Bend-effects on the residence time distribution of solid food particles in a holding tube

S. GRABOWSKI and H.S. RAMASWAMY

Department of Food Science and Agricultural Chemistry, Macdonald Campus of McGill University, Ste Anne-de-Bellevue, QC, Canada H9X 3V9. *Received 12 June 1997; accepted 13 May 1998.*

Grabowski, S. and Ramaswamy, H.S. 1998. **Bend-effects on the residence time distribution of solid food particles in a holding tube.** Can. Agric. Eng. **40**:121-126. The residence time distribution (RTD) of individual food particles in the curved section (180°) of a holding tube of an aseptic processing simulator was investigated. Process variables were the radius of curvature (R=0.1 and 0.2 m) of the bend, type, size and shape of the food particles and type of carrier liquid (water or pectin solutions). The results obtained by a videotaping technique indicated that the linear velocity of food particles in the curved section (bend) was reduced from about 8% (R=0.2 m) to about 15% (R=0.1 m) in comparison to the velocity in the straight section. Particle size and shape, and viscosity of the carrier liquid influenced the velocity of the food particle in the curved section, but only the shape effect was similar to that in straight part of the tube.

La distribution des temps de séjour (DTS) de particules individuelles d'aliments lors du passage dans un tube de chauffage aseptique est un paramètre important. La DTS de particules lors du passage dans un coude à 180° est présenté dans cette étude. Les variables prises en compte sont le rayon de courbure (R=0.1 et 0.2 m), le type, la grosseur et la forme des particules ainsi que le type de liquide porteur (eau ou solutions d'eau et pectines). Les résultats obtenus par visualisation (vidéo) indiquent que la vitesse linéaire des particules lors du passage dans le coude est réduite de 8 à 15 % (R=0.2 m et 0.1 m respectivement) par rapport à la vitesse dans la section droite. La dimension et la forme des particules, ainsi que la viscosité du fluide porteur influencent également la vitesse des particules lors du passage dans le coude. Seul la forme des particules a le même effet dans la section droite et dans la section courbée.

INTRODUCTION

Some micro-organisms cause foods to spoil and also food-borne pathogens can cause safety problems to humans. The primary purpose of food preservation is to maintain or enhance the safety and quality of foods. It often involves one or more of the following methods to inactivate or inhibit undesirable microorganisms: heating, cooling, drying, addition of salt, sugar, chemicals or antibiotics and radiation treatment.

Aseptic processing and packaging has been a commercial and technological success for liquid foods with reported advantages of low processing costs, continuity, high quality and adaptation to diversified packaging materials (David 1992). The extension of this technology to low-acid liquid foods containing discrete particles has been difficult and not fully approved by Canadian and US governmental food safety agencies. The major question for the regulatory approval appears to be uncertainties associated with residence time distribution (RTD) of solid particles and lack of appropriate methodology for biological validation (Anonymous 1996). Following the recent NCFST-CAPPS workshops for establishing guidelines for the process, Tetra-Pack has filed and obtained FDA clearance for a hypothetical product opening the door for its commercial exploration (Palaniappan and Sizer 1997; Larkin 1997).

Literature data on heat transfer and RTD characteristics in aseptic processing were recently reviewed by Ramaswamy et al. (1995, 1997). The majority of published studies on RTD involved a straight section of the holding tube, while some have concentrated on the system as a whole. Only limited information is available on the RTD in the curved section of the holding tube. Recently, Salengke and Sastry (1995, 1996) published experimental data on RTD of solid food particles in the curved section of a holding tube while Liu and Zuritz (1995) presented a mathematical simulation for the flow of a single solid particle in a carrier liquid. Because of lack of availability data on bend effects on RTD, the main objective of this study was to investigate the effect of curvature of the holding tube on the relative particle-to-liquid velocity for the flow of model/food particles within a carrier liquid.

THEORETICAL FORMULATION

Two-phase solid/liquid particulate flow systems are governed by Navier-Stokes and continuity equations for the liquid phase and particle dynamic balances for the discrete solid phase (Smoldyrev 1982). A general solution for these equations is difficult and needs several assumptions. For tube flow in a curved section, Liu and Zuritz (1995) developed and solved a Lagrangian type of mathematical model for the flow of a single solid particle within a carrier liquid. The authors assumed the following simplifications for the flow characteristics: (1) laminar flow, (2) Newtonian carrier liquid, (3) negligible particle-particle interaction, and (4) constant physical properties of the system. The solution of this model gives some qualitative rather than quantitative results as none of the four assumptions is truly valid for the typical flow in aseptic processing conditions. Especially in the curved section (bend) of the holding tube, the centrifugal force (Eq. 1) which affects the solid particles, results in some turbulisation of the flow and increases the particle-wall and particle-particle interactions.

$$F_c = m_p u_p^2 / R \tag{1}$$

where:

F_c = centrifugal force,
m_p = particle mass,
u_p = linear velocity of the particle, and
R = radius of curvature of the tube.

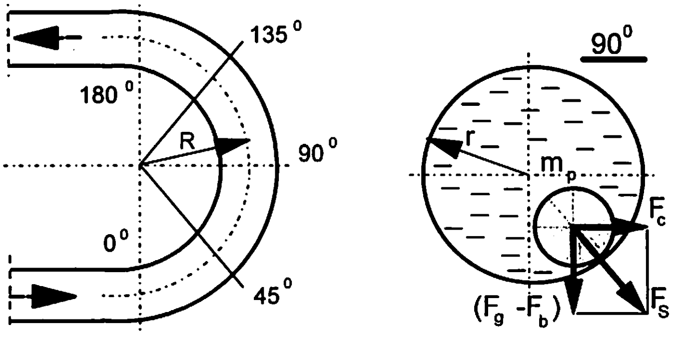


Fig. 1. Simplified scheme of solid particle flow within the carrier liquid in curved section of the holding tube.

For the particle with a density higher than the density of the carrier liquid, the theoretical balance of forces (Fig. 1) results in the following two effects:

1. Reduction in the particle linear (downstream) velocity as the particle-wall friction force (Q) increases in the curved section of the tube:

$$Q = fF_s \qquad (2)$$

where:

Q = particle-wall friction force,
f = coefficient of friction between particle and tube wall, and
F_s = resulting stress force between the particle and the tube surface, defined by Eq. (3):

$$F_s = [(F_g - F_b)^2 + F_c^2]^{0.5} \qquad (3)$$

where:

F_g, F_b = gravity and buoyant forces, respectively, and
F_c centrifugal force acting on the particle.

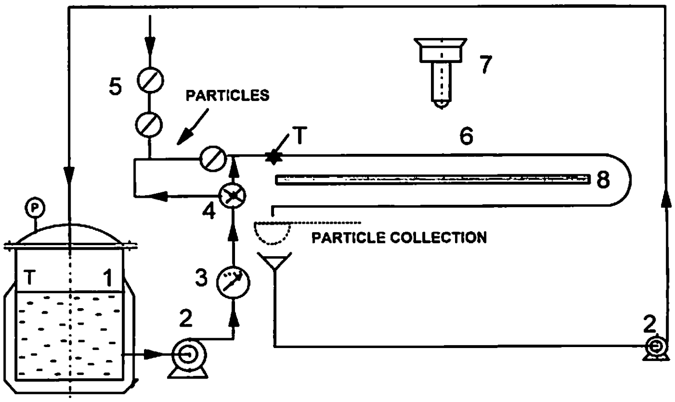
2. Change in the cross-sectional position of the particle at the bend, i.e., the particle tends to be pulled away from the bottom, somewhat lifting it along the outer wall of the tube (Fig. 1).

Both these effects are qualitatively predictable from theory as well as from the mathematical model presented by Liu and Zuritz (1995); however, because of the non-Newtonian character of the carrier liquid and the effects of other variables, results from experimental studies still appear to be the best source for scale-up considerations (Salengke and Sastry 1995, 1996).

MATERIALS and METHODS

Experimental set-up

Figure 2 shows a schematic diagram of the experimental set-up. A glass holding tube consisting of two straight tubes and a curved section connecting them (3.8 m total length and 50.8 mm internal diameter) was used to simulate a section of the holding tube. Two different bends with radii of curvature 0.1 and 0.2 m were used in the experiment (one at a time). The other details of the experimental set-up are described elsewhere (Grabowski and Ramaswamy 1995a, 1995b). Food particles were introduced one-by-one into the system through a special entry port. A video-camera (Panasonic, AG-190) equipped with a digital stop-watch (0.1 s interval) was used to record the flow of solid particles within the carrier liquid inside each section of the holding tube. After the experiment, the video-tape was analyzed using a VCR (Video deck VT-39EM, Hitachi, Japan) utilizing its forward and backward slow motion features.



1: Steam kettle
2: Variable-speed pump
3: Flow meter
4: Three-way valve of by-pass system
5: Port for particle entry
6: Glass holding tube (two straight and one bend section
7: Video-camera
8: Source of light
T: Thermocouple location

Fig. 2. Schematic diagram of experimental set-up.

Solid particles

Fresh locally purchased vegetables (carrot, parsnip, and potato) were cut to the required size and shape using a set of knives, cork-borers, or French-fry maker. Linear dimension of the particles were: for cubes 10 or 15 mm and for cylinders with length equal to diameter: 10 and 15 mm. After blanching for one min in boiling water, several vegetable particles were used one at a time, in the experiment. The remaining particles were used for density measurements. Average densities of parsnip, carrot and potato were 980, 1020, and 1070 kg/m^3, respectively, with a maximum variability of ±40 kg/m^3. Nylon spheres of average density 1140 ±10 kg/m^3 (Hoover Precision Products, Sault Ste. Marie, MI) of four different diameters (12.7, 15.6, 19.0 and 22.3 mm), nylon cylinders and square rods cut to the

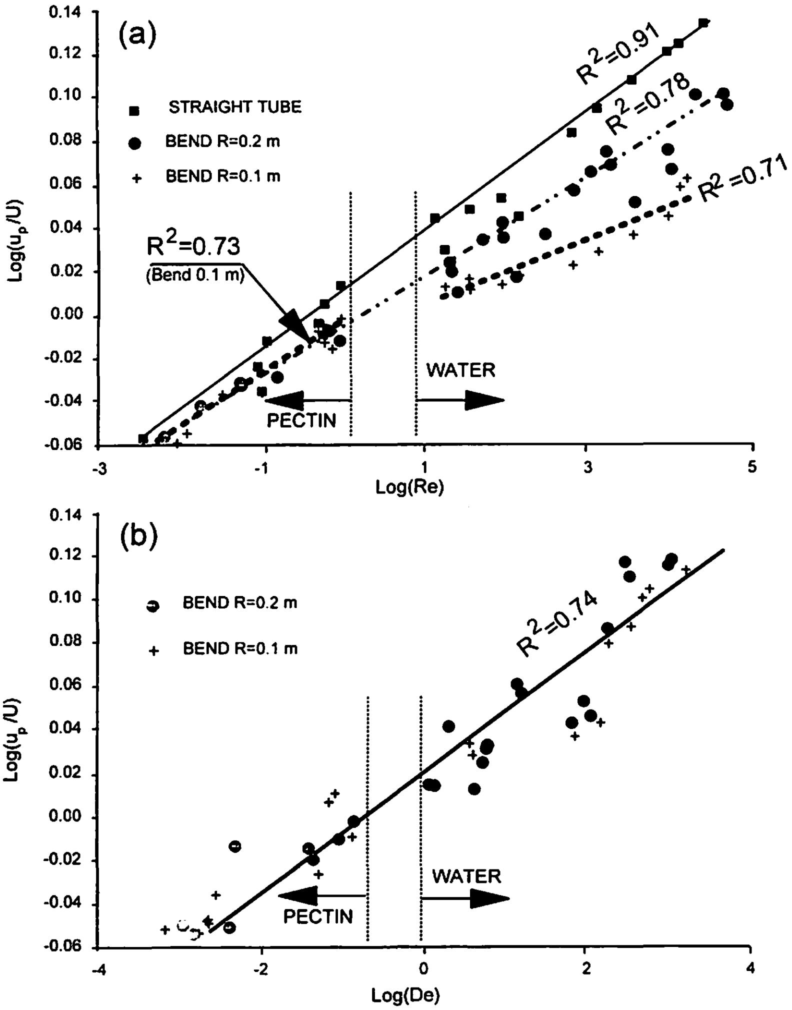


Fig. 3. Relative particle-to-liquid velocity as a function of: (a) carrier liquid flow Reynolds number, (b) Dean number.

appropriate lengths (equal to the diameter of the spheres) were used as model spherical, cylindrical, and cubical particles.

Carrier liquid

The carrier liquids used were water (Newtonian liquid) and food grade pectin (Amcan, Toronto, ON) solutions (non-Newtonian liquid) of different concentrations (0.2-1.2% w/w). To vary the density of the liquid, commercial sugar (Redpath Sugars, Montreal, QC) was added to the water/pectin solution. The temperature of the liquid was kept constant during each test run at 20, 50 or 80 °C (±1 °C). The rheological characteristics of the pectin solutions were measured using a Haake RV-20 rotational viscometer (Haake, Germany). The coefficient of consistency (K) and the flow behavior index (n) were computed according to the power law equation:

$$\tau = K\gamma^n \qquad (4)$$

where:

τ = shear stress, and
γ = shear rate.

For low concentration pectin solutions (up to 0.5%) the values of both these parameters were in good agreement with published data (Ramaswamy and Basak 1992).

Statistical analysis

Statistical analysis of the experimental data was performed using SAS 6.11 software (SAS Institute Inc., Cary, NC). All necessary calculations preceding statistical analysis were performed using Lotus-123 software (Version 5) from Lotus Development Corporation (Cambridge, MA).

RESULTS and DISCUSSION

General trends for particle velocity in the curved section

In the range of experimental conditions, the maximum centrifugal acceleration of a solid particle in the flow through the bend was about 1.5 m/s^2. Considering the effect of centrifugal force only (Eqs. 1-3), the reduction in the particle flow velocity in the bend compared with the straight tube should be about 2%. Salengke and Sastry (1995, 1996) found a maximum reduction of solid particle velocity in the bend to be in the range of 3.5-7% as compared to 8-15% found in this study (higher values with the shorter bend). Highest values were obtained for the flow of the largest spherical particle (Nylon spheres, d_p = 22.3 m) with water as the carrier liquid at the highest temperature (80 °C). Salgenke and Sastry (1995, 1996) performed their study with a relatively higher viscosity solution (0.5 w/w% of aqueous solution of sodium carboxymethylcellulose) at room temperature. The large differences in viscosity of carrier liquids should be an explanation for discrepancies between these two cases. The particle linear velocity at a bend is affected more in a carrier fluid of lower viscosity than higher. Figure 3a presents some illustrations of this observation in the form of a relation between particle relative velocity (u_p/U) and carrier liquid tube flow Reynolds number, where u_p is the linear velocity of solid particle and U is the average linear velocity of liquid. Definition of tube flow Reynolds number is based on average linear velocity of liquid, its density and dynamic viscosity, and diameter of the tube. At least three different curves were obtained: first (upper curve) for the flow in the straight part of the tube (average value from the first and last section of holding tube); second for the bend with radius of 0.2 m and the third for the bend with radius 0.1 m (lower curve). These three curves were closer to each other (within ±15%) for high viscosity liquids (pectin/water solutions over 0.5%), but deviated in the low viscosity liquid (water). Thus it can be concluded that the viscosity of the carrier liquid tends to dampen the effect of curvature for the flow of a solid particle in the bend section of the holding tube.

Simplified correlation equation

To compensate effect of curvature on the flow of liquids in curved sections of pipelines, Dean (1928) (cited by Fairbank and So 1987) proposed a dimensionless number, De (Dean number):

$$De = (r / R)^{0.5}\,\mathrm{Re} \qquad (5)$$

where:

r, R = internal and curvature radii of a holding tube, respectively, and

Re = carrier liquid tube flow Reynolds number.

The Dean number, widely used for describing flow through bends (Fairbank and So 1987), combines the effect of curvature (r/R) with other flow variables defined by tube flow Reynolds number ($\mathrm{Re} = Ud\rho/\eta$) i.e. viscosity ($\eta$), velocity (U), and density (ρ) of the carrier liquid and the diameter of the tube (d). Figure 3b presents experimental results recalculated for the curved section only in the form of relative particle velocity (u_p/U) vs De. Generally only one line of experimental points was achieved; however, data were spread over a wide band ($R^2 = 0.74$). In an attempt to improve the relationship and to be able to use a more general model which could describe flow through holding tubes, a correction factor (Bend number, B) was added to the correlation equations of the straight tube to accommodate the bend effects:

$$B = 1 - (r / R)^{0.5} \qquad (6)$$

Bend number (B) was chosen as the best describing function of experimental data from other possible dimensionless numbers with tube-to-curvature radius ratio power factors, for example, 1 and 2. For the straight tube, the B value is equal to 1 while for the curved section it is less than one - with lower values for bends of shorter radii of curvature. The basic model for the correlations for the straight tube was taken from our previous experiments (Grabowski and Ramaswamy 1995b) which were carried out with the same equipment under a similar range of experimental variables and conditions. Statistical analysis of our experimental data gave the following general dimensionless equations for both straight and bend sections:

- for particle maximum velocity (from 5-10 repetitions) ($R^2 = 0.84$):

$$G\mathrm{Re}_{p,f} = 1.5G\mathrm{Re}^{1.12}\,Ar_p^{-0.06}(d_p / d)^{1.35}\psi^{0.08}B^{0.13} \qquad (7)$$

- for particle mean velocity (R= 0.87):

$$G\mathrm{Re}_p = 1.35G\mathrm{Re}^{1.2}\,Ar_p^{-0.09}(d_p / d)^{1.6}\psi^{0.2}B^{0.12} \qquad (8)$$

The validity of both equations (Eqs. 7 and 8) is limited to tube Reynolds number up to 30 000; Archimedes number up to 2×10^8; relative particle size (d_p/d) in the range 0.12-0.65; particle sphericity (Ψ) in the range 0.8-1; density simplex (a) other than zero; and tube to bend radius ratio less than 0.5. The illustration of experimental vs calculated data using Eq. 8 is presented in Fig. 4. Due to differences in rheological properties of water and pectin solutions, two group of points (upper for water and lower for pectin solution) appeared. The spread of data within each group is due to differences in other parameters and secondary flow of the carrier liquid in the bend (Fairbank and So 1987).

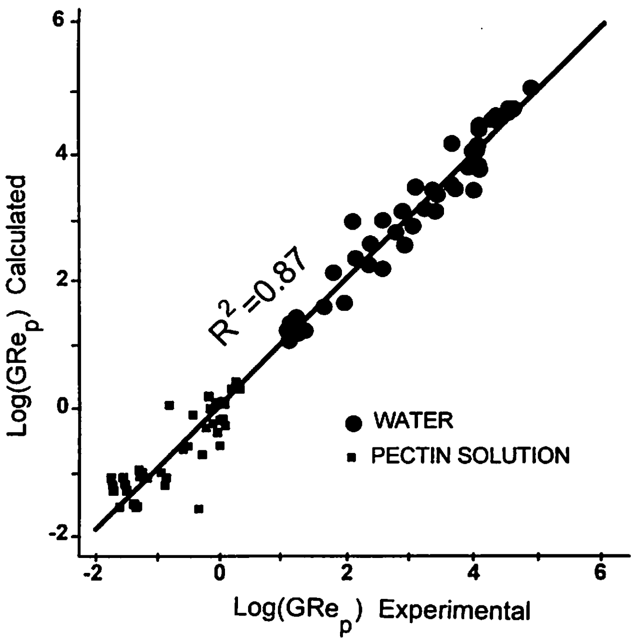


Fig. 4. Comparison of calculated (Eq. 7) and experimental particle generalized Reynolds number (Gre_p) data.

Effect of particle size and shape

Previous studies (Grabowski and Ramaswamy 1995b) have shown larger particles to have higher tube-flow linear velocities in a straight tube. This has been mainly credited to the larger cross-sectional area occupied by the larger solid particle in the holding tube. In the curved section of the tube, the centrifugal force (Eq. 1), which reduces the particle's linear velocity, has a greater influence on the particle of larger mass (and of size, assuming uniform density). Thus, the reduction of the linear velocity in the bend section of the tube in comparison to a straight tube will be stronger for the larger particle. The net effect which is an increase in velocity due to the larger surface area in the tube cross-section minus the drag action of centrifugal force may still be positive, i.e. with an increase in particle size, the overall relative particle velocity may still show an increasing trend (Fig. 5) but will be somewhat lowered.

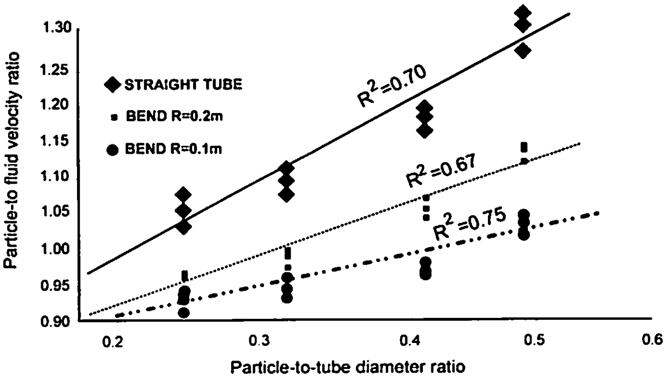


Fig. 5. Comparison of particle size effect on the particle-to-liquid velocity ratio in the bend and the straight section of the holding tube.

Fairbank and So (1987) in their detailed study of the liquid velocity profiles in the bends, reported that the liquid maximum velocity in the bends moves away from the centerline toward the outer wall due to the formation of secondary flow, which also causes the particle to move in a similar manner. Experimental tests with solid particles of the same material (vegetables or nylon) but different shape (spheres, cylinders, and cubes) showed a tendency in the bend section of the tube similar to that in the straight part.

CONCLUSIONS

A typical aseptic processing system consists of several straight and curved sections of a holding tube to make the design compact. This study indicates that the curved section of the tube contributes more residence time for the solid particles than the straight part of the tube of the same length (measured along the center-line of the tube). The single particle approach used here was reported for the evaluation of fastest particle residence time (Ramaswamy and Grabowski 1998). Scale-up and development of holding tube as a whole system could be based on RTD in the straight section of the tube as the bend part of the tube contributes longer residence times. For quantifying the effect of curvature, a correction factor (B) was found to be appropriate. Viscosity of the carrier liquid and particle size and shape affected the particle velocity in the curved section of the tube, the shape effect, however, was similar to that in the straight tube.

ACKNOWLEDGMENT

The authors acknowledge financial support for the research from the Natural Sciences and Engineering Research Council of Canada (NSERC) Grants Program.

REFERENCES

Anonymous. 1996. Finally: Aseptic multiphase foods? *Food Engineering* 68(10): 35-36.

David, J.R.D. 1992. Aseptic processing of foods: market advantages and microbiological risks. In *Advances in Aseptic Processing Technologies,* eds. R.K. Singh and P.E. Nelson, 189-216. London, UK and New York, NY: Elsevier Applied Science.

Dean, W.R. 1928. The streamline motion of fluid in a curved pipe. *Philosophical Magasin* 30: 673-693.

Fairbank, J.A. and M. So. 1987. Upstream and downstream influence of pipe curvature on the flow through a bend. *Heat and Fluid Flow* 8: 211-217.

Grabowski, S. and H.S. Ramaswamy. 1995a. Incipient carrier fluid velocity for particulate flow in a holding tube. *Journal of Food Engineering* 24: 123-136.

Grabowski, S. and H.S. Ramaswamy. 1995b. Characterization of single particle tube flow at elevated temperatures. *Journal of Food Process Engineering* 18: 343-361.

Larkin, J.W. 1997. Workshop targets. Continuous multiphase aseptic processing of foods. *Food Technology* 51 (10): 43-44.

Liu, Y. and C.A. Zuritz. 1995. Mathematical modeling of solid-liquid two phase flow: An application to aseptic processing. *Journal of Food Process Engineering* 18: 135-163.

Palaniappan, S. and C.E. Sizer. 1997. Aseptic processing validated for foods containing particulate. *Food Technology* 51 (8): 60-66

Ramaswamy, H.S., K.A. Abdelrahim, B.K. Simpson and J.P. Smith. 1995. Residence time distribution (RTD) of particulate foods: A review. *Food Research International* 28: 291-310.

Ramaswamy, H.S., G. Awuah and B.K. Simpson. 1997. Heat transfer and lethality considerations in aseptic processing of liquid/particulate mixtures: A review. *Critical Review in Food Science and Nutrition* 37: 253-286.

Ramaswamy, H.S. and S. Basak. 1992. Pectin and raspberry concentrate effects on the rheology of stirred commercial yogurt. *Journal of Food Science* 57: 357-360.

Ramaswamy, H.S. and S. Grabowski. 1998. Identification of fastest velocity particle in a tube flow: Single vs multi-particle approach. *Journal of Food Science* 63: 565-570.

Salengke, S. and S.K. Sastry. 1995. Residence time distribution of cylindrical particles in a curved section of a holding tube: the effect of particle size and flow rate. *Journal of Food Process Engineering* 18: 363-381.

Salengke, S. and S.K. Sastry. 1996. Residence time distribution: the effect of particle concentration and bend radius. *Journal of Food Engineering* 27: 159-176.

Smoldyrev, A.Y. 1982. *Pipeline Transport - Principles of Design.* Rockville, Md: Terraspace Inc.

NOMENCLATURE

A_p	surface area of the particle (m^2)
Ar_p	particle Archimedes number [abs ($g\ d_p^3\ a/\nu^2$)]
A_{sph}	surface area of equivalent sphere (with diameter d_p) (m^2)
a	density simplex [$(\rho_s-\rho)/\rho$]
B	bend number [$1-(r/R)^{0.5}$]
De	Dean number [$(r/R)^{0.5}$ Re]
d, D	internal and curvature diameter of holding tube, respectively (m)
d_p	particle diameter (equivalent) [$(6V_p/\pi)^{0.33}$] (m)
F_b, F_c, F_g, F_s	buoyancy, centrifugal, gravity, and resulting forces (N)
f	coefficient of friction between solid particle and tube wall
GRe	generalized tube flow Reynolds number [$U\ d\ \rho/\eta$]
GRe_p	generalized particle Reynolds number [$u_p\ d_p\ \rho/\eta$]
$Gre_{p,f}$	generalized fastest particle Reynolds number[$u_{p,f} d_p \rho/\eta$]
g	acceleration due to gravity (m/s^2)
K	consistency coefficient ($Pa \cdot s^n$)
m_p	mass of single particle (kg)
n	flow behavior index
Q	particle-wall friction force (N)
Re_p	particle Reynolds number (Newtonian fluid)[$u_p d_p \rho/\eta$]
r, R	internal and curvature radius of holding tube, respectively (m)
T	temperature (^0C)

U	linear, average velocity of carrier fluid $[4V/(\pi d^2)]$ (m/s)
u_p	linear particle velocity - average value from several replications (m/s)
$u_{p,f}$	fastest particle velocity from all replications (m/s)
V	carrier fluid volumetric flow rate (m^3/s)
V_p	volume of the particle (m^3)
η, ν	dynamic and kinematic effective viscosity, respectively (Pa·s), (m^2/s)
Ψ	sphericity of the particle $[A_{sph}/A_p]$
ρ, ρ_s	density of fluid and solid particles, respectively (kg/m^3)
τ	shear stress (N/m^2)
γ	shear rate or velocity gradient (1/s)