obtained. It can be concluded that the low density particles tend to slide much more than the heavier particles, because of the higher drag force they are subjected to. In the smaller tube this effect was more evident for the lower flow rates (Fig. 4a). Fluid viscosity and particle diameter are also significant, particularly in the larger tube (95% significance level). The larger particles slide more than the smaller particles. Particles moving in less viscous fluids also tend to slide considerably.

CONCLUSIONS

The operating variables (flow rate, tube inclination, tube width) and the system parameters (densities, fluid viscosity, particle size) affect both the rotational and the linear velocity of the particles, but in a different way. As both velocities will influence the heat transfer coefficient, it becomes evident that the consideration of both in heat transfer studies is important to understand the effect of the operating and system variables in the aseptic processing of particulate fluids.

The effects on the particle linear velocity were independent of the tube diameter and were in fact similar to the results that have been reported for a continuous tubular processing system, which shows that the conclusions of the present work yield good indications for more complex flow conditions and that scale-up from the pilot tubular system is reasonable. However, the effects on the rotational velocity were more complex, with the diameter of the tube having a significant influence. Scale-up is therefore not straightforward. This was attributed to a greater sensitivity of the rotational velocity to the fluid velocity profile and fluid-particle surface interaction.

Particle density was the parameter that most affected the ratio between particle rotational and linear velocity, with the low density particles sliding much more at the wall. It is curious to note that increasing the particle diameter leads to an higher particle linear velocity and therefore to a lower fluid-to-particle relative velocity, since the rotational velocity increased.

It may be expected that both the particle movement relative to the fluid and its rotational movement will affect the boundary layer surrounding the particle and therefore the heat transfer rates. Therefore, the effect of the particle diameter on the heat transfer rate may depend on the relative effects of the rotational and linear velocity of the particle. This result therefore shows that estimating heat transfer coefficients on the basis of the fluid-to-particle relative velocity as often proposed in literature may produce conservative results, because the effects of the rotational movements on the boundary layer are not taken into consideration. For the range of variables in the present work, nondimensional correlations published in literature (Froszling 1938; Whitaker 1972; Zuritz and Sastry 1987) suggest a range of variation of the Nusselt number caused by the particle linear velocity relative to the fluid between 2 and 25 (heat transfer coefficient range around 50 to 2500 W/m²K), which is what would be expected if the particles do not rotate. However, similar correlations also indicate that the Nusselt number has an equal range of variation (3-25) for rotational velocities of the order of magnitude of those determined experimentally in this work (which would be the effect expected if particles rotated in an otherwise stagnant fluid).

For the range of variables in the present work, nondimensional correlations published in literature (Froszling 1938; Whitaker 1972; Zuritz and Sastry 1987) suggest a ragne of variation of the Nusselt number caused by the particle linear velocity relative to the fluid between 3 and 25 (heat transfer coefficient range around 50 to 2500 W/m²K), which is what would be expected if the particles do not rotate. However, similar correlations also indicate that the Nusselt number has an equal range of variations (3-25) for rotational velocities of the order of magnitude of those determined experimentally in this work (which would be the effect expected if particles rotated in an otherwise stagnant fluid).

ACKNOWLEDGMENTS

The authors are thankful to Juna Nacional de Investigação Científica e Tecnológica and to the CEC (Flair Programme) for financial support. The authors would like to acknowledge the invaluable support of ARSOPI, the metallurigical company where the flow visualization system used in this work was built. A special reference is given to Mr. Armando Pinho and Mr. Ernesto Ferreira for consultation.

REFERENCES

BAPTISTA, P.N., OLIVEIRA, F.A.R., OLIVEIRA, J.C. and STRAUß, A. 1994. A general analysis of the residence time distribution of particles in the aseptic processing of particulate fluid foods in tubular systems. In *Minimal Processing of Foods and Process Optimization* (R.P Singh and F.A.R. Oliveira, eds.) pp. 153–167, CRC Press, Boca Raton.

BERRY, M.R. 1989. Predicting fastest particle residence time. In *Proceedings of the First International Congress in Aseptic Processing Technologies* (J.V. Chambers, ed.) pp. 6–17, Indianapolis, IN.

BOX, G., HUNTER, W.G. and HUNTER, J.S. 1978. *Statistics for Experimenters*, pp. 306–351, John Wiley & Sons, New York.

DIGNAN, D.M., BERRY, M.R., PFLUG, I.J. and GARDINE, T.D. 1989. Safety considerations in establishing aseptic processes for low-acid foods containing particulates. Food Technol. *43*, 118–121, 131.

DUTTA, B. and SASTRY, S.K. 1990a. Velocity distributions of food particles suspensions in holding tube flow: experimental and modelling studies on average particles velocities. J. Food Sci. *55*, 1448–1453.

DUTTA, B. and SASTRY, S.K. 1990b. Velocity distributions of food particles suspensions in holding tube flow: Characteristics and fastest-particle velocities. J. Food Sci. *55*, 1703–1710.

FROSZLING, N. 1938. Gerl. Beitr. zur Geophysik, 52, 170 [In Kramers, H. 1946. Heat transfer from spheres to flowing media. Physica *12*, 61–80].

PALMIERI, L., CACACE, D., DIPOLLINA, G. and DALL'AGLIO, G. 1992. Residence time distribution of food suspensions containing large particles when flowing in tubular systems. J. Food Engr. *17*, 225–239.

SALENGKE 1993. Residence time distribution of model food particles in the curved section of a holding tube. M.S. Thesis. The Ohio State University, Columbus, OH.

SANDEEP, K.P. and ZURTIZ, C.A. 1994. Residence time distribution of multiple particles in non-Newtonian holding tube flow: statistical analysis. J. Food Sci. *59*, 1314–1317.

SASTRY, S.K. and ZURITZ, C.A. 1987. A model for particle suspension flow in a tube. *American Society of Agricultural Engineering*, Paper No. 87-6537.

SUBRAMANIAM, G. and ZURITZ, C.A. 1990. A study of drag forces on solid spherical particles in power law bounded flow: applications to aseptic processing. J. Food Process Engineering *12*, 137–158.

WHITAKER, S. 1972. Forced convection heat transfer correlations for flow in pipes, past flat plates, single cylinders, single spheres, and for flow in packed beds and tube bundles. AIChemE J. *18*, 361–371.

YANG and SWARTZEL. 1992. Particle residence time distributions in two-phase flow in straight round conduit. J. Food Sci. *57*, 497–502.

ZURITZ, C.A. and SASTRY, S.K. 1987. Convective heat transfer coefficients for non-Newtonian flow past food-shaped particulates. ASAE, Paper No. 87-6538, St. Joseph, MI.