THE UNIVERSITY OF MANITOBA

DETERMINATION OF FLUID-TO-PARTICLE HEAT TRANSFER COEFFICIENTS IN EXPERIMENTAL ASEPTIC PROCESSING SYSTEMS

by

Gaurav Tewari

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DETERMINATION OF FLUID-TO-PARTICLE HEAT TRANSFER COEFFICIENTS IN EXPERIMENTAL ASEPTIC PROCESSING SYSTEMS

BY

GAURAV TEWARI

A Thesis/Practicum submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

DEDICATED TO

MY MUMMY

ABSTRACT

Aseptic processing of liquid foods with particulates is one of the most promising thermal processing techniques because it ensures improved product quality, low energy consumption, and reduced waste generation. Mathematical models of aseptic process schedules require the knowledge of fluid-to-particle heat transfer coefficient (h_{fp}). Fluid-to-particle heat transfer coefficient was determined experimentally during flow of fluid over one or more particles. The effects of different process parameters (e.g. particle-particle interaction, carrier fluid viscosity, carrier fluid temperature, and flow rate) on h_{fp} were quantified. The h_{fp} value for the sample particle (silicone sphere) decreased when individual particles at different orientations (0°, 30°, 45°, and 60°) were introduced upstream whereas h_{fp} value increased significantly (ANOVA $p \leq 0.0001$) from 154 to 176 $W \bullet m^{-2} \bullet K^{-1}$ when multiple particles were introduced upstream of the sample particle. The h_{fp} value decreased from 176 to 54 $W \bullet m^{-2} \bullet K^{-1}$ with an increase in carrier fluid viscosity from $0.4 x 10^{-3}$ to $33.3 x 10^{-3}$ $Pa \bullet s$. The h_{fp} values increased from 49 to 202 $W \bullet m^{-2} \bullet K^{-1}$ and 53 to 94 $W \bullet m^{-2} \bullet K^{-1}$ with an increase in carrier fluid temperature (from 60° to 80°C) and flow rate (from 0.27×10^{-3} to 2.82×10^{-3} m^3/s), respectively. The results of this study can be used for the development of models of aseptic processing schedules in multiparticulate liquid systems.

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1. INTRODUCTION

Sterilization of canned foods is essential to ensure safety to the consumer by assuring destruction of microbial growth. Thermal processing of canned foods is an important technique for achieving commercial sterilization of canned foods, therefore heat transfer in canned food systems has been a matter of interest to researchers. During heating of foods, microbial destruction is also accompanied by nutrient degradation, which is of particular concern to the process designer. This problem can be overcome by using high-temperature-short-time (HTST) processes for sterilization of canned foods as these processes ensure quality retention because of minimization of nutrient degradation and maintenance of degree of sterilization (Stoforos 1988). Agitation of canned liquid foods (with or without particulates) results in high heat transfer rates. Thermal processes with high heat transfer rates from heating source to the food result in better quality (Ball and Olson 1957). Retort method (traditional method of sterilization) and aseptic method are two thermal processing techniques for commercial sterilization of canned foods. Convection is the main mode of heat transfer between heat source and fluid; and also at fluid-particle interface, during these thermal processing techniques.

The traditional method of sterilization of food i.e. retort method, involves sterilization after filling of food in a can. This results in many problems such as the low rate of heat penetration to the slowest heating point in the container, the long processing time required to deliver the required lethality, destruction of the nutritional and sensory characteristics of the food, low productivity, and high energy costs (Ball and Olson 1957, Smith et al. 1990, Ramaswamy et al. 1995). To overcome these problems, interest is increasing in the application of aseptic processing technology which involves sterilization of food and packages separately. Many researchers (Heppell 1985; Chandarana et al. 1990; Stoforos and Merson 1991; Ganesan et al. 1992; Maesmans et al. 1992; Balasubramaniam and Sastry 1994a, 1994b, 1994c, 1996a, 1996b; Zitoun and Sastry 1994) are trying to extend this technology to liquid foods with particulates. The fluid surrounding the particles is heated by convection from an outside heat source. Convection also takes place at the fluid-particle interface, while heat is accumulated into the particles by conduction.

The major hurdle to be overcome in the use of aseptic processing technology for liquid foods with particulates is the assurance of microbiological safety of the product. Microbial and enzyme activation are heat induced, therefore activity in the food product will depend on the thermal history of each component during the sterilization process (Chang and Toledo 1989). Determination of aseptic process schedules is rather complicated because of the difficulties involved in accurate measurement of temperature within particles moving with a flowing fluid in a closed system under pressure. For this reason, mathematical modelling of heat transfer is necessary for the process design, which requires the knowledge of convective fluid-to-particle heat transfer coefficient (h_{fp}) as an input parameter (Clark 1978). Unfortunately, the determination of h_{fp} is a difficult exercise because of difficulty in monitoring time-temperature data within a particle. Due to scarcity of data, U.S. Food and Drug Administration has agreed to use conservative but realistic values of h_{fp}, to improve product quality without sacrificing safety (Pflug et al. 1990). Extensive research has been done in aseptic processing of liquid foods with particulates (Heppell 1985; Chandarana et al. 1990; Stoforos and Merson 1991; Ganesan et al. 1992; Maesmans et al. 1992; Balasubramaniam and Sastry 1994a, 1994b, 1994c, 1996a, 1996b; Zitoun and Sastry 1994) to determine h_{fp}, by using different techniques to monitor time-temperature data (Sastry 1990). The published literature in the field of aseptic processing of liquid foods with particulates relates to the determination of h_{fp} using single particle, whereas commercial aseptic processing technique consists of multiparticulate system and presence of other particles may significantly affect h_{fp} (Bhamidipati and Singh 1994). Therefore, the main objectives of this research were:

1. to determine h_{fp} for a single particle using stationary particle technique (Sastry 1990, Balasubramaniam and Sastry 1994c),
2. to determine h_{fp} for a single particle in a multiparticulate system incorporating the effect of different orientations of particles on h_{fp}, and
3. to determine the effects of process parameters such as carrier fluid viscosity, carrier fluid temperature, and flow rate on h_{fp}.

2. REVIEW OF LITERATURE

2.1 Retort Method: Liquid Filled Can

2.1.1 Mathematical model of heat transfer

Under the assumption that temperature of fluid surrounding a can is uniform, an energy balance for liquid inside the can yields (Stoforos 1988):

$$hA_c(T_m - T_f) = m_f C_{pf} \frac{dT_f}{dt} \qquad (1)$$

where h = overall heat transfer coefficient between the external medium and the internal liquid, if T_m is temperature of heating medium (K) or internal heat transfer coefficient between the can wall and inside liquid, if T_m is temperature of the inside can wall ($W{\bullet}m^{-2}{\bullet}K^{-1}$),

A_c = total can surface area (m^2),

T_f = temperature of liquid inside the can at time t (K),

m_f = mass of liquid inside the can (kg),

C_{pf} = specific heat of liquid inside the can ($J{\bullet}kg^{-1}{\bullet}K^{-1}$), and

t = time (s).

Equation (1) is used to determine h during retort processing of liquid filled cans.

2.1.2 Effect of mode of rotation

In retort method, cans filled with liquid food are heated by a heating medium (water or steam) for commercial sterilization. Conley et al. (1951) reported the impact of rotation of cans on increase of heat transfer rates and the resulting decrease of sterilization times. Many researchers (Tsurkerman et al. 1971, Quast and Siozawa 1974, Naveh and Kopelman 1980, Anantheswaran and Rao 1985) studied the effect of mode of rotation (axial and end-over-end) on heat transfer coefficients. Quast and Siozawa 1974, Tsurkerman et al. 1971 working with Newtonian fluids (sucrose solutions) and non-Newtonian fluids (carboxylmethylcellulose), reported that heat transfer rates for cans being axially rotated were 2 to 4 times the rates for stationary processing.

Naveh and Kopelman (1980) used specially constructed brass cylindrical cans (filled with glucose syrup) for heat transfer experiments. They examined the effect of end-over-end (Fig. 2.1) and axial rotation on overall heat transfer coefficient and reported two to three times greater overall heat transfer coefficient for end-over-end rotation than for axial rotation. The end-over-end rotation involves rotation of the central axis of the can around an axis perpendicular to the central axis of the can i.e. end-over-end agitation is the motion imparted to a can when one end is in contact with the circumference of a revolving drum (Conley et. al 1951).

Quast and Siozawa (1974) reported that there was no significant effect of reversing the direction of rotation on heat transfer rates, whereas Hotani and Mihori (1983) reported that reversing the direction of rotation every 15 to 45 s (from clockwise to anticlockwise or vice-versa) resulted in higher heat transfer rates and more uniform heating. Hotani and Mihori (1983) conducted their tests when the fluid was at less than 70°C which may have caused different heat transfer rates because parameters affecting heating characteristics are generally more dominant at early stages of heating when fluid temperature gradients are high. Quast and Siozawa (1974) made observations during later stages of heating when fluid temperature reached 96°C.

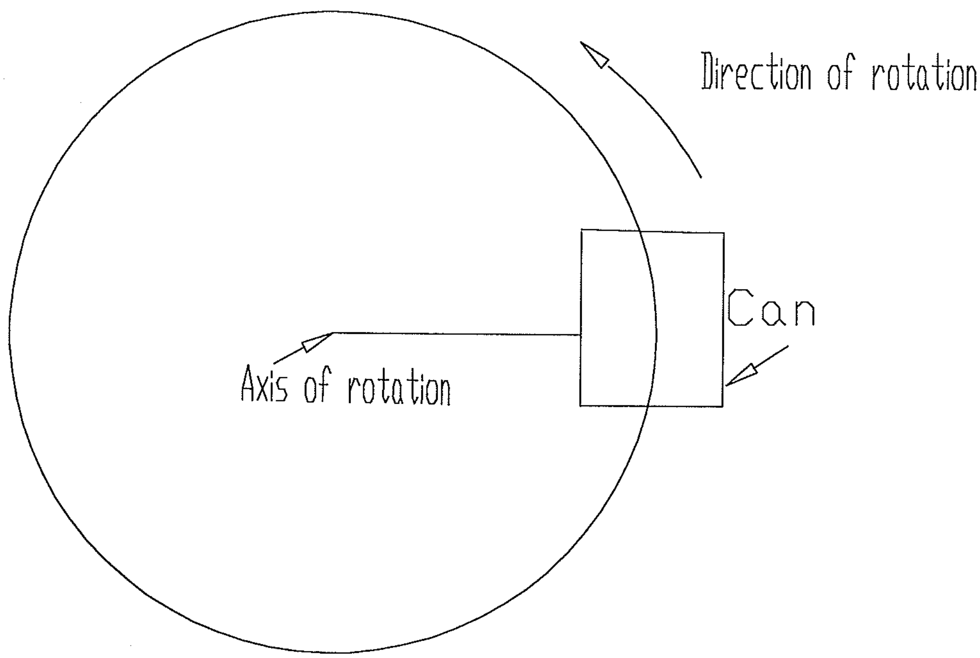

Fig. 2.1 Schematic diagram of the end-over-end rotation of can (Source: Conley et al. 1951).

Anantheswaran and Rao (1985) also studied the effect of end-over-end rotation on heat transfer rates to Newtonian fluids in two copper cans (length to diameter ratio of 0.73 and 1.37) over the range of 0-39 rpm and 0-15 cm radius of rotation. The test fluids were distilled water, aqueous sucrose solutions, and glycerine. A laboratory agitating sterilizer was used for heat transfer studies. Steam at atmospheric pressure (100.6 kPa) was used as the heating medium. They reported that end-over-end rotation of the cans improved the heat transfer rates to the test fluids by 49 to 79%. The above results are attributed to the fact that the more vigorous the mixing, the higher the fluid velocity and thus higher heat transfer rates.

2.1.3 Effect of rotational speed

Clifcorn et al. (1950) performed experiments by rotating a can containing liquid at different speeds to obtain maximum rate of heat penetration. They found that selection of proper speed may give more turbulence within the can contents and thus high heat transfer rates. They calculated the optimal rotational speed by using the formula $RN^2 = 35\ 196$ (centrifugal force = gravity force), where R is the distance from axis of rotation to the centre of can's contents, and N is the speed of rotation. They used tomato pulp of varying viscosities and reported that optimum rotational speed is a function of fluid viscosity and concluded that for more viscous fluids, the rotational speed should be decreased to achieve optimum conditions. Conley et al. (1951) reported that as the speed of rotation increases beyond the optimum, the centrifugal forces create a decrease in the mobility of the contents and thus decrease the heat transfer rates.

Naveh and Kopelman (1980) reported that increasing the rotational speed (0 to 120 rpm) resulted in a continuous increase of the overall heat transfer coefficient during heating processes, whereas asymptotic values of heat transfer coefficient were obtained with cans agitating at relatively low speeds of 40-70 rpm during cooling phase. Their experiments were carried out on transparent plexiglass cylinders filled with glucose solutions of varying viscosities (0.012-1.8 Pa•s). They attributed their observations to the fact that viscosity of liquid is higher during cooling phase compared to that during heating (Clifcorn et al. 1950 made their observations during cooling phase). These studies (Clifcorn et al. 1950, Conley et al. 1951, Naveh and Kopelman 1980) were conducted using Newtonian fluids. Anantheswaran and Rao (1985) working with non-Newtonian fluids (aqueous guar gum solutions) found that the overall heat transfer coefficients continuously increased with an increase in rotational speed from 0 to 38.5 rpm. The above observations can be attributed to the fact that the more the agitation, the higher the heat transfer rates.

2.1.4 Effect of distance between can and axis of rotation

Clifcorn et al. (1950) reported that the distance between the centre of a can and the axis of rotation affects the rate of heating. Conley et. al (1951) studied the effect of speed of rotation on the cooling rate of a can containing 6:1 orange concentrate when cooled from 96°C to 38°C in 21°C water and reported that the optimum speed of rotation was dependent on the distance between the bottom of can and the axis of rotation.

Naveh and Kopelman (1980) reported an increase in overall heat transfer coefficient when rotating cans moved from central to off-centre axis of rotation. Anantheswaran and Rao (1985) studied the effect of distance between the centre of can and the axis of rotation on the heat transfer rates with 60% sucrose solution during the end-over-end rotation and reported that there is no significant effect of this distance on heat transfer rates, but their investigation was based on limited range of distance between the centre of can and the axis of rotation (0 to 14.9 cm). In a commercial end-over-end agitating retort, the heating rates were independent of distance between the centre of can and the axis of rotation (Anonymous 1983).

2.1.5 Effect of headspace

Headspace volume (total volume of can minus volume of the can filled with liquid) is one of the important factors that influences the heat transfer rates during processing of rotating canned liquids. Quast and Siozawa (1974) found that the overall heat transfer coefficient increased significantly with an increase in headspace for viscous fluids, but it decreased slightly for fluids with low viscosity. This can be attributed to the fact that less headspace in more viscous fluids means less agitation of rotating fluids and thus results in low heat transfer coefficient. Naveh and Kopelman (1980) reported that the overall heat transfer coefficient approached a constant value with increasing headspace volume (2-3% of total internal can volume).

Anantheswaran and Rao (1985) reported that headspace volume between 3 and 9% did not affect the heat transfer rates. Berry and Kohnhorst (1985) studied the effect of headspace on heat transfer rates by performing tests on commercial cans filled with homogeneous, milk based concentrate. A multistage preheat process that increased the product temperature in steps was used in this investigation. After heating to 123.9°C for less than 1 min, the cans were cooled rapidly by spraying water at the top. They reported that agitation of the product was enhanced by the presence of headspace. Decreasing headspace resulted in lower heat transfer rates. They also pointed out that the headspace effects were more significant for more viscous products (15×10^{-3} Pa•s).

2.1.6 Effect of fluid viscosity

Fluid viscosity is the most important parameter affecting heat transfer coefficient. The effect of viscosity on heat transfer coefficient appears in correlation equations among Nusselt, Reynolds, and Prandtl numbers (Ranz and Marshall 1952, Kramers 1946, Whitaker 1972, Anantheswaran and Rao 1985).

Quast and Siozawa (1974) reported that heat transfer increased for decreasing viscosities. Many other researchers (Anantheswaran and Rao 1985, Peralta and Merson 1983, Rao et al. 1985) also found similar results. This can be explained by the fact that more viscous fluids result in less agitation because of restriction of flow and thus low heat transfer rates.

2.2 Retort Method: Liquid Foods with Particulate

2.2.1 Mathematical model of heat transfer

An energy balance on the can contents yields (Stoforos 1988):

$$U_o A_c (T_{st} - T_f) = m_f C_{pf} \frac{dT_f}{dt} + m_p C_{pp} \frac{dT_p}{dt} \qquad (2)$$

where U_o = overall heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$),

T_{st} = temperature of the heating medium (steam) (K),

T_p = temperature of particle (K),

m_p = mass of particles inside the can (kg), and

C_{pp} = specific heat of particles inside the can ($J \cdot kg^{-1} \cdot K^{-1}$).

Boundary condition at the particle surface is (Stoforos 1988):

$$m_p C_{pp} \frac{dT_p}{dt} = h_{fp} A_p (T_f - T_p) \qquad (3)$$

where h_{fp} = fluid-to-particle heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$), and

Ap = surface area of particle (m^2).

Equations (2) and (3) were used to determine U_o and h_{fp} during retort processing of liquid foods with particulates.

2.2.2 Effect of mode of rotation

Lekwauwa and Hayakawa (1986) determined h_{fp} for spherical potato particles in water during end-over-end rotation. They compared the measured time-temperature profile at the centre of a potato particle with the predicted profile using a computer model, developed to simulate thermal responses of a packaged liquid-solid food, and determined h_{fp} values between 60 and 2613 $W \cdot m^{-2} \cdot K^{-1}$.

Chang and Toledo (1990) determined h_{fp} by measuring time-temperature history at the centre of a 2 cm potato cube heated at 75°C in a stationary retort and found h_{fp} value of 400 $W \cdot m^{-2} \cdot K^{-1}$. Weng et al. (1991) also determined h_{fp} from water to spherical polyacetal and nylon particle (2 cm diameter) in static retort and found h_{fp} value of 103 $W \cdot m^{-2} \cdot K^{-1}$.

2.2.3 Effect of rotational speed

The heat transfer coefficient increases with an increase in can rotational speed (Lenz and Lund 1978, Hassan 1984, Deniston et al. 1987). Lenz and Lund (1978) studied heat transfer and lethality in canned-liquid foods (water or 60% sucrose solution) containing particles processed in an agitated retort at a steam temperature of 121°C. Fluid-to-particle heat transfer coefficient was determined for spherical lead particles, immobilized at the centre of a rotating can. Changing the rotational speed from 3.5 to 8 rpm resulted in an average increase of h_{fp} by 150 $W{\bullet}m^{-2}{\bullet}K^{-1}$.

Hassan (1984) studied heating of potatoes, Teflon, and aluminum spheres in deionized water and silicone fluids of various kinematic viscosities (1.5×10^{-6}, 50×10^{-6}, and 350×10^{-6} m^2/s at 25°C) in a single can rotating axially. He reported that varying the can rotational speed (9.3- 101 rpm) had negligible effect on h_{fp} than on the overall heat transfer coefficient. He was unable to explain the reason behind this negligible effect.

Deniston et al. (1987) determined heat transfer rates to steam-heated, axially rotating cans containing potato spheres in water. They attributed the insensitivity of h_{fp} to can rotational speed (9.3-101 rpm) to three experimental conditions resulting in small change in relative particle-fluid velocity: 1) closeness of density of potato particle (1063 kg/m^3) to that of water, so that particle settling due to gravity was minimal, 2) because the particle was located at the can centre, centrifugal force acting on it was small, and 3) stiffness of the thermocouple wire hindered the particle motion.

Stoforos (1988) reported that increasing the rotational speed resulted in higher h_{fp} as long as the increasing rpm affected the relative particle-to-fluid velocity. At high rotational speed (100 rpm), the can contents in his experiments behaved as a solid body due to centrifugal forces and he found tremendous drop in h_{fp} (from 2071 to 410 $W \cdot m^{-2} \cdot K^{-1}$) when Teflon particles heated in silicone fluid at about 50°C were rotated at 100 rpm instead of at 54.5 rpm.

2.2.4 Effect of fluid viscosity

Lenz and Lund (1978) found lower h_{fp} for particles processed in a 60% aqueous sucrose solution than for solids processed in water. Hassan (1984) reported that the overall heat transfer coefficient (U_o) and h_{fp} decreased as the fluid viscosity increased. He demonstrated that under equal processing conditions, U_o and h_{fp} to Teflon particles were lowered when more viscous fluids (silicone oils of kinematic viscosities 1.5×10^{-6}, 50×10^{-6}, and 350×10^{-6} m^2/s) were used instead of water. The same pattern was observed for aluminum particles. Stoforos (1988) reported a decrease in U_o and h_{fp} with increasing fluid viscosity (from water to silicone oils). This can be attributed to the fact that more viscous fluids result in less agitation i.e. low particle-to-fluid relative velocity and thus low heat transfer.

2.2.5 Effect of particle interaction

The presence of particulate matter during agitated processing alters the flow pattern of pure fluid (Rao and Anantheswaran 1988). The amount of solid in the can influences the relative particle-to-fluid velocity and thus heat transfer rates.

Lenz and Lund (1978) added food (peas, carrot, or radish) particles of equal diameter to the test system containing lead spheres and simulated more closely velocities and interactions of particles and fluids under real processing conditions and reported no significant effect on h_{fp}. They immobilized particles in the rotating cans which might have caused particle to particle interaction different from what may be expected under real processing condition. They reported a decrease in U_o for liquid with particles. They attributed this to the decreased relative particle-to-fluid velocity due to the drag exerted on fluid by the particles.

Deniston et al. (1987) reported slight increase in h_{fp} with increasing particle volume fraction and lowering of h_{fp} value for higher particle contents. They attributed this to the tight packing in the can (higher particle volume fraction), which restricted the particle free movement. Stoforos (1988) mentioned that the mixing effect by moving particles contributes to a homogeneous temperature distribution in the can, especially for highly viscous products.

2.2.6 Effect of particle properties

Fluid-to-particle heat transfer coefficient will remain unaffected by the "type of particle" as long as the specific properties of particle under study (such as density or surface roughness) do not affect the particle-fluid pattern. When particles are allowed to move freely in the can, their different densities can influence their behaviour in the fluid and thus result in different h_{fp} values. Hassan (1984) found higher h_{fp} for potato than for Teflon particles processed in water. Also, Teflon particles exhibited higher h_{fp} than aluminum particles of the same size, when processed in silicone fluids. Stoforos (1988) also reported similar results. He attributed this to high thermal diffusivity of the aluminum particles which resulted in faster heat conduction in the aluminum particles as compared to Teflon particles.

2.2.7 Effect of particle-size

Lenz and Lund (1978) and Hassan (1984) studied the effect of different sizes (2.22 to 3.49 cm) of potato, Teflon, and aluminum spheres on heat transfer coefficients. They reported an increase in both U_o and h_{fp} with an increase in particle diameter for particles heated in water. Also, Lekwauwa and Hayakawa (1986) reported higher h_{fp} values with an increase in particle size (from 0.89 to 2.30 cm). They also reported that temperature difference between fluid and particles increased as the particle-size increased. Deniston et al. (1987) reported that potato particle size (2.22, 2.86, or 3.5 cm diameter) did not influence the h_{fp}.

2.3 Importance of Fluid-to-Particle Heat Transfer Coefficient and Different Techniques Used For its Determination

Aseptic processing is currently of great interest to the food industry because of its advantages over in-container sterilized foods, pasteurized chilled foods, frozen, or dehydrated foods. It ensures improved product quality, low energy consumption, and reduction in waste generation (environment friendly). De Ruyter and Brunet (1973) developed a mathematical model for a food product containing spherical particles processed in a swept-surface heat exchanger system. Their model assumes an infinite convective heat transfer coefficient at the particle-fluid interface.

Manson and Cullen (1974) developed a thermal process simulation model for aseptic processing of foods containing cylindrical particles (assuming an infinite heat transfer coefficient). They incorporated the residence time distribution (Singh and Lee 1990, Ramaswamy et al. 1995) in the model and reported that an increase in ratio of assumed heat exchanger residence time to bulk average residence time from 0 to 1.0 decreases the probable number of survivors per container from 230.0 to 2.8×10^{-18}. Sawada and Merson (1985) developed a model for particulate sterilization using water fluidized beds. Sastry (1986) developed a model for aseptic processing of particulate foods which considered the effects of particle-size, residence time distribution, and estimated values of convective coefficients, while being applicable to particles of regular and irregular shapes. He assumed a Nusselt number of 2.0 in the simulation, i.e. finite h_{fp}.

The models for the aseptic processing of particulate foods require h_{fp} as an input parameter. Determination of h_{fp} requires time-temperature data. Monitoring time-temperature data in a particulate food system is quite difficult because of difficulty in measuring surface or centre temperature of moving particles. To monitor time-temperature data, researchers (Heppell 1985; Chandarana et al. 1988, 1990; Stoforos and Merson 1991; Ganesan et al. 1992; Balasubramaniam and Sastry 1994a, 1994b, 1994c, 1996a, 1996b; Zitoun and Sastry 1994) have used many techniques which can be broadly classified as stationary particle method or moving particle method. Stationary particle method involves placement of a particle with an implanted temperature transducer in a flowing fluid stream and measurement of particle and fluid temperatures during the experiment. Moving particle method involves monitoring time-temperature data of a particle as it moves though a holding tube using different approaches e.g. microbiological indicator method, moving thermocouple method, melting point method, temperature-pill method, liquid crystal method. The h_{fp} is then determined by a suitable heat transfer model (Sastry 1990).

2.3.1 Stationary particle method

Chang and Toledo (1989) used this technique to determine h_{fp} and developed a simulation model for temperature distribution within a solid (sweet potato cut into 3.8 cm cube) undergoing transient heating with isothermal boundary condition (constant fluid temperature). They also modified the model to account for changing boundary conditions i.e. to simulate temperature in a suspended solid when fluid temperature changes and initial particle temperature is nonuniform. They placed the sweet potato cube in a model system with continuously flowing water at constant temperature (75°C). Their model system consisted of the stationary "sweet potato cube" fitted with a thermocouple and the fluid pumped from a water bath at a constant temperature (75°C). They reported h_{fp} value of 303 $W \cdot m^{-2} \cdot K^{-1}$ for "sweet potato cube" in water. They also simulated particle heating and microbial and enzyme inactivation in nonisothermal holding tubes and concluded that the higher the preheat temperature the smaller the temperature rise required to reach a level where rapid microbial and enzyme inactivation occurs. Their model system was not similar to a real aseptic processing system where a heat exchanger heats up the fluid to aseptic processing temperature (>120°C) and the flow profile of the heated fluid is also different. Their experiments were performed on a single particle and effects of different parameters such as fluid temperature and particle-particle interaction on h_{fp} were not examined.

Zuritz et al. (1990) determined h_{fp} for mushroom-shaped aluminum castings immersed in a power-law pseudoplastic fluid (sodium carboxylmethylcellulose). Their setup consisted of a 0.16 m^3 capacity steam-jacketed kettle equipped with motor-driven blades and a positive displacement pump with variable speed motor to control the fluid flow rate. The process temperature was maintained at 71°C. The mushroom particle was mounted on the end of a 4.5 cm diameter, 95 mm long glass tube and located axially in a 50 mm diameter, 1.5 m long transparent plexiglass tube. They reported h_{fp} values between 548 and 1175 $W{\bullet}m^{-2}{\bullet}K^{-1}$ for ranges of particle size (20.65 to 28.17 mm) and fluid flow (0.089 to 0.267 kg/s). They examined the effect of flow rate and particle size on h_{fp} but failed to maintain the flow profile in the test-section because the thermocouple (connected to the particle's centre) was inserted into the processing tube through a rubber stopper fitted into the test-section, which would have affected the flow profile (no specifications such as projection of rubber stopper in the tube, distance of stopper from the particle, were given in the paper to judge the extent of problem caused by this). Also, the processing temperature was 71°C whereas aseptic processing temperatures are above 120°C.

Chandarana et al. (1990) determined h_{fp} for six specially constructed silicone cubes, immobilized in a process simulator which consisted of a 14.7 cm diameter cylindrical stainless steel chamber. The test fluids (2-3% starch solution and water) were heated to 129.4°C (aseptic processing temperature). They found values of h_{fp} between 65 and 107 $W{\bullet}m^{-2}{\bullet}K^{-1}$ for water and between 56 and 89 $W{\bullet}m^{-2}{\bullet}K^{-1}$ for starch solution. They were the first to predict h_{fp} in a multiparticulate system and examined the effect of flow rate and fluid viscosity on h_{fp}, but failed to examine the effect of particle-particle interaction on h_{fp} as silicone particles were immobilized in different chambers having no interaction with each other.

Awuah et al. (1995) used the stationary particle method to evaluate h_{fp} by two analytical methods (rate and ratio methods) from transient time-temperature data obtained from regular objects (sphere and infinite cylinder made from Nylon, polypropylene, polymethylmethacrylate, and Teflon). The rate method was based on heating rate at any given location while the ratio method was based on the ratio of temperature gradient at two locations. The two methods were compared in an aseptic processing unit (Ramaswamy et al. 1992) using food grade 1% CMC solution as the carrier fluid at 100°C at a volumetric flow rate of 1.85×10^{-5} m^3/s. Awuah et al. (1995) reported that depending on the ambient condition, test-particle type, size, and shape, h_{fp} values ranged between 15 and 420 $W \bullet m^{-2} \bullet K^{-1}$ and concluded that the rate method gave more consistent and conservative h_{fp} than the ratio method.

The experiments using the stationary particle method are comparatively easy to perform and are adaptable to aseptic processing temperature and opaque fluid media. However, the flow fields are not necessarily similar to true flow field surrounding a particle in a tube or heat exchanger flow (Sastry 1990).

2.3.2 Moving particle method

2.3.2.1 Microbiological indicators

In the microbiological indicator method, a test microorganism is inoculated within test particles (typically alginate) and the particles are processed in a continuous heat-hold-cool system. The particles containing spores are retrieved and the survivors are enumerated.

Hunter (1972) was the first to use this approach to estimate h_{fp} in aseptic processing of liquid foods with particulates. He used Bacillus anthracis as the microbiological indicator and determined h_{fp} values (using Heisler charts) in the range of 1750-2808 $W \cdot m^{-2} \cdot K^{-1}$ for Reynolds number in the range of 40 700 to 42 900. Heppell (1985) also estimated h_{fp} values by measuring the destruction of microbiological spores of Bacillus stearothermophilus immobilized in 3.1 mm diameter alginate particles in a continuous heat-hold-cool system. The mean values of h_{fp} ranged from 2180 to 7870 $W \cdot m^{-2} \cdot K^{-1}$ for Reynolds number in the range of 5250 to 50 000. Weng et al. (1991) used an immobilized peroxidase in dodecane as the microbiological indicator and estimated h_{fp} by using finite difference method to solve heat transfer equation with boundary condition of variable temperature for particles.

The microbiological indicator method does not require transparent carriers. In this method, there are uncertainties involved in: (a) monitoring unique time-temperature profile, (b) placing the indicator within the particle, and (c) relation to biological variation. This approach, however, is best suited to biological validation of a thermal process i.e. to determine the biological changes within the test particles (Sastry 1990).

2.3.2.2 Moving thermocouple method

Sastry et al. (1989) were the first to use this approach to determine h_{fp} in an aseptic processing system. The experimental procedure involved the introduction of a specially constructed metal-transducer particle (hollow aluminum sphere of diameter 0.0239 m and density 1006 kg/m^3) from the upstream of the test section. As particle flowed through the test section, its temperature was measured using a thermocouple wire attached to the particle from the downstream end. The matching of particle and thermocouple velocities was accomplished by measuring velocities of unattached particle beforehand using photoelectric sensors, and adjusting a motor to the appropriate speed to provide automated withdrawal of thermocouple. Newton's law of heating (valid for Biot number <0.1), was used to calculate the h_{fp}:

$$\ln\frac{(T_p-T_f)}{(T_i-T_f)}=-h_{fp}\frac{A_p t}{m_p C_{pp}} \tag{4}$$

where T_i = initial particle-surface temperature (K).

They reported h_{fp} values in the range of 2039 to 2507 $W{\bullet}m^{-2}{\bullet}K^{-1}$ for different experimental conditions. Sastry et al. (1990) also used the same approach to examine the effect of flow rate and particle-size on the h_{fp}.

Balasubramaniam and Sastry (1994a) also used this approach (with some modification) to determine h_{fp}. In their study, thermocouple-attached particle was introduced from the upstream end instead of pulling it from the downstream end. This modification reduced the time involved in matching velocities of thermocouple-attached particle to that of a free particle. They reported h_{fp} values in the range of 363 to 1522 $W{\bullet}m^{-2}{\bullet}K^{-1}$ for different experimental conditions.

The advantages of this method are: 1) rapid and accurate temperature measurement is possible using carefully calibrated thermocouple, 2) the method is adaptable to opaque carriers, and, 3) the method is adaptable to high pressures and temperatures. The presence of thermocouple interferes with particle motion resulting in a conservative h_{fp}. These difficulties are likely to be greatly increased for a multiparticle system with particles having random motion throughout the processing fluid (Sastry 1990).

2.3.2.3 **Time-temperature integrator (TTI)**

A time-temperature integrator (TTI) is a small device that shows a time-temperature dependent and an irreversible change that imitates the changes of a quality parameter undergoing the same variable temperature exposure (Balasubramaniam and Sastry 1994c). Maesmans et al. (1992) studied the use of TTI for the estimation of h_{fp} values. They concluded that all integrator systems e.g. microbiological, enzymic, will require proper calibration of the response of TTI in any carrier material (real food or model food system) and under specific processing conditions.

The main advantage of time-temperature-integrator (TTI) method is that it does not require transparent carriers and, therefore, can be used under opaque conditions. The main disadvantages of TTI method are: 1) uncertainties involved in monitoring unique time-temperature profile for the determination of h_{fp} and in monitoring temperature gradients, and 2) non-adaptability to real aseptic processing system because much experimentation is required for its proper calibration for different processing conditions (Balasubramaniam and Sastry 1994c).

2.3.2.4 **Thermal memory cell**

A thermal memory cell consists of a metal oxide semiconductor (MOS) and a capacitive sensor. It uses the change in concentration of metal ions (determined by the measurement of charge of metal ions as they move across MOS and an equivalent point method (EPM) to determine the equivalent time and equivalent temperature of the process (Balasubramaniam and Sastry 1994c). Ganesan et al. (1992) determined lethality values

(Ball and Olson 1957) for several combinations of time-temperature curves in the isothermal hold temperature range of 120 to 150°C. This method is complicated and is not easily adaptable to aseptic processing system.

2.3.2.5 **Melting point indicator**

The melting points of certain polymers are indicated by changes in colors at their melting points. Therefore, polymers of various melting points within transparent particles can be used, and the time-temperature data can be obtained (Balasubramaniam and Sastry 1994c). The heat transfer coefficient can then be calculated from the time-temperature data for different particles.

Mwangi et al. (1993) estimated h_{fp} values of polymethyl methacrylate particles of 8.0, 9.6, and 12.7 mm diameter, suspended in a glycerine-water mixture. The melting point indicators in the temperature range of 52-79°C were placed inside the particles by making spherical cavities inside the particles. A scraped surface heat exchanger was used to heat the fluid. They reported h_{fp} values in the range of 58-1301 $W \bullet m^{-2} \bullet K^{-1}$ over the Reynolds numbers of 73 to 370. They also determined the effect of flow rate and particle size on h_{fp} but did not determine the effect of particle-particle interaction on h_{fp}.

The main disadvantage of the melting point indicator method is that it is limited to transparent fluids whereas in the food industry opaque conditions are prevalent. Also, an accurate estimation of the location of temperature indicator within a particle is difficult and complex mathematical models are needed for determination of h_{fp}.

2.3.2.6 Temperature pill method

A temperature pill is a remote electronic temperature sensor. It uses a quartz crystal as the temperature sensing element, which resonates at a temperature-dependent frequency and invokes a coil circuit and thus generates a magnetic signal (Balasubramaniam and Sastry 1996 b). An external receiver converts the magnetic signal back to a temperature reading. The temperature history of a particle (with the temperature pill installed inside) can be monitored as it moves through a test section by moving an external antenna along with the particle.

Balasubramaniam and Sastry (1996b) used this technique to monitor the temperature at the centre of a cylindrical particle as it moved through a test section. A finite element algorithm was used to calculate h_{fp} from the time-temperature data.

The main advantage of the temperature pill sensor is that it can be used for noninvasive monitoring of particle temperature at a selected location (point) and the data from temperature pill method represent local (at the selected location) heat transfer coefficients. The temperature pill sensor, in its present form cannot be used under UHT process temperatures, because quartz crystals (used in temperature pill sensor) cannot withstand a high temperature (121-130°C).

2.3.2.7 Liquid crystal method

Liquid crystal is a chemical compound which changes its color in response to surface temperature changes due to rearrangement of molecular structure (Cooper et al. 1975, Balasubramaniam and Sastry 1995). On heating, liquid crystal materials turn from colourless to red (27°C) to green (37°C) and then to blue (45°C) with increasing temperatures (25-45°C) (Stoforos 1988). By calibrating the color-temperature response of the liquid crystal material against a standard temperature sensor, it is possible to determine the temperature of a liquid-crystal coated surface (Balasubramaniam and Sastry 1994c).

The specific gravity of the liquid crystal capsule is about 1.02 and hence the capsules are nearly buoyant and can be easily coated on a simulated food particle. Only a small amount of 0.01-0.02% by mass is needed for good visualization (Moffat 1990). Stoforos and Merson (1991) used selected colors from the Munsell scale as standards for the calibration and estimated h_{fp} for spherical particles in axially-rotating cylindrical vessels. They reported a h_{fp} value of 2326 $W \bullet m^{-2} \bullet K^{-1}$ for Teflon particles (2.54 cm) processed with deionized water in a cylinder rotating at 102 rpm.

There is always a possibility of error in judging the color, therefore, Balasubramaniam and Sastry (1994a) used an image analysis system for quantitative color measurement. They determined temperature history of a liquid crystal coated particle by videotaping and analyzing the color changes (defined by hue values) using an image analysis interface system and suitable software. Calibration was done by videotaping the surface color changes and recording the corresponding thermocouple readings simultaneously. They found a color-temperature relationship as:

$$T=25.3-0.2H+0.0007H^2 \qquad (5)$$

where H is the hue value.

The test fluid was an aqueous solution of sodium carboxylmethylcellulose. They also predicted the effect of particle size and flow rate on h_{fp}. They reported h_{fp} values in the range of 397 to 1630 $W \cdot m^{-2} \cdot K^{-1}$ for different experimental conditions. Because the liquid crystal used in the study had a working temperature range of 26-45°C, and the fluid was heated to 45°C, the equation is valid only under these test conditions. Also the liquid crystal has to be calibrated under in-situ conditions because proper calibration is necessary while using image analysis system for color-measurement.

Balasubramaniam and Sastry (1994b) also used the above approach to determine h_{fp} in flow of particle through a horizontal scraped surface heat exchanger. The color-temperature relationship for this system was:

$$T=29.5-0.07H+0.0012H^2 \qquad (6)$$

The liquid crystal used in the study had a working temperature range of 29-59.5°C, therefore, the above equation is valid only under these conditions.

Zitoun and Sastry (1994) were able to estimate the effect of particle radial location on h_{fp} using this method and gave color-temperature relation as:

$$T=3+0.3H \qquad (7)$$

They determined h_{fp} values in the range of 551 to 887 $W \cdot m^{-2} \cdot K^{-1}$ for cubic particles (made from aluminum sheet metal) in CMC fluid heated to 45°C at different experimental conditions of flow-rate, fluid viscosity, and particle-size.

Although experimental conditions were the same, three different calibration equations between temperature and hue were reported (Balasubramaniam and Sastry 1994a, 1994b; Zitoun and Sastry 1994) in the above studies. This points to the fact that at present there is no standard calibration procedures for colors in an image processing system. Colors obtained at same temperature could be different because of the differences in lighting chambers, types of light bulbs, color-temperature, and external environment (dust formation from the environment on the top of the light bulb). The performance of an image processing system depends on camera, frame-grabber, hardware used, and imaging background. The above studies were performed for low temperature range (<60°C) whereas aseptic processing temperatures are above 120°C. The above studies were performed on a single particle and effect of particle-particle interaction on h_{fp} was not examined.

Liquid crystal could help in understanding of heat transfer between fluid and the particle in continuous flow processes by providing mapping of solid surface temperature under these conditions. This method is useful for determining h_{fp} values in continuous flow through scraped-surface heat exchangers, where the conventional sensors such as thermocouple could not be used (Balasubramaniam and Sastry 1994c). The main disadvantages of this are: 1) it cannot be used for opaque fluids, 2) it cannot be used under UHT conditions, since the liquid crystal cannot be used above 115°C, and 3) color-calibration is a serious problem while using image analysis system for color-measurement.

2.3.2.8 Relative velocity method

The relative velocity method is a flow field visualization technique, to experimentally determine the relative velocity between fluid and particles. This is done by videotaping the motion of small fluid tracers and particles. The videotape is replayed at selected moments to determine the relative velocity by measuring the time elapsed for a selected tracer to pass over a particle. Values of h_{fp} are then calculated from relative velocity using empirical Nusselt number correlations reported by Ranz and Marshall (1952), Kramers (1946) and Whitaker (1972) (for Re>2x10^5), given by Eqs.(8)-(10), respectively (Balasubramaniam and Sastry 1994c):

$$Nu=2.0+0.6Re^{0.5}Pr^{0.33} \tag{8}$$

$$Nu=2.0+1.3Pr^{0.15}+0.66Pr^{0.31}Re^{0.5} \tag{9}$$

$$Nu=2.0+(0.4Re^{0.5}+0.06Re^{0.67})Pr^{0.4}\left(\frac{\mu_\infty}{\mu_0}\right)^{0.25} \tag{10}$$

where Nu = Nusselt number $((h_{fp}\ D)/k_f)$,

Re = Reynolds number $((\rho\ D\ v)/\mu_\infty)$,

Pr = Prandtl number $((\mu_\infty\ C_{pf})/k_f)$,

μ_∞ = viscosity evaluated at the free-stream temperature (Pa•s),

μ_0 = viscosity evaluated at the mean wall temperature (Pa•s),

D = diameter of particle (m),

v = particle-fluid relative velocity (m/s),

ρ = fluid-density (kg/m^3), and

k_f = thermal conductivity of fluid (W•m^{-1}•K^{-1}).

Balasubramaniam and Sastry (1994a) used this method to determine h_{fp} for aluminum spheres processed in CMC. Finely ground polystyrene particles ($\leq$ 1 mm) were used as tracers to visualize the flow field around the moving aluminum particle of 22.3

mm diameter. The aluminum particle was introduced from upstream and its motion was videotaped. The h_{fp} were calculated using Eqs. 8-10. The h_{fp} values ranged from 825 to 1063 $W \cdot m^{-2} \cdot K^{-1}$ for different experimental conditions.

Zitoun and Sastry (1994) also used this method to determine h_{fp} and were the first to examine the effect of radial location on h_{fp}. They used cubic particles, made from aluminum sheet metal. Due to the lack of a relationship similar to Eqs. 8-10 for cubic particles, they defined Nusselt number (Nu) as:

$$Nu = \frac{h_{fp} . L_p}{k_f} \tag{11}$$

where L_p = characteristic length of cube (diameter of a sphere having volume equivalent to the cube) (m).

The dimensionless correlations (Eqs. 8-10) are applicable only to spherical particles, therefore, some error may occur in the calculated h_{fp}. They reported h_{fp} values in the range of 287 to 1277 $W \cdot m^{-2} \cdot K^{-1}$ for their experimental conditions. The calculated h_{fp} values depended on the selection of an equation from Eqs. 8-10.

The main disadvantage of this method is that the relative velocity determination is based on translational velocity difference between particle and fluid, and does not consider the agitation caused by rotation. The applicability of the method lies in the effectiveness of the correlations used (Eqs. 8-10). Its principal utility lies in visualizing the complex flow profiles during continuous flow and verifying the results from other heat transfer based techniques. The method requires the production of high quality video images and post-processing of recorded images (Balasubramaniam and Sastry 1994c).

2.3.2.9 Transmitter particle technique

Bhamidipati and Singh (1994, 1995) were the first to use this technique for the determination of h_{fp} by continuously monitoring the particle centre temperature. The temperature sensor system consists of: 1) disposable sensors (transmitting particle, with a shape closest to that of a cylinder and of dimensions 22.6-mm (high) by 10.7-mm (diameter), and 2) an ambulatory receiver with cable and antenna coil. The antenna coil is moved along the outer surface of the tube as the sensor moves in the tube to determine sensor temperatures. The density and specific heat of the sensor had to be determined experimentally. The test fluid was CMC solution of 0.5-1.2% concentration in water. The fluid was heated to 82°C. They reported h_{fp} values in the range of 108 to 196 $W \cdot m^{-2} \cdot K^{-1}$ for the CMC concentrations of 0.5-1.2%. Their experiments were based on a single particle.

The main advantage of this technique is that there is no disturbance to the particle trajectories while particle temperature is measured. The major disadvantages are that the density of the transmitter particle is considerably higher than real food particles, complex modelling is required to adapt this technique to aseptic processing system, and monitoring temperature in a multiparticulate system is difficult.

2.4 Effects of Various Parameters on h_{fp}

2.4.1 Fluid viscosity

Fluid viscosity is an important factor affecting h_{fp}. Chandarana et al. (1990)

noticed that for silicone cubes, values of h_{fp} were higher (66 to 107 $W \cdot m^{-2} \cdot K^{-1}$) in water (Newtonian fluids) than in starch solutions (non-Newtonian fluids) under the same conditions (56 to 90 $W \cdot m^{-2} \cdot K^{-1}$). They concluded that h_{fp} increases with a decrease in fluid viscosity. Zuritz et al. (1990) also reported that h_{fp} increases from 548 to 1175 $W \cdot m^{-2} \cdot K^{-1}$ with a decrease in mean apparent viscosity from 11.84 to 2.08 Pa•s of the CMC solution in water.

Balasubramaniam and Sastry (1994a) used moving thermocouple, relative velocity, and liquid crystal methods to determine the effect of fluid viscosity on the h_{fp} using CMC solution as the test fluid. They reported that an increase in CMC concentration from 0.2 to 0.8%, decreases the h_{fp} values from 746 to 565 $W \cdot m^{-2} \cdot K^{-1}$, 825 to 765 $W \cdot m^{-2} \cdot K^{-1}$, and 1332 to 949 $W \cdot m^{-2} \cdot K^{-1}$ for moving thermocouple, relative velocity, and liquid crystal methods, respectively. From their findings it can be concluded that the effect of fluid viscosity on h_{fp} was more significant in the liquid crystal method.

Zitoun and Sastry (1994) also reported lower h_{fp} values (551-331 $W \cdot m^{-2} \cdot K^{-1}$) for higher concentration of CMC (0.2-0.8%) at a flow rate of 2.52 m^3/s. Similar pattern was observed for other flow rates (3.76 and 5.05 m^3/s). Bhamidipati and Singh (1994) also reported that the values of h_{fp} increased from 108 to 196 $W \cdot m^{-2} \cdot K^{-1}$ as CMC concentration decreased from 1.2 to 0.5%.

The above results can be attributed to the fact that higher fluid viscosity provides more resistance to fluid flow and thus decreases the relative particle-to-fluid velocity at the interface resulting in low h_{fp}. All of the above studies, except for Chandarana et al. (1990) were based on a single particle.

2.4.2 Flow rate

From the study of the traditional method of processing (retort method) of canned foods, it was concluded that high heat transfer rates are expected with higher flow rates (higher rotational speed in case of retort method), i.e. higher relative particle-to-fluid velocity. Therefore, many researchers studied the effect of flow rate on h_{fp} during aseptic processing of liquid foods with particulate.

Chang and Toledo (1989) reported an increase in h_{fp} values from 239 to 303 $W{\bullet}m^{-2}{\bullet}K^{-1}$ with an increase in relative velocity from 0 to 0.86 cm/s for sweet potato cube immersed in an isothermal (75°C) fluid (water and 35% sucrose solution). Sastry et al. (1989) also reported higher h_{fp} values (2039-2507 $W{\bullet}m^{-2}{\bullet}K^{-1}$) for higher flow rates (2.69×10^{-4}-6.68×10^{-4} m^3/s) for a hollow aluminum sphere processed in water.

Zuritz et al. (1990) investigated the effect of fluid flow rate on the h_{fp} from CMC solution to a stationary mushroom-shaped aluminum particle. They reported an increase in h_{fp} values from 548 to 1175 $W{\bullet}m^{-2}{\bullet}K^{-1}$ as fluid flow rate increased from 0.089 to 0.267 kg/s.

Mwangi et al. (1993) found the same trend for h_{fp} values with flow rates for polymethyl methacrylate particles suspended in solutions of glycerine in water. They found that h_{fp} values increased from 58 to 1301 $W{\bullet}m^{-2}{\bullet}K^{-1}$ for Reynolds number from 73 to 370. Balasubramaniam and Sastry (1994a) used moving thermocouple, relative velocity, and liquid crystal methods to determine the effect of flow rate on the h_{fp}. They found that an increase in flow rate from 2.21×10^{-4} to 5.05×10^{-4} m^3/s increased the h_{fp} values from 818 to 1138 $W{\bullet}m^{-2}{\bullet}K^{-1}$, 1166 to 1248 $W{\bullet}m^{-2}{\bullet}K^{-1}$, and 1240 to 1305

$W{\bullet}m^{-2}{\bullet}K^{-1}$ for aluminum spheres processed in CMC solution (0.5% concentration) using moving thermocouple, relative velocity, and liquid crystal methods, respectively. Similar trend was observed for other CMC concentrations (0.2 and 0.8%). The results show that moving thermocouple method has the most significant effect of fluid flow rate on the h_{fp}.

Zitoun and Sastry (1994) also reported that with increasing flow rates (2.52-5.05 m^3/s), the h_{fp} values increased (551-887 $W{\bullet}m^{-2}{\bullet}K^{-1}$), using CMC solution as the test fluid (0.2% concentration). Other concentrations of CMC (0.4 and 0.8%) also showed similar trends. The above results can be attributed to the fact that the higher the fluid flow rate, the higher the relative particle-fluid velocity and thus the higher the h_{fp}.

2.4.3 Particle-size

Particle-size is an important parameter which directly affects the penetration of heat into the particle from the surrounding fluid. Zuritz et al. (1990) reported an increase in h_{fp} (548-700 $W{\bullet}m^{-2}{\bullet}K^{-1}$) with an increase in mushroom-shaped aluminum particle dimension (2.06-2.82 cm equivalent spherical diameter) immersed in CMC solution flowing in a tube. Earlier, Chandarana et al. (1988) reported an increase in the h_{fp} values with a decrease in cube dimensions (2.5 to 1 cm cube). They attributed this to the fact that increasing the surface area to volume ratio enhances heat transfer. The contradiction between the results of these two studies may be due to the difference in their experimental setup. Zuritz et al. (1990) performed their experiments in a small tube (of realistic commercial dimension) whereas Chandarana et al. (1988) used a flow chamber where fluid pattern was not limited by the presence of tube wall and its size, and obtained results using classical heat transfer correlations (Eq. 9).

Mwangi et al. (1993) reported an increase in the h_{fp} with an increase in particle-size (8.0-12.7 mm) for Reynolds numbers 73-370. Balasubramaniam and Sastry (1994a) studied the effect of particle-size (22.3-12.8 mm) on the h_{fp} and reported that the results did not show any trend. They performed experiments in laminar flow and were unable to control the radial location of the particle, whose effect becomes significant under laminar flow. Zitoun and Sastry (1994) reported an increase in the h_{fp} with a decrease in particle size (11.9-11.7 mm) (they were able to control the radial location of the particle). Their study was also conducted in the laminar flow. Earlier Sastry et al. (1990) showed an increase in the h_{fp} with an increase in particle size. The differences between the two results can be explained by the difference in the flow pattern in the two studies i.e., turbulent in case of Sastry et al. (1990) and laminar in case of Zitoun and Sastry (1994). The effect of particle size in restricting the flow path is not as pronounced in the laminar flow as it is in the turbulent flow (Sastry et al. 1990). Also the contradiction between the two results (Mwangi et al. 1993 and Zitoun and Sastry 1994) can be attributed to the fact that radial location of particles was not controlled in the former study (Mwangi et al. 1993), which affects the flow pattern during laminar flow. All of the above studies were based on a single particle.

2.4.4 Particle radial location

Particle radial location varies depending on the difference in the density of fluid and particle and influences the h_{fp}. Zitoun and Sastry (1994), using liquid crystal method and flow visualization techniques, were able to determine the effect of particle radial location on the h_{fp}. They were able to explain the flow-behaviour when particle moves from centre to bottom of the tube. When the particle moved to the bottom, it experienced a significant velocity gradient on its surface because fluid surrounding the bottom of the particle moved slower than fluid at the centre of the tube. This may either rotate the particle or it may slide the particle against the tube-wall thereby increasing relative particle-fluid velocity and thus raise h_{fp}.

2.4.5 **Fluid temperature**

Fluid temperature is also an important parameter affecting the h_{fp}. Bhamidipati and Singh (1994) used transmitter particle technique to determine the h_{fp} and to examine the effect of fluid temperature on the h_{fp}. They reported an increase in the h_{fp} (109-196 $W \bullet m^{-2} \bullet K^{-1}$) as the fluid temperature was increased (22.2-82.2°C).

2.4.6 **Particle-particle interaction**

Particle-particle interaction has a significant effect on the h_{fp} because presence of particles changes the flow pattern which could affect the h_{fp}. Dutta and Sastry (1990a, 1990b) performed work on particle-particle interaction. They studied velocity distribution of model food particles (spherical with diameter 9.5 mm and made of polystyrene of density 1044.5 kg/m^3) suspended in CMC solutions. Their experimental setup consisted of a transparent holding tube through which model particles in CMC solution were pumped at room temperature and the particle motion was videotaped. They described the velocity distribution by a log normal distribution described by Lawless (1982) (cited by Dutta and Sastry 1990a). They observed that with increases in pump speed (100-140 rpm), particle concentration (0.2-0.8%), and CMC concentration (0.2-0.8%), the normalized fastest particle velocity increased. They noticed that axially located particles moved the fastest and those adjacent to the wall (either bottom or top) moved the slowest. They also observed that particles not only collided but also interacted hydrodynamically by an attraction-repulsion mechanism that appeared to be caused by pressure changes in the interparticle gap. Similar observation was made by Davis et al. (1986), who reported that a significant pressure pulse exists between particles approaching one another within a liquid. This may cause deformation of particles before collision. Dutta and Sastry (1990a, 1990b) also found that the nature of particle-particle interaction changed greatly with particle concentration because particle motion became highly restricted at high concentrations. They also noticed that some particles changed velocity during passage through the tube, depending upon the radial position and their interaction with other particles. They did not examine the effect of particle-particle interaction on the h_{fp} but velocity profiles of particles during aseptic processing of liquid foods with particulates was well defined in their study.

2.5 Summary

Two methods, the stationary particle method and moving particle method, have been used to monitor time-temperature data of particles to determine h_{fp} during aseptic processing of liquid foods with particulates. Published literature indicates that h_{fp} is affected by carrier fluid viscosity, flow rate, carrier fluid temperature, and particle radial location. Most of the studies were conducted using a single particle. Only a few researchers have attempted to study the effect of particle-particle interaction on h_{fp} in a multiparticulate system, which is a real aseptic processing condition.

Moving particle methods are not practical in a multiparticulate system but can be used for studying effects of different process parameters on h_{fp}. Stationary particle method can be easily adapted to a multiparticulate system but does not simulate the flow fields of a real system exactly. The thesis research was conducted to determine h_{fp} in a multiparticulate system incorporating the effect of particle-particle interaction on h_{fp} using the stationary particle method.

3. MATERIALS AND METHODS

3.1 Preparation of Sample

The silicone spheres (0.0127-m diameter) were fabricated using a specially designed mould (Fig. 3.1), made of Teflon. The mould was split in two halves, allowing the placement of a thermocouple and a fishing wire through it. The spheres were made from a silicone rubber compound (RTV11, General Electric, Waterford, NY) (Table 3.1), which was a two-part silicone material - a base compound (RTV11) and a curing agent (Dibutyl tin dilaurate(DBT)).

The RTV11 and DBT were mixed, as per the instructions given in the product data sheet (supplied by the manufacturer) in a mixing container 4-5 times larger than the volume of RTV11. Eight grams of RTV11 was weighed and an appropriate amount (two drops) of curing agent (Table 3.2) (0.5% DBT by mass) was added to it. The RTV11 and DBT were thoroughly mixed for about 5 min using a clean glass rod by scraping the sides and bottom of the container carefully to produce a homogeneous mixture. After mixing, a syringe was filled with the prepared mixture and was injected into the mould through a hole at the top of the mould. After 24 h, silicone sphere was removed out of the mould and was considered cured.

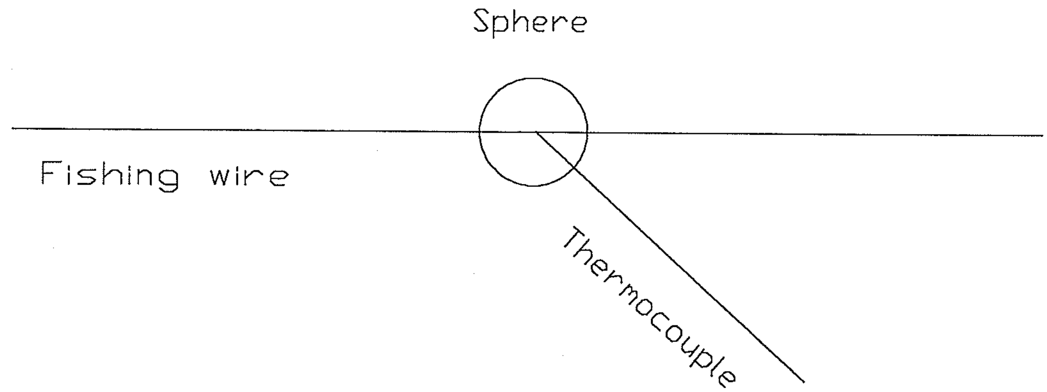

Fig.3.1 Sphere (0.0127-m diameter) with a thermocouple embedded at its centre.

Table 3.1. Properties of the silicone rubber base compound (RTV11, General Electric, Waterford, NY) with 0.5% Dibutyl tin dilaurate (DBT) curing agent.

Property	Value
Specific gravity	1.19
Useful temperature range (°C)	-54 to 204
Thermal conductivity (k) ($W \cdot m^{-1} \cdot K^{-1}$)	0.2926
Specific heat (C_p) ($J \cdot kg^{-1} \cdot K^{-1}$)	1463

Table 3.2. Measuring guide for the addition of the curing agent (General Electric, Waterford, NY).

RTV11 Mass (g)	Number of drops for two DBT Concentrations	
	0.1%	0.5%
100	5 drops	25 drops
454	23 drops	115 drops

3.2 Preparation of Carrier Fluid

Water or carboxymethylcellulose (CMC) (Cabiochem Corporation, La Jolla, CA) solutions at different concentrations (0.2 and 0.4%) were used as a carrier fluid. The CMC solutions were prepared in a tank equipped with a stirrer and a steam jacket. Measured amounts of CMC (400 and 800 g) were added to 200 L water at 65°C and the solution was stirred until CMC was mixed thoroughly as determined by visual inspection.

3.3 Experimental Setup

3.3.1 Experimental setup (a)

The experimental setup (a) consisted of a storage tank, centrifugal pump, plate type heat exchanger, high-temperature-short-time (HTST) controller, diversion valve, and processing tube (Fig. 3.2). A stainless steel storage tank (capacity 200 L) was used to store water. The centrifugal pump (Model N6124 FK11, Leeson Electric Co., Toronto, ON), pumped water from the storage tank to the plate type heat exchanger in a loop (Fig. 3.2).

The plate type heat exchanger (M/C 5383, Type HX, 696-895, APV, London, England) heated water to 73.6°C, which was forwarded to the processing tube. The HTST controller (Chart No. 324804-A12, Anderson Instrument Co. Inc., Fultonville, NY) was used to set the temperature of the carrier fluid at a fixed temperature. The diversion valve (Model 1-1/2" FD-7500-5-240 w/6, Alloy Products Corp., Waukesha, WI) allowed the forward flow of the carrier fluid to the processing tube when the temperature of the carrier fluid reached the set temperature.

The processing tube (0.046-m inner diameter and 0.9 m in length) was fabricated

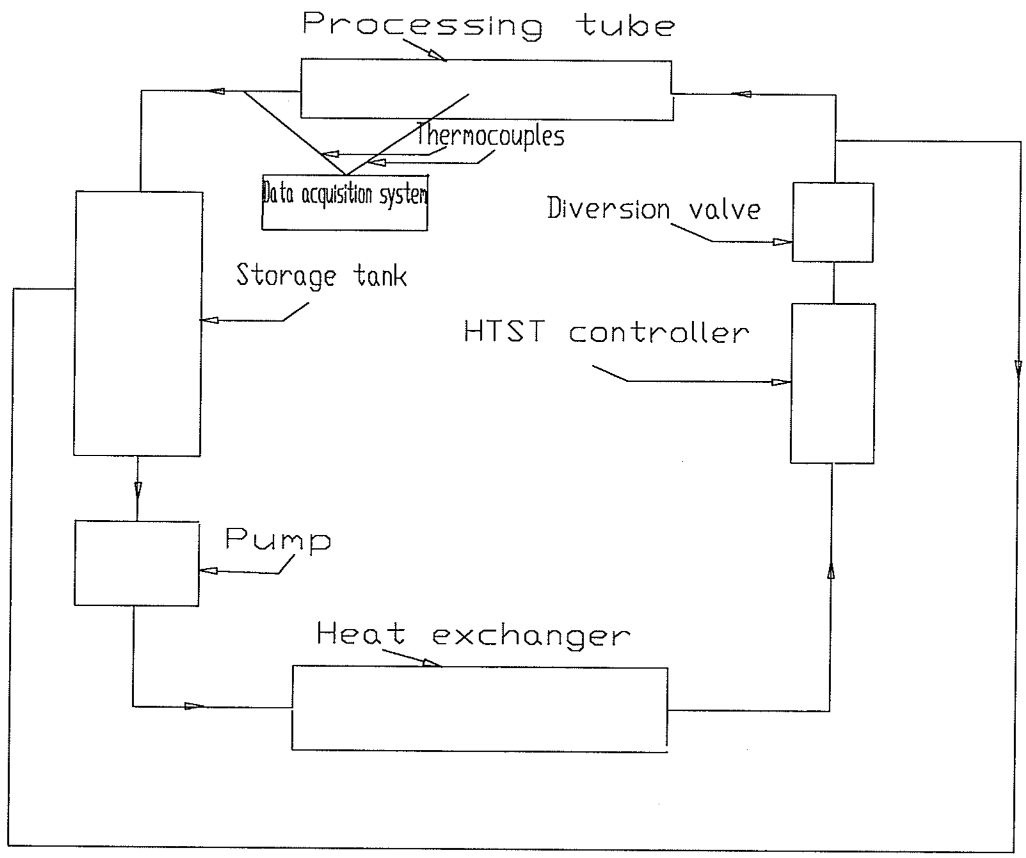

Fig. 3.2 Schematic diagram of the experimental setup (a).

using stainless steel. Two posts were made inside the tube at both ends to attach the fishing wire, with sample spheres on it. Silicone spheres (0.0127-m diameter) were used in the experiments to simulate food particles. Spheres in different orientations (making angles of 30°, 45°, and 60° from the horizontal plane of the sample sphere) were also fabricated by attaching spheres on 2 mm diamater aluminum stiff wires (Fig. 3.3). Particle (sphere)-centre temperature and fluid temperature were measured using Teflon-coated copper constantan thermocouple probes (Thermoelectric, Bradford, ON). Thermocouples were calibrated using calibration thermometers having resolution of 0.1°C. It should however, be noted that the thermocouples have an inherent error of about ±0.5°C. A data acquisition system (Omega, 5508TC, Stanford, CT) was used to record time-temperature data at the centre of the sphere and the fluid temperature.

3.3.2 Experimental setup (b)

The experimental setup (b) (Fig. 3.4) was developed to examine the effect of carrier fluid temperature on h_{fp} in the multiparticulate system because the experimental setup (a) did not have the provision of setting different carrier fluid temperatures and flow rates. The setup consisted of a storage tank, centrifugal pump, diversion knobs, temperature controller, and processing tube. Fibre glass was used to insulate the setup.

The centrifugal pump (Model ACE-S33, Type A, Monarch industries, Winnipeg, MB) pumped water from the storage tank to the processing tube. The temperature controller (Omega, CN 9000A, Stanford, CT) was used to set the temperature of the carrier fluid at a fixed temperature. The heating coils (Omega, Stanford, CT), which were connected to the storage tank, heated carrier fluid to the set temperature. The diversion

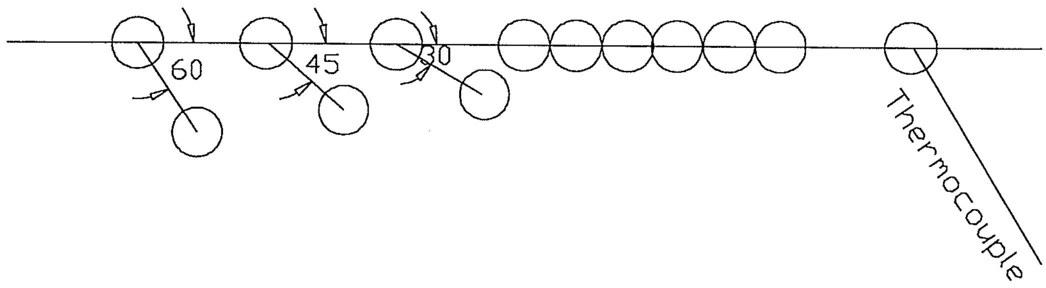

Fig. 3.3 Multiparticulate system (12 particles with the sample sphere) consisting of particles at different orientations (0°, 30°, 45°, and 60°).

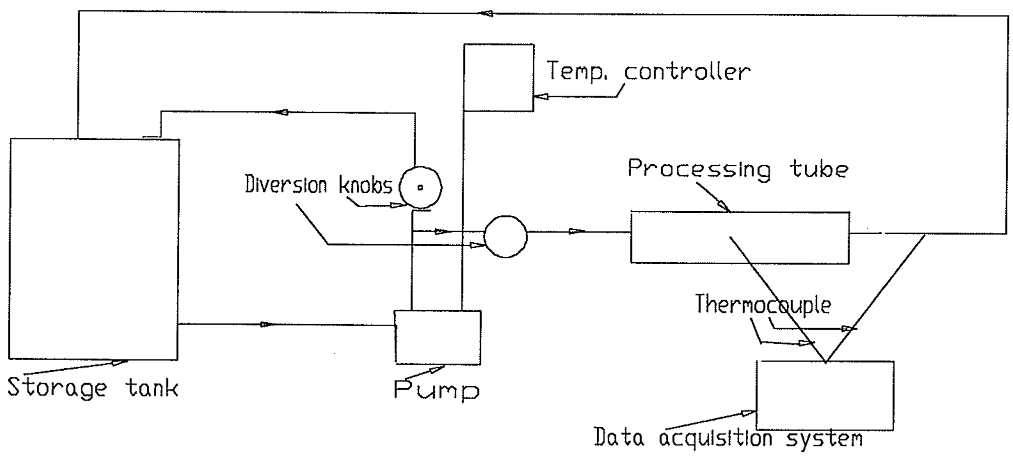

Fig. 3.4 Schematic diagram of the experimental setup (b).

knobs were manually operated to adjust the flow rate and to allow the forward flow of the carrier fluid to the processing tube only when the temperature of the carrier fluid reached the set temperature. The processing tube, thermocouple, silicone sphere, and data acquisition system were the same as in the experimental setup (a).

3.4 Experimental Plan

The objective of these experiments was to obtain time-temperature data at the centre of the silicone spheres, when water or CMC solution was used as the carrier fluid for determination of h_{fp}. The experimental plan is summarised in the Table 3.3.

Table 3.3. Experimental plan for determination of h_{fp} as it is affected by particle-particle interaction, carrier fluid viscosity, carrier fluid temperature, and flow rate.

Parameter	Setup used	No. of levels	Details of level
a) Sample sphere	$a^{*\zeta}$	1	Silicone-sphere with a thermocouple embedded at its centre (36 952)**
b) Sample sphere with spheres at different orientations	$a^{*\zeta}$	5	0°, 30°,45°, 60°, and multiparticles
c) CMC concentrations	$a^{*\psi}$	3	0.0, 0.2, and 0.4%
d) Temperature of carrier fluid (flow rate= 2.82×10^{-3} m^3/s)	$b^{\psi\zeta}$	3	60°, 70°, and 80°C
e) Flow rate of carrier fluid (temperature= 70°C)	$b^{\psi\zeta}$	3	0.27×10^{-3},1.24×10^{-3}, and 2.82×10^{-3} m^3/s

* Temperature was 73.6°C and flow rate of water was 5.2×10^{-4} m^3/s.
ζ Water was used as carrier fluid.
ψ Multiparticles were used for these tests.
** Reynolds number based on pipe diameter and velocity of flow in the pipe.

3.5 Experimental Procedure

The thermocouple-embedded silicone-sphere was placed at the centre of the processing tube using a fishing wire which was tied to the two end posts. Then the processing tube was connected to the experimental setup (a) or (b) and the thermocouple was attached to the data acquisition system. The temperature of the carrier fluid was set to the desired level. Once the carrier fluid reached the set-temperature, it was diverted to the processing tube and the temperatures at the centre of the sphere with time were recorded using data acquisition system onto a disk. After each experiment, the processing tube was cooled to room temperature using tap water and another sample particle was attached.

3.6 Measurement of Flow Rate

The flow rate was measured using a 40 L bucket, a stop watch, and a weighing scale. The bucket was weighed on the weighing scale and the scale was set to zero. The system was started and the carrier fluid was collected in the bucket for 1 min and was weighed again. The reading of the scale gave the mass flow rate in kg/min. Using the principle that mass flow rate of carrier fluid is constant throughout the system, flow rate in the processing tube was calculated. The flow was measured five times for each test condition and average flow rate was calculated.

3.7 Measurement of Viscosity of CMC Solution

The viscosity of CMC solution was measured by Cannon-Fenske Routine viscometer (Cannon Instrument Co., State College, PA) (Fig. 3.5). The following steps were used in the measurement of viscosity:

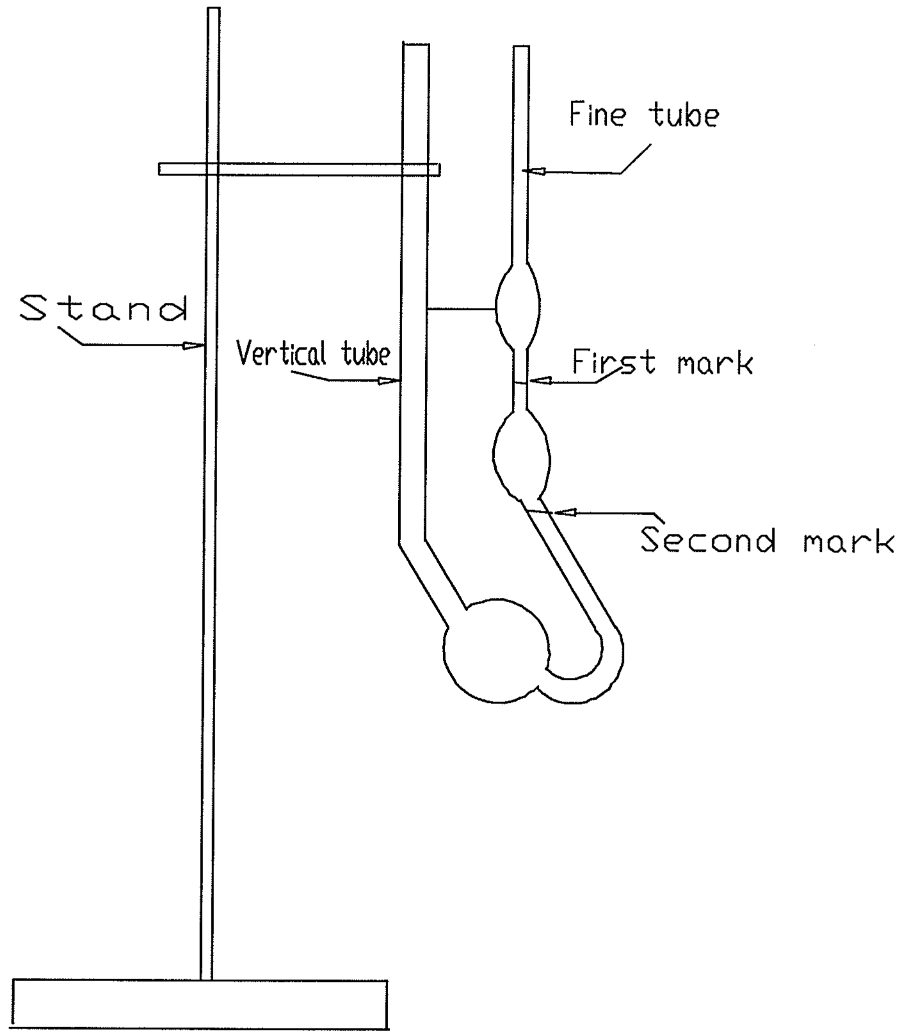

Fig. 3.5 Cannon-Fenske Routine Viscometer (Cannon Instrument Co., State College, PA).

a) The viscometer was cleaned using distilled water.

b) The CMC solution was charged into the viscometer by inverting the instrument, immersing the fine tube in the CMC solution and applying suction to the vertical tube and drawing CMC solution to the second mark in the fine tube.

c) The viscometer (filled with the CMC solution) was placed into the holder, and inserted into the constant temperature bath at 73.6°C.

d) The viscometer was allowed to sit in the constant temperature water bath for 10 min to bring the CMC solution to the bath temperature, because viscosity of the CMC solution was to be measured at 73.6°C. After this, a suction was applied to the fine tube and the solution was drawn slightly above the first mark.

e) The efflux time was measured as the solution was allowed to flow freely down the first mark to the second mark in the fine tube.

f) The kinematic viscosity of the sample was calculated by multiplying the efflux time (in seconds) by the viscometer constant (0.235764 mm^2/s^2 at 73.6°C).

4. DATA ANALYSIS

4.1 Mathematical Treatment

The heat transfer to a sphere when dipped into a constant temperature medium is governed by (Incropera and DeWitt 1985):

$$\frac{\partial\theta}{\partial t}=\alpha\left(\frac{\partial^2\theta}{\partial r^2}+\frac{2}{r}\frac{\partial\theta}{\partial r}\right) \tag{12}$$

where $\theta=(T_\infty-T_r)/(T_\infty-T_i)$,

t=time (s),

r=distance from the centre of the sphere (m),

T_∞=temperature of the heating medium (°C),

T_r=temperature of the sphere at time t and at a distance r (°C),

T_i=initial temperature of the sphere (°C), and

α= thermal diffusivity ($k/(\rho\ C_p)$), (m^2/s).

For uniform initial temperature and convective boundary conditions, the analytical solution to Eq. 12 is as follows (Schneider 1955, Luikov 1968, Incropera and DeWitt 1985):

$$\theta=\sum_{n=1}^{\infty} C_n \exp(-\xi_n^2 Fo)\frac{1}{\xi_n r^*}\sin(\xi_n r^*) \tag{13}$$

where Fo=Fourier number=$(\alpha\ t)/r_0^2$,

r_0=radius of sphere (m),

$r^* = r/r_0$,

$$C_n = \frac{4[\sin(\xi_n) - \xi_n \cos(\xi_n)]}{2\xi_n - \sin(2\xi_n)} \tag{14}$$

and the discrete values of ξ_n are positive roots of the transcendental equation (Incropera and DeWitt 1985):

$$1 - \xi_n \cot(\xi_n) = Bi \tag{15}$$

where Bi=Biot number=$(h_{fp}\ r_0)/k$.

For a sphere, Heisler (1947) has shown that for Fo$\geq$ 0.2, the foregoing series solution (Eq. 13) can be approximated by a single term as (Incropera and DeWitt 1985):

$$\theta = \theta_0 \frac{1}{\xi_1 r^*} \sin(\xi_1 r^*) \tag{16}$$

where θ_0 represents the temperature-ratio $((T_\infty - T_0)/(T_\infty - T_i))$ at the centre of the sphere (T_0=temperature at the centre of sphere at time t) and is of the form:

$$\theta_0 = C_1 \exp(-\xi_1^2 Fo) \tag{17}$$

By substituting an expression for Fo, Eq. 17 becomes:

$$\theta_0 = C_1 \exp(-\xi_1^2 \alpha \frac{t}{r_0^2}) \tag{18}$$

4.1.1 Calculation of h_{fp}

Knowing the thermal diffusivity (α), radius of sphere (r_0), and time-temperature data at the centre of the sphere, C_1 and ξ_1 were obtained by performing non-linear regressions for each of the five replicates at different experimental conditions. The value of ξ_1 was substituted in Eq. 15 to give Bi. From Bi, k, and r_0, h_{fp} was calculated. The reported h_{fp} is the mean of the five replicates at different experimental conditions. Awuah et al. (1995) reported that this method (which they called as "the rate method") gave consistent data and conservative values for h_{fp} and they preferred the rate method over "the temperature ratio method".

4.2 Estimation of Mean Relative Percent Error (%) and Standard Error

The predicted temperatures were calculated using Eq. 18 for experimental time ≥ 49 s because it is valid for Fo≥ 0.2 i.e. for t ≥ 49 s. The predicted temperatures were calculated by using average values of C_1 and ξ_1 that were determined by performing non-linear regression to Eq. 18 using SAS (SAS 1985) for each of the five replicates. The mean relative percent error and standard error were estimated using Eqs. 19 and 20, respectively:

$$P=\left[\frac{\sum_{n=1}^{n=N}\frac{|P_n-M_n|}{M_n}}{N}\right]\times 100\% \qquad (19)$$

where P=Mean relative percent error (%),

N=total number of data points (time steps +1),

P_n=predicted temperature at n^{th} (n=1 to N) time (°C), and

M_n=measured temperature at n^{th} (n=1 to N) time (°C).

$$SE=\sqrt{\frac{\sum_{n=1}^{n=N}(P_n-M_n)^2}{df}} \qquad (20)$$

where SE=Standard error (°C), and

df=degrees of freedom (N-1).

5. RESULTS AND DISCUSSION

5.1 Time-Temperature Profiles

Figures 5.1-5.13 give mean experimental and predicted (using Eq. 18) time-temperature profiles at the centre of the sample particle for different experimental conditions. The mean relative percent errors (%) and standard errors for all the replicates at different experimental conditions were less than 4% and 2.5°C, respectively (Table 5.1). The variation among replicates was less than 2% for most of the measured temperatures (Appendix A). Therefore, it can be concluded that the experimental and predicted temperatures are in excellent agreement.

5.2 Effect of Process Parameters on h_{fp}

The effect of process parameters such as particle-particle interaction, carrier fluid viscosity, carrier fluid temperature, and flow rate on h_{fp} were examined. As shown below, the data fall partially in the range of heat transfer coefficients reported by earlier researchers [Chandarana et al. (1990): 66-107 $W \cdot m^{-2} \cdot K^{-1}$; Mwangi et al. (1993): 59-1301 $W \cdot m^{-2} \cdot K^{-1}$; Bhamidipati and Singh (1994): 108-196 $W \cdot m^{-2} \cdot K^{-1}$]. It is to be noted that experimental conditions and techniques used in different studies vary widely.

5.2.1 Particle-particle interaction

Convection is the main mode of heat transfer during aseptic processing by continuous flow of liquid foods with particles. The essential feature of a convective heat-transfer or a convective mass transfer process is the transport of energy or mass to or from a surface by both molecular conduction processes and gross fluid movement (Kays and Crawford 1993). Any change in the flow field around the particle may result

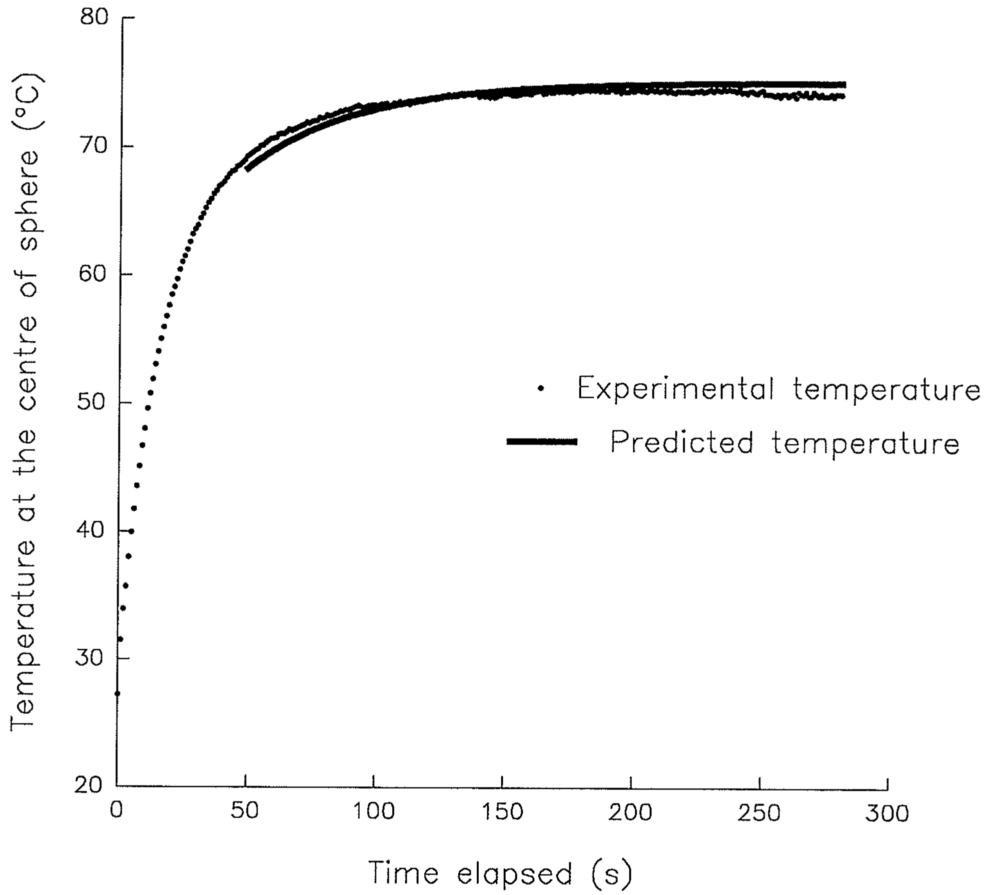

Fig. 5.1 Time-temperature profile for heating the sample sphere (0.0127-m diameter) with 73.6°C water flowing at $5.2x10^{-4}$ m^3/s.

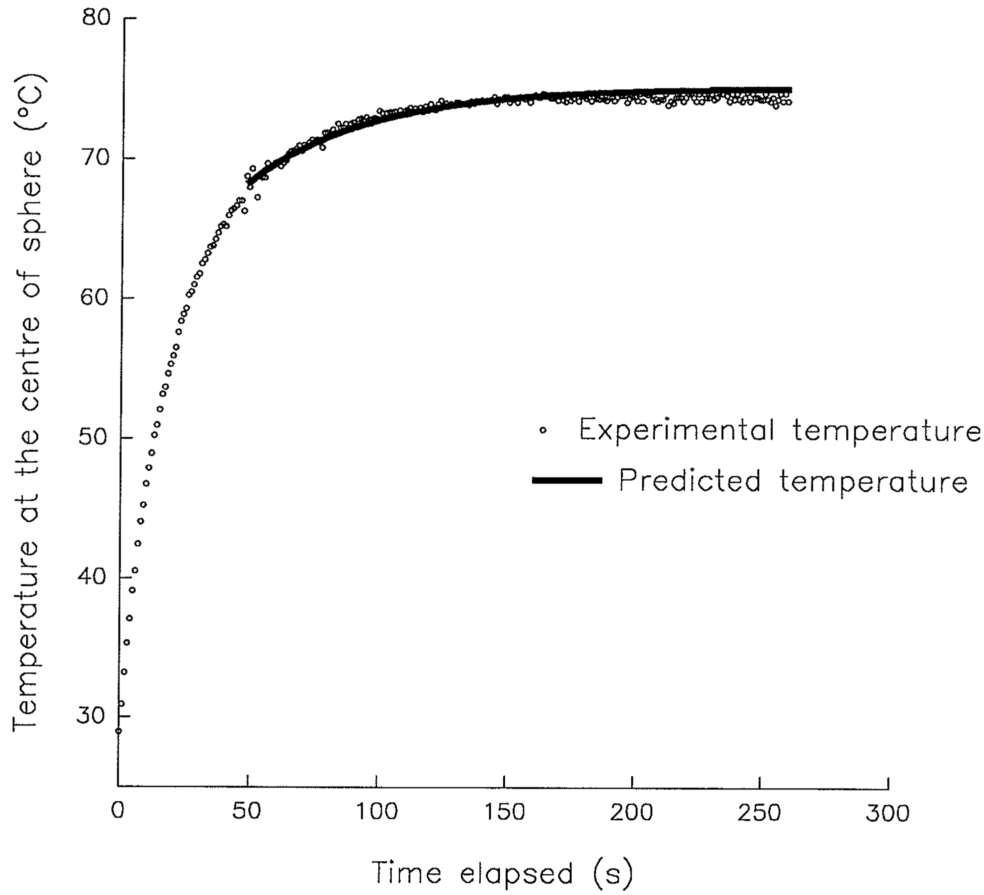

Fig. 5.2 Time-temperature profile for heating the sample sphere (0.0127-m diameter) in the presence of another sphere (0.0127-m diameter) at a distance of 0.0254 m upstream at an angle of 0° from the horizontal plane of the sample sphere, with 73.6°C water flowing at 5.2×10^{-4} m^3/s.

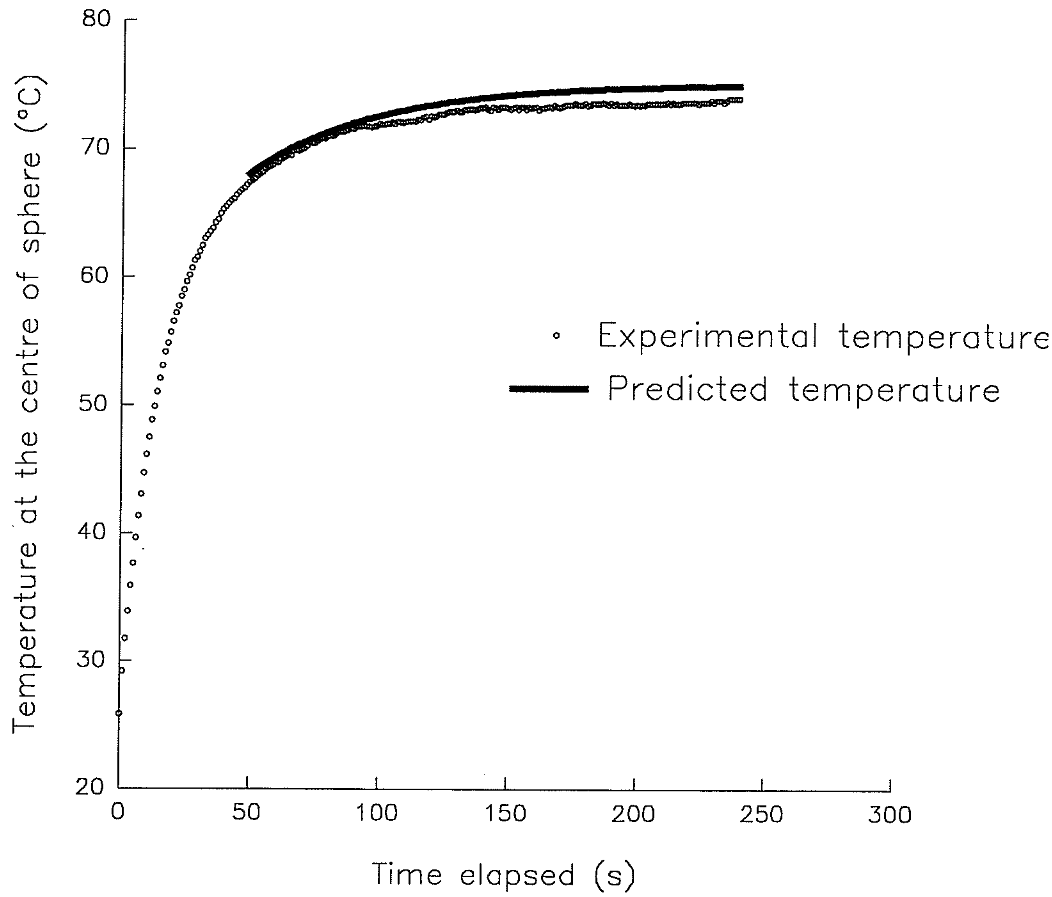

Fig. 5.3 Time-temperature profile for heating the sample sphere (0.0127-m diameter) in the presence of another sphere (0.0127-m diameter) at a distance of 0.0254 m upstream at an angle of 30° from the horizontal plane of the sample sphere, with 73.6°C water flowing at 5.2×10^{-4} m^3/s.

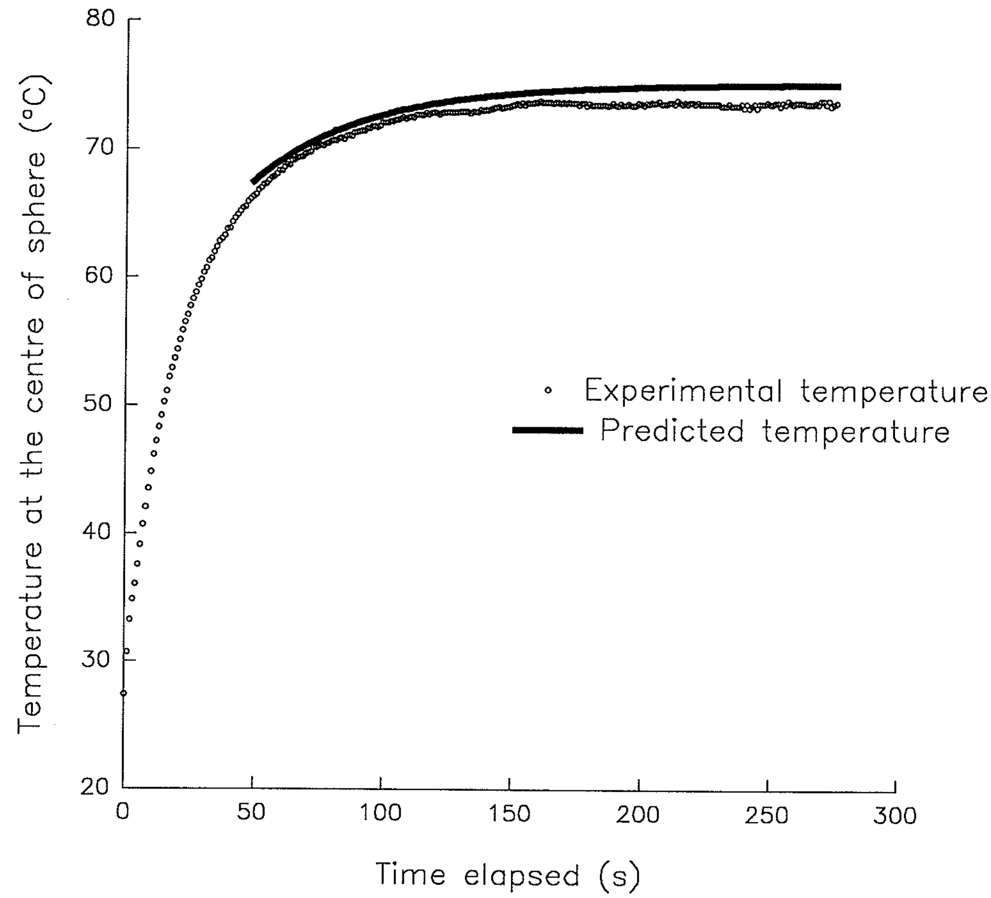

Fig. 5.4 Time-temperature profile for heating the sample sphere (0.0127-m diameter) in the presence of another sphere (0.0127-m diameter) at a distance of 0.0254 m upstream at an angle of 45° from the horizontal plane of the sample sphere, with 73.6°C water flowing at 5.2×10^{-4} m^3/s.

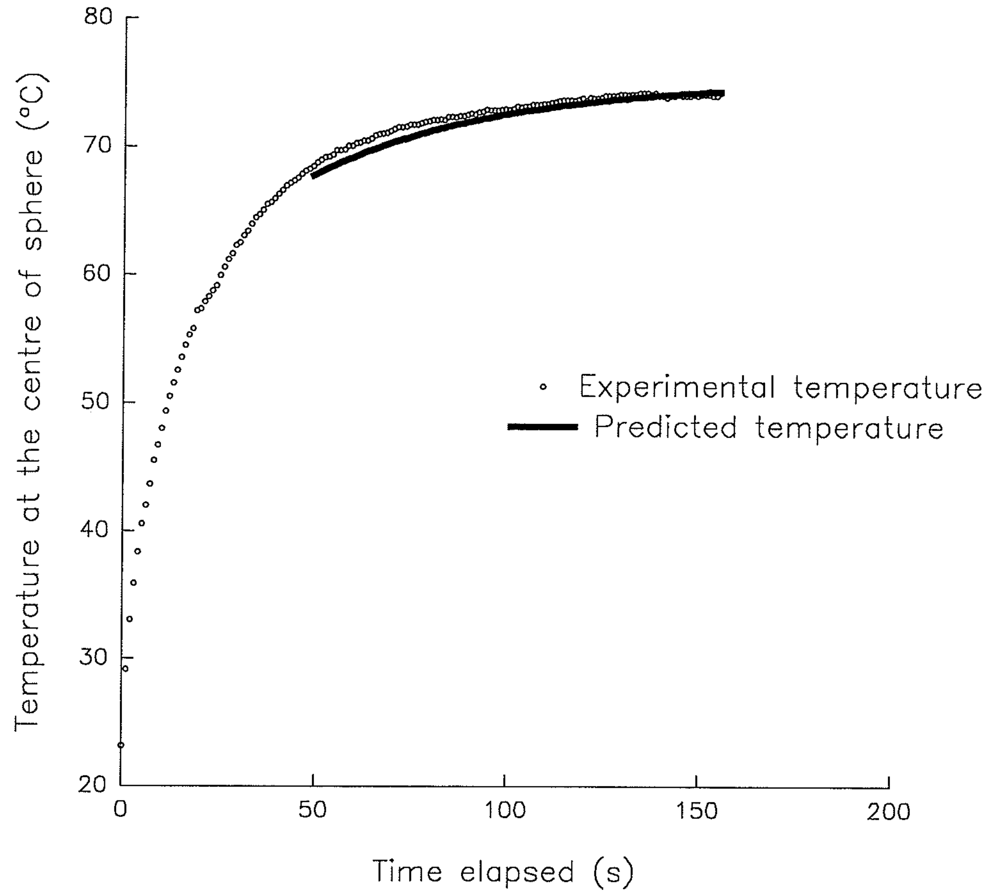

Fig. 5.5 Time-temperature profile for heating the sample sphere (0.0127-m diameter) in the presence of another sphere (0.0127-m diameter) at a distance of 0.0254 m upstream at an angle of 60° from the horizontal plane of the sample sphere, with 73.6°C water flowing at 5.2×10^{-4} m^3/s.

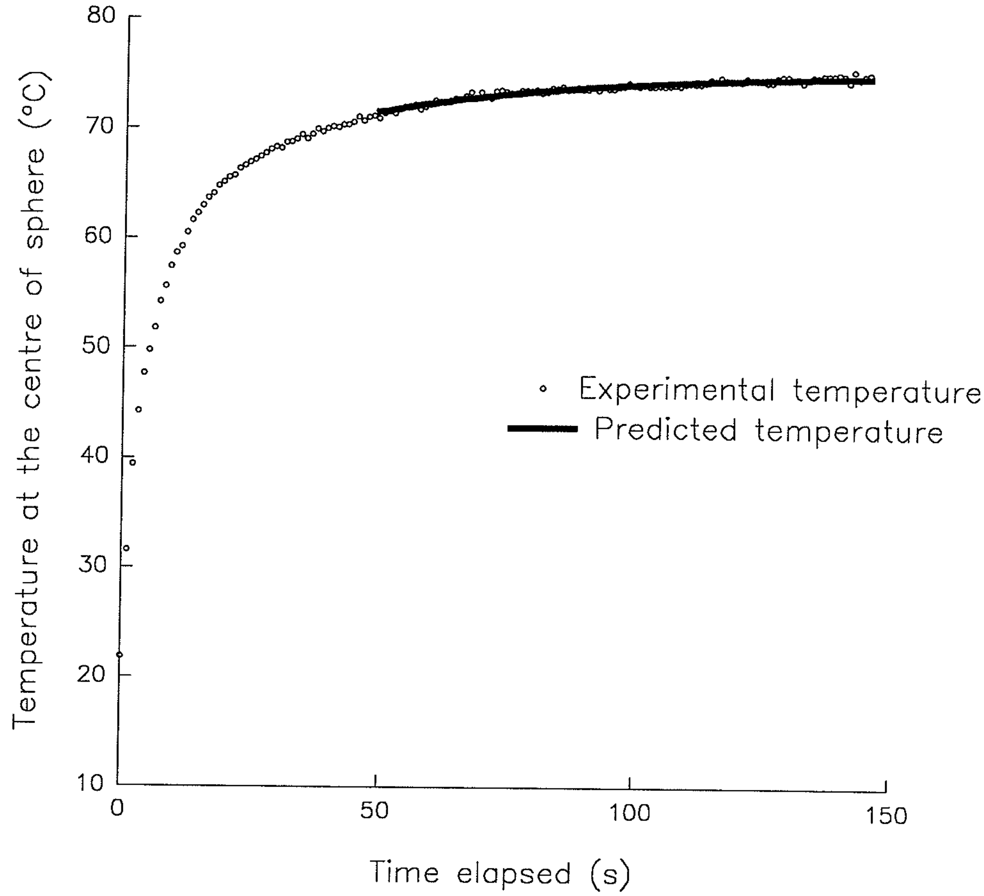

Fig. 5.6 Time-temperature profile for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 73.6°C water flowing at 5.2×10^{-4} m^3/s.

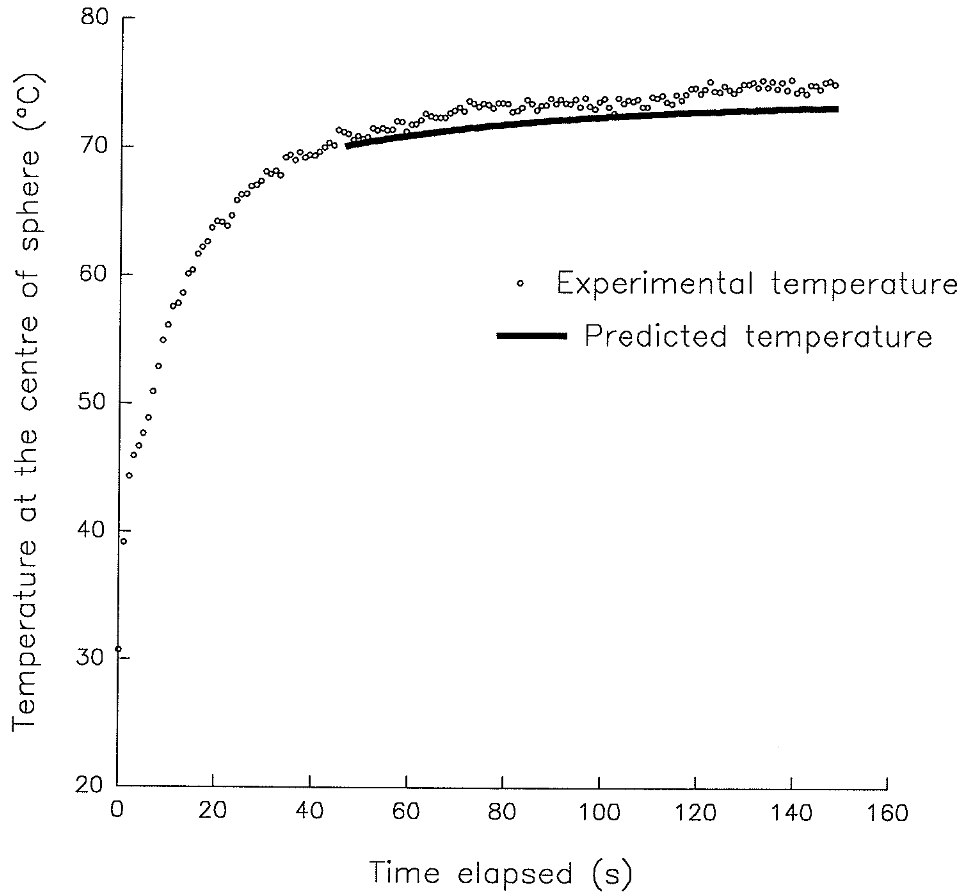

Fig. 5.7 Time-temperature profile for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 73.6°C CMC solution (0.2% concentration, viscosity=9.3×10^{-3} Pa•s, flow rate=5.2×10^{-4} m^3/s).

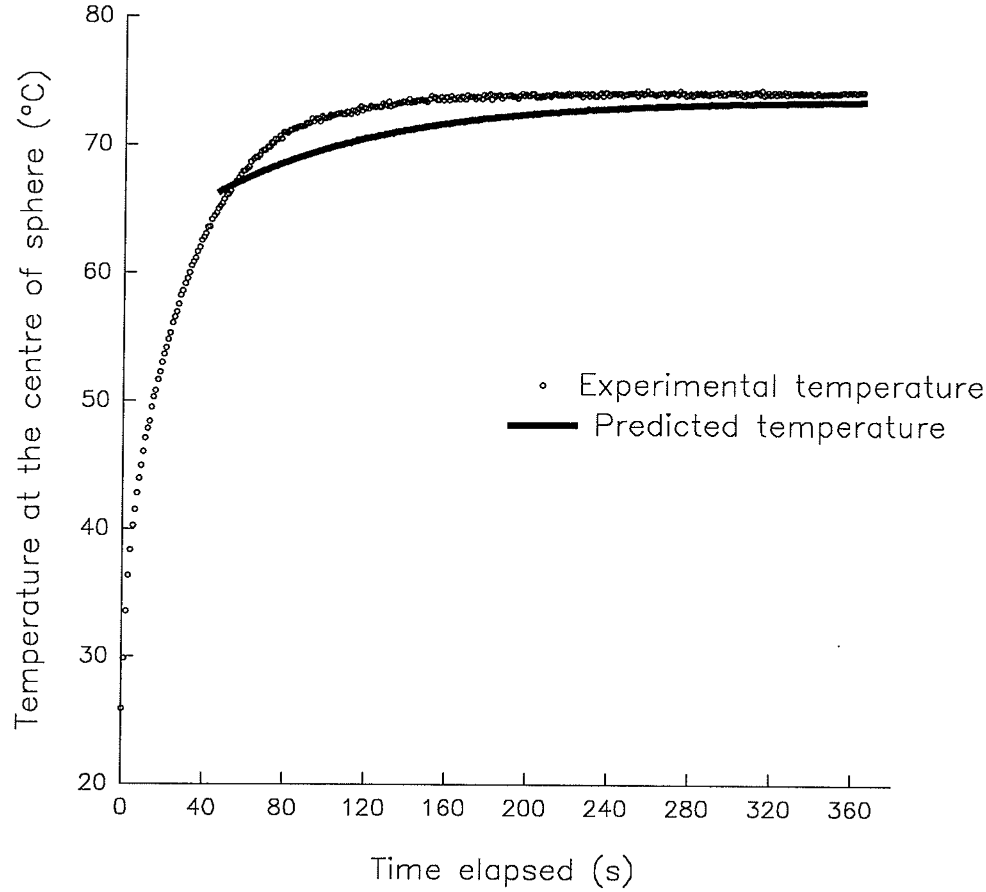

Fig. 5.8 Time-temperature profile for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 73.6°C CMC solution (0.4% concentration, viscosity=33.3×10^{-3} Pa•s, flow rate=5.2×10^{-4} m^3/s).

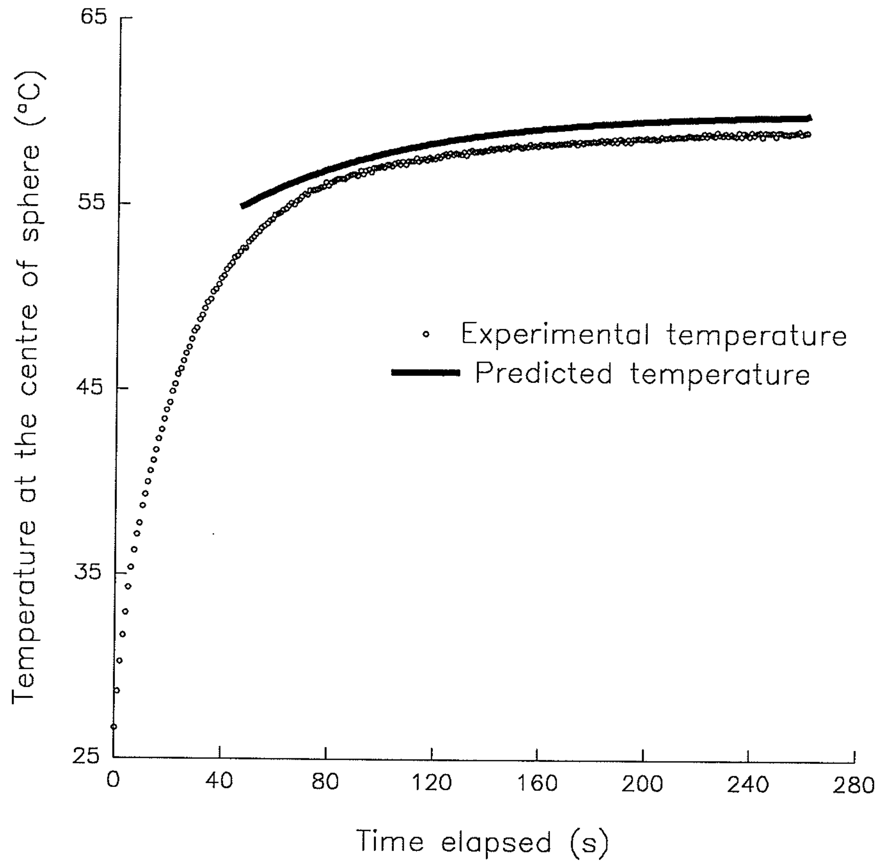

Fig. 5.9 Time-temperature profile for heating the sample sphere (0.0127-m diameter) in the multiparticulate system with 60°C water flowing at 2.82×10^{-3} m^3/s.

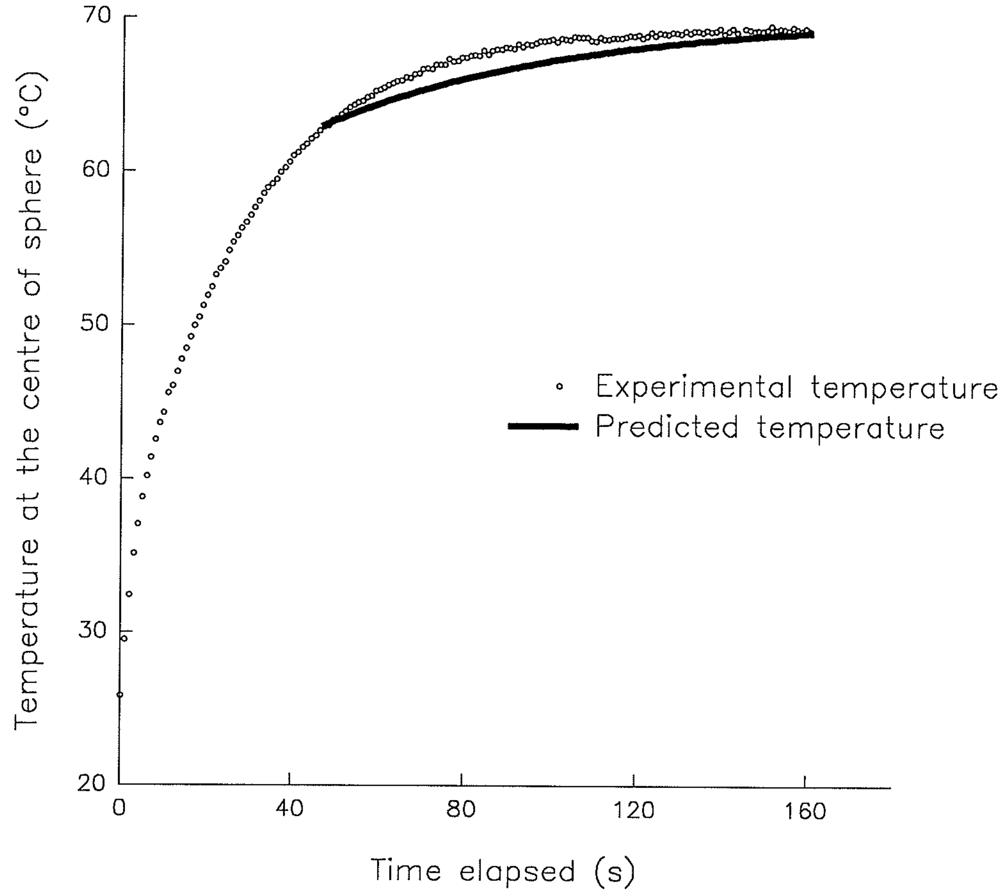

Fig. 5.10 Time-temperature profile for heating the sample sphere (0.0127-m diameter) in the multiparticulate system with 70°C water flowing at 2.82×10^{-3} m^3/s.

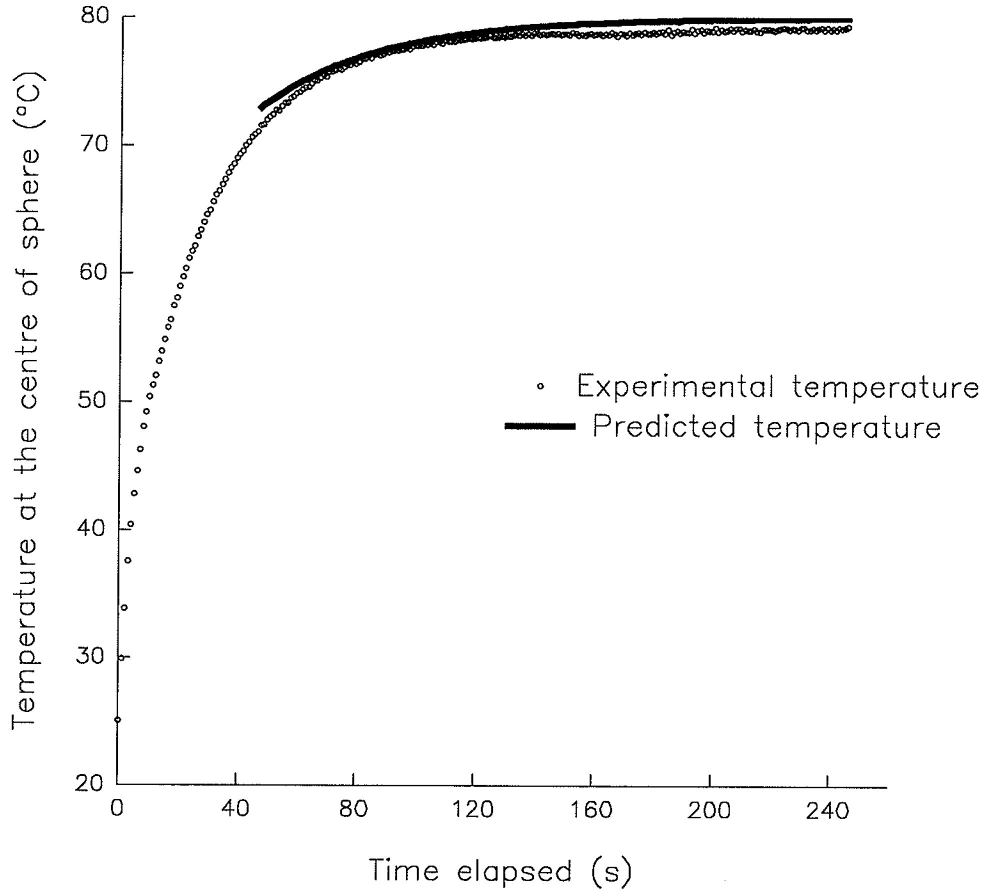

Fig. 5.11 Time-temperature profile for heating the sample sphere (0.0127-m diameter) in the multiparticulate system with 80°C water flowing at 2.82×10^{-3} m^3/s.

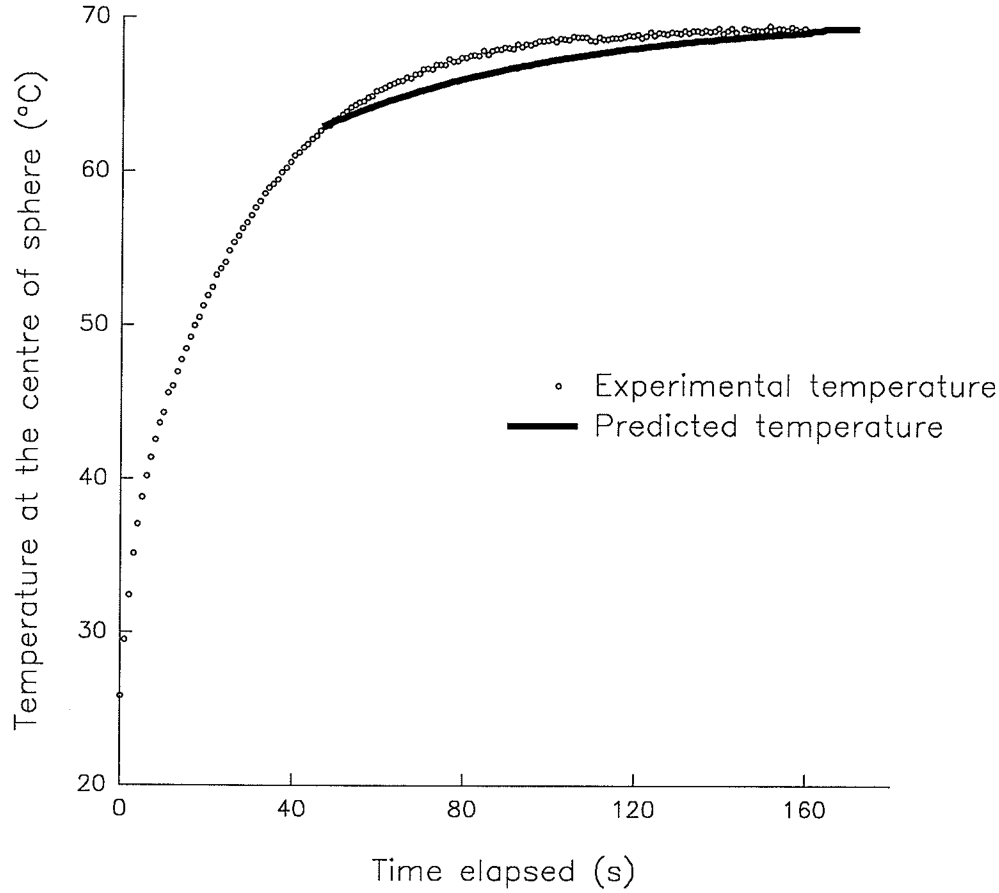

Fig. 5.12 Time-temperature profile for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 70°C water flowing at 0.27×10^{-3} m^3/s.

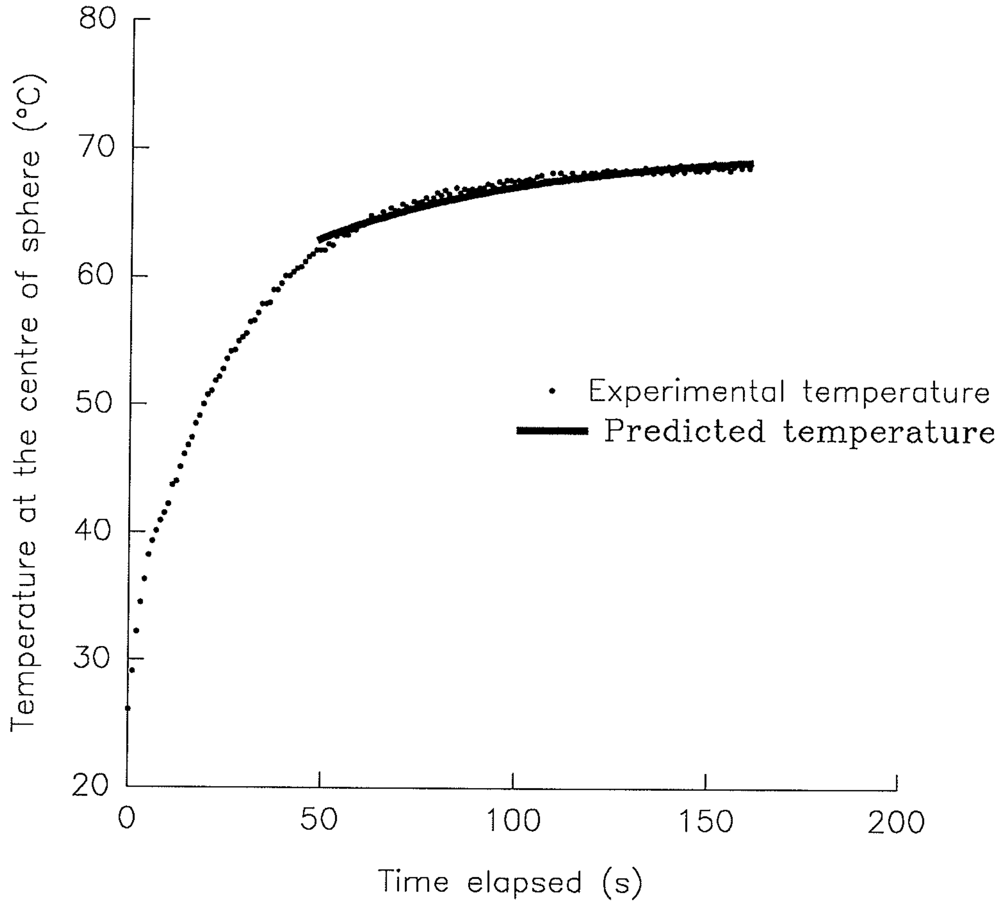

Fig. 5.13 Time-temperature profile for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 70°C water flowing at 1.24×10^{-3} m^3/s.

Table 5.1 Mean relative percent errors (%) and standard errors between predicted and measured temperatures for different experimental conditions and individual replicates.

Experimental conditions$^{\Psi}$	Replicate#1		Replicate#2		Replicate#3		Replicate#4		Replicate#5	
	P*	SE**	P*	SE**	P*	SE**	P*	SE**	P*	SE**
Single particle	2.0	1.4	2.4	1.7	1.7	1.4	1.7	1.3	1.1	0.8
Single particle with 0° particle	0.6	0.5	0.6	0.5	0.7	0.7	0.6	0.5	0.6	0.5
Single particle with 30° particle	0.4	0.4	2.4	1.8	0.5	0.4	2.0	1.5	1.1	0.8
Single particle with 45° particle	0.4	0.4	2.5	1.8	0.3	0.3	2.1	1.5	1.3	1.0
Single particle with 60° particle	1.8	1.4	0.4	0.4	1.8	1.3	0.4	0.3	0.8	0.6
Multiparticulate system	0.4	0.4	0.4	0.3	0.4	0.3	0.6	0.5	0.5	0.3
Fluid viscosity= 9.3×10^{-3} Pa•s	1.8	1.5	1.8	1.5	2.0	1.5	1.8	1.5	2.0	1.5
Fluid viscosity= 33.3×10^{-3} Pa•s	1.8	1.5	1.8	1.5	2.0	1.6	2.0	1.6	2.0	1.6
Fluid temperature= 60°C	3.8	2.1	0.8	0.5	0.4	0.3	1.6	1.0	1.3	0.8
Fluid temperature= 70°C	3.4	2.4	2.4	1.7	1.5	1.1	1.7	1.2	0.6	0.5
Fluid temperature= 80°C	2.0	1.6	0.4	0.3	0.8	0.8	0.6	0.5	0.8	0.7
Flow rate= 0.27×10^{-3} m^3/s	3.2	2.3	4.0	2.4	3.3	2.2	3.7	2.3	3.4	2.2
Flow rate= 1.24×10^{-3} m^3/s	1.5	1.1	2.1	1.5	1.8	1.3	1.7	1.3	2.7	1.8

Ψ Details given in Table 3.3
* Mean relative percent error (%)
** Standard error (°C)

in thickening or thinning of the boundary layer around the particle, thereby decreasing or increasing the fluid-to-particle heat transfer.

The present research examined the effect of presence of particles at different orientations on h_{fp} and thus indirectly, on the flow field around the sample particle. The h_{fp} values were significantly influenced (ANOVA $p \leq 0.0001$) by the presence of particles in the processing tube (Table 5.2).

The h_{fp} values decreased slightly when another particle at different orientations (0°, 30°, 45°, and 60°) was introduced upstream at a distance of 0.0254 m from the sample particle i.e. the particle with thermocouple attached at its centre. This trend may be explained by the fact that in the presence of another particle at different orientations, fluid velocity (v) is divided into two components ($v \cos\beta$ and $v \sin\beta$, where β=angle of orientation of the particle). Therefore, the fluid velocity (v) approaching the sample particle decreases, which may have resulted in thickening of the boundary layer around the sample particle, thereby decreasing the h_{fp}. This effect could help in assigning h_{fp} value while modelling aseptic process schedules in situations where the sample particle is approached by other particles making same angle from the horizontal plane of the sample particle.

The h_{fp} values of the sample particle increased when multiple particles were introduced upstream (Table 5.2). Depending upon the flow rate, Mwangi et al. (1993) also reported an enhancement in heat transfer between 80 and 200% with an increase in solid fraction (0-3.2%). This effect is caused by the disturbance of the flow field around a particle by the presence of other particles in the suspension at high Reynolds number.

Table 5.2 **Fluid-to-particle heat transfer coefficients (h_{fp}) for the sample sphere on its own and in the presence of other particles at different orientations.**

	h_{fp}* ($W \cdot m^{-2} \cdot K^{-1}$)				
Alone	Orientation				Multiparticles
	0°	30°	45°	60°	
154	130	122	146	125	176

* Mean of five replicates.

In the multiparticulate system, different velocity components (due to different orientations of particles) cause agitation or turbulence in the fluid flow. This disturbance or agitation may have resulted in the thinning of the boundary layer around the sample particle, thereby increasing the h_{fp}.

5.2.2 Carrier fluid viscosity

Figure 5.14 shows that with an increase in the viscosity of the carrier fluid (CMC) from $0.4x10^{-3}$ Pa•s (0% CMC) to $33.33x10^{-3}$ Pa•s (0.4% CMC), h_{fp} values decreased from 176 to 54 $W•m^{-2}•K^{-1}$ for the multiparticulate system (fluid-temperature=73.6±0.5°C, flow rate=5.2×10^{-4} m^3/s). Equivalent change in Re was 36 952 to 422. The similar results were observed by earlier researchers (Chandarana et al. 1990, Zuritz et al. 1990, Balasubramaniam and Sastry 1994a, Zitoun and Sastry 1994, Bhamidipati and Singh 1994) for a single particle. This shows that the effect of carrier fluid viscosity on h_{fp} in the multiparticulate system is the same as for a single particle irrespective of the agitation or disturbance caused by the presence of other particles. The higher fluid viscosity provides more resistance to fluid flow and thus decreases the agitation at the interface (thickening of the boundary layer around the particle), thereby decreasing the h_{fp}. The error bars in Fig. 5.14 were calculated using the column averaging and standard deviation of a column of data (using SigmaPlot 5.0).

5.2.3 Carrier fluid temperature

Figure 5.15 shows that with an increase in carrier fluid (water) temperature from 60°C to 80°C, h_{fp} values increased from 49 to 202 $W•m^{-2}•K^{-1}$ for the multiparticulate system using experimental setup (b) (flow rate=2.82×10^{-3} m^3/s). By incorporating the

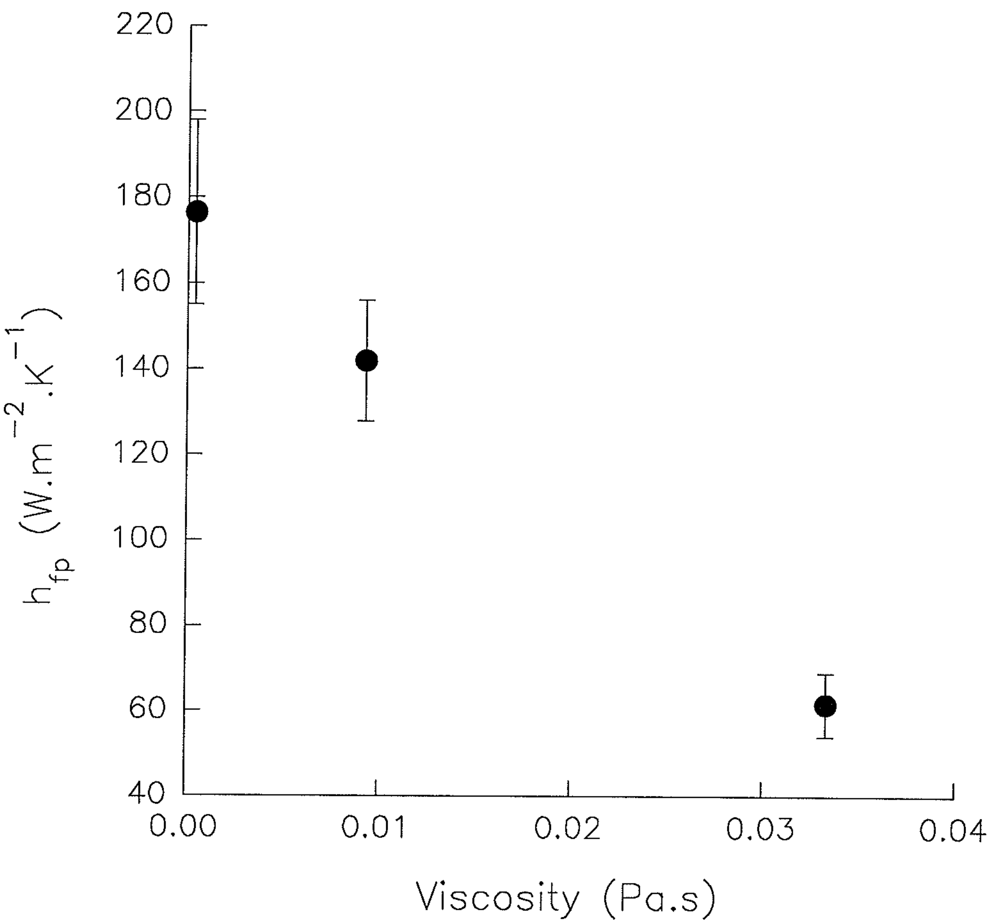

Fig. 5.14 Fluid-to-particle heat transfer coefficient (h_{fp}) ($W \cdot m^{-2} \cdot K^{-1}$), in the multiparticulate system during flow of CMC solution of different concentrations (0, 0.2, and 0.4%, viscosity= 0.4×10^{-3}, 9.3×10^{-3}, and 33.3×10^{-3} Pa•s, respectively, flow rate=5.2×10^{-4} m^3/s) at 73.6°C.

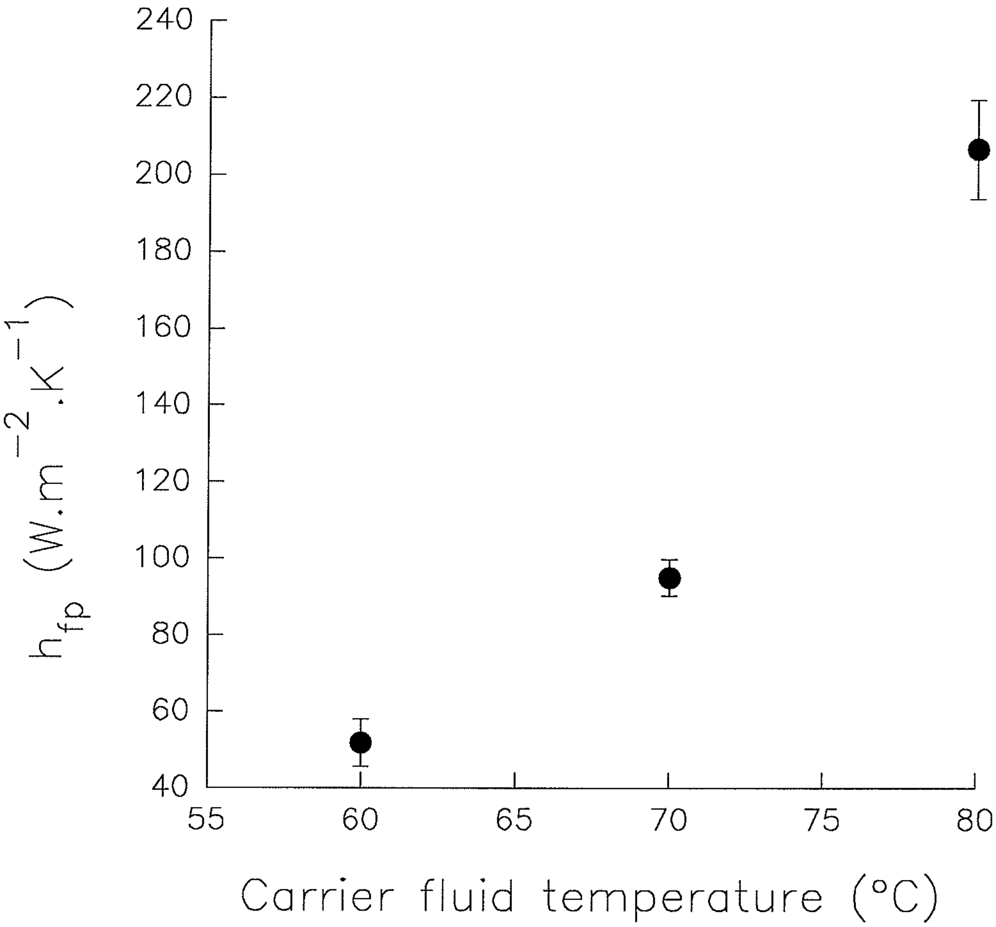

Fig. 5.15 Fluid-to-particle heat transfer coefficient (h_{fp}) (W•m^{-2}•K^{-1}), in the multiparticulate system during flow of water (flow rate=2.82x10^{-3} m^3/s) at different carrier fluid temperatures (60°, 70°, and 80°C).

effect of temperature on ρ and μ (fluid viscosity), the Re changed from 163 285 to 216 724. At higher temperatures and more agitation, molecules of the carrier fluid have higher kinetic energy, thereby thinning the boundary layer at the particle interface, and increasing the h_{fp}. The error bars in Fig. 5.15 were also calculated using the column averaging and standard deviation of a column of data (using SigmaPlot 5.0).

5.2.4 Flow rate

Figure 5.16 shows that with an increase in flow rate from $0.27x10^{-3}$ (Re=18 068) to $2.82x10^{-3}$ (Re=188 710) m^3/s, h_{fp} values increased from 53 to 94 $W•m^{-2}•K^{-1}$ for the multiparticulate system using experimental setup (b) (carrier fluid temperature=70°C). The coefficient of variations for measured flow rate ($0.27x10^{-3}$, $1.24x10^{-3}$, and $2.82x 10^{-3}$ m^3/s) were 7.5, 6.4, and 5.2%, respectively. The same pattern was also observed by earlier researchers (Chang and Toledo 1989, Zuritz et al. 1990, Mwangi et al. 1993, Balasubramaniam and Sastry 1994a, Zitoun and Sastry 1994). The higher flow rate results in more agitation of the carrier fluid molecules, thereby thinning the boundary layer at the particle interface, and increasing the h_{fp}. The error bars in Fig. 5.16 were also calculated using the column averaging and standard deviation of a column of data (using SigmaPlot 5.0).

5.3 Practical Significance of h_{fp}

Design and optimization of aseptic processes for particulate foods depend strongly on the value of h_{fp} during continuous flow processes because heat transfer by convection is governed by fluid motion. To obtain sterilization of a particle, its integrated time-temperature history must be known so that the processing value or thermal death time

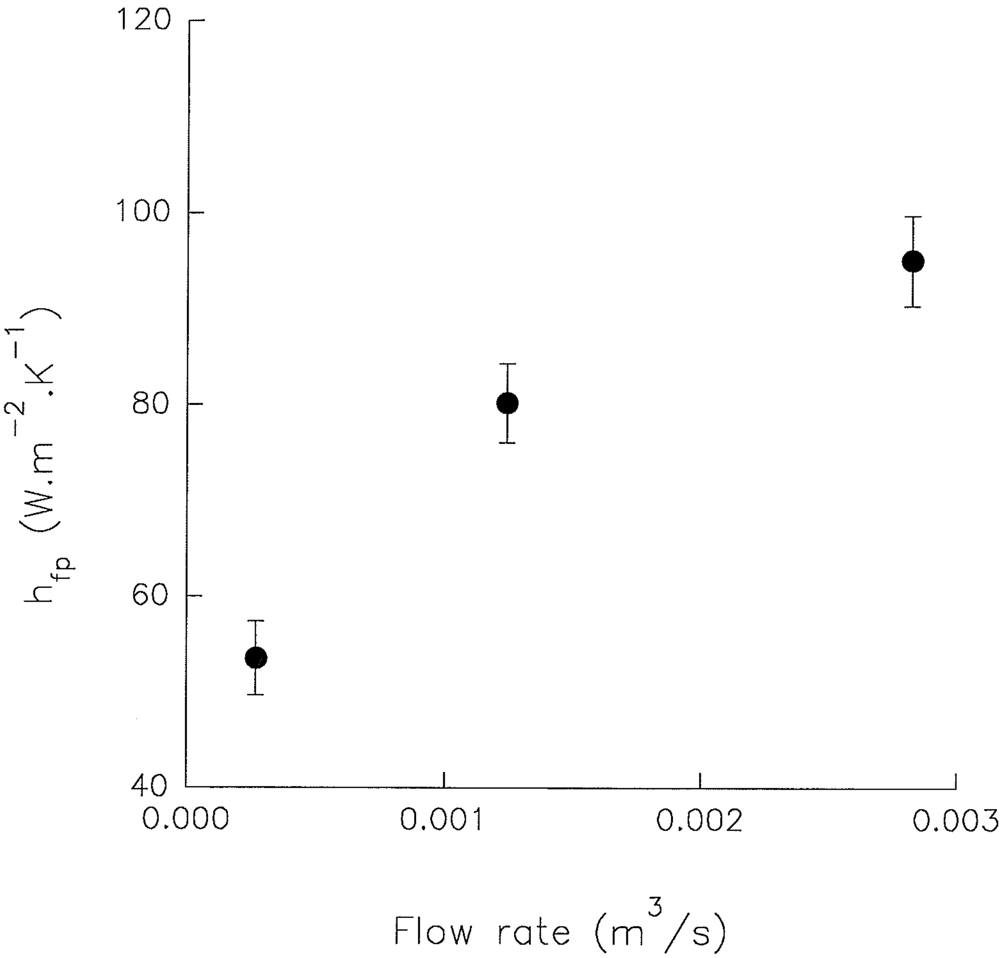

Fig. 5.16 Fluid-to-particle heat transfer coefficient (h_{fp}) (W•m^{-2}•K^{-1}), in the multiparticulate system during flow of water at 70°C at different flow rates (0.27x10^{-3}, 1.24x10^{-3}, and 2.82x10^{-3} m^3/s).

(F_o) can be calculated:

$$F_o=\int_0^t 10^{\left(\frac{T-T_{ref}}{z}\right)} . dt \qquad (21)$$

where F_o=processing value (s),

t=total processing time (s),

T=particle-temperature at time t (°C),

T_{ref}=reference temperature (°C), and

z=temperature change needed to change D-value (decimal reduction time, s) by 90% (°C).

Modelling of aseptic processing is necessary as monitoring of temperature history of a particle is quite difficult as the particle moves in the aseptic processing system.

Modelling of the aseptic process schedules needs heating medium temperature and h_{fp} as input parameters so that time-temperature profiles for the particle can be obtained which can be substituted in Eq. 21 to find the processing value (F_o). The present research determined the h_{fp} value incorporating the effect of particle-particle interaction which can be useful in the studies related to a multiple particle system. A slight decrease in the h_{fp} value was found when the sample particle was placed with another particle making an angle with the horizontal plane of the sample particle. This shows that while assigning a specific h_{fp} value as an input parameter to the mathematical model, a complete monitoring of the particle-particle interaction should be done at the same time. There is always a possibility that the particles may have same orientations with the sample particle which may result in low h_{fp}. Thus knowledge of h_{fp} is important to design aseptic process schedules and much work need to be done to assure complete sterilization during aseptic processing of liquid foods with particles.

6. CONCLUSIONS

Based on the results of this research the following specific conclusions can be drawn:

1. The fluid-to-particle heat transfer coefficient (h_{fp}) for the sample particle was 154 $W \bullet m^{-2} \bullet K^{-1}$ which increased to 176 $W \bullet m^{-2} \bullet K^{-1}$ in the multiparticulate system.

2. The h_{fp} value decreased from 176 to 54 $W \bullet m^{-2} \bullet K^{-1}$ when the carrier fluid viscosity increased from $0.4x10^{-3}$ to $33.33x10^{-3}$ $Pa \bullet s$.

3. The h_{fp} value increased from 49 to 202 $W \bullet m^{-2} \bullet K^{-1}$ when the carrier fluid temperature increased from 60 to 80°C.

4. The h_{fp} value increased from 53 to 94 $W \bullet m^{-2} \bullet K^{-1}$ when the flow rate increased from 0.27×10^{-3} to 2.82×10^{-3} m^3/s.

7. SUGGESTIONS FOR FUTURE RESEARCH

1. Fluid-to-particle heat transfer coefficient (h_{fp}) should be determined for the real food particles using the same experimental unit that was used in this study. The h_{fp} values should also be determined at aseptic temperatures (121°C-130°C).

2. A finite element method should be used to calculate h_{fp} using the time-temperature data from this study. This method can later be used for irregular-shaped food particles.

3. More advanced techniques for temperature measurement (which allow free movement of sample particle), like transmitter particle technique, should be used to monitor time-temperature data at the centre of the particle (in the multiparticulate system).

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APPENDIX A

Table A1: Time-temperature data for heating the sample sphere (0.0127-m diameter) with 73.6°C water flowing at 5.2×10^{-4} m^3/s (five replicates).

Time	T*1	T2	T3	T4	T5	Avg.**	Std.***
0	26.3	25.4	26.5	26.9	26.8	26.4	0.6
1	29.3	31.9	30.0	30.9	30.8	30.6	1.0
2	31.8	31.3	32.8	34.0	34.8	32.9	1.5
3	34.3	31.5	35.1	36.5	36.0	34.7	2.0
4	36.3	34.0	37.2	38.9	38.2	36.9	1.9
5	37.9	36.0	39.3	40.6	39.8	38.7	1.8
6	39.8	38.0	41.2	42.5	41.7	40.6	1.8
7	41.4	39.8	43.0	44.4	43.2	42.3	1.8
8	43.1	41.2	44.7	45.8	44.8	43.9	1.8
9	44.4	42.7	46.4	47.5	46.2	45.4	1.9
10	46.0	44.0	47.8	49.1	47.5	46.9	2.0
11	47.5	45.5	49.4	50.5	49.1	48.4	1.9
12	48.2	46.7	50.7	51.5	50.2	49.5	2.0
13	49.8	48.0	51.8	52.9	51.1	50.7	1.9
14	50.8	49.0	52.9	53.8	52.2	51.7	1.9
15	51.8	50.1	53.8	55.2	52.8	52.7	1.9
16	52.9	51.2	55.2	56.0	53.6	53.8	1.9
17	53.6	51.9	55.9	56.9	54.8	54.6	1.9
18	54.5	52.9	56.9	58.0	55.2	55.5	2.0
19	55.5	53.8	57.7	58.7	56.2	56.4	1.9
20	56.0	54.6	58.5	59.5	56.9	57.1	2.0
21	56.6	55.3	59.2	60.2	57.3	57.7	2.0
22	57.4	55.9	59.8	60.5	58.3	58.4	1.8
23	57.8	56.4	60.5	61.3	59.0	59.0	2.0
24	58.4	57.3	61.2	61.9	59.5	59.7	1.9
25	59.1	57.7	61.5	62.3	60.1	60.1	1.8
26	59.4	58.5	62.0	62.9	60.1	60.6	1.8
27	60.1	59.1	62.9	63.4	60.6	61.2	1.8
28	60.5	59.5	63.3	64.1	61.5	61.8	1.9
29	60.8	59.9	63.6	64.5	61.9	62.1	1.9
30	61.5	60.2	63.8	64.8	62.3	62.5	1.8
31	61.9	60.9	64.5	65.5	62.3	63.0	1.9
32	62.3	61.3	64.8	65.8	62.7	63.4	1.8
33	62.9	61.5	65.2	66.2	63.6	63.9	1.9
34	63.0	62.0	65.8	66.2	63.8	64.2	1.8
35	63.6	62.3	66.3	66.5	64.2	64.6	1.8
36	63.8	62.4	66.6	67.0	64.5	64.9	1.9
37	64.0	63.0	66.9	67.2	64.5	65.1	1.8
38	64.5	63.6	67.2	67.4	65.1	65.5	1.7

Table A1: Time-temperature data for heating the sample sphere (0.0127-m diameter) with 73.6°C water flowing at 5.2×10^{-4} m^3/s (five replicates) (contd.).

Time	$T^{*}1$	T2	T3	T4	T5	Avg.**	Std.**
39	64.5	63.6	67.4	67.6	64.9	65.6	1.8
40	64.8	63.8	67.4	67.7	65.5	65.9	1.7
41	65.1	64.1	68.0	67.8	65.8	66.2	1.7
42	65.4	64.7	68.3	68.0	65.9	66.4	1.6
43	65.5	64.9	68.4	68.1	66.0	66.6	1.6
44	65.8	64.9	68.8	68.1	66.2	66.8	1.6
45	65.9	65.5	68.5	68.4	66.7	67.0	1.4
46	65.9	65.9	68.8	68.3	66.7	67.1	1.3
47	66.5	65.9	68.9	68.7	67.0	67.4	1.3
48	66.6	65.9	69.4	68.5	67.2	67.5	1.4
49	66.7	66.3	69.4	68.9	67.7	67.8	1.3
50	67.2	66.6	69.9	68.9	67.4	68.0	1.4
51	67.2	66.6	69.9	68.9	67.8	68.1	1.3
52	67.6	67.0	70.0	68.8	68.3	68.3	1.2
53	67.4	67.0	70.0	69.2	68.0	68.3	1.3
54	67.8	67.4	70.3	69.5	68.4	68.7	1.2
55	68.0	67.3	70.5	69.4	68.3	68.7	1.2
56	68.3	67.4	70.5	69.6	68.7	68.9	1.2
57	68.4	67.6	70.7	69.6	68.8	69.0	1.2
58	68.5	67.8	71.0	69.5	69.1	69.2	1.2
59	68.4	67.6	71.0	69.5	69.4	69.2	1.3
60	68.8	67.8	71.3	69.6	69.1	69.3	1.3
61	68.9	68.0	71.3	69.9	69.5	69.5	1.2
62	68.7	68.3	71.3	69.8	69.4	69.5	1.2
63	68.9	68.5	71.3	69.6	69.5	69.6	1.0
64	69.2	68.3	71.6	69.9	69.9	69.8	1.2
65	68.9	68.5	71.8	70.0	69.9	69.8	1.3
66	69.4	68.5	71.8	69.9	69.8	69.9	1.2
67	69.4	68.5	71.6	69.9	70.0	69.9	1.1
68	69.4	68.8	71.7	70.0	70.0	70.0	1.1
69	69.8	68.9	71.7	69.9	70.6	70.2	1.0
70	69.6	68.8	71.8	70.0	70.6	70.2	1.1
71	69.8	69.1	72.0	70.2	70.3	70.3	1.1
72	69.9	69.4	71.8	70.5	70.7	70.5	0.9
73	69.9	69.4	72.0	70.2	70.5	70.4	1.0
74	70.2	69.2	72.2	70.2	70.9	70.5	1.1
75	70.3	69.4	72.1	70.2	71.0	70.6	1.0
76	70.2	69.2	72.1	70.5	70.7	70.5	1.0

Table A1: Time-temperature data for heating the sample sphere (0.0127-m diameter) with 73.6°C water flowing at 5.2×10^{-4} m^3/s (five replicates) (contd.).

Time	T*1	T2	T3	T4	T5	Avg.**	Std.**
77	70.5	69.6	72.2	70.7	71.1	70.8	1.0
78	70.3	69.6	72.1	70.5	71.1	70.7	0.9
79	70.5	69.8	72.4	70.6	71.0	70.8	1.0
80	70.5	69.8	72.4	70.9	71.4	71.0	1.0
81	70.5	69.8	72.4	70.6	71.3	70.9	1.0
82	70.5	70.2	72.1	70.6	71.6	71.0	0.8
83	70.6	70.6	72.2	70.9	71.3	71.1	0.7
84	70.6	70.5	72.4	70.9	71.6	71.2	0.8
85	70.6	70.7	72.4	71.0	71.8	71.3	0.8
86	70.9	71.1	72.4	70.6	72.0	71.4	0.8
87	70.6	71.0	72.1	71.0	72.1	71.4	0.7
88	70.9	71.0	72.5	71.0	71.8	71.4	0.7
89	70.9	71.4	72.1	71.0	71.8	71.4	0.5
90	70.9	71.6	72.2	70.9	72.2	71.5	0.7
91	71.3	71.6	72.4	71.0	72.4	71.7	0.6
92	71.0	71.4	72.4	71.3	72.4	71.7	0.6
93	71.3	71.6	72.2	71.1	72.2	71.7	0.5
94	71.3	71.6	72.0	70.9	72.1	71.5	0.5
95	71.1	71.7	72.1	70.9	72.4	71.6	0.6
96	71.4	71.7	72.4	71.3	72.2	71.8	0.5
97	71.4	71.8	72.4	71.1	72.1	71.8	0.5
98	71.4	71.8	72.2	71.3	72.2	71.8	0.4
99	71.6	71.8	72.2	71.0	72.2	71.8	0.5
100	71.6	71.8	71.8	71.0	72.5	71.7	0.5
101	71.7	71.8	72.2	71.4	72.4	71.9	0.4
102	71.7	71.8	72.1	71.4	72.2	71.9	0.3
103	71.6	72.0	72.0	71.4	72.5	71.9	0.4
104	72.0	71.8	71.8	71.1	72.4	71.8	0.4
105	71.7	71.8	71.8	71.1	72.1	71.7	0.4
106	71.7	72.0	71.8	71.6	72.6	71.9	0.4
107	72.1	71.7	72.1	71.4	72.4	71.9	0.4
108	71.7	71.8	72.0	71.7	72.6	72.0	0.4
109	72.0	72.0	72.0	71.6	72.2	71.9	0.2
110	72.1	71.8	72.1	71.6	72.2	72.0	0.3
111	72.0	71.8	72.0	71.6	72.4	71.9	0.3
112	72.2	71.8	72.1	71.1	72.4	71.9	0.5
113	72.2	71.8	72.0	71.4	72.6	72.0	0.5
114	72.1	72.0	71.7	71.8	72.4	72.0	0.3

Table A1: Time-temperature data for heating the sample sphere (0.0127-m diameter) with 73.6°C water flowing at 5.2×10^{-4} m^3/s (five replicates) (contd.).

Time	T* 1	T2	T3	T4	T5	Avg.**	Std.**
115	72.2	72.0	71.8	72.0	72.4	72.1	0.2
116	72.0	72.1	71.6	72.0	72.8	72.1	0.4
117	72.2	72.0	71.8	72.1	72.8	72.2	0.4
118	72.2	72.1	72.0	72.1	72.4	72.2	0.2
119	72.2	72.1	71.6	72.4	72.8	72.2	0.4
120	72.4	72.2	71.8	72.4	72.6	72.3	0.3
121	72.1	72.1	72.0	72.4	72.6	72.2	0.3
122	72.2	72.4	71.7	72.6	72.5	72.3	0.4
123	72.5	72.2	71.8	72.6	72.5	72.3	0.3
124	72.2	72.4	71.8	72.4	73.1	72.4	0.4
125	72.4	72.4	72.1	72.6	72.9	72.5	0.3
126	72.6	72.4	72.0	72.8	72.8	72.5	0.3
127	72.5	72.5	71.8	72.9	73.1	72.6	0.5
128	72.6	72.4	71.7	72.9	73.2	72.6	0.6
129	72.6	72.5	71.8	72.8	73.2	72.6	0.5
130	72.5	72.5	71.7	72.9	72.8	72.5	0.5
131	72.8	72.5	71.7	72.9	73.3	72.6	0.6
132	72.6	72.6	71.6	73.1	73.5	72.7	0.7
133	72.5	72.4	71.8	73.1	72.8	72.5	0.5
134	72.8	72.8	71.6	73.1	73.5	72.7	0.7
135	72.5	72.6	71.6	73.1	73.3	72.6	0.7
136	72.8	72.4	71.8	73.2	73.2	72.7	0.6

* Temperature (°C)
** Average of five replicates
*** Standard deviation (°C)

Table A2: Time-temperature profile for heating the sample sphere (0.0127-m diameter) in presence of another sphere (0.0127-m diameter) at a distance of 0.0254 m upstream at an angle of 0° from the horizontal plane of the sample sphere, with 73.6°C water flowing at 5.2×10^{-4} m^3/s (five replicates).

Time	T*1	T2	T3	T4	T5	Avg.**	Std.***
0	28.9	28.8	29.3	28.3	29.5	28.9	0.4
1	30.6	30.2	32.0	30.3	31.4	30.9	0.7
2	32.4	33.1	33.6	33.4	33.6	33.2	0.4
3	34.0	35.3	35.5	35.9	35.9	35.3	0.7
4	36.2	36.8	37.8	37.1	37.5	37.1	0.6
5	38.8	39.0	39.5	39.0	39.0	39.1	0.3
6	40.7	40.1	40.8	40.0	41.0	40.5	0.4
7	43.0	41.7	42.7	42.1	42.6	42.4	0.5
8	44.3	43.9	44.2	43.4	44.3	44.0	0.3
9	45.9	44.7	45.6	45.2	44.7	45.2	0.5
10	47.0	45.9	47.0	46.6	47.2	46.7	0.5
11	48.3	47.9	48.6	47.5	47.2	47.9	0.5
12	49.2	48.7	49.0	49.0	48.7	48.9	0.2
13	50.5	49.6	50.7	49.9	50.5	50.2	0.4
14	51.7	50.5	51.3	50.5	50.9	51.0	0.5
15	52.4	51.7	52.2	52.3	51.7	52.1	0.3
16	53.4	52.9	53.6	52.9	53.0	53.1	0.3
17	54.3	53.1	54.1	53.3	53.4	53.7	0.5
18	55.3	54.4	54.4	54.0	55.0	54.6	0.5
19	56.1	55.0	55.5	54.8	55.0	55.3	0.5
20	56.7	55.5	56.3	54.4	56.7	55.9	0.8
21	57.5	57.0	57.3	54.4	56.3	56.5	1.1
22	58.4	57.2	58.1	57.1	57.4	57.6	0.5
23	59.1	57.5	59.1	58.4	57.9	58.4	0.6
24	59.2	58.6	59.3	58.5	58.8	58.9	0.3
25	59.8	58.9	59.5	59.3	59.1	59.3	0.3
26	60.7	59.5	60.9	60.0	60.2	60.3	0.5
27	61.2	60.5	60.6	59.8	60.5	60.5	0.4
28	61.6	61.0	60.9	61.0	60.5	61.0	0.4
29	62.3	61.2	61.7	61.2	61.4	61.5	0.4
30	62.4	62.0	61.7	61.3	61.4	61.8	0.4
31	63.0	62.3	62.3	62.3	62.7	62.5	0.3
32	63.5	62.3	63.3	62.0	62.9	62.8	0.6
33	63.8	62.8	63.1	62.8	63.7	63.2	0.4
34	63.9	63.7	64.2	63.7	63.0	63.7	0.4

Table A2: Time-temperature profile for heating the sample sphere (0.0127-m diameter) in presence of another sphere (0.0127-m diameter) at a distance of 0.0254 m upstream at an angle of 0° from the horizontal plane of the sample sphere, with 73.6°C water flowing at 5.2×10^{-4} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
35	64.6	63.9	63.5	63.1	63.8	63.8	0.5
36	64.5	64.2	63.9	64.2	64.4	64.3	0.2
37	65.1	64.1	65.2	64.8	64.6	64.7	0.4
38	65.5	64.8	65.8	65.3	64.6	65.2	0.4
39	65.5	65.1	66.0	65.3	64.8	65.3	0.4
40	65.7	65.1	65.3	64.5	65.2	65.2	0.4
41	66.2	65.9	65.9	66.0	65.7	65.9	0.1
42	66.4	66.2	66.6	65.9	66.6	66.3	0.3
43	66.4	66.4	66.7	65.7	66.9	66.4	0.4
44	66.9	66.4	66.7	66.0	67.1	66.6	0.4
45	67.3	66.7	67.3	66.4	67.4	67.0	0.4
46	67.7	66.2	67.2	66.4	67.5	67.0	0.6
47	67.8	61.6	67.4	67.4	67.1	66.3	2.4
48	68.0	73.9	67.8	67.0	67.1	68.7	2.6
49	68.0	68.9	67.7	67.7	67.6	68.0	0.5
50	68.5	69.9	68.1	68.1	67.7	68.5	0.8
51	68.4	69.9	68.0	67.4	68.0	68.3	0.8
52	68.5	69.9	68.1	68.8	68.4	68.7	0.6
53	68.8	68.5	69.2	68.7	68.5	68.7	0.3
54	69.3	69.9	69.2	65.9	69.1	68.7	1.4
55	69.2	69.9	69.2	69.2	68.8	69.3	0.4
56	69.5	69.9	69.2	68.9	68.7	69.2	0.4
57	69.6	68.9	69.4	69.8	69.0	69.3	0.3
58	69.6	69.5	69.8	68.7	69.9	69.5	0.4
59	70.2	69.8	69.8	69.1	69.9	69.7	0.4
60	70.3	69.3	69.3	69.9	69.6	69.7	0.4
61	70.2	70.3	68.4	69.3	69.2	69.5	0.7
62	70.3	70.0	69.0	69.6	69.6	69.7	0.4
63	70.4	69.8	68.5	70.2	70.6	69.9	0.7
64	71.0	70.3	69.8	70.8	69.9	70.3	0.5
65	70.7	70.0	70.3	70.9	70.9	70.6	0.3
66	71.1	70.6	70.1	70.4	70.7	70.6	0.3
67	71.3	70.9	70.9	70.3	70.2	70.7	0.4
68	71.0	70.9	70.9	70.6	71.4	70.9	0.3
69	71.4	70.6	69.8	70.9	70.4	70.6	0.5
70	71.5	71.0	70.3	70.6	71.5	71.0	0.5

Table A2: Time-temperature profile for heating the sample sphere (0.0127-m diameter) in presence of another sphere (0.0127-m diameter) at a distance of 0.0254 m upstream at an angle of 0° from the horizontal plane of the sample sphere, with 73.6°C water flowing at 5.2×10^{-4} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
71	71.3	71.4	70.2	71.0	70.6	70.9	0.4
72	71.7	71.4	71.3	70.9	70.7	71.2	0.4
73	71.8	72.0	71.1	71.1	70.7	71.4	0.5
74	71.8	71.3	70.0	71.4	71.5	71.2	0.6
75	71.8	72.1	70.6	71.0	71.4	71.4	0.5
76	72.0	71.8	70.3	71.5	70.3	71.2	0.7
77	72.0	71.5	67.7	71.3	71.5	70.8	1.6
78	72.0	72.1	71.7	72.4	71.3	71.9	0.4
79	72.2	71.7	72.2	72.0	71.4	71.9	0.3
80	72.1	72.4	71.1	71.4	71.6	71.7	0.5
81	72.5	72.2	72.0	71.4	72.5	72.1	0.4
82	72.2	72.0	71.4	72.1	71.5	71.8	0.3
83	72.5	72.8	72.2	72.6	72.5	72.5	0.2
84	72.5	72.5	72.5	72.1	71.5	72.2	0.4
85	72.8	72.4	72.0	72.1	72.1	72.3	0.3
86	72.8	72.8	72.4	72.4	72.2	72.5	0.2
87	72.9	72.4	71.4	71.5	72.5	72.1	0.6
88	72.5	72.5	72.4	72.9	72.4	72.5	0.2
89	72.8	72.8	72.5	72.5	72.5	72.6	0.1
90	72.8	72.5	72.0	72.1	72.6	72.4	0.3
91	72.9	72.6	72.8	72.6	73.3	72.8	0.2
92	73.1	72.6	73.1	72.5	73.2	72.9	0.3
93	73.1	73.1	72.4	72.4	73.1	72.8	0.4
94	73.2	72.9	72.8	72.6	73.3	73.0	0.3
95	72.8	72.5	73.2	73.1	72.5	72.8	0.3
96	72.9	72.6	73.1	72.6	72.9	72.8	0.2
97	72.9	73.3	73.2	72.9	72.2	72.9	0.4
98	73.5	72.6	72.5	72.9	72.9	72.9	0.3
99	73.3	73.3	73.6	73.7	73.2	73.4	0.2
100	73.5	73.1	73.3	73.2	73.5	73.3	0.2
101	73.1	72.8	72.8	72.8	72.9	72.9	0.1
102	73.5	73.1	73.2	73.1	73.7	73.3	0.3
103	73.5	73.3	73.2	73.2	73.4	73.3	0.1
104	73.3	73.2	73.5	72.8	73.9	73.3	0.4
105	73.5	73.6	72.5	73.5	73.9	73.4	0.5
106	73.2	73.1	73.3	72.8	73.5	73.2	0.2

Table A2: Time-temperature profile for heating the sample sphere (0.0127-m diameter) in presence of another sphere (0.0127-m diameter) at a distance of 0.0254 m upstream at an angle of 0° from the horizontal plane of the sample sphere, with 73.6°C water flowing at 5.2×10^{-4} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
107	73.5	73.3	73.6	73.9	73.1	73.5	0.3
108	73.3	73.2	73.3	72.6	73.2	73.1	0.3
109	73.6	73.3	73.3	73.1	73.7	73.4	0.2

* Temperature (°C)
** Average of five replicates
*** Standard deviation (°C)

Table A3: Time-temperature data for heating the sample sphere (0.0127-m diameter) in presence of another sphere (0.0127-m diameter) at a distance of 0.0254 m upstream at an angle of 30° from the horizontal plane of the sample sphere, with 73.6°C water flowing at 5.2×10^{-4} m^3/s (five replicates).

Time	T*1	T2	T3	T4	T5	Avg.**	Std.***
0	26.2	24.7	26.9	25.4	25.9	25.8	1.0
1	29.7	28.2	30.2	28.7	29.4	29.3	0.9
2	32.0	30.5	33.0	31.5	31.8	31.7	1.0
3	34.0	32.5	35.3	33.8	34.0	33.9	1.2
4	35.8	34.3	37.5	36.0	35.8	35.9	1.3
5	37.2	35.7	39.5	38.0	37.5	37.6	1.6
6	39.3	37.8	41.6	40.1	39.5	39.6	1.6
7	40.8	39.3	43.3	41.8	41.2	41.3	1.7
8	42.7	41.2	44.9	43.4	42.9	43.0	1.5
9	44.5	43.0	46.5	45.0	44.6	44.7	1.4
10	45.9	44.4	47.9	46.4	46.1	46.1	1.4
11	47.3	45.8	49.2	47.7	47.4	47.5	1.4
12	48.7	47.2	50.5	49.0	48.8	48.8	1.3
13	49.9	48.4	51.4	49.9	49.9	49.9	1.3
14	50.7	49.2	52.9	51.4	50.9	51.0	1.5
15	52.0	50.5	53.7	52.2	52.1	52.1	1.3
16	53.0	51.5	54.7	53.2	53.1	53.1	1.3
17	53.9	52.4	56.0	54.5	54.1	54.1	1.5
18	54.6	53.1	56.7	55.2	54.8	54.8	1.5
19	55.4	53.9	57.5	56.0	55.6	55.7	1.5
20	56.4	54.9	58.2	56.7	56.5	56.5	1.4
21	57.0	55.5	58.9	57.4	57.1	57.2	1.4
22	57.5	56.0	59.5	58.0	57.7	57.7	1.4
23	58.4	56.9	60.2	58.7	58.5	58.5	1.4
24	58.6	57.1	60.9	59.4	58.9	59.0	1.6
25	59.3	57.8	61.4	59.9	59.5	59.6	1.5
26	59.9	58.4	61.9	60.4	60.1	60.1	1.4
27	60.3	58.8	62.6	61.1	60.6	60.7	1.6
28	61.0	59.5	63.1	61.6	61.2	61.3	1.5
29	61.3	59.8	63.3	61.8	61.4	61.5	1.4
30	61.7	60.2	63.8	62.3	61.9	62.0	1.5
31	62.0	60.5	64.4	62.9	62.3	62.4	1.6
32	62.7	61.2	64.8	63.3	62.9	63.0	1.5
33	63.0	61.5	65.1	63.6	63.2	63.2	1.5
34	63.3	61.8	65.3	63.8	63.4	63.5	1.5
35	63.5	62.0	65.6	64.1	63.7	63.8	1.5
36	63.9	62.4	66.0	64.5	64.1	64.2	1.5

Table A3: Time-temperature data for heating the sample sphere (0.0127-m diameter) in presence of another sphere (0.0127-m diameter) at a distance of 0.0254 m upstream at an angle of 30° from the horizontal plane of the sample sphere, with 73.6°C water flowing at $5.2x10^{-4}$ m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
37	64.2	62.7	66.3	64.8	64.4	64.5	1.5
38	64.8	63.3	66.6	65.1	64.9	64.9	1.4
39	65.1	63.6	67.0	65.5	65.2	65.3	1.4
40	65.3	63.8	67.1	65.6	65.4	65.5	1.4
41	65.6	64.1	67.4	65.9	65.7	65.8	1.4
42	65.9	64.4	67.5	66.0	65.9	66.0	1.3
43	66.0	64.5	67.7	66.2	66.1	66.1	1.3
44	66.4	64.9	67.8	66.3	66.4	66.4	1.2
45	66.7	65.2	68.0	66.5	66.6	66.6	1.1
46	66.9	65.4	68.2	66.7	66.8	66.8	1.2
47	67.1	65.6	68.2	66.7	67.0	66.9	1.1
48	67.3	65.8	68.7	67.2	67.2	67.2	1.2
49	67.5	66.0	68.8	67.3	67.5	67.4	1.1
50	67.7	66.2	68.9	67.4	67.6	67.6	1.1
51	68.0	66.5	68.9	67.4	67.8	67.7	1.0
52	68.1	66.6	69.2	67.7	68.0	67.9	1.1
53	68.4	66.9	69.2	67.7	68.2	68.1	1.0
54	68.7	67.2	69.2	67.7	68.3	68.2	0.9
55	68.8	67.3	69.5	68.0	68.5	68.4	1.0
56	69.1	67.6	69.5	68.0	68.7	68.6	0.9
57	69.1	67.6	69.8	68.3	68.8	68.7	1.0
58	69.2	67.7	69.8	68.3	68.9	68.8	0.9
59	69.5	68.0	69.9	68.4	69.1	69.0	0.9
60	69.5	68.0	69.9	68.4	69.1	69.0	0.9
61	69.8	68.3	70.2	68.7	69.4	69.2	0.9
62	69.8	68.3	70.3	68.8	69.4	69.3	0.9
63	70.0	68.5	70.3	68.8	69.6	69.5	0.9
64	70.2	68.7	70.4	68.9	69.8	69.6	0.9
65	70.0	68.5	70.4	68.9	69.7	69.5	0.9
66	70.4	68.9	70.7	69.2	70.0	69.9	0.9
67	70.4	68.9	70.9	69.4	70.1	69.9	0.9
68	70.3	68.8	70.9	69.4	70.0	69.9	0.9
69	70.6	69.1	70.9	69.4	70.2	70.0	0.9
70	70.7	69.2	70.9	69.4	70.3	70.1	0.9
71	70.9	69.4	71.1	69.6	70.4	70.3	0.9
72	71.0	69.5	71.4	69.9	70.6	70.5	0.9

Table A3: Time-temperature data for heating the sample sphere (0.0127-m diameter) in presence of another sphere (0.0127-m diameter) at a distance of 0.0254 m upstream at an angle of 30° from the horizontal plane of the sample sphere, with 73.6°C water flowing at 5.2×10^{-4} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
73	71.1	69.6	71.3	69.8	70.7	70.5	0.9
74	71.0	69.5	71.4	69.9	70.6	70.5	0.9
75	71.1	69.6	71.5	70.0	70.8	70.6	0.9
76	71.3	69.8	71.7	70.2	70.9	70.8	0.9
77	71.3	69.8	71.8	70.3	71.0	70.8	0.9
78	71.3	69.8	71.8	70.3	71.0	70.8	0.9
79	71.4	69.9	72.0	70.5	71.1	71.0	0.9
80	71.5	70.0	72.0	70.5	71.2	71.0	0.9
81	71.5	70.0	72.0	70.5	71.2	71.0	0.9
82	71.7	70.2	72.1	70.6	71.3	71.2	0.9
83	71.8	70.3	72.2	70.7	71.5	71.3	0.9
84	72.0	70.5	72.2	70.7	71.5	71.4	0.9
85	71.8	70.3	72.4	70.9	71.5	71.4	0.9
86	72.0	70.5	72.4	70.9	71.6	71.4	0.9
87	72.0	70.5	72.5	71.0	71.6	71.5	0.9
88	72.1	70.6	72.6	71.1	71.8	71.6	0.9
89	72.1	70.6	72.5	71.0	71.7	71.6	0.9
90	72.2	70.7	72.6	71.1	71.9	71.7	0.9
91	72.4	70.9	72.6	71.1	72.0	71.8	0.9
92	72.4	70.9	72.6	71.1	72.0	71.8	0.9
93	72.2	70.7	72.9	71.4	72.0	71.8	1.0
94	72.4	70.9	72.6	71.1	72.0	71.8	0.9
95	72.4	70.9	72.6	71.1	72.0	71.8	0.9
96	72.2	70.7	72.6	71.1	71.9	71.7	0.9
97	72.4	70.9	72.6	71.1	72.0	71.8	0.9
98	72.4	70.9	72.8	71.3	72.0	71.9	0.9
99	72.5	71.0	72.9	71.4	72.1	72.0	0.9
100	72.4	70.9	72.9	71.4	72.0	71.9	0.9
101	72.4	70.9	72.9	71.4	72.0	71.9	0.9
102	72.5	71.0	72.9	71.4	72.1	72.0	0.9
103	72.5	71.0	72.9	71.4	72.1	72.0	0.9
104	72.5	71.0	73.1	71.6	72.2	72.1	0.9
105	72.5	71.0	72.9	71.4	72.1	72.0	0.9
106	72.5	71.0	73.2	71.7	72.2	72.1	1.0
107	72.6	71.1	73.1	71.6	72.3	72.1	0.9
108	72.5	71.0	73.1	71.6	72.2	72.1	0.9

Table A3: Time-temperature data for heating the sample sphere (0.0127-m diameter) in presence of another sphere (0.0127-m diameter) at a distance of 0.0254 m upstream at an angle of 30° from the horizontal plane of the sample sphere, with 73.6°C water flowing at $5.2x10^{-4}$ m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
109	72.5	71.0	73.2	71.7	72.2	72.1	1.0
110	72.8	71.3	73.1	71.6	72.4	72.2	0.9
111	72.5	71.0	73.3	71.8	72.3	72.2	1.0
112	72.5	71.0	73.3	71.8	72.3	72.2	1.0
113	72.6	71.1	73.2	71.7	72.3	72.2	0.9
114	72.6	71.1	73.5	72.0	72.4	72.3	1.0
115	72.6	71.1	73.3	71.8	72.4	72.3	1.0
116	72.8	71.3	73.6	72.1	72.5	72.5	1.0
117	72.9	71.4	73.6	72.1	72.6	72.5	1.0
118	72.8	71.3	73.3	71.8	72.5	72.3	0.9
119	73.1	71.6	73.6	72.1	72.7	72.6	0.9
120	73.1	71.6	73.5	72.0	72.7	72.5	0.9
121	73.1	71.6	73.6	72.1	72.7	72.6	0.9
122	73.2	71.7	73.7	72.2	72.9	72.7	0.9
123	73.2	71.7	73.7	72.2	72.9	72.7	0.9
124	73.2	71.7	73.7	72.2	72.9	72.7	0.9
125	73.2	71.7	73.9	72.4	72.9	72.8	1.0
126	73.5	72.0	73.9	72.4	73.1	73.0	0.9
127	73.5	72.0	73.9	72.4	73.1	73.0	0.9

* Temperature (°C)

** Average of five replicates

*** Standard deviation (°C)

Table A4: Time-temperature profile for heating the sample sphere (0.0127-m diameter) in presence of another sphere (0.0127-m diameter) at a distance of 0.0254 m upstream at an angle of 45° from the horizontal plane of the sample sphere, with 73.6°C water flowing at 5.2×10^{-4} m^3/s (five replicates).

Time	T* 1	T2	T3	T4	T5	Avg.**	Std.***
0.0	27.5	26.0	28.7	27.2	27.4	27.4	1.1
1.0	30.8	29.3	32.1	30.6	30.7	30.7	1.2
2.0	33.4	31.9	34.6	33.1	33.3	33.3	1.1
3.0	35.2	33.7	36.1	34.6	34.9	35.0	1.0
4.0	36.1	34.6	37.5	36.0	36.0	36.0	1.2
5.0	37.5	36.0	39.1	37.6	37.6	37.5	1.3
6.0	39.1	37.6	40.6	39.1	39.1	39.1	1.2
7.0	40.7	39.2	42.1	40.6	40.7	40.7	1.2
8.0	42.3	40.8	43.3	41.8	42.0	42.1	1.0
9.0	43.6	42.1	44.9	43.4	43.5	43.5	1.1
10.0	45.0	43.5	46.0	44.5	44.8	44.9	1.0
11.0	46.5	45.0	47.3	45.8	46.1	46.2	1.0
12.0	47.6	46.1	48.3	46.8	47.2	47.3	1.0
13.0	48.7	47.2	49.3	47.8	48.3	48.4	0.9
14.0	49.7	48.2	50.2	48.7	49.2	49.4	0.9
15.0	50.7	49.2	51.3	49.8	50.3	50.4	0.9
16.0	51.7	50.2	52.0	50.5	51.1	51.3	0.9
17.0	52.7	51.2	53.1	51.6	52.2	52.4	0.9
18.0	53.6	52.1	53.7	52.2	52.9	53.1	0.9
19.0	54.4	52.9	54.4	52.9	53.7	53.9	0.9
20.0	55.1	53.6	55.1	53.6	54.4	54.6	0.9
21.0	55.8	54.3	55.8	54.3	55.1	55.3	0.9
22.0	56.7	55.2	56.5	55.0	55.9	56.1	0.9
23.0	57.2	55.7	57.2	55.7	56.5	56.7	0.9
24.0	57.9	56.4	57.7	56.2	57.0	57.3	0.9
25.0	58.5	57.0	58.5	57.0	57.8	58.0	0.9
26.0	59.1	57.6	59.1	57.6	58.3	58.6	0.9
27.0	59.6	58.1	59.5	58.0	58.8	59.1	0.9
28.0	60.2	58.7	60.0	58.5	59.4	59.6	0.9
29.0	60.6	59.1	60.5	59.0	59.8	60.1	0.9
30.0	61.2	59.7	61.0	59.5	60.3	60.6	0.9
31.0	61.4	59.9	61.4	59.9	60.7	60.9	0.9
32.0	62.0	60.5	62.0	60.5	61.2	61.5	0.9
33.0	62.3	60.8	62.1	60.6	61.5	61.7	0.9
34.0	62.7	61.2	62.7	61.2	61.9	62.2	0.9
35.0	63.1	61.6	63.1	61.6	62.4	62.6	0.9

Table A4: Time-temperature profile for heating the sample sphere (0.0127-m diameter) in presence of another sphere (0.0127-m diameter) at a distance of 0.0254 m upstream at an angle of 45° from the horizontal plane of the sample sphere, with 73.6°C water flowing at 5.2×10^{-4} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
36.0	63.4	61.9	63.7	62.2	62.8	63.0	0.9
37.0	63.7	62.2	63.8	62.3	63.0	63.2	0.9
38.0	63.9	62.4	64.1	62.6	63.3	63.5	0.9
39.0	64.4	62.9	64.6	63.1	63.8	64.0	0.9
40.0	64.5	63.0	64.6	63.1	63.8	64.0	0.9
41.0	64.9	63.4	65.2	63.7	64.3	64.5	0.9
42.0	65.2	63.7	65.5	64.0	64.6	64.8	0.9
43.0	65.5	64.0	65.7	64.2	64.9	65.1	0.9
44.0	65.6	64.1	66.2	64.7	65.1	65.3	0.9
45.0	66.0	64.5	66.3	64.8	65.4	65.6	0.9
46.0	66.2	64.7	66.3	64.8	65.5	65.7	0.9
47.0	66.4	64.9	66.9	65.4	65.9	66.1	0.9
48.0	66.7	65.2	67.0	65.5	66.1	66.3	0.9
49.0	67.0	65.5	67.1	65.6	66.3	66.5	0.9
50.0	67.0	65.5	67.4	65.9	66.5	66.6	0.9
51.0	67.4	65.9	67.7	66.2	66.8	67.0	0.9
52.0	67.5	66.0	67.8	66.3	66.9	67.1	0.9
53.0	67.8	66.3	68.1	66.6	67.2	67.4	0.9
54.0	67.8	66.3	68.2	66.7	67.3	67.5	0.9
55.0	68.1	66.6	68.5	67.0	67.6	67.7	0.9
56.0	68.4	66.9	68.7	67.2	67.8	68.0	0.9
57.0	68.4	66.9	68.8	67.3	67.8	68.0	0.9
58.0	68.7	67.2	68.9	67.4	68.0	68.2	0.9
59.0	68.9	67.4	69.2	67.7	68.3	68.5	0.9
60.0	68.9	67.4	69.2	67.7	68.3	68.5	0.9
61.0	69.2	67.7	69.5	68.0	68.6	68.8	0.9
62.0	69.3	67.8	69.6	68.1	68.7	68.9	0.9
63.0	69.3	67.8	69.6	68.1	68.7	68.9	0.9
64.0	69.8	68.3	69.9	68.4	69.1	69.3	0.9
65.0	69.9	68.4	69.9	68.4	69.1	69.4	0.9
66.0	70.0	68.5	70.0	68.5	69.3	69.5	0.9
67.0	70.0	68.5	70.2	68.7	69.3	69.6	0.9
68.0	70.2	68.7	70.2	68.7	69.4	69.7	0.9
69.0	70.3	68.8	70.4	68.9	69.6	69.9	0.9
70.0	70.4	68.9	70.4	68.9	69.7	69.9	0.9
71.0	70.6	69.1	70.4	68.9	69.8	70.0	0.9

Table A4: Time-temperature profile for heating the sample sphere (0.0127-m diameter) in presence of another sphere (0.0127-m diameter) at a distance of 0.0254 m upstream at an angle of 45° from the horizontal plane of the sample sphere, with 73.6°C water flowing at 5.2×10^{-4} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
72.0	70.9	69.4	70.9	69.4	70.1	70.4	0.9
73.0	70.9	69.4	70.9	69.4	70.1	70.4	0.9
74.0	70.9	69.4	71.0	69.5	70.2	70.4	0.9
75.0	71.1	69.6	71.0	69.5	70.3	70.6	0.9
76.0	71.0	69.5	71.0	69.5	70.2	70.5	0.9
77.0	71.1	69.6	71.1	69.6	70.4	70.6	0.9
78.0	71.1	69.6	71.3	69.8	70.4	70.7	0.9
79.0	71.4	69.9	71.3	69.8	70.6	70.9	0.9
80.0	71.4	69.9	71.4	69.9	70.7	70.9	0.9
81.0	71.4	69.9	71.4	69.9	70.7	70.9	0.9
82.0	71.5	70.0	71.5	70.0	70.8	71.0	0.9
83.0	71.7	70.2	71.5	70.0	70.9	71.1	0.9
84.0	71.4	69.9	71.5	70.0	70.7	70.9	0.9
85.0	71.7	70.2	71.8	70.3	71.0	71.2	0.9
86.0	71.8	70.3	71.8	70.3	71.1	71.3	0.9
87.0	71.7	70.2	71.8	70.3	71.0	71.2	0.9
88.0	72.0	70.5	72.1	70.6	71.3	71.5	0.9
89.0	72.0	70.5	72.1	70.6	71.3	71.5	0.9
90.0	72.1	70.6	72.1	70.6	71.3	71.6	0.9
91.0	72.0	70.5	72.4	70.9	71.4	71.6	0.9
92.0	72.0	70.5	72.4	70.9	71.4	71.6	0.9
93.0	72.2	70.7	72.5	71.0	71.6	71.8	0.9
94.0	72.1	70.6	72.6	71.1	71.6	71.8	0.9
95.0	72.4	70.9	72.6	71.1	71.8	72.0	0.9
96.0	72.4	70.9	72.6	71.1	71.8	72.0	0.9
97.0	72.2	70.7	72.6	71.1	71.7	71.9	0.9
98.0	72.4	70.9	72.8	71.3	71.8	72.0	0.9
99.0	72.5	71.0	73.1	71.6	72.0	72.2	0.9
100.0	72.5	71.0	73.1	71.6	72.0	72.2	0.9
101.0	72.6	71.1	72.9	71.4	72.0	72.2	0.9
102.0	72.8	71.3	73.1	71.6	72.2	72.4	0.9
103.0	72.8	71.3	73.1	71.6	72.2	72.4	0.9
104.0	72.8	71.3	73.2	71.7	72.2	72.4	0.9
105.0	72.8	71.3	73.2	71.7	72.2	72.4	0.9
106.0	73.1	71.6	73.2	71.7	72.4	72.6	0.9
107.0	73.1	71.6	73.3	71.8	72.4	72.6	0.9

Table A4: Time-temperature profile for heating the sample sphere (0.0127-m diameter) in presence of another sphere (0.0127-m diameter) at a distance of 0.0254 m upstream at an angle of 45° from the horizontal plane of the sample sphere, with 73.6°C water flowing at 5.2×10^{-4} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
108.0	73.1	71.6	73.2	71.7	72.4	72.6	0.9
109.0	73.1	71.6	73.3	71.8	72.4	72.6	0.9
110.0	73.1	71.6	73.5	72.0	72.5	72.7	0.9
111.0	73.1	71.6	73.3	71.8	72.4	72.6	0.9
112.0	73.3	71.8	73.5	72.0	72.6	72.9	0.9
113.0	73.2	71.7	73.6	72.1	72.6	72.8	0.9
114.0	73.3	71.8	73.5	72.0	72.6	72.9	0.9
115.0	73.3	71.8	73.5	72.0	72.6	72.9	0.9
116.0	73.5	72.0	73.6	72.1	72.8	73.0	0.9
117.0	73.5	72.0	73.5	72.0	72.7	73.0	0.9
118.0	73.5	72.0	73.6	72.1	72.8	73.0	0.9
119.0	73.6	72.1	73.6	72.1	72.8	73.1	0.9
120.0	73.6	72.1	73.5	72.0	72.8	73.1	0.9
121.0	73.3	71.8	73.6	72.1	72.7	72.9	0.9
122.0	73.6	72.1	73.5	72.0	72.8	73.1	0.9
123.0	73.6	72.1	73.6	72.1	72.8	73.1	0.9
124.0	73.6	72.1	73.6	72.1	72.8	73.1	0.9
125.0	73.6	72.1	73.6	72.1	72.8	73.1	0.9
126.0	73.5	72.0	73.7	72.2	72.8	73.1	0.9
127.0	73.6	72.1	73.6	72.1	72.8	73.1	0.9
128.0	73.6	72.1	73.6	72.1	72.8	73.1	0.9
129.0	73.6	72.1	73.7	72.2	72.9	73.1	0.9
130.0	73.6	72.1	73.7	72.2	72.9	73.1	0.9
131.0	73.6	72.1	73.7	72.2	72.9	73.1	0.9
132.0	73.6	72.1	73.7	72.2	72.9	73.1	0.9
133.0	73.5	72.0	73.6	72.1	72.8	73.0	0.9
134.0	73.6	72.1	73.7	72.2	72.9	73.1	0.9
135.0	73.6	72.1	73.7	72.2	72.9	73.1	0.9
136.0	73.6	72.1	73.7	72.2	72.9	73.1	0.9
137.0	73.6	72.1	74.0	72.5	73.1	73.2	0.9
138.0	73.6	72.1	73.9	72.4	73.0	73.2	0.9
139.0	73.7	72.2	73.9	72.4	73.1	73.3	0.9
140.0	73.6	72.1	74.0	72.5	73.1	73.2	0.9
141.0	73.7	72.2	74.0	72.5	73.1	73.3	0.9
142.0	73.7	72.2	74.1	72.6	73.2	73.4	0.9
143.0	73.7	72.2	74.3	72.8	73.3	73.4	0.9

Table A4: Time-temperature profile for heating the sample sphere (0.0127-m diameter) in presence of another sphere (0.0127-m diameter) at a distance of 0.0254 m upstream at an angle of 45° from the horizontal plane of the sample sphere, with 73.6°C water flowing at 5.2×10^{-4} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
144.0	73.9	72.4	74.3	72.8	73.3	73.5	0.9
145.0	73.7	72.2	74.1	72.6	73.2	73.4	0.9
146.0	73.7	72.2	74.3	72.8	73.3	73.4	0.9
147.0	73.9	72.4	74.3	72.8	73.3	73.5	0.9
148.0	73.9	72.4	74.3	72.8	73.3	73.5	0.9
149.0	74.0	72.5	74.3	72.8	73.4	73.6	0.9
150.0	73.9	72.4	74.6	73.1	73.5	73.6	1.0
151.0	74.1	72.6	74.4	72.9	73.5	73.7	0.9
152.0	74.0	72.5	74.4	72.9	73.5	73.6	0.9
153.0	74.1	72.6	74.6	73.1	73.6	73.8	0.9
154.0	74.1	72.6	74.3	72.8	73.5	73.7	0.9
155.0	74.1	72.6	74.6	73.1	73.6	73.8	0.9
156.0	74.1	72.6	74.6	73.1	73.6	73.8	0.9
157.0	74.1	72.6	74.6	73.1	73.6	73.8	0.9
158.0	74.1	72.6	74.7	73.2	73.7	73.8	0.9
159.0	74.1	72.6	74.7	73.2	73.7	73.8	0.9
160.0	74.3	72.8	74.7	73.2	73.7	73.9	0.9
161.0	74.1	72.6	74.7	73.2	73.7	73.8	0.9
162.0	74.3	72.8	74.6	73.1	73.7	73.9	0.9
163.0	74.3	72.8	74.6	73.1	73.7	73.9	0.9
164.0	74.1	72.6	74.7	73.2	73.7	73.8	0.9
165.0	74.1	72.6	74.6	73.1	73.6	73.8	0.9
166.0	74.1	72.6	74.7	73.2	73.7	73.8	0.9
167.0	74.3	72.8	74.6	73.1	73.7	73.9	0.9
168.0	74.1	72.6	74.6	73.1	73.6	73.8	0.9
169.0	74.1	72.6	74.7	73.2	73.7	73.8	0.9
170.0	74.1	72.6	74.6	73.1	73.6	73.8	0.9

* Temperature (°C)
** Average of five replicates
*** Standard deviation (°C)

Table A5: Time-temperature data for heating the sample sphere (0.0127-m diameter) in presence of another sphere (0.0127-m diameter) at a distance of 0.0254 m upstream at an angle of 60° from the horizontal plane of the sample sphere, with 73.6°C water flowing at 5.2×10^{-4} m^3/s (five replicates).

Time	$T^{*}1$	T2	T3	T4	T5	Avg.**	Std.***
0	24.4	22.9	23.4	21.9	23.1	23.6	0.9
1	30.8	29.3	29.0	27.5	29.1	29.7	1.2
2	34.7	33.2	32.8	31.3	33.0	33.6	1.2
3	37.8	36.3	35.5	34.0	35.9	36.5	1.4
4	40.7	39.2	37.5	36.0	38.4	39.1	1.8
5	43.3	41.8	39.3	37.8	40.5	41.5	2.2
6	44.7	43.2	40.7	39.2	42.0	42.9	2.2
7	46.2	44.7	42.6	41.1	43.6	44.5	1.9
8	47.7	46.2	44.7	43.2	45.5	46.2	1.7
9	48.9	47.4	46.0	44.5	46.7	47.4	1.6
10	50.2	48.7	47.3	45.8	48.0	48.7	1.6
11	51.4	49.9	48.7	47.2	49.3	50.0	1.5
12	52.4	50.9	50.0	48.5	50.5	51.1	1.4
13	53.4	51.9	51.2	49.7	51.5	52.2	1.4
14	54.4	52.9	52.2	50.7	52.5	53.2	1.4
15	55.5	54.0	53.0	51.5	53.5	54.2	1.5
16	56.4	54.9	54.1	52.6	54.5	55.1	1.4
17	57.1	55.6	55.0	53.5	55.3	55.9	1.3
18	57.5	56.0	55.5	54.0	55.8	56.4	1.2
19	59.5	58.0	56.4	54.9	57.2	58.0	1.7
20	59.2	57.7	57.0	55.5	57.3	58.0	1.4
21	59.5	58.0	57.8	56.3	57.9	58.4	1.1
22	59.8	58.3	58.4	56.9	58.3	58.8	1.0
23	60.0	58.5	58.9	57.4	58.7	59.2	0.9
24	60.3	58.8	59.5	58.0	59.2	59.5	0.9
25	61.2	59.7	60.2	58.7	59.9	60.3	0.9
26	61.9	60.4	60.9	59.4	60.6	61.0	0.9
27	62.4	60.9	61.4	59.9	61.2	61.6	0.9
28	62.8	61.3	62.0	60.5	61.7	62.1	0.9
29	63.5	62.0	62.6	61.1	62.3	62.7	0.9
30	63.7	62.2	62.8	61.3	62.5	62.9	0.9
31	64.2	62.7	63.4	61.9	63.1	63.4	0.9
32	64.6	63.1	63.7	62.2	63.4	63.8	0.9
33	65.2	63.7	64.2	62.7	64.0	64.4	0.9
34	65.6	64.1	64.8	63.3	64.4	64.8	0.9
35	65.9	64.4	65.1	63.6	64.7	65.1	0.9

Table A5: Time-temperature data for heating the sample sphere (0.0127-m diameter) in presence of another sphere (0.0127-m diameter) at a distance of 0.0254 m upstream at an angle of 60° from the horizontal plane of the sample sphere, with 73.6°C water flowing at $5.2x10^{-4}$ m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
36	66.3	64.8	65.3	63.8	65.1	65.5	0.9
37	66.7	65.2	65.7	64.2	65.5	65.9	0.9
38	66.9	65.4	65.9	64.4	65.6	66.0	0.9
39	67.3	65.8	66.2	64.7	66.0	66.4	0.9
40	67.7	66.2	66.4	64.9	66.3	66.8	1.0
41	67.8	66.3	66.9	65.4	66.6	67.0	0.9
42	68.1	66.6	67.3	65.8	66.9	67.3	0.9
43	68.4	66.9	67.4	65.9	67.1	67.6	0.9
44	68.7	67.2	67.5	66.0	67.4	67.8	0.9
45	68.8	67.3	67.8	66.3	67.6	68.0	0.9
46	68.9	67.4	68.2	66.7	67.8	68.2	0.8
47	69.3	67.8	68.4	66.9	68.1	68.5	0.9
48	69.3	67.8	68.7	67.2	68.2	68.6	0.8
49	69.5	68.0	68.9	67.4	68.5	68.8	0.8
50	69.8	68.3	69.2	67.7	68.7	69.1	0.8
51	69.9	68.4	69.5	68.0	68.9	69.3	0.8
52	70.0	68.5	69.8	68.3	69.1	69.4	0.8
53	70.2	68.7	69.8	68.3	69.2	69.5	0.8
54	70.3	68.8	69.9	68.4	69.3	69.7	0.8
55	70.6	69.1	70.3	68.8	69.7	70.0	0.8
56	70.6	69.1	70.3	68.8	69.7	70.0	0.8
57	70.7	69.2	70.3	68.8	69.8	70.1	0.8
58	71.0	69.5	70.6	69.1	70.0	70.4	0.8
59	70.9	69.4	70.7	69.2	70.0	70.3	0.8
60	71.1	69.6	70.9	69.4	70.2	70.5	0.8
61	71.1	69.6	71.0	69.5	70.3	70.6	0.8
62	71.3	69.8	71.1	69.6	70.4	70.7	0.8
63	71.3	69.8	71.1	69.6	70.4	70.7	0.8
64	71.4	69.9	71.3	69.8	70.6	70.9	0.8
65	71.7	70.2	71.5	70.0	70.9	71.1	0.8
66	71.7	70.2	71.7	70.2	70.9	71.2	0.8
67	71.7	70.2	71.8	70.3	71.0	71.2	0.8
68	72.0	70.5	71.7	70.2	71.1	71.4	0.8
69	72.0	70.5	72.0	70.5	71.2	71.5	0.8
70	72.1	70.6	72.1	70.6	71.3	71.6	0.8

Table A5: Time-temperature data for heating the sample sphere (0.0127-m diameter) in presence of another sphere (0.0127-m diameter) at a distance of 0.0254 m upstream at an angle of 60° from the horizontal plane of the sample sphere, with 73.6°C water flowing at $5.2 x 10^{-4}$ m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
71	72.2	70.7	72.2	70.7	71.5	71.7	0.8
72	72.2	70.7	72.2	70.7	71.5	71.7	0.8
73	72.2	70.7	72.4	70.9	71.5	71.8	0.8
74	72.4	70.9	72.5	71.0	71.7	71.9	0.8
75	72.4	70.9	72.5	71.0	71.7	71.9	0.8
76	72.4	70.9	72.5	71.0	71.7	71.9	0.8
77	72.4	70.9	72.8	71.3	71.8	72.0	0.8
78	72.6	71.1	72.6	71.1	71.9	72.1	0.8
79	72.8	71.3	72.6	71.1	72.0	72.2	0.8
80	72.8	71.3	72.8	71.3	72.0	72.3	0.8
81	72.8	71.3	72.8	71.3	72.0	72.3	0.8
82	72.8	71.3	72.9	71.4	72.1	72.3	0.8
83	72.8	71.3	72.8	71.3	72.0	72.3	0.8
84	73.1	71.6	73.1	71.6	72.3	72.6	0.7
85	73.1	71.6	73.1	71.6	72.3	72.6	0.7
86	72.9	71.4	73.1	71.6	72.2	72.5	0.8
87	73.1	71.6	73.2	71.7	72.4	72.6	0.8
88	73.1	71.6	73.2	71.7	72.4	72.6	0.8
89	73.2	71.7	73.2	71.7	72.4	72.7	0.8
90	73.3	71.8	73.3	71.8	72.6	72.8	0.7
91	73.2	71.7	73.3	71.8	72.5	72.7	0.8
92	73.3	71.8	73.5	72.0	72.6	72.9	0.8
93	73.3	71.8	73.6	72.1	72.7	72.9	0.8
94	73.3	71.8	73.9	72.4	72.8	73.0	0.8
95	73.5	72.0	73.6	72.1	72.8	73.0	0.8
96	73.5	72.0	73.6	72.1	72.8	73.0	0.8
97	73.5	72.0	73.6	72.1	72.8	73.0	0.8
98	73.5	72.0	73.7	72.2	72.8	73.1	0.8
99	73.6	72.1	73.7	72.2	72.9	73.1	0.8
100	73.6	72.1	73.6	72.1	72.8	73.1	0.7
101	73.7	72.2	73.6	72.1	72.9	73.2	0.8
102	73.9	72.4	73.9	72.4	73.1	73.4	0.8
103	73.7	72.2	73.9	72.4	73.1	73.3	0.8
104	73.9	72.4	73.9	72.4	73.1	73.4	0.8
105	73.9	72.4	73.9	72.4	73.1	73.4	0.8

* Temperature (°C)
** Average of five replicates
*** Standard deviation

Table A6: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system with 73.6°C water flowing at 5.2×10^{-4} m^3/s (five replicates).

Time	T*1	T2	T3	T4	T5	Avg.**	Std.***
0	23.8	22.6	22.3	19.5	21.0	21.8	1.7
1	26.8	35.3	33.6	29.3	32.8	31.6	3.5
2	37.4	42.3	40.8	38.4	38.1	39.4	2.1
3	42.6	46.6	46.0	43.3	42.7	44.2	1.9
4	46.2	49.9	48.2	46.6	47.5	47.7	1.5
5	49.2	51.6	50.0	48.7	49.5	49.8	1.1
6	51.6	53.4	52.7	50.6	50.9	51.8	1.2
7	54.0	55.7	54.4	53.3	53.7	54.2	0.9
8	56.3	56.7	55.7	54.8	54.7	55.6	0.9
9	57.2	58.5	57.9	56.7	56.8	57.4	0.8
10	59.6	59.6	57.9	57.8	58.2	58.6	0.9
11	60.0	60.0	59.3	57.9	58.6	59.2	0.9
12	61.9	61.3	60.5	59.2	59.8	60.5	1.1
13	63.0	62.3	60.3	60.7	61.9	61.6	1.1
14	63.7	62.8	61.6	61.0	62.1	62.2	1.0
15	64.4	63.7	62.3	62.3	62.1	62.9	1.0
16	65.2	64.4	63.3	62.8	62.6	63.6	1.1
17	64.9	64.8	64.1	63.3	63.4	64.1	0.8
18	66.9	65.1	63.5	63.7	64.6	64.7	1.3
19	66.6	65.7	64.4	64.2	64.6	65.1	1.0
20	66.3	66.0	65.2	65.5	64.6	65.5	0.7
21	67.7	66.4	64.9	64.5	64.9	65.7	1.3
22	67.7	66.7	65.7	65.2	66.3	66.3	1.0
23	68.1	67.4	66.2	65.7	65.7	66.6	1.1
24	69.1	66.9	66.0	65.7	66.9	66.9	1.3
25	69.2	67.3	66.7	66.6	66.0	67.2	1.2
26	69.2	67.8	66.6	66.9	66.9	67.5	1.1
27	69.6	68.0	67.1	66.9	67.1	67.7	1.1
28	69.9	68.0	67.8	66.9	67.8	68.1	1.1
29	69.9	67.8	67.8	67.8	68.2	68.3	0.9
30	70.3	68.4	67.8	67.3	67.3	68.2	1.3
31	70.2	68.9	68.4	68.2	68.0	68.7	0.9
32	70.7	69.1	68.4	67.7	68.1	68.8	1.2
33	70.7	69.1	68.8	68.0	68.5	69.0	1.0
34	71.3	69.5	69.1	68.9	68.5	69.5	1.1
35	70.3	69.3	68.8	68.2	68.7	69.1	0.8
36	71.0	69.6	69.2	68.5	69.1	69.5	0.9
37	71.4	70.0	69.5	69.2	69.6	69.9	0.9

Table A6: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system with 73.6°C water flowing at 5.2×10^{-4} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
38	70.7	69.9	69.9	68.5	69.6	69.7	0.8
39	71.3	70.2	69.5	69.5	69.6	70.0	0.8
40	71.7	70.3	69.6	69.3	70.2	70.2	0.9
41	71.8	70.0	70.2	68.9	69.8	70.1	1.1
42	71.5	70.6	70.0	69.8	69.9	70.4	0.7
43	71.8	70.7	70.4	68.9	69.9	70.4	1.1
44	72.0	70.7	70.3	69.3	70.7	70.6	0.9
45	72.6	70.9	70.7	70.2	71.0	71.1	0.9
46	72.2	71.0	70.6	69.5	70.3	70.7	1.0
47	72.2	71.0	70.6	69.9	71.5	71.0	0.9
48	72.4	70.7	71.5	70.6	70.6	71.2	0.8
49	72.0	71.0	71.0	69.8	71.0	70.9	0.8
50	72.2	71.3	71.5	70.7	71.5	71.5	0.5
51	72.5	71.5	71.4	71.0	71.7	71.6	0.6
52	72.1	71.5	71.4	70.7	71.3	71.4	0.5
53	73.1	71.8	71.4	71.1	71.8	71.8	0.7
54	71.8	72.2	72.0	71.5	72.5	72.0	0.4
55	73.1	72.0	71.8	71.3	72.4	72.1	0.7
56	72.5	72.1	72.1	72.0	72.2	72.2	0.2
57	72.0	72.1	71.7	71.1	72.0	71.8	0.4
58	72.2	72.1	72.0	72.1	71.7	72.0	0.2
59	72.0	72.0	72.4	72.2	72.6	72.2	0.3
60	72.4	73.1	71.8	72.9	72.9	72.6	0.5
61	73.2	72.1	72.2	72.8	72.1	72.5	0.5
62	72.1	72.5	72.6	72.5	72.6	72.5	0.2
63	72.5	72.8	72.5	72.2	72.9	72.6	0.3
64	72.8	72.4	72.9	72.9	72.8	72.7	0.2
65	72.5	72.6	72.2	72.6	73.6	72.7	0.5
66	73.3	72.9	72.8	72.9	73.1	73.0	0.2
67	73.1	73.7	72.8	73.3	74.0	73.4	0.5
68	72.1	73.3	72.8	72.9	73.5	72.9	0.5
69	72.9	72.6	73.7	73.9	73.6	73.4	0.5
70	72.4	72.9	73.2	73.3	73.3	73.0	0.4
71	72.6	72.9	72.6	72.9	73.2	72.9	0.2
72	73.1	72.9	73.7	73.9	73.7	73.5	0.4
73	73.2	73.5	73.5	73.5	74.0	73.5	0.3
74	72.9	73.5	73.3	73.7	73.7	73.4	0.3
75	72.6	73.3	73.2	72.9	74.4	73.3	0.7

Table A6: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system with 73.6°C water flowing at 5.2×10^{-4} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
76	72.9	74.0	72.9	73.2	73.3	73.3	0.4
77	73.5	72.9	73.3	74.1	73.9	73.5	0.5
78	73.2	73.5	73.6	73.5	74.0	73.5	0.3
79	73.6	73.3	73.9	73.2	73.5	73.5	0.3
80	73.6	73.5	73.5	74.0	73.5	73.6	0.2
81	72.9	73.5	73.5	72.9	73.6	73.3	0.3

* Temperature (°C)

** Average of five replicates

*** Standard deviation (°C)

Table A7: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 73.6°C CMC solution (0.2% concentration, viscosity=9.3×10^{-3} Pa•s) flowing at 5.2×10^{-4} m^3/s (five replicates).

Time	T*1	T2	T3	T4	T5	Avg.**	Std.***
0	31.7	30.6	30.7	29.5	31.0	30.7	0.8
1	41.0	41.0	41.0	31.7	41.0	39.1	4.2
2	45.3	44.4	45.3	41.0	45.3	44.3	1.9
3	46.0	45.9	46.0	45.3	46.1	45.9	0.3
4	46.7	46.7	46.8	46.1	46.7	46.6	0.3
5	47.9	47.9	47.9	46.7	47.9	47.7	0.5
6	49.0	49.0	49.1	47.9	49.1	48.8	0.5
7	51.4	51.4	50.9	49.2	51.4	50.9	1.0
8	53.3	53.3	52.9	51.5	53.3	52.8	0.8
9	55.3	55.3	55.3	53.3	55.5	54.9	0.9
10	56.4	56.4	57.1	54.3	56.4	56.1	1.1
11	57.8	57.8	57.8	56.4	57.9	57.5	0.6
12	57.8	57.8	57.8	57.8	57.8	57.8	0.0
13	58.8	58.8	58.8	57.8	58.8	58.6	0.4
14	60.6	60.6	60.0	58.8	60.6	60.1	0.8
15	60.3	60.3	60.3	60.6	60.3	60.4	0.1
16	62.0	62.0	62.0	60.3	62.0	61.7	0.7
17	62.3	62.3	62.3	62.0	62.3	62.2	0.1
18	62.7	62.7	62.7	62.3	62.7	62.6	0.2
19	63.9	63.9	63.9	62.7	63.9	63.7	0.6
20	64.5	64.5	64.5	63.1	64.5	64.2	0.6
21	64.1	64.1	64.1	64.5	64.1	64.2	0.2
22	63.8	63.8	63.8	64.1	63.8	63.9	0.1
23	64.8	64.8	64.8	64.0	64.8	64.6	0.3
24	66.2	66.2	66.0	64.8	66.2	65.9	0.6
25	66.4	66.4	66.4	66.2	66.0	66.3	0.2
26	66.3	66.3	66.3	66.4	66.3	66.3	0.1
27	67.1	67.1	67.1	66.3	67.1	67.0	0.4
28	67.0	67.0	67.0	67.1	67.0	67.0	0.1
29	67.4	67.4	67.4	67.0	67.4	67.3	0.2
30	68.2	68.2	68.2	67.4	68.2	68.1	0.4
31	67.8	67.8	67.8	68.2	67.8	67.9	0.2
32	68.2	68.2	68.2	67.8	68.2	68.2	0.2
33	67.4	67.4	67.7	68.2	68.2	67.8	0.4
34	69.6	69.6	69.6	67.5	69.6	69.2	1.0
35	69.3	69.3	69.3	69.6	69.3	69.4	0.1
36	68.9	68.9	68.9	69.3	68.9	69.0	0.2

Table A7: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 73.6°C CMC solution (0.2% concentration, viscosity=9.3×10^{-3} Pa•s) flowing at 5.2×10^{-4} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
37	69.8	69.8	69.8	68.9	69.8	69.6	0.4
38	69.1	69.1	69.1	69.8	69.1	69.2	0.3
39	69.5	69.5	69.5	69.1	69.5	69.4	0.2
40	69.3	69.3	69.3	69.5	69.3	69.4	0.1
41	69.8	69.8	69.8	69.3	69.8	69.7	0.2
42	70.0	70.0	70.0	69.8	70.0	70.0	0.1
43	70.6	70.6	70.0	70.0	70.6	70.4	0.3
44	69.8	69.8	70.0	70.6	70.6	70.1	0.4
45	71.7	71.7	71.7	70.1	71.7	71.4	0.7
46	70.9	70.9	71.8	71.7	70.9	71.2	0.5
47	71.1	71.1	71.1	70.9	71.1	71.1	0.1
48	70.4	70.4	70.5	71.1	70.4	70.6	0.3
49	71.0	71.0	71.0	70.4	71.0	70.9	0.2
50	70.6	70.6	70.6	71.0	70.6	70.7	0.2
51	70.9	70.9	70.9	70.6	70.9	70.8	0.1
52	71.7	71.7	71.7	70.9	71.7	71.5	0.4
53	71.3	71.3	71.3	71.7	71.3	71.4	0.2
54	71.5	71.5	71.6	71.3	71.5	71.5	0.1
55	71.3	71.3	71.3	71.6	71.3	71.3	0.2
56	71.4	71.4	71.5	71.3	71.4	71.4	0.1
57	72.2	72.2	72.0	71.4	72.3	72.0	0.4
58	71.4	71.4	72.4	72.2	72.4	72.0	0.5
59	70.9	70.9	71.0	71.4	72.0	71.2	0.5
60	72.0	72.0	72.0	71.0	72.0	71.8	0.4
61	71.8	71.8	71.8	72.0	71.8	71.8	0.1
62	72.2	72.2	72.2	71.8	72.2	72.1	0.2
63	72.8	72.8	72.8	72.2	72.8	72.7	0.2
64	72.2	72.2	72.2	72.8	72.8	72.4	0.3
65	72.2	72.2	72.2	72.2	72.8	72.3	0.2
66	72.4	72.4	72.4	72.2	72.4	72.3	0.1
67	72.4	72.4	72.4	72.4	72.4	72.4	0.0
68	72.8	72.8	72.8	72.4	72.8	72.7	0.2
69	72.9	72.9	72.9	72.8	72.9	72.9	0.1
70	73.2	73.2	73.2	72.9	73.2	73.1	0.1
71	72.8	72.8	72.8	73.2	72.8	72.9	0.2
72	73.9	73.9	73.9	72.8	73.9	73.7	0.5
73	73.3	73.3	73.3	73.9	73.3	73.4	0.2

Table A7: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 73.6°C CMC solution (0.2% concentration, viscosity=9.3×10^{-3} Pa•s) flowing at 5.2×10^{-4} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
74	73.2	73.2	73.2	73.3	73.2	73.2	0.1
75	73.5	73.5	73.5	73.3	73.5	73.4	0.1
76	73.3	73.3	73.3	73.5	73.3	73.4	0.1
77	73.1	73.1	73.1	73.3	73.1	73.1	0.1
78	73.6	73.6	73.6	73.1	73.6	73.5	0.2
79	73.5	73.5	73.5	73.6	73.5	73.5	0.1
80	73.5	73.5	73.5	73.5	73.5	73.5	0.0
81	72.4	72.4	73.4	73.5	72.4	72.8	0.6
82	73.1	73.1	73.1	72.4	73.1	72.9	0.3
83	73.2	73.2	73.2	73.1	73.2	73.2	0.0
84	73.9	73.9	73.9	73.2	73.9	73.7	0.3
85	73.3	73.3	73.3	73.9	73.3	73.4	0.2
86	72.6	72.6	73.6	73.3	72.6	73.0	0.5
87	73.5	73.5	73.5	72.6	73.5	73.3	0.4

* Temperature (°C)
** Average of five replicates
*** Standard deviation (°C)

Table A8: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 73.6°C CMC solution (0.4% concentration, viscosity=33.33×10^{-3} Pa.s) flowing at 5.2×10^{-4} m^3/s (five replicates).

Time	$T^{*}1$	T2	T3	T4	T5	Avg.**	Std.***
0	21.3	22.9	30.3	31.4	23.5	25.9	4.6
1	27.8	28.1	34.5	32.5	26.2	29.8	3.5
2	31.8	31.1	36.9	36.3	31.5	33.5	2.9
3	34.0	34.5	39.4	39.1	34.6	36.3	2.7
4	36.6	36.1	41.0	41.0	36.9	38.3	2.5
5	38.7	37.7	42.7	42.9	39.3	40.2	2.4
6	39.7	39.4	43.7	44.2	40.4	41.5	2.3
7	41.6	40.6	44.7	45.5	41.7	42.8	2.2
8	42.7	41.6	46.0	46.2	43.2	43.9	2.1
9	43.4	42.1	46.9	47.9	44.5	45.0	2.4
10	44.7	43.6	47.9	48.3	45.6	46.0	2.0
11	45.6	45.3	48.9	49.2	46.5	47.1	1.8
12	46.5	46.0	49.5	50.0	47.2	47.8	1.8
13	47.0	46.6	49.7	50.5	48.2	48.4	1.7
14	48.0	47.3	51.4	51.4	49.3	49.5	1.9
15	49.2	48.3	51.6	52.7	49.6	50.3	1.8
16	49.9	49.0	52.4	52.3	50.5	50.8	1.5
17	50.5	49.9	53.0	54.0	51.0	51.7	1.8
18	51.2	50.5	53.7	54.3	51.6	52.2	1.7
19	51.7	51.6	54.3	54.8	52.4	53.0	1.5
20	52.7	52.2	55.0	55.3	53.0	53.6	1.4
21	53.0	52.7	55.5	56.0	53.4	54.1	1.5
22	53.7	53.3	56.3	56.4	54.3	54.8	1.4
23	54.4	53.6	56.7	57.0	55.0	55.3	1.5
24	55.5	54.7	57.2	57.2	55.8	56.1	1.1
25	55.7	55.3	57.7	57.9	56.1	56.5	1.2
26	56.4	55.7	57.9	58.5	56.3	57.0	1.2
27	56.5	56.4	58.8	58.9	57.1	57.5	1.2
28	57.5	57.1	59.1	59.8	57.9	58.3	1.1
29	57.8	57.4	59.6	59.8	58.5	58.6	1.1
30	58.6	57.9	60.0	60.5	58.6	59.1	1.1
31	58.9	58.4	60.5	60.9	59.2	59.6	1.1
32	59.2	59.2	61.0	60.7	59.8	60.0	0.9
33	60.0	59.2	61.4	61.9	60.3	60.6	1.1
34	60.2	60.0	61.7	61.9	60.5	60.9	0.9
35	60.6	60.3	62.0	61.9	60.9	61.1	0.8
36	61.0	60.6	62.4	62.8	61.3	61.6	0.9

Table A8: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 73.6°C CMC solution (0.4% concentration, viscosity=33.33×10^{-3} Pa.s) flowing at 5.2×10^{-4} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
37	61.2	61.6	62.8	62.7	61.7	62.0	0.7
38	62.0	61.7	63.3	63.3	62.6	62.6	0.7
39	62.0	61.7	63.5	63.8	62.7	62.7	0.9
40	62.4	62.4	63.8	63.8	62.8	63.1	0.7
41	63.1	62.4	64.5	64.2	63.5	63.6	0.8
42	63.0	62.8	63.9	64.5	63.7	63.6	0.7
43	63.5	63.4	64.8	64.8	64.2	64.1	0.7
44	63.7	63.5	65.5	65.1	64.5	64.4	0.8
45	64.5	63.8	65.3	65.3	64.2	64.6	0.7
46	64.6	64.5	65.7	65.3	64.8	65.0	0.5
47	64.8	64.8	65.6	65.9	65.1	65.2	0.5
48	65.1	64.8	66.3	65.6	65.3	65.4	0.6
49	65.5	64.9	66.3	66.4	65.6	65.7	0.6
50	65.9	65.6	66.6	66.6	65.6	66.1	0.5
51	65.9	65.7	66.9	66.4	65.9	66.2	0.5
52	65.9	65.7	66.9	67.1	66.4	66.4	0.6
53	66.7	66.3	67.3	67.1	66.4	66.8	0.4
54	66.4	66.2	67.4	67.4	67.0	66.9	0.6
55	66.7	66.6	67.4	67.8	67.3	67.2	0.5
56	67.5	66.4	67.8	67.8	67.3	67.4	0.6
57	67.0	66.9	68.0	68.4	68.0	67.6	0.7
58	67.7	67.5	68.2	68.4	67.5	67.9	0.4
59	67.5	67.1	68.2	68.7	68.1	67.9	0.6
60	67.5	67.5	68.4	68.7	68.4	68.1	0.5
61	68.1	68.0	68.4	68.7	68.2	68.3	0.3
62	68.5	68.4	68.8	69.1	68.5	68.7	0.3
63	68.8	68.2	69.1	69.2	68.9	68.8	0.4
64	68.7	68.5	69.1	69.5	69.2	69.0	0.4
65	68.9	68.2	69.2	69.6	69.1	69.0	0.5
66	68.7	68.7	69.6	69.9	68.9	69.1	0.6
67	69.2	68.7	69.5	70.0	69.8	69.4	0.5
68	69.2	69.2	69.8	70.2	69.3	69.5	0.4
69	69.2	69.2	69.6	70.3	69.5	69.6	0.5
70	68.9	69.2	70.3	70.6	70.0	69.8	0.7
71	69.3	69.2	70.0	70.6	69.8	69.8	0.6
72	69.8	69.6	70.2	70.6	70.6	70.1	0.5
73	69.6	69.6	70.3	70.9	70.0	70.1	0.5

Table A8: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 73.6°C CMC solution (0.4% concentration, viscosity=33.33×10^{-3} Pa.s) flowing at 5.2×10^{-4} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
74	70.0	70.0	70.4	71.0	70.4	70.4	0.4
75	70.0	69.8	70.6	71.1	70.4	70.4	0.5
76	70.0	70.4	70.7	71.3	70.7	70.6	0.5
77	70.3	69.8	70.6	71.0	70.6	70.4	0.5
78	70.3	70.7	71.3	71.4	71.1	71.0	0.4
79	70.9	70.6	70.9	71.7	70.7	70.9	0.4
80	70.7	70.2	70.7	71.5	71.3	70.9	0.5
81	70.4	70.9	71.4	71.7	71.1	71.1	0.5
82	70.9	70.9	71.3	71.7	71.0	71.1	0.4
83	70.9	70.7	71.3	71.7	71.7	71.2	0.4
84	70.7	70.9	71.3	71.8	71.5	71.2	0.5
85	71.3	71.1	71.1	71.5	71.7	71.3	0.2
86	70.9	70.9	71.5	71.8	71.8	71.4	0.5
87	71.3	70.9	71.5	71.8	71.4	71.4	0.4
88	70.9	71.1	71.7	71.8	71.7	71.4	0.4
89	71.4	71.3	71.7	72.0	72.0	71.7	0.3
90	71.3	71.7	71.8	71.8	71.7	71.7	0.2
91	71.1	71.3	71.8	72.1	72.2	71.7	0.5
92	71.8	71.7	72.2	72.4	72.0	72.0	0.3
93	71.7	71.4	71.7	72.2	72.0	71.8	0.3
94	71.3	72.0	72.2	72.2	72.2	72.0	0.4
95	72.0	71.7	72.1	72.2	72.0	72.0	0.2
96	71.1	71.7	71.8	72.1	72.4	71.8	0.5
97	72.1	72.1	72.2	72.2	72.2	72.2	0.1
98	72.0	72.0	71.8	72.4	72.5	72.1	0.3
99	71.4	72.0	72.4	72.1	72.4	72.0	0.4
100	71.7	72.0	72.4	72.2	72.4	72.1	0.3
101	72.0	72.2	72.4	72.5	72.4	72.3	0.2
102	71.7	72.4	72.4	72.4	72.4	72.2	0.3
103	72.1	72.2	72.5	72.5	72.2	72.3	0.2
104	71.8	72.2	72.5	72.5	72.8	72.4	0.4
105	72.1	72.5	72.5	72.8	72.2	72.4	0.3
106	72.0	72.4	72.4	72.6	72.9	72.4	0.4
107	72.1	72.2	72.6	72.6	72.2	72.4	0.3
108	72.1	72.1	72.5	72.8	72.4	72.4	0.3
109	72.2	72.4	72.5	72.6	73.1	72.6	0.3
110	72.2	72.8	72.5	72.5	72.8	72.6	0.2

Table A8: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 73.6°C CMC solution (0.4% concentration, viscosity=33.33×10^{-3} Pa.s) flowing at 5.2×10^{-4} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
111	72.2	72.2	72.4	72.5	72.6	72.4	0.2
112	72.4	72.8	72.8	72.8	72.5	72.6	0.2
113	72.4	72.8	72.6	72.8	72.8	72.7	0.2
114	72.5	72.2	72.8	72.5	72.5	72.5	0.2
115	72.1	73.1	72.8	72.9	73.1	72.8	0.4
116	72.8	72.6	72.9	73.2	73.3	73.0	0.3
117	72.5	72.6	72.5	72.9	72.8	72.7	0.2
118	72.5	73.1	73.1	73.2	72.5	72.9	0.3
119	72.5	72.8	72.9	73.2	72.5	72.8	0.3
120	72.2	72.9	72.9	73.1	73.1	72.8	0.3
121	73.1	73.1	72.9	73.1	72.9	73.0	0.1
122	72.8	73.1	72.9	73.1	73.1	73.0	0.1
123	72.8	72.8	72.9	73.2	73.1	72.9	0.2
124	72.9	72.5	73.3	73.2	72.8	72.9	0.3
125	72.8	72.8	73.1	73.2	73.1	73.0	0.2
126	72.8	73.1	73.1	73.1	72.9	73.0	0.1
127	73.1	72.9	73.2	73.5	73.5	73.2	0.2
128	73.1	72.9	73.2	73.1	73.3	73.1	0.2
129	72.8	73.1	73.1	73.5	73.1	73.1	0.2
130	73.3	73.5	73.2	73.3	73.5	73.4	0.1
131	72.9	73.1	73.1	72.9	73.2	73.0	0.1
132	73.5	72.8	73.2	73.1	73.1	73.1	0.2
133	73.1	72.9	73.3	73.1	73.5	73.2	0.2
134	73.3	73.1	73.2	73.3	73.2	73.2	0.1
135	73.3	73.1	73.2	73.3	73.5	73.3	0.2
136	73.3	73.1	73.3	73.5	73.1	73.2	0.2
137	73.3	73.3	73.5	73.5	73.3	73.4	0.1
138	73.5	73.3	73.2	73.5	73.5	73.4	0.1
139	73.3	73.5	73.1	73.3	73.3	73.3	0.1
140	73.5	73.3	73.6	73.5	73.9	73.5	0.2
141	73.3	73.1	72.9	73.5	73.7	73.3	0.3
142	73.5	73.2	73.5	73.5	73.5	73.4	0.1
143	73.5	73.1	73.3	73.3	73.6	73.4	0.2
144	73.3	73.6	73.1	73.6	73.7	73.5	0.3
145	73.7	73.1	73.3	73.6	73.6	73.5	0.3
146	73.5	73.6	73.2	73.7	73.6	73.5	0.2
147	73.3	73.3	73.3	73.6	73.6	73.4	0.2

Table A8: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 73.6°C CMC solution (0.4% concentration, viscosity=33.33x10^{-3} Pa.s) flowing at 5.2x10^{-4} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
148	73.3	72.8	73.3	73.7	74.1	73.5	0.5
149	73.3	73.2	73.3	73.6	73.5	73.4	0.2
150	73.6	73.1	73.3	73.6	74.1	73.5	0.4
151	73.9	73.7	73.5	73.9	74.0	73.8	0.2
152	73.5	73.6	73.5	73.7	74.0	73.7	0.2
153	73.9	73.2	73.7	74.0	73.7	73.7	0.3
154	73.3	73.2	73.5	73.6	73.9	73.5	0.3
155	73.6	73.5	73.3	73.3	73.7	73.5	0.2
156	73.9	73.3	73.5	73.6	74.1	73.7	0.3
157	73.3	73.3	73.5	73.7	73.7	73.5	0.2
158	73.7	73.6	73.5	73.7	73.9	73.7	0.2
159	73.9	73.5	73.3	73.6	74.1	73.7	0.3
160	73.5	73.5	73.2	73.5	73.9	73.5	0.2

* Temperature (°C)
** Average of five replicates
*** Standard deviation (°C)

Table A9: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 60°C water flowing at 2.82×10^{-3} m^3/s (five replicates).

Time	T^*1	T2	T3	T4	T5	Avg.**	Std.***
0	26.6	27.5	25.8	26.5	26.6	26.6	0.6
1	28.3	29.7	28.3	27.8	28.9	28.6	0.7
2	29.9	32.0	29.6	29.5	30.2	30.2	1.0
3	31.1	33.4	31.5	30.8	31.5	31.7	1.0
4	32.3	34.9	32.8	31.8	32.7	32.9	1.2
5	33.4	36.3	34.5	33.3	33.9	34.3	1.2
6	34.5	37.4	36.1	33.9	34.9	35.3	1.4
7	35.5	38.7	36.8	34.7	35.6	36.3	1.5
8	36.2	39.4	37.8	35.6	36.6	37.1	1.5
9	36.9	39.7	38.7	36.2	37.2	37.7	1.4
10	37.8	40.7	39.5	37.2	38.0	38.6	1.4
11	38.4	41.1	40.3	38.0	38.7	39.3	1.4
12	39.3	41.6	40.8	38.5	39.5	40.0	1.2
13	39.7	42.1	41.4	39.4	40.1	40.6	1.2
14	40.4	42.6	42.1	39.8	40.7	41.1	1.2
15	41.0	43.3	42.6	40.4	41.1	41.7	1.2
16	41.6	43.6	43.3	41.1	41.9	42.3	1.1
17	42.1	44.3	43.7	41.4	42.4	42.8	1.2
18	42.7	44.7	44.2	42.1	43.0	43.4	1.1
19	43.3	45.0	44.7	42.6	43.6	43.8	1.0
20	43.7	45.6	45.2	43.2	43.7	44.3	1.0
21	44.3	46.0	45.6	43.7	44.6	44.9	0.9
22	44.7	46.5	46.3	44.2	44.7	45.3	1.0
23	45.3	47.0	46.6	44.6	45.5	45.8	1.0
24	45.3	47.3	47.0	44.9	46.0	46.1	1.1
25	45.7	47.6	47.6	45.5	46.2	46.5	1.0
26	46.2	48.2	47.7	46.0	46.6	46.9	1.0
27	46.5	48.3	48.2	46.3	47.0	47.3	0.9
28	46.9	48.7	48.7	46.7	47.5	47.7	1.0
29	47.3	49.3	48.9	47.0	48.0	48.1	1.0
30	47.6	49.3	49.3	47.2	48.0	48.3	1.0
31	48.2	49.9	49.5	47.7	48.6	48.8	0.9
32	48.3	49.9	49.9	48.0	48.9	49.0	0.9
33	48.6	50.3	50.3	48.6	49.0	49.4	0.9
34	49.0	50.7	50.3	48.7	49.7	49.7	0.8
35	49.3	50.6	50.7	49.0	49.7	49.9	0.8
36	49.5	51.3	50.9	49.5	50.2	50.3	0.8
37	49.6	51.3	51.0	49.7	50.3	50.4	0.8

Table A9: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 60°C water flowing at 2.82×10^{-3} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
38	49.7	51.6	51.6	49.9	50.5	50.7	0.9
39	50.2	51.9	51.7	50.3	50.9	51.0	0.8
40	50.3	52.0	52.0	50.3	51.0	51.1	0.9
41	50.6	52.4	52.4	50.6	51.3	51.5	0.9
42	51.0	52.4	52.4	51.0	51.4	51.7	0.7
43	51.0	52.7	52.6	51.0	51.7	51.8	0.8
44	51.3	53.0	52.7	51.4	52.2	52.1	0.8
45	51.4	53.0	52.9	51.6	52.2	52.2	0.7
46	51.6	53.3	53.3	51.6	52.4	52.4	0.9
47	51.9	53.3	53.4	52.0	52.6	52.6	0.7
48	51.6	53.4	53.4	52.2	52.6	52.6	0.8
49	51.7	53.9	53.9	52.3	53.0	52.9	0.9
50	52.0	54.1	53.7	52.6	53.0	53.1	0.9
51	51.9	54.1	54.3	52.6	53.3	53.2	1.0
52	52.2	54.4	54.3	52.9	53.3	53.4	1.0
53	52.4	54.3	54.4	53.1	53.4	53.5	0.8
54	52.4	54.4	54.8	53.1	53.9	53.7	1.0
55	52.6	54.6	54.7	53.4	53.9	53.8	0.9
56	52.6	54.7	55.0	53.4	54.1	54.0	1.0
57	52.9	54.8	55.1	53.7	54.1	54.1	0.9
58	53.0	55.0	55.1	53.7	54.1	54.2	0.9
59	53.0	55.3	55.4	53.7	54.7	54.4	1.0
60	53.3	55.1	55.3	54.3	54.6	54.5	0.8
61	53.4	55.3	55.3	54.3	54.6	54.6	0.8
62	53.3	55.4	55.7	54.4	54.7	54.7	0.9
63	53.6	55.5	55.5	54.3	54.8	54.8	0.9
64	53.6	55.5	55.7	54.6	55.3	54.9	0.9
65	53.7	55.8	56.1	54.7	55.0	55.1	1.0
66	53.9	55.5	56.0	54.6	55.0	55.0	0.8
67	53.9	55.8	56.3	55.0	55.1	55.2	0.9
68	54.0	56.0	56.1	55.1	55.1	55.3	0.8
69	54.1	56.1	56.4	55.0	55.5	55.4	0.9
70	54.1	56.3	56.5	55.1	55.7	55.5	1.0
71	54.4	56.1	56.4	55.1	55.5	55.5	0.8
72	54.4	56.3	56.7	55.4	56.0	55.7	0.9
73	54.4	56.5	56.7	55.4	55.7	55.7	0.9
74	54.6	56.4	56.7	55.4	56.0	55.8	0.8
75	54.4	56.5	56.8	55.7	55.7	55.8	0.9

Table A9: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 60°C water flowing at 2.82×10^{-3} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
76	54.7	56.4	57.0	55.5	56.1	55.9	0.9
77	54.7	56.4	57.0	55.7	56.1	56.0	0.8
78	54.7	56.8	57.2	56.1	56.1	56.2	1.0
79	54.8	56.5	56.8	55.7	56.3	56.0	0.8
80	54.8	57.0	57.1	56.0	56.1	56.2	0.9
81	55.0	56.8	57.2	56.0	56.4	56.3	0.9
82	55.0	56.8	57.2	56.1	56.7	56.4	0.9
83	55.0	57.0	57.5	56.3	56.3	56.4	0.9
84	55.1	56.8	57.2	56.1	56.7	56.4	0.8
85	55.0	57.1	57.2	56.3	56.4	56.4	0.9
86	55.0	57.2	57.4	56.3	56.7	56.5	1.0
87	55.3	57.1	57.2	56.4	57.0	56.6	0.8
88	55.3	57.2	57.4	56.5	56.7	56.6	0.8
89	55.3	57.2	57.5	56.3	57.0	56.6	0.9
90	55.3	57.2	57.2	56.4	56.7	56.6	0.8
91	55.3	57.5	57.7	56.8	57.0	56.8	1.0
92	55.3	57.4	57.4	56.3	57.1	56.7	0.9
93	55.5	57.2	57.8	56.7	57.0	56.8	0.8
94	55.3	57.5	57.8	57.0	57.0	56.9	1.0
95	55.4	57.2	57.7	56.5	57.0	56.8	0.9
96	55.5	57.7	57.5	57.1	57.2	57.0	0.8
97	55.5	57.5	57.8	56.7	57.4	57.0	0.9
98	55.5	57.5	57.9	57.0	57.2	57.0	0.9
99	55.5	57.8	57.9	57.0	57.2	57.1	1.0
100	55.7	57.5	57.9	56.8	57.2	57.0	0.9
101	55.8	57.8	57.8	57.1	57.2	57.2	0.8
102	55.5	57.9	57.9	57.0	57.4	57.2	1.0
103	55.7	57.7	57.8	57.0	57.4	57.1	0.8
104	55.7	57.9	58.1	57.2	57.2	57.2	0.9
105	55.8	57.8	58.1	57.1	57.7	57.3	0.9
106	55.8	57.8	57.9	57.2	57.2	57.2	0.8
107	55.8	58.1	58.1	57.1	57.5	57.3	0.9
108	56.0	57.8	57.9	57.0	57.4	57.2	0.8
109	56.0	57.9	58.2	57.4	57.4	57.4	0.9
110	56.0	57.8	58.2	57.2	57.5	57.3	0.9
111	56.1	57.8	58.1	57.4	57.4	57.3	0.8
112	56.1	58.1	58.4	57.2	57.8	57.5	0.9
113	56.0	57.9	58.2	57.1	57.7	57.4	0.9

Table A9: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 60°C water flowing at 2.82×10^{-3} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
114	56.3	58.1	58.1	57.5	57.4	57.5	0.7
115	56.1	57.9	58.5	57.2	57.7	57.5	0.9
116	56.1	57.9	58.2	57.4	57.5	57.4	0.8
117	56.1	58.1	58.4	57.4	57.8	57.5	0.9
118	56.1	58.1	58.2	57.2	57.8	57.5	0.9
119	56.3	57.9	58.1	57.5	57.7	57.5	0.7
120	56.3	58.4	58.4	57.4	57.8	57.6	0.9
121	56.3	58.1	58.4	57.4	57.8	57.6	0.8
122	56.4	58.2	58.4	57.7	57.8	57.7	0.8
123	56.4	58.4	58.5	57.7	57.9	57.8	0.8
124	56.4	58.1	58.4	57.7	57.8	57.7	0.8
125	56.4	58.4	58.6	57.7	57.9	57.8	0.9
126	56.4	58.2	58.5	57.7	57.8	57.7	0.8
127	56.4	58.4	58.5	57.8	57.9	57.8	0.8
128	56.4	58.2	58.6	57.7	57.9	57.8	0.9
129	56.4	58.1	58.4	57.9	57.8	57.7	0.8
130	56.5	58.4	58.8	57.7	57.9	57.9	0.9
131	56.4	58.4	58.4	57.5	57.8	57.7	0.8
132	56.5	58.4	58.4	58.1	58.1	57.9	0.8
133	56.7	58.6	58.6	57.9	57.9	58.0	0.8
134	56.4	58.4	58.5	57.9	58.1	57.9	0.8
135	56.5	58.4	58.6	57.8	58.1	57.9	0.8
136	56.7	58.6	58.6	57.8	57.9	57.9	0.8
137	56.5	58.2	58.6	57.9	58.2	57.9	0.8
138	56.7	58.6	58.6	58.1	57.8	58.0	0.8
139	56.5	58.4	58.8	57.9	58.2	58.0	0.9
140	56.7	58.4	58.8	58.2	58.4	58.1	0.8
141	56.7	58.6	58.6	57.9	58.1	58.0	0.8
142	56.7	58.5	58.9	58.1	58.2	58.1	0.8
143	56.7	58.6	58.9	58.4	57.9	58.1	0.9
144	56.7	58.6	58.9	57.8	58.4	58.1	0.9
145	56.7	58.5	58.8	58.4	58.4	58.1	0.8
146	56.8	58.6	58.9	58.1	58.2	58.1	0.8
147	56.7	58.5	58.6	58.1	58.4	58.1	0.8
148	56.8	58.6	58.9	58.4	58.1	58.2	0.8
149	56.8	58.6	58.9	58.1	58.4	58.2	0.8
150	56.8	58.6	58.9	58.4	58.5	58.2	0.8
151	57.0	58.4	58.9	58.2	58.4	58.2	0.7

Table A9: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 60°C water flowing at 2.82×10^{-3} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
152	56.7	58.6	58.6	58.2	58.4	58.1	0.8
153	56.8	58.5	58.9	58.4	58.2	58.2	0.8
154	57.0	58.6	58.9	57.9	58.4	58.2	0.8
155	57.0	58.6	58.9	58.5	58.5	58.3	0.8
156	57.0	58.5	59.1	58.2	58.2	58.2	0.8
157	56.8	58.6	58.9	58.2	58.5	58.2	0.8
158	56.8	58.6	58.9	58.4	58.2	58.2	0.8
159	57.1	58.5	59.3	58.1	58.5	58.3	0.8
160	57.0	58.9	58.6	58.4	58.5	58.3	0.8
161	57.0	58.6	59.2	58.5	58.2	58.3	0.8
162	57.1	58.9	58.9	58.1	58.5	58.3	0.8
163	57.0	58.6	58.9	58.4	58.4	58.2	0.8
164	57.0	58.5	59.3	58.2	58.5	58.3	0.9
165	57.0	58.8	58.9	58.4	58.5	58.3	0.8
166	57.1	58.8	59.1	58.5	58.2	58.3	0.8
167	57.2	58.8	59.1	58.1	58.5	58.3	0.7
168	57.0	58.9	58.9	58.5	58.4	58.3	0.8
169	57.1	58.8	59.2	58.2	58.5	58.4	0.8
170	57.0	58.8	59.1	58.4	58.5	58.3	0.8
171	57.1	58.9	59.2	58.5	58.5	58.4	0.8
172	57.2	58.6	59.1	58.4	58.6	58.4	0.7
173	57.0	58.9	58.9	58.4	58.4	58.3	0.8
174	57.2	58.6	59.2	58.4	58.6	58.4	0.7
175	57.1	58.6	58.9	58.2	58.9	58.4	0.8
176	57.2	58.9	59.2	58.5	58.4	58.4	0.8
177	57.2	58.6	59.3	58.2	58.6	58.4	0.8
178	57.1	58.9	59.2	58.5	58.4	58.4	0.8
179	57.1	58.8	59.2	58.6	58.6	58.5	0.8
180	57.2	58.8	59.1	58.4	58.6	58.4	0.7
181	57.2	58.9	59.2	58.5	58.5	58.5	0.8
182	57.2	58.8	59.5	58.4	58.8	58.5	0.8
183	57.2	58.9	59.1	58.5	58.4	58.4	0.7
184	57.0	59.1	59.5	58.5	58.6	58.5	1.0
185	57.4	58.9	59.1	58.2	58.9	58.5	0.7
186	57.1	58.9	59.1	58.5	58.5	58.4	0.8
187	57.2	58.9	59.3	58.4	58.9	58.6	0.8
188	57.2	58.8	59.2	58.5	58.5	58.4	0.7
189	57.1	58.9	59.3	58.8	58.8	58.6	0.9

Table A9: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 60°C water flowing at 2.82×10^{-3} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
190	57.2	58.8	59.5	58.4	58.8	58.5	0.8
191	57.2	58.9	59.1	58.5	58.5	58.4	0.7
192	57.2	59.1	59.2	58.5	58.8	58.6	0.8
193	57.4	58.6	59.2	58.4	58.6	58.4	0.7
194	57.4	58.9	59.2	58.8	58.8	58.6	0.7
195	57.4	58.6	59.5	58.5	58.9	58.6	0.8
196	57.4	59.1	59.3	58.5	58.9	58.6	0.8
197	57.2	59.1	59.3	58.5	58.8	58.6	0.8
198	57.5	58.9	59.3	58.4	58.8	58.6	0.7
199	57.4	58.9	59.3	58.8	58.9	58.7	0.8
200	57.5	58.8	59.3	58.5	58.8	58.6	0.7
201	57.5	58.8	59.2	58.5	58.9	58.6	0.6
202	57.4	58.9	59.2	58.8	58.9	58.6	0.7
203	57.5	58.8	59.2	58.5	58.8	58.6	0.6
204	57.5	58.6	59.1	58.8	58.9	58.6	0.6
205	57.5	58.9	59.3	58.8	58.9	58.7	0.7
206	57.5	58.8	59.5	58.6	58.9	58.7	0.7
207	57.5	58.9	59.2	58.8	58.9	58.7	0.7
208	57.5	59.1	59.5	58.6	58.8	58.7	0.7
209	57.7	58.8	59.2	58.8	58.9	58.7	0.6
210	57.7	59.1	59.2	58.8	58.8	58.7	0.6
211	57.5	58.9	59.5	58.8	58.9	58.7	0.7
212	57.5	58.8	59.2	58.9	59.1	58.7	0.7
213	57.5	59.1	59.5	58.6	58.8	58.7	0.7
214	57.8	59.1	59.2	58.5	59.1	58.7	0.6
215	57.7	59.1	59.3	58.9	59.1	58.8	0.7
216	57.8	58.9	59.5	58.6	58.9	58.8	0.6
217	57.7	58.8	59.3	58.9	58.9	58.7	0.6
218	57.7	59.1	59.5	58.8	58.8	58.8	0.7
219	57.5	58.9	59.5	58.6	59.1	58.7	0.7
220	57.7	59.2	59.2	58.9	58.9	58.8	0.6
221	57.7	59.2	59.5	59.1	59.1	58.9	0.7
222	57.7	58.9	59.3	58.9	58.9	58.8	0.6
223	57.8	59.1	59.5	59.1	58.9	58.9	0.6
224	57.7	59.2	59.5	58.6	59.2	58.8	0.7
225	57.5	59.1	59.2	58.9	59.1	58.8	0.7
226	57.8	59.2	59.5	59.1	59.2	58.9	0.7
227	57.8	59.1	59.5	58.9	58.9	58.8	0.6

Table A9: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 60°C water flowing at 2.82×10^{-3} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
228	57.8	58.9	59.3	59.1	58.9	58.8	0.6
229	57.8	59.2	59.5	58.8	59.2	58.9	0.7
230	57.7	58.9	59.5	58.8	59.1	58.8	0.7
231	57.8	59.1	59.5	58.9	59.1	58.9	0.6
232	57.8	58.9	59.6	58.6	58.9	58.8	0.7
233	57.5	58.9	59.5	58.9	58.9	58.8	0.7
234	57.9	59.2	59.5	58.9	59.2	58.9	0.6
235	57.5	58.8	59.5	59.1	58.9	58.8	0.7
236	57.8	59.2	59.2	59.2	59.2	58.9	0.6
237	57.8	59.2	59.5	58.9	58.9	58.9	0.6
238	57.7	59.1	59.2	58.9	58.9	58.8	0.6
239	57.8	59.2	59.6	58.9	59.2	58.9	0.7
240	57.8	59.1	59.5	58.9	58.9	58.8	0.6
241	57.8	59.1	59.5	59.2	59.1	58.9	0.7
242	57.9	59.2	59.5	58.9	59.2	58.9	0.6
243	57.8	58.8	59.5	58.8	58.8	58.7	0.6
244	57.8	59.2	59.5	59.2	59.2	59.0	0.7
245	57.9	59.2	59.8	58.8	58.9	58.9	0.7
246	57.8	58.9	59.5	59.2	59.2	58.9	0.7
247	57.9	59.1	59.6	59.1	59.1	58.9	0.6
248	57.7	58.9	59.5	58.8	58.9	58.8	0.7
249	57.9	59.2	59.3	59.2	59.2	59.0	0.6
250	57.9	59.1	59.8	58.9	59.1	58.9	0.7
251	57.8	59.1	59.5	59.1	59.1	58.9	0.6
252	57.8	58.9	59.6	58.9	59.2	58.9	0.7
253	57.8	59.1	59.6	58.9	58.9	58.9	0.7
254	57.9	58.9	59.5	59.1	59.2	58.9	0.6
255	57.9	59.2	59.6	58.9	58.9	58.9	0.6
256	57.9	59.1	59.3	59.2	59.2	58.9	0.6
257	57.9	59.1	59.6	59.2	59.3	59.0	0.6
258	57.8	59.1	59.8	58.9	58.9	58.9	0.7
259	57.8	58.9	59.5	59.2	59.2	58.9	0.7
260	58.1	59.1	59.6	58.9	59.2	59.0	0.6
261	57.8	59.2	59.5	59.2	59.2	59.0	0.7
262	57.9	59.1	59.5	59.3	59.5	59.1	0.7
263	57.9	59.3	59.8	59.1	59.2	59.1	0.7
264	57.8	59.2	59.5	59.2	59.5	59.0	0.7
265	58.1	59.1	59.5	59.2	59.1	59.0	0.5

Table A9: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 60°C water flowing at 2.82×10^{-3} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
266	58.1	59.3	59.5	59.1	59.2	59.0	0.6
267	57.9	59.2	59.5	59.3	59.2	59.0	0.6
268	57.9	59.2	59.8	59.2	59.1	59.0	0.7
269	58.1	59.2	59.5	59.2	59.2	59.0	0.5
270	57.9	59.1	59.5	59.1	59.1	58.9	0.6
271	58.1	59.2	59.8	58.9	59.2	59.0	0.6
272	57.9	59.1	59.5	59.3	59.2	59.0	0.6
273	58.1	59.2	59.8	59.2	59.2	59.1	0.6
274	58.1	59.2	59.8	59.1	59.2	59.1	0.6

* Temperature (°C)
** Average of five replicates
*** Standard deviation (°C)

Table A10: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 70°C water flowing at 2.82×10^{-3} m^3/s (five replicates).

Time	T^*1	T2	T3	T4	T5	Avg.**	Std.***
0	25.9	25.8	25.6	26.6	25.2	25.8	0.5
1	30.9	29.7	28.7	29.6	28.4	29.5	1.0
2	33.7	33.6	31.7	32.7	30.5	32.4	1.4
3	36.9	36.1	34.5	35.0	33.1	35.1	1.5
4	38.5	38.5	36.3	36.8	34.9	37.0	1.6
5	40.4	40.4	38.4	38.7	36.1	38.8	1.8
6	41.9	41.4	40.1	39.8	37.5	40.2	1.7
7	43.3	43.2	41.0	40.6	38.8	41.4	1.9
8	44.6	44.0	42.6	41.4	40.1	42.5	1.8
9	45.7	45.2	43.9	42.0	41.3	43.6	1.9
10	46.5	46.0	44.7	42.7	41.6	44.3	2.1
11	48.0	46.6	45.9	44.2	43.2	45.6	1.9
12	48.3	47.7	46.2	44.5	43.6	46.1	2.0
13	49.3	48.3	46.7	45.6	44.7	46.9	1.9
14	50.2	48.7	47.7	46.6	45.5	47.7	1.8
15	50.6	49.7	48.2	47.3	46.5	48.5	1.7
16	51.6	50.3	49.2	47.9	47.2	49.2	1.8
17	51.9	51.0	49.7	49.0	48.0	49.9	1.5
18	52.7	51.6	50.2	49.6	48.5	50.5	1.7
19	53.3	52.2	51.0	50.5	49.3	51.2	1.5
20	53.9	52.7	51.6	51.3	50.2	51.9	1.4
21	54.4	53.6	52.4	51.6	50.3	52.5	1.6
22	55.0	54.1	53.1	52.4	51.6	53.3	1.3
23	55.5	54.7	53.4	52.7	51.9	53.7	1.5
24	56.1	55.0	53.9	53.3	52.2	54.1	1.5
25	56.7	55.4	54.7	54.1	53.3	54.8	1.3
26	57.2	56.3	55.1	54.7	53.4	55.3	1.5
27	57.7	56.5	55.8	54.8	54.1	55.8	1.4
28	57.9	57.2	56.3	55.5	54.6	56.3	1.3
29	58.6	57.4	56.5	55.8	55.0	56.7	1.4
30	58.9	57.8	57.1	56.1	55.7	57.1	1.3
31	59.3	58.5	57.4	57.0	56.0	57.6	1.3
32	59.9	58.6	57.9	57.1	56.7	58.1	1.3
33	60.0	59.2	58.5	57.7	57.2	58.5	1.1
34	60.6	59.9	58.5	58.4	57.2	58.9	1.3
35	61.0	59.8	59.2	58.4	57.5	59.2	1.3
36	61.0	60.3	59.3	58.5	58.1	59.5	1.2
37	61.6	60.6	59.6	59.5	58.4	59.9	1.2

Table A10: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 70°C water flowing at 2.82×10^{-3} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
38	61.7	60.9	60.2	59.5	58.8	60.2	1.2
39	61.9	61.4	60.3	60.0	59.2	60.6	1.1
40	62.7	61.7	60.7	60.6	59.2	61.0	1.3
41	62.6	61.6	61.3	60.6	60.0	61.2	1.0
42	63.1	62.4	61.2	60.9	60.0	61.5	1.2
43	63.3	62.3	61.4	61.2	60.6	61.7	1.0
44	63.4	62.8	62.1	61.3	60.7	62.1	1.1
45	63.9	62.8	62.0	61.7	60.9	62.3	1.2
46	63.9	63.0	62.6	62.1	61.4	62.6	0.9
47	64.2	63.5	62.7	62.3	61.7	62.9	1.0
48	64.6	63.7	62.6	62.6	61.4	63.0	1.2
49	64.6	63.9	63.4	62.6	62.0	63.3	1.1
50	64.9	64.1	63.3	62.6	62.3	63.4	1.1
51	65.1	64.2	63.7	63.1	62.3	63.7	1.1
52	65.3	64.5	63.7	63.0	62.8	63.9	1.1
53	65.7	64.5	63.9	63.7	62.8	64.1	1.1
54	65.6	64.6	64.2	63.9	63.0	64.3	1.0
55	65.9	65.1	64.2	63.8	63.4	64.5	1.0
56	66.2	65.3	64.2	63.8	63.1	64.5	1.2
57	66.2	65.2	64.8	64.2	63.7	64.8	1.0
58	66.4	65.6	64.5	64.2	63.7	64.9	1.1
59	66.7	65.6	65.2	64.6	63.8	65.2	1.1
60	66.4	65.9	65.3	64.6	64.2	65.3	0.9
61	67.0	66.0	65.2	64.8	64.2	65.4	1.1
62	66.6	65.9	65.6	65.3	64.5	65.6	0.8
63	67.1	66.3	65.5	65.1	64.6	65.7	1.0
64	67.4	66.3	65.6	65.2	64.6	65.8	1.1
65	67.0	66.4	65.9	65.6	64.5	65.9	0.9
66	67.5	66.7	65.9	65.3	64.9	66.1	1.1
67	67.3	66.6	65.7	65.9	64.8	66.1	0.9
68	67.7	66.6	66.2	65.7	65.3	66.3	0.9
69	67.5	67.0	66.3	65.7	65.1	66.3	1.0
70	67.8	67.0	66.4	66.2	65.6	66.6	0.8
71	68.0	67.3	66.6	66.0	65.5	66.7	1.0
72	67.8	67.3	66.6	65.9	65.5	66.6	1.0
73	68.1	67.3	66.9	66.4	65.9	66.9	0.8
74	68.2	67.5	66.7	66.3	65.7	66.9	1.0
75	68.1	67.3	66.9	66.4	66.0	66.9	0.8

Table A10: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 70°C water flowing at 2.82×10^{-3} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
76	68.4	67.7	67.3	66.7	66.3	67.3	0.8
77	68.5	67.8	66.9	66.4	66.0	67.1	1.0
78	68.1	67.5	67.3	66.7	66.3	67.2	0.7
79	68.7	67.8	67.1	67.1	66.2	67.4	0.9
80	68.4	68.1	67.1	66.9	66.4	67.4	0.8
81	68.7	67.7	67.4	67.3	66.6	67.5	0.8
82	68.7	68.1	67.3	67.0	66.7	67.5	0.8
83	68.5	68.4	67.5	66.7	66.4	67.5	0.9
84	68.9	67.8	67.8	67.5	67.0	67.8	0.7
85	68.7	68.4	67.3	67.1	66.6	67.6	0.9
86	68.9	68.1	67.8	67.4	66.9	67.8	0.8
87	69.1	68.2	68.0	67.3	67.0	67.9	0.8
88	68.9	68.7	67.8	67.4	66.9	67.9	0.9
89	69.3	68.4	68.1	67.3	67.1	68.0	0.9
90	69.1	68.5	67.8	67.5	67.0	68.0	0.8
91	69.2	68.4	67.8	67.5	66.9	68.0	0.9
92	69.3	68.4	68.2	67.8	67.5	68.3	0.7
93	69.2	68.7	67.8	67.7	67.1	68.1	0.8
94	69.5	68.7	68.2	67.5	67.4	68.3	0.8
95	69.2	68.5	68.1	68.0	67.3	68.2	0.7
96	69.3	69.1	68.1	67.8	67.3	68.3	0.9
97	69.8	68.7	68.4	68.1	67.4	68.5	0.9
98	69.5	68.9	68.1	68.1	67.7	68.5	0.7
99	69.8	69.1	68.4	68.0	67.3	68.5	1.0
100	69.6	68.9	68.4	68.1	67.8	68.6	0.7
101	69.3	69.1	68.2	68.0	67.5	68.4	0.8
102	69.8	69.2	68.5	68.1	67.5	68.6	0.9
103	69.5	68.9	68.4	68.2	67.8	68.6	0.6
104	69.8	69.1	68.2	68.1	67.5	68.5	0.9
105	69.8	68.9	68.9	68.4	67.8	68.8	0.7
106	69.5	68.9	68.7	68.5	68.1	68.7	0.5
107	69.9	69.5	68.7	68.1	67.5	68.7	1.0
108	69.9	69.2	68.7	68.1	67.7	68.7	0.9

* Temperature (°C)
** Average of five replicates
*** Standard deviation (°C)

Table A11: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 80°C water flowing at 2.82×10^{-3} m^3/s (five replicates).

Time	T* 1	T2	T3	T4	T5	Avg.**	Std.***
0	25.5	27.5	26.9	25.4	25.5	26.1	1.0
1	30.3	30.9	32.8	28.7	30.2	30.6	1.5
2	34.2	33.9	37.5	32.3	34.5	34.4	1.9
3	38.1	36.6	41.4	36.3	38.0	38.1	2.0
4	40.6	38.7	44.2	39.5	41.0	40.8	2.1
5	42.9	40.4	46.7	42.4	43.3	43.2	2.3
6	44.9	42.6	48.0	44.5	45.2	45.0	2.0
7	46.6	43.7	49.3	45.9	46.9	46.5	2.0
8	48.5	45.5	51.0	48.2	48.9	48.4	2.0
9	49.6	46.5	51.6	49.2	50.2	49.4	1.9
10	51.2	47.2	52.4	50.7	51.2	50.5	2.0
11	52.3	48.6	53.3	51.6	52.2	51.6	1.8
12	53.1	49.3	54.0	52.0	52.6	52.2	1.8
13	54.1	50.6	55.1	53.3	54.0	53.4	1.7
14	54.8	51.4	55.7	54.1	54.4	54.1	1.6
15	55.5	52.0	57.1	55.1	55.1	55.0	1.8
16	56.5	53.1	57.8	56.3	56.5	56.1	1.7
17	57.1	54.3	58.4	56.5	57.0	56.6	1.5
18	58.2	54.8	59.2	57.8	58.1	57.6	1.6
19	58.9	55.8	59.8	58.4	58.6	58.3	1.5
20	59.9	56.3	60.9	59.2	59.2	59.1	1.7
21	60.7	57.2	61.6	60.0	60.2	60.0	1.6
22	61.3	58.2	62.0	60.3	61.2	60.6	1.5
23	61.7	58.6	63.1	61.3	61.6	61.3	1.6
24	62.4	59.5	63.3	62.0	62.4	61.9	1.4
25	62.8	59.9	63.7	62.3	62.6	62.2	1.4
26	63.5	60.6	64.6	63.1	63.4	63.1	1.5
27	64.1	61.3	64.9	63.5	63.9	63.6	1.4
28	64.6	61.4	65.6	64.2	64.2	64.0	1.6
29	65.3	62.6	65.9	65.2	65.1	64.8	1.3
30	65.6	63.0	66.2	65.2	65.3	65.1	1.2
31	66.3	63.4	67.1	65.9	65.6	65.7	1.4
32	67.0	63.9	67.7	66.2	66.4	66.2	1.4
33	67.1	64.1	67.8	66.9	66.6	66.5	1.4
34	67.7	64.6	68.2	67.4	67.4	67.1	1.4
35	68.1	65.6	68.4	67.5	68.0	67.5	1.1
36	68.5	65.6	69.1	68.0	68.0	67.8	1.3
37	69.2	66.0	69.8	68.2	68.4	68.3	1.4

Table A11: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 80°C water flowing at 2.82×10^{-3} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
38	69.3	66.7	69.8	68.8	68.8	68.7	1.2
39	69.8	66.9	70.3	69.2	68.9	69.0	1.3
40	70.3	67.4	70.3	69.5	69.6	69.4	1.2
41	70.0	67.7	70.6	69.9	69.9	69.6	1.1
42	70.9	67.8	71.3	70.2	70.0	70.0	1.3
43	71.3	68.4	71.3	70.3	70.6	70.4	1.2
44	71.4	68.5	71.7	71.1	70.6	70.7	1.3
45	71.8	69.1	71.8	71.0	71.0	70.9	1.1
46	71.7	69.5	72.1	71.0	71.4	71.1	1.0
47	72.4	69.5	72.5	72.0	71.5	71.6	1.2
48	72.4	70.0	72.2	71.7	72.2	71.7	1.0
49	72.6	70.0	73.1	72.2	72.1	72.0	1.2
50	73.2	70.4	73.1	72.2	72.4	72.3	1.1
51	73.2	70.9	73.2	72.4	72.8	72.5	1.0
52	73.6	70.7	73.6	73.1	72.8	72.7	1.2
53	73.6	71.5	73.5	72.6	73.2	72.9	0.8
54	73.7	71.3	73.7	73.1	73.3	73.0	1.0
55	74.1	71.3	74.3	73.6	73.3	73.3	1.2
56	74.1	72.2	74.1	73.2	73.7	73.5	0.8
57	74.4	72.1	74.1	73.9	73.7	73.7	0.9
58	74.6	72.5	74.6	73.9	74.0	73.9	0.8
59	74.6	72.4	74.7	74.1	74.4	74.0	1.0
60	74.8	72.4	75.0	74.4	74.1	74.1	1.0
61	75.4	72.8	75.0	74.3	74.7	74.4	1.0
62	75.2	72.6	75.2	75.0	74.4	74.5	1.1
63	75.6	73.3	75.4	74.7	74.4	74.7	0.9
64	75.4	73.3	75.5	75.0	75.0	74.8	0.9
65	75.8	73.3	75.8	75.4	75.0	75.0	1.0
66	75.8	73.7	75.9	75.1	75.1	75.1	0.9
67	75.8	73.7	75.9	75.5	75.4	75.3	0.9
68	76.3	73.9	76.3	75.6	75.2	75.5	1.0
69	75.9	74.4	76.1	75.5	75.5	75.5	0.6
70	76.1	74.1	76.2	75.9	76.1	75.7	0.9
71	76.3	74.7	76.3	76.1	75.8	75.8	0.7
72	76.3	74.4	76.3	75.9	76.1	75.8	0.8
73	76.5	74.4	76.9	76.1	75.9	75.9	0.9
74	76.5	74.8	76.6	75.9	76.1	76.0	0.7
75	76.5	74.8	76.6	76.3	76.2	76.1	0.7

Table A11: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 80°C water flowing at 2.82×10^{-3} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
76	77.0	75.1	76.9	76.3	76.2	76.3	0.8
77	76.7	75.0	76.6	76.5	76.3	76.2	0.7
78	77.1	74.8	77.0	76.7	76.3	76.4	0.9
79	77.0	75.4	77.1	76.6	76.2	76.5	0.7
80	76.9	75.4	76.9	76.7	76.6	76.5	0.6
81	77.3	75.5	77.4	76.7	76.6	76.7	0.8
82	77.1	75.4	77.3	76.9	76.9	76.7	0.8
83	77.4	75.4	77.6	77.1	77.1	76.9	0.9
84	77.4	75.8	77.6	76.9	76.9	76.9	0.7
85	77.4	76.1	77.6	77.4	77.1	77.1	0.6
86	77.7	75.8	77.7	77.1	77.0	77.1	0.8
87	77.6	75.9	77.6	77.1	76.9	77.0	0.7
88	77.4	75.6	77.4	77.4	77.4	77.1	0.8
89	78.1	76.1	77.8	77.4	77.1	77.3	0.8
90	77.7	76.3	77.7	77.4	77.3	77.3	0.6
91	77.6	76.2	77.8	77.7	77.3	77.3	0.7
92	78.0	76.5	78.2	77.4	77.3	77.5	0.7
93	77.7	76.2	77.7	77.6	77.6	77.3	0.6
94	78.4	76.3	78.0	77.4	77.4	77.5	0.8
95	78.0	76.6	78.2	77.7	77.4	77.6	0.6
96	78.0	76.2	78.0	77.8	77.7	77.5	0.8
97	78.2	76.6	78.2	77.4	77.6	77.6	0.7
98	78.1	76.5	78.1	78.0	77.7	77.7	0.7
99	78.4	76.6	78.0	78.1	78.0	77.8	0.7
100	78.5	76.6	78.5	77.7	77.4	77.7	0.8
101	78.1	76.6	78.2	78.0	78.0	77.8	0.7
102	78.6	76.9	78.5	77.7	77.8	77.9	0.7
103	78.4	76.9	78.4	78.0	77.7	77.9	0.6
104	78.5	76.6	78.2	78.2	78.0	77.9	0.8
105	78.4	76.9	78.5	78.0	77.8	77.9	0.6
106	78.5	76.6	78.5	78.2	78.1	78.0	0.8
107	78.8	76.9	78.6	78.0	78.2	78.1	0.8
108	78.4	77.0	78.8	78.0	77.7	78.0	0.7
109	78.6	76.9	78.5	78.4	78.2	78.1	0.7
110	78.6	77.0	78.8	78.1	78.1	78.1	0.7
111	78.6	76.9	78.6	78.2	78.1	78.1	0.7
112	78.9	77.1	78.4	78.2	78.2	78.2	0.6
113	78.8	77.1	79.0	78.0	78.0	78.2	0.8

Table A11: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 80°C water flowing at 2.82×10^{-3} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
114	78.6	77.1	78.8	78.5	78.1	78.2	0.7
115	79.0	77.3	78.6	78.2	78.2	78.3	0.7
116	78.6	77.1	79.0	78.4	78.2	78.3	0.7
117	79.0	77.1	78.8	78.5	78.2	78.3	0.7
118	78.9	77.4	78.9	78.4	78.2	78.4	0.6
119	78.6	77.3	79.0	78.5	78.1	78.3	0.7
120	79.0	77.4	78.8	78.5	78.4	78.4	0.6
121	78.6	77.3	79.2	78.5	78.1	78.3	0.7
122	79.0	77.1	78.8	78.5	78.4	78.4	0.7
123	79.2	77.6	79.0	78.5	78.4	78.5	0.6
124	79.0	77.3	79.3	78.6	78.4	78.5	0.8
125	79.0	77.4	79.0	78.5	78.5	78.5	0.7
126	78.9	77.4	79.0	78.4	78.4	78.4	0.6
127	78.8	77.4	79.0	78.8	78.2	78.4	0.6
128	79.3	77.4	78.8	78.5	78.6	78.5	0.7
129	78.9	77.6	79.2	78.5	78.2	78.5	0.6
130	79.2	77.7	78.8	78.6	78.6	78.6	0.5
131	79.2	77.7	79.0	78.4	78.4	78.5	0.6
132	78.8	77.7	79.3	78.8	78.4	78.6	0.6
133	79.2	77.4	78.9	78.8	78.6	78.6	0.7
134	79.2	77.7	79.5	78.5	78.5	78.7	0.7
135	79.2	77.4	79.0	79.0	78.6	78.7	0.7
136	79.0	78.0	79.2	78.6	78.8	78.7	0.5
137	79.0	77.7	79.3	78.8	78.5	78.7	0.6
138	79.0	77.7	79.0	78.6	78.6	78.6	0.6
139	79.5	78.0	79.2	78.8	78.6	78.8	0.6
140	79.2	77.4	79.0	79.0	78.5	78.6	0.7
141	79.2	77.8	79.2	78.8	78.8	78.7	0.6
142	79.0	78.1	79.3	78.6	78.8	78.8	0.5
143	78.9	77.6	79.2	78.8	78.4	78.6	0.6
144	79.2	78.2	79.2	78.6	78.9	78.8	0.4
145	78.9	77.8	79.3	78.9	78.4	78.7	0.6
146	79.5	77.8	78.8	78.8	78.8	78.7	0.6
147	79.2	78.0	79.0	78.6	79.0	78.8	0.5
148	78.9	77.7	79.0	78.9	78.4	78.6	0.6
149	79.2	78.0	78.8	78.8	79.0	78.7	0.5
150	78.9	78.0	78.9	78.9	78.8	78.7	0.4
151	79.2	77.8	78.5	78.9	78.8	78.6	0.5

Table A11: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 80°C water flowing at 2.82x10^{-3} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
152	79.6	78.1	78.8	78.8	79.0	78.9	0.5
153	79.0	77.8	78.8	79.2	78.8	78.7	0.5
154	79.3	78.0	78.5	78.6	78.8	78.6	0.5
155	79.2	78.2	78.5	78.9	78.8	78.7	0.4

* Temperature (°C)
** Average of five replicates
*** Standard deviation (°C)

Table A12: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 70°C water flowing at $0.27x10^{-3}$ m^3/s (five replicates).

Time	T^*1	T2	T3	T4	T5	Avg.**	Std.***
0	26.3	24.8	25.6	25.2	25.4	25.5	0.6
1	26.9	25.4	26.1	25.7	25.9	26.0	0.6
2	27.2	25.7	26.5	26.1	26.3	26.4	0.6
3	28.7	27.2	28.0	27.6	27.8	27.9	0.6
4	29.1	27.6	28.3	27.9	28.1	28.2	0.6
5	29.2	27.7	28.5	28.1	28.3	28.4	0.6
6	31.0	29.5	30.2	29.9	30.0	30.1	0.6
7	32.7	31.2	32.0	31.6	31.8	31.9	0.6
8	33.3	31.8	32.6	32.2	32.4	32.4	0.6
9	34.6	33.1	33.8	33.5	33.7	33.7	0.6
10	34.9	33.4	34.1	33.8	33.9	34.0	0.5
11	35.2	33.7	34.4	34.0	34.2	34.3	0.6
12	36.2	34.7	35.4	35.0	35.2	35.3	0.6
13	38.2	36.7	37.4	37.0	37.2	37.3	0.6
14	39.0	37.5	38.3	37.9	38.1	38.2	0.6
15	40.0	38.5	39.3	38.9	39.1	39.2	0.6
16	40.9	39.4	40.1	39.7	39.9	40.0	0.6
17	40.6	39.1	39.8	39.5	39.6	39.7	0.6
18	40.3	38.8	39.5	39.2	39.4	39.4	0.6
19	41.0	39.5	40.2	39.9	40.1	40.1	0.6
20	41.6	40.1	40.8	40.4	40.6	40.7	0.6
21	41.4	39.9	40.7	40.3	40.5	40.5	0.6
22	41.8	40.3	41.1	40.7	40.9	41.0	0.6
23	42.3	40.8	41.5	41.1	41.3	41.4	0.6
24	42.8	41.3	42.1	41.7	41.9	42.0	0.6
25	42.4	40.9	41.6	41.3	41.4	41.5	0.6
26	42.7	41.2	41.9	41.5	41.7	41.8	0.6
27	42.2	40.7	41.5	41.1	41.3	41.4	0.6
28	42.6	41.1	41.9	41.5	41.7	41.8	0.6
29	42.9	41.4	42.2	41.8	42.0	42.1	0.6
30	42.3	40.8	41.6	41.2	41.4	41.5	0.6
31	42.8	41.3	42.0	41.6	41.8	41.9	0.6
32	42.2	40.7	41.4	41.1	41.2	41.3	0.6
33	42.5	41.0	41.7	41.3	41.5	41.6	0.6
34	42.9	41.4	42.1	41.8	41.9	42.0	0.6
35	42.2	40.7	41.4	41.0	41.2	41.3	0.6
36	43.1	41.6	42.3	42.0	42.1	42.2	0.6
37	43.1	41.6	42.3	41.9	42.1	42.2	0.6

Table A12: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 70°C water flowing at 0.27×10^{-3} m^3/s (five replicates).

Time	T^*1	T2	T3	T4	T5	Avg.**	Std.***
38	43.1	41.6	42.4	42.0	42.2	42.3	0.6
39	43.6	42.1	42.8	42.4	42.6	42.7	0.6
40	43.7	42.2	42.9	42.6	42.8	42.8	0.6
41	43.1	41.6	42.4	42.0	42.2	42.2	0.7
42	43.4	41.9	42.6	42.3	42.5	42.5	0.6
43	43.5	42.0	42.8	42.4	42.6	42.7	0.6
44	43.8	42.3	43.1	42.7	42.9	42.9	0.7
45	43.1	41.6	42.3	42.0	42.1	42.2	0.6
46	43.2	41.7	42.5	42.1	42.3	42.4	0.6
47	44.5	43.0	43.8	43.4	43.6	43.6	0.6
48	45.6	44.1	44.9	44.5	44.7	44.8	0.6
49	45.8	44.3	45.0	44.7	44.8	44.9	0.6
50	45.1	43.6	44.3	43.9	44.1	44.2	0.6
51	46.3	44.8	45.6	45.2	45.4	45.5	0.6
52	46.5	45.0	45.7	45.3	45.5	45.6	0.6
53	46.6	45.1	45.9	45.5	45.7	45.7	0.6
54	46.1	44.6	45.3	45.0	45.2	45.2	0.6
55	46.1	44.6	45.3	45.0	45.2	45.2	0.6
56	46.2	44.7	45.4	45.0	45.2	45.3	0.6
57	46.4	44.9	45.7	45.3	45.5	45.6	0.6
58	46.4	44.9	45.7	45.3	45.5	45.6	0.6
59	46.4	44.9	45.7	45.3	45.5	45.6	0.6
60	46.7	45.2	46.0	45.6	45.8	45.9	0.6
61	46.9	45.4	46.1	45.7	45.9	46.0	0.6
62	47.0	45.5	46.2	45.9	46.1	46.1	0.6
63	46.1	44.6	45.4	45.0	45.2	45.3	0.6
64	46.1	44.6	45.4	45.0	45.2	45.3	0.6
65	46.3	44.8	45.5	45.1	45.3	45.4	0.6
66	46.5	45.0	45.8	45.4	45.6	45.7	0.6
67	46.5	45.0	45.8	45.4	45.6	45.7	0.6
68	46.7	45.2	45.9	45.6	45.7	45.8	0.6
69	46.8	45.3	46.1	45.7	45.9	46.0	0.6
70	46.8	45.3	46.1	45.7	45.9	46.0	0.6
71	46.1	44.6	45.4	45.0	45.2	45.2	0.6
72	48.0	46.5	47.2	46.8	47.0	47.1	0.6
73	47.2	45.7	46.5	46.1	46.3	46.4	0.6
74	47.2	45.7	46.5	46.1	46.3	46.4	0.6
75	47.4	45.9	46.6	46.3	46.4	46.5	0.6

Table A12: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 70°C water flowing at 0.27×10^{-3} m^3/s (five replicates).

Time	T* 1	T2	T3	T4	T5	Avg.**	Std.***
76	47.5	46.0	46.8	46.4	46.6	46.7	0.6
77	47.4	45.9	46.6	46.3	46.4	46.5	0.6
78	47.7	46.2	46.9	46.5	46.7	46.8	0.6
79	47.7	46.2	46.9	46.5	46.7	46.8	0.6
80	47.7	46.2	46.9	46.5	46.7	46.8	0.6
81	48.8	47.3	48.0	47.7	47.9	47.9	0.6
82	48.9	47.4	48.2	47.8	48.0	48.1	0.6
83	48.9	47.4	48.2	47.8	48.0	48.1	0.6
84	48.2	46.7	47.5	47.1	47.3	47.3	0.6
85	48.1	46.6	47.3	46.9	47.1	47.2	0.6
86	49.2	47.7	48.5	48.1	48.3	48.3	0.6
87	49.3	47.8	48.6	48.2	48.4	48.5	0.6
88	49.2	47.7	48.5	48.1	48.3	48.3	0.6
89	49.3	47.8	48.6	48.2	48.4	48.5	0.6
90	49.3	47.8	48.6	48.2	48.4	48.5	0.6
91	49.3	47.8	48.6	48.2	48.4	48.5	0.6
92	50.5	49.0	49.7	49.4	49.5	49.6	0.6
93	50.6	49.1	49.9	49.5	49.7	49.8	0.6
94	50.6	49.1	49.9	49.5	49.7	49.8	0.6
95	51.8	50.3	51.0	50.6	50.8	50.9	0.6
96	51.6	50.1	50.9	50.5	50.7	50.8	0.6
97	51.8	50.3	51.0	50.6	50.8	50.9	0.6
98	51.8	50.3	51.0	50.6	50.8	50.9	0.6
99	51.9	50.4	51.1	50.8	51.0	51.0	0.6
100	51.8	50.3	51.0	50.6	50.8	50.9	0.6
101	51.8	50.3	51.0	50.6	50.8	50.9	0.6
102	52.1	50.6	51.3	50.9	51.1	51.2	0.6
103	52.9	51.4	52.1	51.7	51.9	52.0	0.6
104	52.9	51.4	52.1	51.8	52.0	52.0	0.6
105	53.0	51.5	52.2	51.9	52.1	52.1	0.6
106	52.0	50.5	51.3	50.9	51.1	51.1	0.6
107	52.1	50.6	51.4	51.0	51.2	51.2	0.6
108	52.2	50.7	51.5	51.1	51.3	51.4	0.6
109	52.8	51.3	52.0	51.6	51.8	51.9	0.6
110	52.8	51.3	52.0	51.6	51.8	51.9	0.6
111	52.8	51.3	52.0	51.6	51.8	51.9	0.6
112	52.8	51.3	52.0	51.6	51.8	51.9	0.6
113	52.8	51.3	52.0	51.6	51.8	51.9	0.6

Table A12: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 70°C water flowing at 0.27×10^{-3} m^3/s (five replicates).

Time	T* 1	T2	T3	T4	T5	Avg.**	Std.***
114	52.8	51.3	52.0	51.6	51.8	51.9	0.6
115	52.8	51.3	52.0	51.6	51.8	51.9	0.6
116	53.9	52.4	53.1	52.8	52.9	53.0	0.6
117	53.9	52.4	53.1	52.8	52.9	53.0	0.6
118	54.0	52.5	53.3	52.9	53.1	53.1	0.6
119	54.0	52.5	53.3	52.9	53.1	53.1	0.6
120	54.0	52.5	53.3	52.9	53.1	53.1	0.6
121	55.1	53.6	54.4	54.0	54.2	54.2	0.6
122	55.1	53.6	54.4	54.0	54.2	54.2	0.6
123	55.1	53.6	54.4	54.0	54.2	54.2	0.6
124	55.1	53.6	54.3	53.9	54.1	54.2	0.6
125	55.2	53.7	54.5	54.1	54.3	54.4	0.6
130	56.4	54.9	55.6	55.2	55.4	55.5	0.6
131	56.4	54.9	55.6	55.2	55.4	55.5	0.6
132	56.4	54.9	55.6	55.2	55.4	55.5	0.6
133	56.4	54.9	55.6	55.2	55.4	55.5	0.6
134	56.4	54.9	55.6	55.2	55.4	55.5	0.6
135	57.4	55.9	56.7	56.3	56.5	56.6	0.6
136	58.7	57.2	57.9	57.5	57.7	57.8	0.6
137	58.7	57.2	57.9	57.5	57.7	57.8	0.6
138	58.7	57.2	57.9	57.5	57.7	57.8	0.6
139	58.7	57.2	57.9	57.5	57.7	57.8	0.6
140	58.7	57.2	57.9	57.5	57.7	57.8	0.6
141	58.8	57.3	58.0	57.6	57.8	57.9	0.6
142	59.9	58.4	59.1	58.7	58.9	59.0	0.6
143	59.9	58.4	59.2	58.8	59.0	59.1	0.6
144	59.9	58.4	59.2	58.8	59.0	59.1	0.6
145	59.9	58.4	59.2	58.8	59.0	59.1	0.6
146	60.0	58.5	59.3	58.9	59.1	59.2	0.6
147	60.0	58.5	59.3	58.9	59.1	59.2	0.6
148	60.1	58.6	59.4	59.0	59.2	59.3	0.6
149	60.1	58.6	59.4	59.0	59.2	59.3	0.6
150	60.8	59.3	60.1	59.7	59.9	60.0	0.6
151	61.3	59.8	60.5	60.2	60.4	60.4	0.6
152	61.3	59.8	60.5	60.2	60.4	60.4	0.6
153	61.3	59.8	60.5	60.2	60.4	60.4	0.6
154	61.3	59.8	60.5	60.2	60.4	60.4	0.6
155	61.3	59.8	60.5	60.2	60.4	60.4	0.6

Table A12: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 70°C water flowing at 0.27×10^{-3} m^3/s (five replicates).

Time	T^*1	T2	T3	T4	T5	Avg.**	Std.***
156	61.3	59.8	60.5	60.2	60.4	60.4	0.6
157	61.3	59.8	60.5	60.2	60.4	60.4	0.6
158	61.3	59.8	60.5	60.2	60.4	60.4	0.6
159	61.3	59.8	60.5	60.2	60.4	60.4	0.6
160	61.3	59.8	60.5	60.2	60.4	60.4	0.6
161	62.4	60.9	61.7	61.3	61.5	61.6	0.6
162	62.4	60.9	61.7	61.3	61.5	61.6	0.6
163	62.4	60.9	61.7	61.3	61.5	61.6	0.6
164	62.4	60.9	61.7	61.3	61.5	61.6	0.6
165	62.4	60.9	61.7	61.3	61.5	61.6	0.6
166	62.4	60.9	61.7	61.3	61.5	61.6	0.6
167	62.4	60.9	61.7	61.3	61.5	61.6	0.6
168	62.4	60.9	61.7	61.3	61.5	61.6	0.6
169	62.9	61.4	62.2	61.8	62.0	62.1	0.6
170	62.9	61.4	62.2	61.8	62.0	62.1	0.6
171	63.0	61.5	62.3	61.9	62.1	62.2	0.6
172	63.2	61.7	62.5	62.1	62.3	62.4	0.6
173	63.2	61.7	62.5	62.1	62.3	62.4	0.6
174	63.2	61.7	62.5	62.1	62.3	62.4	0.6
175	63.2	61.7	62.5	62.1	62.3	62.4	0.6
176	63.2	61.7	62.5	62.1	62.3	62.4	0.6
177	63.2	61.7	62.5	62.1	62.3	62.4	0.6
178	63.2	61.7	62.5	62.1	62.3	62.4	0.6
179	63.2	61.7	62.5	62.1	62.3	62.4	0.6
180	63.2	61.7	62.5	62.1	62.3	62.4	0.6
182	64.1	62.6	63.4	63.0	63.2	63.3	0.6
183	64.1	62.6	63.4	63.0	63.2	63.3	0.6
184	64.1	62.6	63.4	63.0	63.2	63.3	0.6
185	64.1	62.6	63.4	63.0	63.2	63.3	0.6
186	64.1	62.6	63.4	63.0	63.2	63.3	0.6
187	64.1	62.6	63.4	63.0	63.2	63.3	0.6
188	65.1	63.6	64.4	64.0	64.2	64.3	0.6
189	66.2	64.7	65.5	65.1	65.3	65.4	0.6
190	66.2	64.7	65.5	65.1	65.3	65.4	0.6
191	66.7	65.2	66.0	65.6	65.8	65.9	0.6
192	66.7	65.2	66.0	65.6	65.8	65.9	0.6
193	66.7	65.2	66.0	65.6	65.8	65.9	0.6
194	66.7	65.2	66.0	65.6	65.8	65.9	0.6

Table A12: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 70°C water flowing at 0.27×10^{-3} m^3/s (five replicates).

Time	T* 1	T2	T3	T4	T5	Avg.**	Std.***
195	66.8	65.3	66.1	65.7	65.9	66.0	0.6
196	66.8	65.3	66.1	65.7	65.9	66.0	0.6
197	66.8	65.3	66.1	65.7	65.9	66.0	0.6
198	66.8	65.3	66.1	65.7	65.9	66.0	0.6
199	67.1	65.6	66.4	66.0	66.2	66.3	0.6
200	67.8	66.3	67.1	66.7	66.9	67.0	0.6
201	68.2	66.7	67.5	67.1	67.3	67.4	0.6
202	68.2	66.7	67.5	67.1	67.3	67.4	0.6
203	68.8	67.3	68.1	67.7	67.9	68.0	0.6
204	69.0	67.5	68.3	67.9	68.1	68.1	0.6
205	69.1	67.6	68.4	68.0	68.2	68.2	0.6
206	69.1	67.6	68.4	68.0	68.2	68.2	0.6
207	69.1	67.6	68.4	68.0	68.2	68.2	0.6
208	69.1	67.6	68.4	68.0	68.2	68.2	0.6
209	69.1	67.6	68.4	68.0	68.2	68.2	0.6
210	69.1	67.6	68.4	68.0	68.2	68.2	0.6
211	69.8	68.3	69.1	68.7	68.9	69.0	0.6
212	69.8	68.3	69.1	68.7	68.9	69.0	0.6
213	69.8	68.3	69.1	68.7	68.9	69.0	0.6
213	69.8	68.3	69.1	68.7	68.9	69.0	0.6
214	69.8	68.3	69.1	68.7	68.9	69.0	0.6
215	69.8	68.3	69.1	68.7	68.9	69.0	0.6
216	69.8	68.3	69.1	68.7	68.9	69.0	0.6
217	69.8	68.3	69.1	68.7	68.9	69.0	0.6
218	69.8	68.3	69.1	68.7	68.9	69.0	0.6
219	69.8	68.3	69.1	68.7	68.9	69.0	0.6
220	69.8	68.3	69.1	68.7	68.9	69.0	0.6

* Temperature (°C)
** Average of five replicates
*** Standard deviation (°C)

Table A13: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 70°C water flowing at 1.24×10^{-3} m^3/s (five replicates).

Time	$T^{*}1$	T2	T3	T4	T5	Avg.**	Std.***
0	26.1	24.6	25.4	25.0	25.3	25.4	0.6
1	29.1	27.8	29.1	28.1	28.5	28.7	0.6
2	32.2	29.9	32.0	31.1	31.3	31.4	0.9
3	34.5	32.5	34.7	33.9	33.9	33.9	0.9
4	36.3	34.3	36.6	35.7	35.7	35.7	0.9
5	38.2	35.5	38.4	37.8	37.5	37.3	1.2
6	39.3	36.9	39.8	39.5	38.9	38.7	1.1
7	40.1	38.2	41.0	40.4	39.9	39.7	1.0
8	40.9	39.5	42.1	42.0	41.1	40.9	1.0
9	41.5	40.7	43.2	43.3	42.2	41.8	1.1
10	42.2	41.0	43.9	44.1	42.8	42.4	1.3
11	43.7	42.6	45.2	45.3	44.2	43.8	1.1
12	44.0	43.0	45.7	45.6	44.5	44.2	1.1
13	45.1	44.1	46.5	46.1	45.5	45.3	0.9
14	46.1	44.9	47.3	47.1	46.4	46.1	1.0
15	46.8	45.9	48.1	47.6	47.1	46.9	0.8
16	47.4	46.6	48.8	48.6	47.8	47.6	0.9
17	48.5	47.4	49.5	49.1	48.7	48.5	0.8
18	49.1	47.9	50.1	49.6	49.2	49.0	0.8
19	50.0	48.7	50.8	50.4	50.0	49.8	0.8
20	50.8	49.6	51.5	51.0	50.7	50.6	0.7
21	51.1	49.7	52.1	51.8	51.2	51.0	0.9
22	51.9	51.0	52.9	52.5	52.1	51.9	0.7
23	52.2	51.3	53.3	52.8	52.4	52.3	0.7
24	52.8	51.6	53.7	53.3	52.8	52.7	0.8
25	53.6	52.7	54.4	54.1	53.7	53.6	0.7
26	54.2	52.8	54.9	54.5	54.1	54.0	0.8
27	54.3	53.5	55.4	55.2	54.6	54.4	0.7
28	55.0	54.0	55.9	55.7	55.1	55.0	0.8
29	55.3	54.4	56.3	55.9	55.5	55.3	0.7
30	55.6	55.1	56.7	56.5	56.0	55.8	0.7
31	56.5	55.4	57.2	56.8	56.5	56.4	0.7
32	56.6	56.1	57.7	57.3	56.9	56.8	0.6
33	57.2	56.6	58.1	57.9	57.5	57.3	0.6
34	57.9	56.6	58.5	57.9	57.7	57.7	0.7
35	57.9	56.9	58.8	58.6	58.0	57.9	0.7
36	58.0	57.5	59.1	58.7	58.3	58.2	0.6
37	59.0	57.8	59.5	59.0	58.8	58.8	0.7

Table A13: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 70°C water flowing at 1.24×10^{-3} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
38	59.0	58.2	59.8	59.6	59.1	59.0	0.6
39	59.5	58.6	60.2	59.7	59.5	59.4	0.6
40	60.1	58.6	60.6	60.1	59.9	59.8	0.8
41	60.1	59.4	60.8	60.7	60.3	60.1	0.5
42	60.4	59.4	61.1	60.6	60.4	60.3	0.6
43	60.7	60.0	61.3	60.8	60.7	60.7	0.5
44	60.8	60.1	61.7	61.5	61.0	60.9	0.6
45	61.2	60.3	61.9	61.4	61.2	61.1	0.6
46	61.6	60.8	62.2	62.0	61.7	61.6	0.5
47	61.8	61.1	62.5	62.1	61.9	61.8	0.5
48	62.1	60.8	62.6	62.0	61.9	61.8	0.6
49	62.1	61.4	62.9	62.8	62.3	62.1	0.6
50	62.1	61.7	63.0	62.7	62.3	62.2	0.5
51	62.6	61.7	63.3	63.1	62.7	62.5	0.6
52	62.5	62.2	63.5	63.1	62.8	62.7	0.5
53	63.2	62.2	63.7	63.3	63.1	63.0	0.6
54	63.4	62.4	63.9	63.6	63.3	63.2	0.6
55	63.3	62.8	64.1	63.6	63.4	63.4	0.5
56	63.3	62.5	64.1	63.6	63.4	63.3	0.6
57	63.7	63.1	64.4	64.2	63.8	63.7	0.5
58	63.7	63.1	64.5	63.9	63.8	63.8	0.5
59	64.1	63.2	64.8	64.6	64.2	64.0	0.6
60	64.1	63.6	64.9	64.7	64.4	64.2	0.5
61	64.3	63.6	65.0	64.6	64.4	64.3	0.5
62	64.8	63.9	65.2	65.0	64.7	64.6	0.5
63	64.6	64.0	65.3	64.9	64.7	64.6	0.5
64	64.7	64.0	65.4	65.0	64.8	64.7	0.5
65	65.1	63.9	65.5	65.3	64.9	64.8	0.6
66	64.8	64.3	65.7	65.3	65.0	64.9	0.5
67	65.4	64.2	65.7	65.1	65.1	65.1	0.6
68	65.2	64.7	65.9	65.6	65.4	65.3	0.4
69	65.2	64.5	65.9	65.7	65.3	65.2	0.6
70	65.7	65.0	66.2	65.8	65.7	65.6	0.4
71	65.5	64.9	66.3	66.0	65.7	65.6	0.5
72	65.4	64.9	66.2	66.0	65.6	65.5	0.5
73	65.9	65.3	66.5	66.3	66.0	65.9	0.5
74	65.8	65.1	66.5	66.1	65.9	65.8	0.5
75	65.9	65.4	66.5	66.3	66.0	66.0	0.4

Table A13: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 70°C water flowing at 1.24×10^{-3} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
76	66.2	65.7	66.9	66.7	66.4	66.3	0.4
77	65.9	65.4	66.7	66.3	66.1	66.0	0.5
78	66.2	65.7	66.8	66.7	66.3	66.2	0.4
79	66.6	65.6	67.0	66.5	66.4	66.4	0.5
80	66.4	65.8	67.0	66.5	66.4	66.4	0.4
81	66.8	66.0	67.1	66.8	66.7	66.6	0.4
82	66.5	66.1	67.1	66.7	66.6	66.6	0.4
83	66.2	65.8	67.1	66.9	66.5	66.4	0.5
84	67.0	66.4	67.4	67.2	67.0	67.0	0.4
85	66.6	66.0	67.2	66.7	66.6	66.6	0.4
86	66.9	66.3	67.4	67.2	67.0	66.9	0.4
87	66.8	66.4	67.5	67.4	67.0	66.9	0.4
88	66.9	66.3	67.5	67.2	67.0	66.9	0.5
89	66.8	66.5	67.6	67.5	67.1	67.0	0.5
90	67.0	66.4	67.6	67.2	67.1	67.0	0.4
91	67.0	66.3	67.6	67.2	67.0	67.0	0.5
92	67.3	66.9	67.9	67.6	67.4	67.4	0.3
93	67.2	66.5	67.7	67.2	67.2	67.1	0.4
94	67.0	66.8	67.9	67.6	67.3	67.2	0.4
95	67.5	66.7	67.8	67.5	67.4	67.3	0.4
96	67.3	66.7	67.9	67.5	67.4	67.3	0.4
97	67.6	66.8	68.1	67.8	67.6	67.5	0.5
98	67.6	67.1	68.1	67.5	67.6	67.6	0.3
99	67.5	66.7	68.1	67.8	67.5	67.4	0.5
100	67.6	67.2	68.2	67.8	67.7	67.7	0.3
101	67.5	66.9	68.0	67.6	67.5	67.5	0.4
102	67.6	66.9	68.2	67.9	67.7	67.6	0.5
103	67.7	67.2	68.2	67.8	67.7	67.7	0.3
104	67.6	66.9	68.1	67.6	67.6	67.6	0.4
105	67.9	67.2	68.4	68.3	67.9	67.8	0.5
106	68.0	67.5	68.3	68.1	68.0	67.9	0.3
107	67.6	66.9	68.3	68.1	67.7	67.6	0.5
108	67.6	67.1	68.3	68.1	67.8	67.7	0.5
109	68.2	67.2	68.1	67.9	67.8	67.8	0.4
110	67.6	67.1	68.0	68.3	67.8	67.6	0.5
111	68.2	67.6	68.3	68.3	68.1	68.0	0.3
112	67.9	67.4	68.2	67.9	67.8	67.8	0.3
113	67.6	67.1	68.2	68.5	67.8	67.6	0.5

Table A13: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 70°C water flowing at 1.24×10^{-3} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
114	68.2	67.8	68.3	68.1	68.1	68.1	0.2
115	67.9	67.2	68.3	68.3	67.9	67.8	0.4
116	67.9	67.5	68.3	68.5	68.0	67.9	0.4
117	68.2	67.6	68.4	68.5	68.2	68.0	0.3
118	68.0	67.5	68.4	68.5	68.1	68.0	0.4
119	68.2	67.8	68.4	68.3	68.2	68.1	0.2
120	68.2	67.8	68.5	68.3	68.2	68.1	0.3
121	67.9	67.2	68.3	68.5	68.0	67.8	0.5
122	68.3	67.8	68.4	68.1	68.1	68.2	0.2
123	68.4	67.8	68.6	68.6	68.4	68.3	0.3
124	68.3	67.5	68.4	68.5	68.2	68.1	0.4
125	68.4	68.1	68.6	68.5	68.4	68.4	0.2
126	68.2	67.6	68.6	68.6	68.2	68.1	0.4
127	68.3	67.8	68.5	68.5	68.3	68.2	0.3
128	68.4	67.8	68.6	68.6	68.4	68.3	0.3
129	68.2	67.5	68.6	68.9	68.3	68.1	0.5
130	68.4	68.1	68.6	68.3	68.3	68.3	0.2
131	68.4	68.1	68.7	68.7	68.5	68.4	0.3
132	68.2	67.9	68.6	68.5	68.3	68.2	0.3
133	68.6	67.9	68.7	68.6	68.5	68.4	0.3
134	68.4	67.8	68.7	68.9	68.5	68.3	0.4
135	68.2	68.1	68.6	68.7	68.4	68.3	0.3
136	68.6	68.1	68.8	68.9	68.6	68.5	0.3
137	68.3	67.8	68.7	68.7	68.4	68.3	0.4
138	68.6	68.1	68.7	68.6	68.5	68.5	0.3
139	68.7	68.1	68.9	68.7	68.6	68.5	0.3
140	68.2	67.8	68.6	68.6	68.3	68.2	0.3
141	68.4	68.1	68.7	68.9	68.5	68.4	0.3
142	68.8	67.9	68.9	68.9	68.6	68.5	0.4
143	68.3	68.1	68.6	68.6	68.4	68.3	0.2
145	68.8	68.1	68.9	68.7	68.6	68.6	0.3
146	68.4	67.9	68.8	68.9	68.5	68.4	0.4
147	68.4	67.8	68.7	68.9	68.5	68.3	0.4
148	68.6	67.9	68.8	68.9	68.5	68.4	0.4
149	68.4	68.1	68.7	68.7	68.5	68.4	0.3
150	68.7	68.1	68.8	68.6	68.5	68.5	0.3
151	69.0	68.3	69.1	69.0	68.9	68.8	0.3
152	68.6	68.1	68.8	68.7	68.5	68.5	0.3

Table A13: Time-temperature data for heating the sample sphere (0.0127-m diameter) in the multiparticulate system, with 70°C water flowing at 1.24×10^{-3} m^3/s (five replicates) (contd.).

Time	T1	T2	T3	T4	T5	Avg.	Std.
153	68.6	68.3	68.9	68.9	68.7	68.6	0.2
154	68.7	68.1	68.8	68.7	68.6	68.5	0.3
155	68.4	68.1	68.8	68.7	68.5	68.4	0.3
156	68.7	68.3	69.0	69.0	68.8	68.7	0.3
157	69.0	68.3	68.8	68.7	68.7	68.7	0.2
158	68.6	68.3	68.7	68.7	68.6	68.5	0.2
159	69.0	68.1	68.9	69.2	68.8	68.6	0.4
160	68.6	68.2	68.7	68.9	68.6	68.5	0.3

* Temperature (°C)
** Average of five replicates
*** Standard deviation