Fluid to Particle Heat Transfer Coefficients in Holding Tube Having Noncircular Cross Section

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ABSTRACT: Convective heat transfer coefficient (h_p) between fluid and particle in continuous tube flow were compared for 2 configurations of holding tubes: one conventional having a circular cross section (CHT) and the other having noncircular cross section (NCHT). A stream of plastic spheres was fed into the holding tube to simulate a food system with particulates. Live vegetative cells of *Bacillus stearothermophilus* were immobilized in aqueous gellan cubes and injected into the holding tubes with water as a carrier medium. The observed inactivation levels were compared with predicted values calculated from transient heat transfer equations solved by an explicit finite difference technique. Mean effective h_p values ranged from 400 to 2500 W/m^2.K for the NCHT and 350 to 1700 W/m^2.K for the CHT at a Reynolds number ranging from 6000 to 13000. The difference in h_p levels between the 2 configurations increased with the flow rate and temperature. Although no relation was observed between h_p values and liquid to particle relative velocity, a trend between pipe Reynolds number and h_p values was observed. The presence of a large number of particles in the holding tube significantly influenced h_p values.

Keywords: heat transfer coefficients, holding tube, Reynolds number, particle

Introduction

Continuous sterilization of liquid foods containing solid particulates has attracted much attention among the researchers recently because of the quality benefits promised by continuous process. However, commercial implementation of this technology remains a distant possibility, mainly because the process has not been understood thoroughly to enable prediction of particulate sterilization. The movement of the particulates in the holding tube and particle temperature profile with time need to be known before lethality can be accurately predicted from measurable process parameters such as carrier fluid temperature and suspension rate of flow.

Aseptic processing of foods with particulates as envisaged today requires heating of the liquid phase of the food, and as the particulates and heated fluid travel through the holding tube, heating of the particulate takes place (Sastry and Zuritz 1987). The heat penetration from the liquid into the solid food particulates is a slow process because of thermal inertia of the particulates. The convective heat transfer coefficient, h_p, at the fluid and particulate boundary needs to be known to predict the time-temperature profile of the particulate. The problem of estimating h_p is compounded by the geometry of the particulates, the existence of a velocity profile within holding tube cross section, and interactions between particulates. Our present knowledge of fluid mechanics restricts the prediction of particulate trajectory within the holding tube only for very simplified flow situations. Heat transfer coefficient (h_p) values for different flow situations have been reported by various researchers (Hunter 1972; Heppel 1985; Chandarana and others 1989; Chang and Toledo 1989; Sastry and others 1990; Zuritz and others 1990; Mwangi and others 1993; Balasubramaniam and Sastry 1994a, 1994b; Cacace and others 1994; Gratzek 1994; Zitoun and Sastry 1994a, 1994b; Awuah and others 1996; Ramaswamy and others 1996; Chen and others 1997; Fu and others 1998; Alhamdan and Sastry 1998).

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Other areas of research interest in aseptic processing include designing a new holding tube or modifying the conventional holding tube so that more uniform residence time distribution and higher heat transfer coefficients could be obtained. Other holding tubes such as one with a square cross section or a holding section consisting of parallel plates for liquid foods (Kessler 1985) and a spiral holding tube for particulates (Sandeep and others 2000) have been reported. However, work on a holding tube with a noncircular cross section showing improvement in heat transfer rates has not been reported.

Earlier work on residence time distribution (RTD) and fastest-particle velocities in a holding tube with noncircular cross section (NCHT) showed that NCHT was superior in these aspects compared with conventional cylindrical holding tube (CHT) (Christie 1997). The objective of the present study was to estimate h_p values for suspensions flowing through NCHT and compare them with corresponding values for a CHT for a simulated liquid-food system with solid particulates.

Materials and Methods

Equations for calculating h_p

The governing equation for thermal conduction into a solid particle is as follows:

$$\rho C_p \frac{dT}{dt} = \nabla.(k\nabla T) \tag{1}$$

where T is space and time dependent temperature, t is time, ρ is the particle density, C_p is the specific heat, and k is particle thermal conductivity. The convective boundary conditions are as follows:

$$k\nabla T.n = h_p(T - T_f) \tag{2}$$

where n is the outward normal vector from the particle surface, T_f is the time dependent fluid temperature, and h_p is the convective heat transfer coefficient. Initial conditions for the particle temperature are as follows:

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$$T(x, y, z, t = 0) = T_0 \quad (3)$$

Equation 1 with the above initial and boundary conditions can be solved analytically for geometric shapes such as finite slab, cylinder, or sphere for unidirectional or multidirectional heat flows. Such analytical solutions expressed in the form of infinite series involving positive roots of the transcendental equation are well known. However, because of changes in material thermophysical properties with temperature and changing temperature of carrier fluid, an analytical solution cannot be used in the present system. In the present study, Eq. 1 is solved by a numerical method. Explicit finite difference methods are well suited for cube-shaped particles because cube surfaces can be aligned with Cartesian coordinate system. Finite difference methods also allow easy incorporation of changes in product thermophysical properties during the process. One such method (Chang and Toledo 1989) consists of dividing the solid into nodes with spacings Δx, Δy, and Δz. Energy balance on each control nodal volume is carried out by taking conductive and convective heat changes into account for the specific node control volume. Nodal temperatures $T^{t+\Delta t}$ after time step Δt are calculated by solving equations involving nodal Biot number and nodal Fourier number, with an initial assumed value of h_p at the solid-liquid interface. Thus, total heat transferred to the particle is estimated for the entire time the particle spends in the holding tube, keeping the time step as per the stability requirement (Chang and Toledo 1989) and keeping the mesh size as small as possible (Haberman 1983).

The thermal destruction of bacteria is a 1st-order reaction described as follows:

$$\frac{dN}{dt} = -\ln \frac{10}{D} N \quad (4)$$

where N is the viable number at the time t and D is the decimal reduction time.

Temperature dependence of D value is described by:

$$D = D_0 10^{(T_0 - T)/z} \quad (5)$$

where D is the decimal reduction time at temperature T, D_0 is the decimal reduction time at reference temperature T_0 and z is the temperature change required to change D value by a factor of 10. The z-value is dependent on activation energy and temperature as shown in Eq. 6:

$$z = \frac{\ln(10)}{E_a / R} T.T_0 \quad (6)$$

where Ea is reaction activation energy.

The temperature dependence of D-value in terms of activation energy is as follows:

$$\frac{D}{D_0} = [e]^{\frac{E_a}{R}\left[\frac{1}{T} - \frac{1}{T_0}\right]} \quad (7)$$

The value of h_p was determined by the iterative technique described by 1st assuming h_p, calculating the temperature history, calculating survivors using microbial decay equation, and selecting the value of h_p for which calculated and experimental values match. The microbial decay equation was integrated with time and volume using the temperature predictions from the explicit finite difference heat transfer model. Using this indirect approach for calculating h_p utilizing microorganisms as time-temperature integrators (TTI), we calculated the decay of live vegetative cells of *Bacillus stearothermophilus* immobilized in gellan cubes. Despite the limitations of natural variability of biological markers, this method is most suitable for the present experimental system in which a stream of particles is introduced in holding tube assembly having bends and elbows. Furthermore, the method actually measures microbial inactivation, the ultimate objective of sterilization process, thus this method is considered adequate for comparing the 2 configurations.

Test organisms

The bacterial culture *B. stearothermophilus* (NCA 1518) was obtained from the American Type Culture Collection (Rockville, Md., U.S.A.). Bacteria were grown in test tubes with 7 mL of nutrient broth (Difco Laboratories, Detroit, Mich., U.S.A.) at 55 °C for 12 h. From this suspension, 15 mL was transferred to a 250-mL flask containing 150 mL of nutrient broth and incubated for 12 h at 55 °C on a shaker. After the incubation period, the flask was removed and cooled to 5 °C. The suspension was centrifuged (5000 × *g* for 5 min), and the cells were resuspended in 10 mL of nutrient broth.

Preparation of inoculated gellan cubes

A medium containing 2% gellan gum, KelcoGel-F (Kelco Div. of Merck & Co, Inc., Rahway, N.J., U.S.A.), 8% nutrient broth, 0.2% dextrose dissolved in 130 mL of distilled water and 20 mL of phosphate buffer (7.1 pH) was prepared. About 30 mL of glass beads were added to the flask containing the medium and autoclaved. In another flask, 300 mL of solution containing 0.25% $CaCl_2$ and 0.1% peptone (Difco) in distilled water was prepared, autoclaved, and allowed to cool to room temperature. The autoclaved gellan medium was cooled to 57 °C in a water bath. The suspension containing the test bacteria was slowly added to this medium while the flask was continuously shaken. The mixture was vigorously agitated by hand for about 30 s and allowed to stand at 57 °C until all the foam had collapsed. Use of thermophilic bacteria allowed mixing the gellan at this high temperature when the viscosity of gellan was low, which resulted in a test sample (gellan cube) with uniform bacterial population density.

A stainless-steel mold subdivided into multiple sections with the proper cube dimensions was flamed and placed on a glass sheet. The gellan medium inoculated with the bacteria was quickly poured into the mold and allowed to cool to room temperature and solidify. After 10 min, the cold sterile $CaCl_2$ solution was slowly poured on the mold to speed up firming of the gellan cubes. After about 15 min, the cubes were pushed out of the mold, transferred in cold $CaCl_2$ solution, and stored for 4 h at 4 °C. It was observed that the absorption of calcium ions lowered the pH of the cubes to an extent that bacteria did not survive in the cubes. This problem was overcome by addition of phosphate buffer solution to the medium during the preparation as described earlier. The final pH of the test cube was 6.75. The cubes were then suspended in a flask containing nutrient broth and used within 2 to 4 h. The cubes were firm enough to remain intact during the thermal treatment and yet soft enough to crush for recovering viable organisms. The 9.8-mm Gellan cubes had a density of 1012 kg/m^3 and mass of 0.965 (±0.005) g. The cubes had an average bacterial population of 7.84 Log_{10} colony-forming units (CFU)/g. The cubes were tested for uniformity of bacterial population throughout the cube volume by taking samples from the surface portion and core portion. No spatial variation in the bacterial population density was observed in the test cubes. Bacterial population remained nearly constant for a period of 48 h under refrigeration. However, for each experimental run, a fresh batch of gellan cubes was used to minimize any change in thermal resistance.

Experimental setup

The experimental setup (Figure 1) consisted of a holding tube of

aluminum alloy (NCHT), fluid delivery and recycling pump, and a system for introducing particles without disrupting the flow. The entire holding tube assembly had 3 straight runs of 2400 mm each with 2 U-bends. Cross section of NCHT is shown in Figure 2. NCHT was installed such that the wider side (xx′) was horizontally oriented. The noncircular cross section had inner dimensions of 18 × 107 mm and had a cross sectional area equivalent to that of a 2-inch nominal size sanitary tube. The hydraulic diameter for NCHT was 32 mm. The entire holding tube was insulated. The 3 straight sections were connected with 4 90° elbows. For comparison purpose, experiments were also conducted using a conventional holding tube (CHT). The CHT consisted of a 2-inch nominal size (40.49-mm inner dia) stainless-steel tube with 2 180° horizontal U-bends. The holding tubes were sloped upward with a slope of 20 mm per 1000 mm straight length. The total volumes for NCHT and CHT were 13.7 L and 14.7 L, respectively.

A positive displacement pump (St. Regis-CP Div., Chicago, Ill., U.S.A.) delivered hot water from an insulated reservoir. A plate heat exchanger continuously heated and maintained the water in the reservoir at the desired temperature. A return line collected hot water from the outlet of the holding tube, and water was pumped back into the reservoir. Water temperature was measured at the inlet and outlet of the holding tube by T-type thermocouples. The temperatures were recorded by a data acquisition board (OMD-5508TC, OMEGA Engineering, Inc, Stanford, Conn., U.S.A.) installed in a personal computer.

Food systems containing solid particles are complex because the particles may be of varying size and shape and may have different physicochemical properties. The h_p is a function of these variables as well as the carrier fluid properties and shape and orientation of the holding tube. The objective of the present study was to compare heat transfer coefficients in 2 geometries of the holding tube cross sections. For this purpose, determination of h_p around a single solid test cube traveling along with a stream of spherical particles was considered adequate. Spherical polystyrene particles (Precision Plastic Balls Co, Franklin Park, Ill., U.S.A.) were used to simulate the suspended particulates in a food system. The spheres had a diameter of 9.5 mm, and the density ranged from 1035 to 1039 kg/m^3. The plastic spheres were fed at the entrance to the holding tube through an opening in the tube. With water as carrier fluid, the hydraulic pressure in the holding tube was not very high and could be easily countered by a short column of water in vertical section at the injection port in the tube. A rotary valve with adjustable RPM was used to feed the holding tube with particulates at the desired rate through the vertical column.

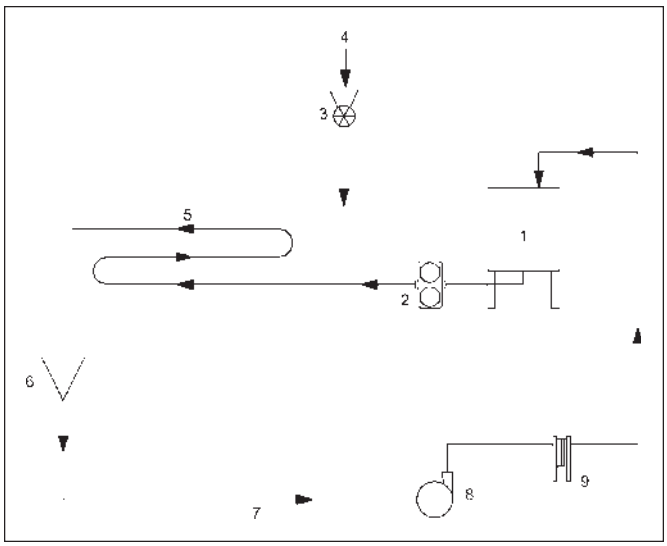

Figure 1—Experimental setup for study heat transfer coefficients in holding tubes (1 = feed tank; 2 = feed pump; 3 = rotary valve; 4 = solids feed; 5 = holding tube; 6 = collecting hopper; 7 = return line; 8 = return pump; 9 = plate heat exchanger)

Experimental procedure

Observations were taken for flow rates of 8.5 and 10.5 L/min, temperatures of 75 °C and 77 °C, and particulate concentrations of 2%, 3%, and 4%. The absence of appropriate containment to hold pressure prevented measurement above 100 °C. Above 80 °C, severe flashing and system instability were encountered; therefore, our tests were conducted below 80 °C. After fluid temperature had stabilized at the desired measurement temperature, about 200 spheres were fed followed by 1 inoculated gellan cube through the injection port. About 400 more spheres were fed at the same rate immediately after the injection of the gellan cube. The retention time for the gellan cube in the holding tube was measured by replaying in a slow motion video recording of stream of fluid and solids exiting the holding tube. The inoculated cube leaving the holding tube was immediately transferred to a flask containing 99 mL sterilized peptone water maintained at 7 °C and well stirred for 1 min. The flasks with the inoculated cube were immediately transferred to a refrigerator and stored at 4 °C for 4 h. Refrigerated storage of cubes for 4 h had no effect on the recovery of viable cells.

Enumeration of viable cells in samples

The cubes were ground in a test tube with 20 mL of the peptone water in which they were stored. A small homogenizer (Omni mixture 17105, Omni Intl., Waterbury, Conn., U.S.A.) was used to grind the gellan cubes. The homogenizer tip was rinsed frequently with the remaining peptone water, and the contents were poured back into the flask and stirred well. The homogenizer tip was washed several times with sterile distilled water after each sample was ground. The cubes were ground at 4000 rpm for 30 s to disperse the surviving cells. Required serial dilutions were made and 5 drops of 20 μL each of the dilution were surface-plated on nutrient agar. The plates were incubated at 55 °C for 12 h. Small but clearly defined colonies were formed after 12 h, which could be easily counted. Longer incubation did not increase the colony count.

Determination of D and Z values

Isothermal holding experiments were carried out to determine D-values for *B. stearothermophilus* in gellan cube. D-values were experimentally determined at 74 °C and 75 °C. These D-values were plotted against temperatures on a semi log scale to determine Z-value for this range of temperature. Activation energy E_a was determined using Eq. 6. D-value at 77 °C could not be determined because of practical difficulties of sampling very small time intervals; therefore, heat treatments were done at 74 °C and 75 °C. D-value at 77 °C was estimated by Eq. 7 using E_a value calculated.

Glass capillaries (Kimex–51, 100-mm length, 1.5-mm inner dia, and 1.8-mm outer dia) were filled with the test material by stabbing into the inoculated gellan cube. The thin cylinder of gellan thus formed was pushed further in the capillary with a sterile steel rod to the center. The ends of the tube were heat-sealed with gas flame. The samples were weighed and numbered. The tubes were 1st heated to 60 °C for 2 min and quickly immersed into an ethyl glycol bath (Brinker Instruments, K-2/RD, Lauda, Germany) maintained at required temperature within ±0.1 °C. At preset time intervals, the tubes were removed in sequence and quickly transferred in ice bath. The heat-treated tubes were kept under refrigeration for 4 h, after which their ends were broken under aseptic conditions and

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the contents were emptied into a tube containing 20 mL of sterile peptone water. The contents were ground and analyzed for surviving bacteria as described previously for gellan cubes.

Determination of heat transfer coefficient (h_p)

The explicit finite difference model (Chang and Toledo 1989) was used to estimate the effective h_p for each particle in the holding tube. The cubical test sample was divided in 9 × 9 × 9 equally spaced nodes, and a time step of 0.1 s was used for calculation.

Thermal conductivity of the gellan was measured using a line heat source probe (Gratzek and Toledo 1993), and specific heat was estimated using the Choi and Okos (1987) formula. Variations in these properties with changing temperature of the gellan cube were taken into account in the computation of h_p. Retention times recorded for each cube and a cooling time of 1 min were used as input. A very high value of h_p value was considered for the cooling process in the flask. The nodal temperature predictions and lethality was calculated using a computer program written in C (Borland C++, Version 4.0, Scotts Valley, Calif., U.S.A.). Heat transfer coefficients were determined iteratively by comparing model-predicted survivor level with the actually observed level. Fluid temperature decrease of 1.2 °C to 1.5 °C along the length of the holding tube occurred. This was due to the heat loss to the environment and heat exchange with the suspended solids. The fluid temperature was assumed to vary linearly from the inlet to outlet temperature along the length of the holding tube. The pipe Reynolds number was calculated at the mean of inlet and outlet temperatures based on average velocity of fluid and hydraulic diameter of the holding tube. Relative velocity of the particle was calculated by taking the ratio of the average velocity of particle in the tube to that of fluid. Average velocity of particle was calculated by dividing the length of the holding tube by retention time of particle.

Results and Discussion

D and Z value determination

The D values for *B. stearothermophilus* in Gellan cubes at 74 °C and 75 °C were found to be 23 s and 12.1 s, respectively. The z-value was observed to be about 3.55 °C. From these values, activation energy was calculated using the Arrhenius equation and used to calculate the D-value at 77 °C of 3.31 s.

Estimated heat transfer coefficients

Heat transfer coefficients varied from 365 to 2700 W/m^2.K in the NCHT and 326 to 1834 W/m^2.K in the CHT. The flow rates were 8.5 and 10.5 L/min, which corresponded to Reynolds numbers ranging from 6300 to 12750. The h_p values at different flow rates and temperatures for both holding tubes are shown in Figure 3.

Six replications were made for each treatment. Mean values of h_p are shown in Table 1. Nusselt number ranged from 20 to 120 for NCHT and from 20 to 100 for CHT. In general, h_p values were significantly higher ($P < 0.05$) in NCHT than in CHT. At lower flow rate and temperature, h_p values in NCHT were generally 25% higher but at higher flow rates and temperatures, the values were 55% higher than in CHT. No significant difference in h_p was observed at different particulate concentration levels studied. On the other hand, significant difference was observed for flow rates and processing temperature, with h_p values increasing with increasing flow rates and temperatures. Previous studies (Sastry and others 1990; Zuritz and others 1990; Mwangi and others 1993; Balasubramaniam and Sastry 1994a, 1994b; Cacace and others 1994; Zitoun and Sastry 1994a, 1994b; Balasubramaniam and Sastry 1996) reported increasing levels of h_p with increase in the flow rate. In yet another study, (Gratzek 1994) no such correlations were reported. For our data, plots of flow rates expressed as pipe Reynolds number against h_p showed significant correlations with R^2 values of 0.74 and 0.82, respectively, for CHT and NCHT (Figure 4). However, there was no correlation between fluid to particle relative velocity and h_p for both tube configurations investigated (Figure 5). One possible reason for this observation could be that the relative velocity, calculated as an average value based on particle velocity and fluid velocity, does not adequately describe conditions around the particle along its travel through the holding tube. The pipe Reynolds number, on the other hand, probably has some significant bearing on the overall movement of the particle in the fluid and hence on the h_p.

The h_p values of 2180 to 7870 W/m^2.K have been reported for the Reynolds number range of 5250 to 50000 (Heppel 1985); 688 to 3005 W/m^2.K for the Reynolds number range of 7300 to 43600 (Sastry and others 1990); and 986 to 2270 W/m^2.K for the Reynolds number range of 2174 to 10422 (Balasubramaniam and Sastry 1994a). Cacace and others (1994) have reported h_p values of 300 to 2000 W/m^2.K for potato cubes containing yeast cells in NaCl solutions under turbulent flow conditions. Gratzek (1994) reported h_p values of 500 to 1250 W/m^2.K for a Reynolds number range of 5000 to 18500 for gellan cube in water. A rigorous comparison of these values is not possible because of differences in particle size, particle to tube diameter ratio, type of

Table 1—Mean heat transfer coefficient (h_p) values for holding tubes with noncircular cross section and circular cross section[a]

Temp (°C)	Flow (L/min)	h_p (W/m^2 K), NCHT Particle concentration (%) 2	3	4	h_p (W/m^2 K), CHT Particle concentration (%) 2	3	4
75	8.5	500	430	600	360	410	430
75	10.5	1520	1410	1700	930	790	1340
77	8.5	950	860	930	560	620	470
77	10.5	2300	2470	2500	1540	1480	1700

[a]NCHT = holding tube with noncircular cross section.
[b]CHT = holding tube with circular cross section.

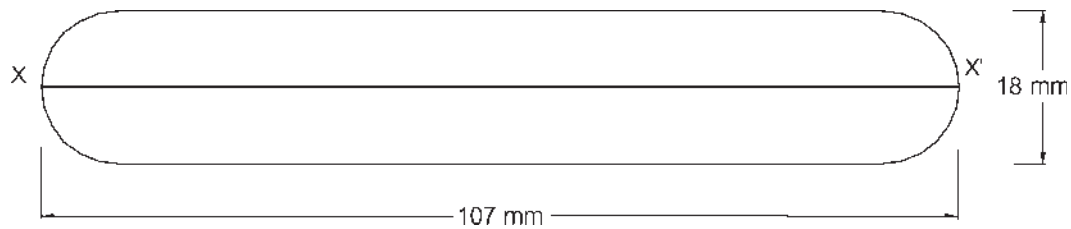

Figure 2—Noncircular cross section of the holding tube

fluid, and temperature in these earlier studies. Furthermore, in all reported work, a single particle in a flowing stream of fluid has been investigated, whereas we used a stream of particulates at a defined concentration along with 1 gellan cube as the test particle.

Our values fall within the bulk of reported values of h_p; however, some trends are notable. Heat transfer coefficient values at lower flow rates were lower than most values reported at comparable Reynolds numbers. It was evident from viewing the exiting particles that at the lower flow rates, the test particles usually traveled along with the rest of the plastic spheres. The plastic spheres and the test particles were not totally neutrally buoyant in the surrounding fluid used in these tests. Whether a particle slides along the bottom of the tube or remains entrained and moves along with the stream depends on the resultant of the gravitational force on the particle and fluid drag forces. It is possible that the gravitational effect could be higher in this case, and particle tended to slide along the bottom wall as it traveled through the tube. Another reason for the low h_p at lower flow rate is that the particle may have been surrounded by other suspended particles. In such circumstances, the water temperature near the cube could be much lower than the fluid bulk due to the heat exchange between the suspending fluid and particles. Thus, a lower value of h_p would be calculated if the bulk mean fluid temperature was used in the calculation. Furthermore, particles moving along the bottom wall would move slower than those particles moving in the main stream. Values of h_p with corresponding particle retention time in the tube are plotted in Figure 6 for CHT and NCHT. These plots show that particles moving slowly (longer residence time) had low h_p values. Similar trend was also observed by Gratzek (1994).

The h_p values at higher flow rates for CHT were within the range reported (Sastry and others 1990; Cacace and others 1994) but were in the upper end of the range. At high flow rates, fluid drag forces overcame gravitational forces and traveled in the main stream rather than the bottom of the tube. The particles in such situations would behave like obstructions causing "Bernouli" or "channeling" type effects, which increase the relative velocity around the particles and the h_p (Zitoun and Sastry 1994a,b). We found an increase in h_p with increasing flow rate to be higher, possibly because of additional increase in the relative velocity developed by the presence of many particles in the stream.

The present model did not account for the possible incursion of water to the particle as pointed out by Gratzek (1994). We used an operating temperatures lower than normally used in aseptic processing; therefore, elevated pressures were not present. However, our main objective was to compare the h_p values for 2 configurations of the holding tubes under the same set of conditions. We found that h_p values to be 28% to 62% higher in NCHT than in CHT in spite of about 36% lower Reynolds number in NCHT at the same volumetric rate of flow. A study of the fastest particle velocity and velocity profile for both holding tube cross sections (Christie and others 2005) had shown that velocity sharply increased from zero at the walls to very close to a maximum a very short distance away from the side walls. The geometry of the NCHT probably allowed the particles to travel in the main fluid stream. Even in the laminar flow in NCHT, a particle may experience significant velocity gradients over its surface, causing it to either rotate or slide along the wall increasing relative velocity and hence the h_p value (Zitoun and Sastry 1994a). Variations in particle trajectory in the holding tube have been responsible for the differences in h_p values within replications in experiments involving turbulent flow regimes (Sastry and others 1990). It is possible that in the case of CHT, the particle, which is known not to follow a specific path along the entire tube length, traveled through regions where the h_p is likely to vary significantly, thereby lowering the average h_p value. In NCHT, on the other hand, the spatial variation in h_p was minimized because of a more uniform velocity distribution. In turbulent flow, the geometry of NCHT is such that particles travel closer to the wall than in CHT. It can be expected that the particles obstruct the fluid flow, causing acceleration of fluid around the particle, and increase the fluid relative velocity around the particle, thereby increasing the h_p value. These results indicate that probably the particle interactions significantly influence the heat transfer phenom-

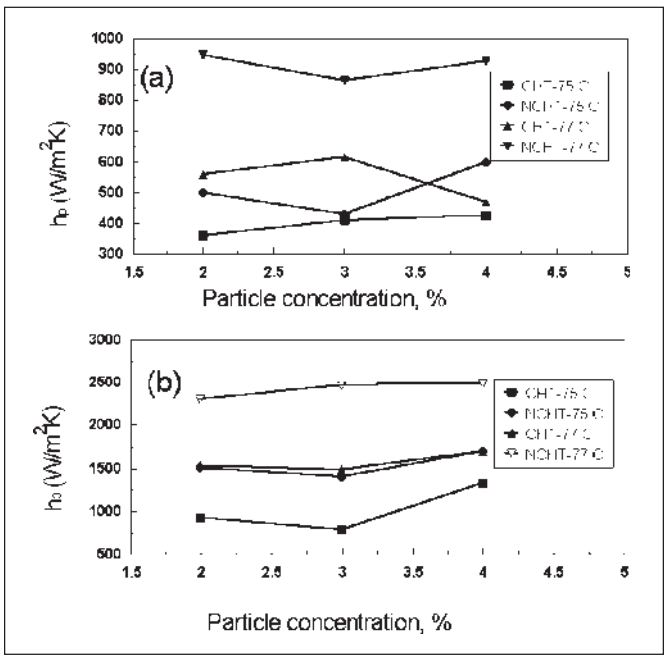

Figure 3—Heat transfer coefficients and particle concentration at flow rates of (a) 8.5 L/min and (b) 10.5 L/min

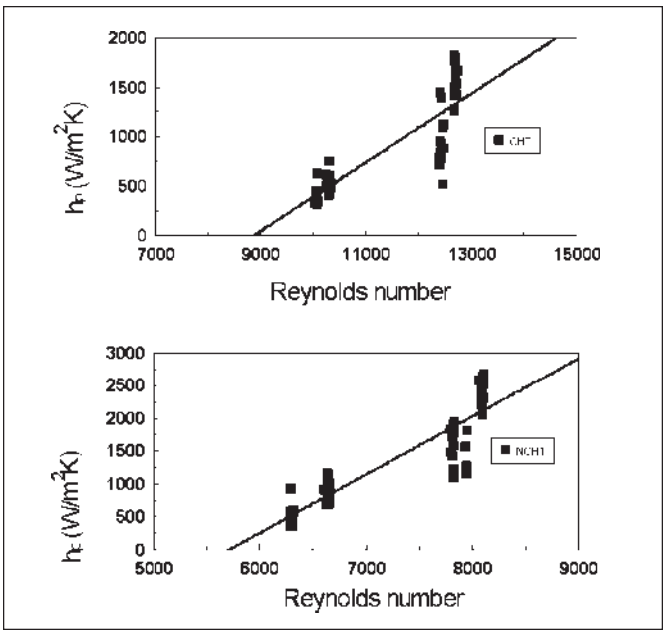

Figure 4—Heat transfer coefficient (h_p) and Reynolds number for (a) circular cross section (CHT) and (b) noncircular cross section (NCHT)

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enon in the holding tube and more studies are needed, especially at higher temperatures, particle concentrations, and fluid viscosities.

Christie (1997) have shown that the maximum to average velocity ratio in NCHT was lower than that in CHT with flatter velocity profile than in CHT. This, together with higher h_p values in NCHT, would mean that the particles would heat faster and receive more uniform heat treatment than in CHT. This will be true especially for particles in which surface convection rather than conduction within the solid governs the heating rate. Even in ohmic heating systems, the more uniform residence time distribution in NCHT may likely improve uniformity of product heating.

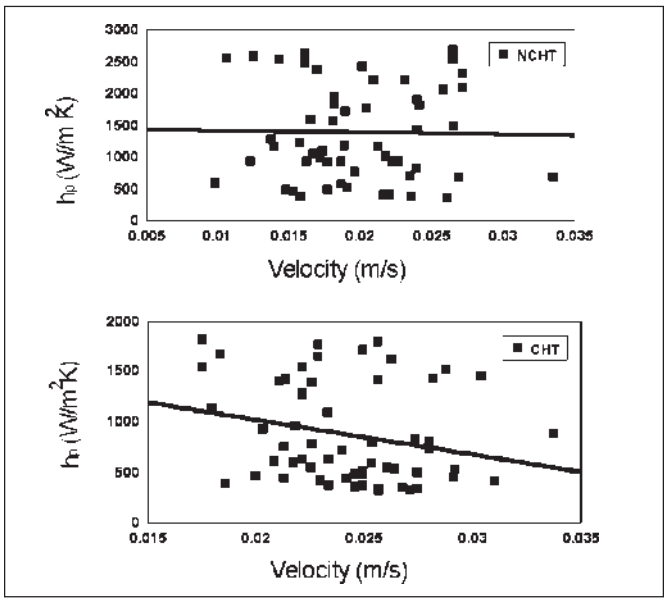

Figure 5—Heat transfer coefficient and relative velocity for (a) noncircular cross section (NCHT) and (b) circular cross ction (CHT)

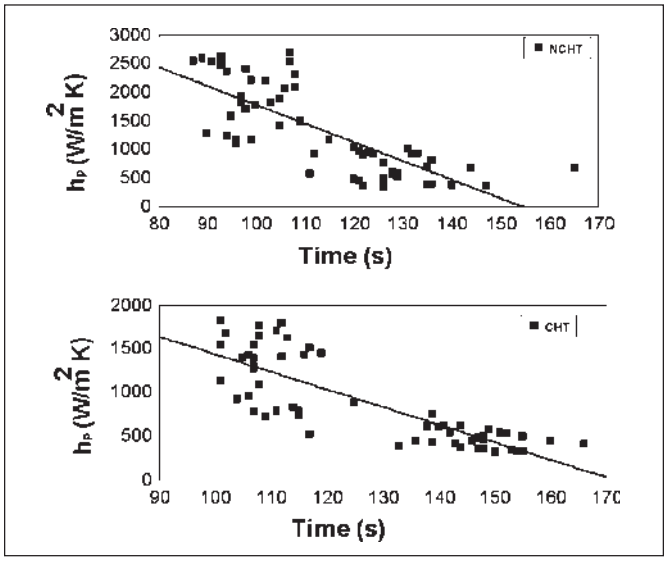

Figure 6—Heat transfer coefficient(h_p) and retention time for (a) noncircular cross section (NCHT) and (b) circular cross section (CHT)

Conclusions

The holding tube having noncircular cross section induced higher fluid-to-particle h_p values than in a conventional cylindrical holding tube; although the Reynolds number was lower in the former. The difference was small at low flow rates and temperature but markedly larger at the higher flow rate and temperature. At low flow rates, the value of h_p was low possibly because of the influence of interactions with other particles. On the other hand, at high flow rates, h_p increased dramatically because of large relative velocities around the particle surface induced by the other particles. Significant correlation was observed between the pipe Reynolds number and h_p values. No such relation was observed for the fluid-to-particle relative velocities on fluid flow rate and measured particle residence time. Because of higher rates of heat transfer in NCHT, this holding tube configuration deserves consideration in aseptic processing systems.

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