Natural Convection Heat Transfer of Hydrophilic Particle Suspension: Implications on Nuclear Waste Remediation

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Abstract

Natural convection of gel suspension has the potential to be applied to particulate recovery systems, such as in the dynamic filtering of radioactive waste particles. In this study, experiments were conducted to assess natural convection of gradually settling gelatin particle suspension in a rectangular cell, relative to single-phase natural convection with bulk temperature stratification, and to derive empirically a transfer relationship. The rectangular cell used had one vertical wall maintained at a lower temperature and the opposite wall at a relative thermal high. Two different sizes of gelatin particles were used. Local heat transfer coefficients were calculated from wall and bulk temperature measurements. Velocity field characteristics were determined using an Ultrasound Velocity Profiler (UVP). Heat transfer results showed both enhancement and de-enhancement in Nusselt number depending on temperature difference and particle size. The four necessary conditions to induce heat transfer enhancement in this setup and effect of sediment layer on heat transfer are discussed. The ultimate goal of this study was to examine a method of a dynamic filtering system that separated particles from wastewater using thermally-induced volumetric expansion and/or contraction of similarly sized functional gels that could be applied conceptually to nuclear waste remediation. For single-phase, the effect

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of thermal stratification on natural convection heat transfer can be accounted for by using a stratification factor, S , and [for dual-phase](#), a stratified Nusselt number ~~given the notation~~ sNu . The reduction in the spread of data point relative to plotting Nu_y against Ra_y , indicates that plotting the stratified local Nusselt number, sNu_y , versus the local Rayleigh number, Ra_y , is appropriate. More importantly the analytical dependence to the Rayleigh number ($Ra_y^{1/4}$ for laminar and $Ra_y^{1/3}$ for turbulent) was preserved and within variations seen in the literature.

Keywords: Hydrophilic particle; velocity profile; single-phase flow; two-phase flow.

1 **Introduction**

2 Decontamination of effluents, such as wastewater that contains radioactive isotopes,
3 heavy metals, or hazardous solid particulates, is a subject of great interest [1-4]. This interest has
4 culminated in rapid growth of waste remediation and minimization directives and procedures.
5 Typically, radioactive waste storage tanks contain hazardous and radioactive matter resulting
6 from the production of nuclear materials, fuel, cladding etc. As the tanks age, the possibility of
7 waste escaping to the environment increases. To minimize the risk of waste migration and
8 exposure to workers, the public, and the environment, the waste must be retrieved and the tanks
9 sealed. A primary remediation procedure for this kind of contamination is to separate metal
10 particulates from the liquid waste. Since the thermal properties of each metallic constituent are
11 different, a natural convection cell can be used to enhance separation. These mobile suspended
12 particulates can therefore adhere to suspended materials like gels. Separating radioactive
13 particles from liquid waste plays an important role in radioactive waste remediation since it
14 reduces the volume of waste to be treated as radioactive. Moreover, if the most radioactive and
15 long-lived isotopes could be greatly separated from a waste stream then the problems of storage
16 and containments would be substantially simplified.

17 A dynamic filtering system can be used to recover particulate solids, such as radioactive
18 particles, from a mixed waste stream using a class of gels, which swell and shrink in response to
19 an applied temperature change. Several gels and gel-like materials are known to undergo an
20 abrupt change, or phase transition, between collapsed and swollen states depending on their
21 composition. For example, poly(acrylamide) swells with increasing temperature, while poly(*N*-
22 alkyl substituted acrylamide) swells with decreasing temperature. These changes can occur in
23 response to minute changes in their physical environment, such as, temperature, solvent

composition, pH, ionic strength, light and electric field [5-12]. These functional materials have been studied for many purposes, including, controlled drug delivery, filtration at molecular level, extraction solvents for proteins, and concentration of dilute suspensions [13-19]. Some of these materials can be obtained from polymers that exhibit lower critical suspension temperatures (LCST). Examples of these include and are not limited to polyethylene oxide, hydroxypropyl cellulose, polyvinyl alcohol and derivatives of poly acrylamides [19].

Natural convection with particles is different from that of single-phase natural convection and is regarded as two-phase flow. Two-phase flows consist of liquid-liquid, liquid-gas, liquid-solid particles, or gas-solid particles. In liquid-solid particles suspension, particles will tend to settle out of suspension and sediment in most cases. The bottlenecks experienced in any analyses arise due to this settling further contributing to a quantitative complication. Sedimentation of particles and natural convection can occur simultaneously. Sedimentation and suspension flows are of importance, especially in the field of solid-liquid separations in the chemical, mining, pulp and paper, wastewater, food, pharmaceutical, ceramic and other industries. Also, the sedimentation of particles from a convecting fluid is a process of much interest to engineers, fluid dynamicists, geologists and metallurgists. For example, the process plays a fundamental role in controlling the settling behavior of phenocrysts in magma chambers, crystals and impurities in metallic castings and carbon microparticles in combustion chambers [20]. Although intensively studied for many years, an understanding of sedimentation and suspension flows is still far from complete.

Unlike single-phase flow, suspension flow introduces a number of additional features, including properties of suspensions (rheology, particle size and shape, particle-particle interaction, surface characteristics, yield stress, concentration, viscosity), individual particles

(orientation and surfactants), and sediments (permeability, porosity and compressibility). Studies on two-phase liquid-solid flows and suspensions in relation to settling and focused on hydrodynamics have been reported [21-33]. Koyaguchi et al. [20] investigated sedimentation of silicon carbide particles from a convective fluid experimentally by using a tank heated from below. They showed that convective motion due to heating from below can be affected by the presence of particles and is controlled by the bulk density of a particulate suspension. Stommel [21] investigated trajectories of the particles sinking slowly through convection cell, which is heated from below, analytically. He classified the trajectories of particles in terms of the quantity, which is the ratio of the settling velocity to the maximum upward water velocity. Most of these studies have primarily dealt with the convective motion due to heating from below.

For liquid-solid particle flow it is also recognized that suspensions of solid particles have great potential to enhance the heat transfer. For two-phase gas-solid particle flow, Murray [34] investigated the mechanisms associated with the enhancement of heat transfer over the front of a tube in a gas-particle cross flow. Plass and Molerus [35] investigated wall-to-suspension heat transfer of solid-liquid pipe flow. In order to clarify how particle in suspension affect the structure of flow, Zisselmar and Molerus [36] investigated solid-liquid pipe flow with regard to turbulence modification using laser-Doppler anemometry. They concluded that the intensity of turbulence is significantly affected by the size of the solid particles. Moreover, as the size of the particles increased, the turbulence intensity was dampened depending on solids concentration as well as on distance from the wall. Mechanisms of heat flow in such suspensions have also been studied using nano-sized particles (see [37]). These nano-sized particles are also referred to as nanofluids. Khanafer et al. [38] investigated heat transfer enhancement in an enclosure utilizing these nanofluids. They concluded that the suspended nano-sized particles substantially increased

the heat transfer rate. Also, the nanofluid heat transfer rate increased with an increase in the nano-sized particle volume fraction. In addition, they found that the presence of nano-sized particles in the fluid altered the structure of the fluid flow. For micron-sized particle suspensions, Hattori et al. [39] investigated transient natural convection of glass beads suspension in a rectangular cell heated and cooled along opposing vertical walls. However their aim was to observe transient changes of natural convection in particle suspension, and as such steady-state natural convection was not investigated.

Hoffman et al. [14, 15, 40] showed that temperature sensitive gels could be used to selectively or non-selectively remove undesirable toxins, to assay for specific substances, and to recover selected products of a biochemical process. This process may also be applied in a non-biochemical situation. The basis of the design proposed in this study is formulated from Hoffman's et al., [14, 15, 40] work. In this scenario, first, a dried (collapsed) temperature sensitive gel is immersed in mixed wastewater, which contains solid particles. The system is heated above lower critical suspension temperature (LCST) so that the gel swells. Since gel is hydrophilic, it absorbs water and may absorb or encapsulate small solid particles. The system is then cooled below LCST so that the gel collapses. In this state, it releases only water, and the solid particles are captured or adhere to the gel. The main focus of this study was to investigate natural convection heat transfer of gelatin suspension in comparison to deionized water. The specific objectives were: (1) to quantify natural convection heat transfer of hydrophilic particle suspension with particle size and particle loading as parameters; (2) to measure temperature profiles in fluid near a heated wall for both single-phase and two-phase natural convection; and (3) to obtain the velocity profiles of natural convection with and without micron-sized, hydrophilic particles of various sizes and particle loading by Ultrasound Velocity Profile (UVP).

93 Additionally, the problem of bulk temperature stratification in natural convection of single-phase
94 was also investigated.

96 **Methods**

97 *Rationale*

98 Since a two-phase flow was the backbone of this study, a selection criterion of the solid
99 phase was established. The solid phase used had to be a readily available low cost material. It
100 also had to be a water-absorbing (hydrophilic) particle, which swells in water; and that it should
101 have the capability of transporting thermal energy from hot to cold in a thermal convection cell.
102 Its diameter was expected to be around 50 to 200 μm , a size ideal for velocity measurement
103 using acoustic velocity measurement methods. Also the particle needed to have a density nearly
104 equal to that of water so that some particles may follow the convective flow and some sediment
105 out as they become heavier. Its solubility in water over an appropriate temperature range (lower
106 than thermally induced evaporation of fluid used) also was to be extremely low. After testing
107 several kinds of particles like tapioca particles, silica gels, gelatin (Knox Gelatine, unflavored)
108 was chosen.

109 Gelatin is a pure protein obtained from animal raw materials containing collagen. It is
110 usually found in granular powder form and its diameter is small enough to meet the selection
111 criterion. Also, it is relatively insoluble in cold water; however dry gelatin swells or hydrates
112 when stirred into cold water. Its solubility increases closer to boiling point of water. The
113 measured bulk density of dried gelatin particle was 680 kg/m^3 , where the bulk density indicates
114 the ratio of mass of gelatin particles to the bulk volume of it. The density of the gelatin particles
115 in water was determined using Archimedes' principle by measuring the volume variation when a

116 weighted amount of particles was introduced into 20 milliliters of distilled water in a graduated
117 cylinder. The gelatin particle density in water was 1390 kg/m^3 . The bulk density is lower than
118 that of true density because the bulk volume includes pore space remaining in the material. The
119 true density of a pure substance is calculated from its components' densities considering
120 conservation of mass and volume. The true density of gelatin is about 1270 kg/m^3 [41].

122 *Medium*

123 Deionized water was used as a working fluid in these experiments and in the circulator
124 baths. About 20 liters of deionized water was needed to fill the experimental cell for a run. In
125 order to prevent air bubbles from attaching to the inner surface of the Plexiglas walls, the water
126 was boiled to allow dissolved gas to escape and then cooled to room temperature in a covered
127 container. The gelatin particles were screen fractionated using United States Standard Testing
128 Sieves (Fisher Scientific Company) and Central Scientific Company's Sieve Shaker (Catalog No.
129 18480). The sieves were placed on the sieve shaker in descending mesh size starting at the top
130 of a stack of four. A small quantity of particles (about 100 g) was placed in the top sieve and the
131 shaker was operated for 10 to 15 minutes. At the end of the shaking period, the sieves were
132 separated and their contents placed in individually labeled plastic bags. The screening was
133 continued until a sufficient quantity of particles was obtained for the experiment. Particles were
134 divided into four groups in concomitance with sieve sizes. The group, which had median
135 particle diameter of $138 \text{ }\mu\text{m}$, was not used because of its large size even though it met the
136 selection criterion. The group, which had a median particle diameter of $60 \text{ }\mu\text{m}$, was combined
137 with the group whose median particle diameter was less than $45 \text{ }\mu\text{m}$, since the individual sized
138 amounts were too little for effective analysis. Thus, two different particle sizes were used in this

study. One consisted of particles that went through the No. 200 sieve, particle diameter, $d_p = d_1$, and the other consists of particles that spanned No. 200 and No. 325, particle diameter, $d_p = d_2$.

The gelatin particle sizes of both wet and dry state were then determined using a SMZ800 Nikon microscope fitted with a digital camera. The determination of a particle size distribution was carried out by measuring the size of a number of particles. Since the gelatin particles have irregular shapes, it was hard to accurately quantify the true diameter. To get over this problem, Martin's diameter method, one that has been widely used was adopted. Martin's diameter was used to obtain a representative size of the individual particles. Martin's diameter is defined as the length of a line, parallel to the fixed direction of scan, which divides the particle into two equal areas (e.g. [42 – 44]). The use of this diameter is based on the proposition that although the smallest diameter of some particles and the largest dimension of others may be determined, the resulting errors tend to be compensating if sufficient particles are measured. Concerning this proposition, at least 100 particles were taken as a sample size. The diameter values obtained for the gelatin particles used for this study were determined. The number of particles in each size interval, Δd , which would be large enough to contain many particles, yet small enough to obtain sufficient detail, was determined. Gelatin particle sizes, $d_p = d_1$, in wet state and $d_p = d_2$ in dry state were determined. The number-average particle diameter in the particle size distribution was obtained from $\bar{d} = \sum n_i d_i / \sum n_i = \sum n_i d_i / N = \sum f_i d_i$ with normalized distribution such

that $\sum_{i=1}^N f_i = 1$. f_i is ordinate corresponding to each size interval as represented by a frequency

value. The variance of the diameter values was determined from

$$\sigma^2 = \sum n_i (d_i - \bar{d})^2 / \sum n_i = \sum f_i (d_i - \bar{d})^2.$$

Tracer particles were used to gauge the velocity profile of particles in the convection cell. The tracer particles used in this study were nylon seeding particles (Expancel microspheres, 091 DU 80, Akzo Nobel). Expancel microspheres are off-white (easy to track), spherically formed particles with a thermoplastic shell encapsulating air. The particle size is about 18 to 24 μm and the measured density of dried particle was $503.6 \pm 4.3 \text{ kg/m}^3$. Expancel microspheres as a tracer provide an ideal particle for two-phase flow velocity measurements. These particles have been used in research dealing with Ultrasound Velocity Profile (UVP) (e.g. [45]). The next part of the experiment was to obtain the suspensions. Particles and fluid were mixed just prior to each run. In some cases, the suspension was kept in a carefully sealed sterile container for reuse. The volume of suspension required for a run added to a fraction of the 20 liters of deionized water used. The concentration of tracer particles was based mainly on experience and was chosen to optimize the velocity measurement results.

Test apparatus

The experiments were carried out in an experimental cell of dimensions 100 cm high by 50.05 cm wide and 2.54 cm depth. The experimental cell itself was made of two Plexiglas sheets 106.7 cm high, 61 cm wide, and 0.943 cm thickness. Ideally the depth of the natural convection cell is supposed to be large enough to avoid interference between the sidewalls and the central region. This was not the case for this study owing to unavoidable limitations on the number of support apparatus that would have to be used with a larger cell. This scaled down version still offered adequate results. The aluminum and PVC square channels were sandwiched between the two Plexiglas sheets on both sides. The aluminum channel was 2.54 cm square cross-sectional area and had a wall thickness of 3.18 mm whereas the PVC channel was 2.54 cm square and 2.0

mm thick. Since aluminum has a higher thermal conductivity, it was placed in the inner side of the cell for the hot and cold ends of the experimental cell. On the other hand, the low thermal conductivity PVC channels were placed at the outer exposed side to prevent heat loss to the ambient. Plexiglas sheets, aluminum and PVC channels were glued with clear, waterproof adhesive (UV6800, Eclectic Products, Inc.). The bottom of the cell was also closed with a PVC channel. The aluminum tubes, which were placed on both ends of the cell were heated and cooled respectively by water running through them. The temperature of both hot and cold walls of the cell was controlled by two constant temperature (refrigerator-heater) LAUDA RM6 Brinkman Instruments circulating baths. Each circulating bath had a 6 liter fluid capacity and -15°C to 120°C temperature range with an accuracy limit of $\pm 0.02^\circ\text{C}$. First, the water from circulating bath flowed downward through the aluminum channels located at the sides. Since the aluminum and PVC channels were connected at the bottom, water flowed from the aluminum channel into the PVC channel. The next cycle of flow was through the PVC channel to discharge water in the circulating bath. To further minimize heat loss the Plexiglas enclosure was insulated with polystyrene. The PVC provided insulation for the sides and bottom. A schematic representation the setup is shown in Figure 1.

Fig. 1 shows an illustration of how deionized water flows through the circulator baths. Ten Chromel-Alumel thermocouples (36 AWG) were attached at length spacing of 10.16 cm from each other along the entire wall surface and covered using a thin (0.05 mm thick) aluminum tape. In order to prevent water from getting into the gap between the thermocouple tip and aluminum tape, the tape was coated with a waterproof adhesive. The actual hot wall temperature was thus the temperature of the aluminum sheet surface. The thermocouples attached to the aluminum sheet recorded this value. To correct for any heat losses, to determine an accurate

value for temperature of the wall, both outer and inner surface temperatures of the aluminum channel were measured. The temperature within the test cell was measured by a traversing thermocouple probe, which consisted of ten Chromel-Alumel 20 AWG thermocouples within a plastic tube of 1.27 cm in diameter. These thermocouples were calibrated using a thermocouple calibrator (CL-307, Omega Engineering, INC.). The temperature at ice point and boiling point were used as checks. The temperature of the thermocouple and reference thermocouple calibrator accuracy limit was ± 2.3 °C. Errors resulting from the measurement techniques were estimated by taking the derivatives of each of the desired parameters with respect to each of the measured quantities. It was assumed that the random error of the temperature differences measured with the type K thermocouples was 0.5 °C. The thermocouples were positioned at: (i) 94.44 cm, (ii) 84.28 cm, (iii) 74.12 cm, (iv) 63.96 cm (v) 53.80 cm, (vi) 43.64 cm, (vii) 33.48 cm, (viii) 23.32 cm, (ix) 13.16 cm, and (x) 3.00 cm from the bottom. A second experimental cell (cell B) was used to measure the temperature difference between the inside and outside of the aluminum tube. Thermocouples were attached to walls in the same way as in the first cell. In the second cell, 32 AGW Chromel-Alumel thermocouples were used for temperature measurements at the hot end wall, and 20 AGW Chromel-Alumel thermocouples were used for the cold end wall. Also on the hot side, five 32 AGW Chromel-Alumel thermocouples were attached to the inside of the aluminum tube on the hot side (Positions (i) 94.44 cm, (ii) 84.28 cm, (vi) 43.64 cm, (viii) 23.32 cm and (x) 3.00 cm). A 0.05 mm thick aluminum sheet also covered each thermocouple in the second cell.

The hot wall temperature (T_{hot}) was obtained from calculating the temperature difference between inside (T_{inside}) and surface (T_{surface}) of the aluminum tube using Fourier's law of heat conduction. Figure 2 shows a cross section diagram of the hot wall, which consisted of an

aluminum channel wall of thickness $L_1 = 3.18$ mm and an aluminum tape of thickness $L_2 = 0.05$ mm. From Fourier's law of heat conduction, if there exists a homogeneous phase, then the local heat flux is proportional to the negative of the local temperature gradient can be obtained from $q_x'' = -k(dT/dx)$ where q_x'' is the heat flux in W/m^2 , or heat transfer rate in the x direction per unit area perpendicular to the direction of transfer. T is the local temperature in $^{\circ}\text{C}$ and x is the coordinate in the heat flow direction in length units like meters. k is the thermal conductivity of the substance in W/m K and is a characteristic of the wall material. The minus sign is a consequence of the fact that heat is transferred in the direction of decreasing temperature.

The temperature gradient within the aluminum channel wall under the steady-state conditions where the temperature distribution is linear was calculated from $dT/dx = (T_{\text{inside}} - T_{\text{surface}})/L_1$, whereas for the aluminum tape, the expression used was $dT/dx = (T_{\text{surface}} - T_{\text{wall}})/L_2$. The heat flux was calculated from the relation $q_x'' = -(k/L_1)(T_{\text{inside}} - T_{\text{surface}}) = -(k/L_2)(T_{\text{surface}} - T_{\text{wall}})$. From the experiment, the value of thermal conductivity for aluminum was obtained from standard tables as 204 W/m K . Thus, the aluminum surface temperature (T_{wall}) can be calculated using the aluminum channel inside wall temperature, T_{inside} , and the aluminum channel surface temperature, T_{surface} from the equation $T_{\text{wall}} = T_{\text{surface}} - (L_2/L_1)(T_{\text{inside}} - T_{\text{surface}}) = T_{\text{surface}} - 0.0157(T_{\text{inside}} - T_{\text{surface}})$. The maximum temperature difference between the aluminum channel inside and surface ($T_{\text{inside}} - T_{\text{surface}}$) was 1.93°C and corresponding temperature difference between the aluminum channel surface and the real wall temperature ($T_{\text{wall}} - T_{\text{surface}}$) was 0.03°C . Therefore since the difference was relatively small, the aluminum surface temperature was used as the sheet temperature for both hot and cold ends.

Velocity Measurement

Velocity of the fluid adjacent to the hot wall of the natural convection cell was obtained by means of a Met-Flow Ultrasound Doppler Velocimetry (UDV). This works by utilizing the pulsed echo technique of ultrasound to detect the Doppler shift of ultrasound waves reflected from moving particles suspended in a fluid (e.g. [46, 47]). Spatial resolution was possible by measuring simultaneously the time after emission of the ultrasound pulse. Hence, a full velocity profile along the ultrasound beam was instantaneously obtained by the UDV in space and time. Three ultrasonic 4 MHz UVP transducers each with an active diameter of 5 mm (diameter of active transmitting area) were fixed vertically on top of the convective cell and used to transmit a short emission of ultrasound along a measuring line into the flow field of interest. When a pulse hit a small solid phase particle suspended within the flow, part of the energy was scattered from the particles and a fraction reflected back. The transducer then switches over to a receiving mode to pick-up the reflected echo.

Flow velocity given from detection of the Doppler shift in the ultrasound frequency, f_d , as particles pass through the measurement volume. The velocity of the suspended particles within the convective cell, u_p , was obtained from, $u_p = (cf_d/2f_0)$, where c was the velocity of ultrasound in the two-phase flow being investigated, f_d the Doppler frequency shift, and f_0 , the ultrasound frequency. In this manner, the velocity of the solid phase gelatin particles could be calculated at each point. UVP uses a beam of ultrasound that is emitted from a transducer to obtain simultaneous velocity measurements along a profile. In order to achieve an accurate velocity profile, the return signal detected from the shift in frequency in the convective cell was gated at certain times, thereby allowing measurements of velocity at up to 128 points along the axis of the ultrasound beam. The distance to the location of each solid phase particle, X , was

calculated from, $X = \frac{1}{2}(ct)$, where t is the time lapse between the emission and reception of ultrasound pulses.

The vertical velocity components were obtained in the vicinity of the hot wall. Three 4 MHz transducers, ~~which has each with a~~ diameter of 8 mm (active diameter ~~is of~~ 5 mm) were fixed vertically on top of the cell (Fig. 3). The distance between the transducers was 12.7 mm. The probes were installed 103 cm above the bottom of the cell and were moved in a traverse direction towards the center of the cell at 1 to 4 mm intervals. The typical UVP online software window displays measured velocity as a function of spatial distance from the ultrasound transducer. The measurement of a velocity profile with UVP required a parametric configuration to calibrate the input values. The parameters used for configuration are: an ultrasound frequency of 4 MHz, a pulse repetition rate of 987 Hz, a measurable depth of 750 mm, a velocity resuspension setting of 0.74 mm/s, a time resuspension (single profile) value of 32.4 ms, velocity of sound in water (at 20°C) standardized at 1,480 m/s, a minimum ultrasound beam diameter setting of 5 mm and a divergence of the ultrasound beam of 2.2°.

Experiment runs

A total of twenty-seven experimental runs were performed. First, six tests with single-phase were made by using cell B in order to examine the characteristics of the experimental cells and to obtain a basic understanding of single-phase natural convection. The rest of the experiments were conducted by using cell A. The suspensions were prepared using deionized water and gelatin particles of average particle sizes $d_1 = 134 \mu\text{m}$ and $d_2 = 230 \mu\text{m}$. The particle loading ϕ_p in weight percent, were $\phi_1 = 0.026 \text{ wt\%}$, $\phi_2 = 0.104 \text{ wt\%}$, $\phi_3 = 0.26 \text{ wt\%}$, and $\phi_4 =$

0.518 wt%. The temperature difference between hot and cold wall was set according to the temperature difference of circulator water bath on both sides ($\Delta T_{\text{Bath}} = T_{\text{HB}} - T_{\text{CB}}$). T_{HB} and T_{CB} were set up temperatures for hot water bath and cold water bath, respectively. ΔT_{Bath} was set at 5°C, 10°C, 15°C, and 20°C for single-phase runs and 10°C and 20°C for the two-phase runs. The corresponding temperature difference between hot and cold wall ($\Delta T = \bar{T}_{\text{hot}} - \bar{T}_{\text{cold}}$) varied according to the surrounding environment, that is, the room temperature also referred to as the ambient temperature in this study. All physical properties of working fluid were evaluated at the film temperature, $T_{\text{film}} = (\bar{T}_{\text{hot}} + \bar{T}_{\text{cold}})/2$, where $\bar{T}_{\text{hot}}$ is the mean temperature of the hot wall surface and $\bar{T}_{\text{cold}}$ is the mean temperature of the cold wall surface. $\bar{T}_{\text{bulk}}$ is the mean bulk temperature within the cell. The Rayleigh number, Ra , is the dimensionless parameter and Ra_H is the Rayleigh number based on height of the cell, $H = 100$ cm, and temperature difference between hot and cold wall, $\Delta T = \bar{T}_{\text{hot}} - \bar{T}_{\text{cold}}$. Other thermophysical properties for water were found from standard tables (for values see [48]).

In a typical run the experimental cell was first cleaned. Then the cold and hot baths were filled with cooled and heated water. Care was taken to check for any water leak. The cell was then filled with deionized and deaired water at room temperature. The circulating water baths for both heating and cooling were then turned on. During the entire run the water bath temperatures was measured every thirty minutes. The thermocouple probe was inserted into the cell and placed in the center of the cell. The centerline temperatures of the cell and hot wall temperatures were measured every thirty minutes until steady-state was attained. Steady-state was achieved when there were no fluctuations greater than 0.2°C in the thermocouple probe readings taken at the center of the cell over a timer interval of thirty minutes. The cold wall temperatures were monitored and recorded every fifteen minutes using a Data Acquisition

System (Personal Daq, IOtech). For runs with gelatin suspension, gelatin particles were mixed into the water and thoroughly dispersed by using an electrical mixer before placing the mixture in the cell. The sediment layer depth was measured at the several locations using a graduated vertical scale. The steady-state was attained after about six hours from start-up. The thermocouple probe was moved along the top length of the cell, and temperature measured with a 54II FLUKE thermocouple thermometer; to obtain temperature profiles.

The acquisition of all temperature data took about twelve hours for each run. Velocity measurements were taken after temperature measurements for several runs. Generally, ultrasound reflecting tracer particles (Expancel 091DU80, diameter is about 20 μm) were added after temperature measurement was taken. The tracer particles were thoroughly mixed before adding them into the test cell. The entire cell was stirred using a long wooden stick, the effect of the tracer particles on temperature determination was assumed negligible. Velocity measurements were taken after three to four hours. The ultrasound transducers were moved along the top of the cell to obtain several readings at different points.

Results and discussion

Figs 4 (A) and (B) show the bulk temperatures measured along a vertical line placed midway between the hot and the cold wall. The temperatures are plotted in a dimensionless way as ratio of the bulk temperature minus the cold wall temperature to the hot plate temperature minus the cold wall temperature. Fig. 4 (A) shows the temperature profiles for single-phase natural convection. It can be observed that the bulk temperatures of the experimental cell are not constant but vary approximately in a linear fashion. The bulk temperature increases with height from the bottom of the cell increases, such that the warmer layers stabilize for the upper position

and there is a gradual cooling towards the bottom. This is called thermal stratification of the fluid. The stratification parameter, S , indicates the effect of the thermal stratification and defined as $S = (T_{\text{top}} - T_{\text{bottom}}) / (T_{\text{hot,y}} - T_{\text{bulk,y}})$. Since both hot wall temperature and bulk temperature are function of the height from the bottom of the cell, S varies with dimensionless height, y/H . In Fig. 4, average stratification parameter, $S_{\text{ave}} = (T_{\text{top}} - T_{\text{bottom}}) / (\bar{T}_{\text{hot,y}} - \bar{T}_{\text{bulk,y}})$, is indicated. For single-phase cases, the S_{ave} values ranged from 0.90 to 1.44 for the experimental runs listed in the graph. Fig. 4(B) shows the bulk temperature profiles for two-phase natural convection for various particle loadings. The graph shows the case of the bath temperature difference of 10 °C and the nominal particle size of 134 μm . It can be seen that there is an inversion of temperature gradient at bottom ($y/H = 0.03$) for the case of particle loading of 0.518 wt%. This is because of sediment layer of gelatin particles at the bottom of the cell.

Figs. 5 and 6 shows temperature contours measured along a vertical and horizontal line for the single-phase and two-phase natural convection. The temperatures are plotted in a dimensionless way as a ratio of the local temperature minus the cold wall temperature, $T - T_{\text{cold}}$, to the hot wall temperature minus the cold plate temperature, $T_{\text{hot}} - T_{\text{cold}}$; that is, $(T - T_{\text{cold}}) / (T_{\text{hot}} - T_{\text{cold}})$. The distance x is the distance from the hot end, and L is the width of the convection cell. The dimensionless length, x/L indicates that lower values are closer to the hot wall. Fig. 5 (top row) and (bottom row) show the temperature contours for single-phase case and two-phase case of particle size of 134 μm for various particle loadings. (Top row) is for bath temperature difference of 10 °C and (bottom row) is for 20 °C. From Fig. 5, for single-phase case, the fluid within the natural convection cell is thermally stratified except in the thermal boundary layers, where the temperature gradients are concentrated. For two-phase cases, the temperature contours are similar to single-phase case except in the sediment layer at bottom of

the cell. For each two-phase case, the temperatures at the bottom, where the dimensionless distance from the hot wall is close to zero, are high compared to single-phase case. The temperature contours show inverted temperature stratification. These inverted contours correspond to the extent of sedimentation along the bottom part of the experimental cell. The different loadings gave rise to different sediment layer depths. From Fig. 5 (top row) for cases of particle loading of 0.026 wt% and 0.518 wt%, the temperature within the cell is higher than single-phase case, whereas for cases of particle loading of 0.104 wt% and 0.260 wt%, temperature contours are similar to single-phase case. Fig. 6 (top row) and (bottom row) show the temperature contours for single-phase case and two-phase case of particle size of 230 mm for various particle loadings. (Top row) is for bath temperature difference of 10 °C and (bottom row) is for 20 °C. From Fig. 4 (A), the temperature within the cell for two-phase cases is higher than that of single-phase case. From Figure 6 (bottom row), the inverted contour due to sediment layer of particles is seen for case of particle loading of 0.260 wt%. For case of particle loading of 0.026 wt%, there is not major difference when it is compared with single-phase case. From Figs. 5 and 6, it is difficult to see a detail temperature gradient near the hot wall since a steep temperature gradient is concentrated in a very small range of x/L .

Heat transfer characteristics

Verification that the natural convection test cell can provide accurate measurements was obtained by comparing measurements for single-phase natural convection with an accepted correlation. For natural convection in enclosures, the mean value of the Nusselt number, Nu_H , for aspect ratio [49], $A \sim 1$, and $10^6 < Ra_H \leq 10^{12}$ as:

$$Nu_H = 0.082 Ra_H^{0.329}. \quad (1)$$

389

390 Nu_H [50] for $1 < A < 2$, $10^{-3} < Pr < 10^5$, $10^3 < Pr/(0.2 + Pr) Ra_H (L/H)^3$ as:

391

$$Nu_H = 0.18 \left(\frac{Pr}{0.2 + Pr} Ra_H \right)^{0.29} \left(\frac{L}{H} \right)^{-0.13} \quad (2)$$

393

394 where Ra_H is the Rayleigh number based on the height of the convection cell, H . Nu_H and Ra_H
 395 are defined as:

396

$$Nu_H = \frac{1}{H} \int_0^H Nu_y dy \quad (3)$$

398

$$Ra_H = \frac{g\beta(T_{\text{hot}} - T_{\text{cold}})H^3}{\nu\alpha} \quad (4)$$

400

401 In the present study, the aspect ratio, A , was 1.98. The deviation between measurement
 402 and correlation for this study is 2.54-15.9 % from Eq. (1) and 0.11-30.3 % from Eq. (2). If we
 403 introduce the notation, “ sNu ”, to represent the Nusselt number in stratified natural convection.
 404 For natural convection of ordinary Pr fluid ($Pr \geq 1$), then [e.g. 45]:

$$sNu \equiv \frac{Nu}{(1 + S)^{1/4}} \sim Ra_H^{1/4}, \quad (5)$$

406 and for natural convection of low Prandtl number ($Pr \ll 1$):

407

$$sNu \equiv \frac{Nu}{(1+S)^{1/2}} \sim Ra_H^{1/4} Pr^{1/4} \quad (6)$$

408

It is worthwhile to note that the stratification parameter appears as part of a factor that modifies

409

the non-stratified Nusselt number. The relationship correctly reduces to the non-stratified case

410

when there is no stratification ($S = 0$).

411

The local Nusselt numbers were also obtained for two-phase natural convection. To form

412

the local Nusselt number, Nu_y , and local Rayleigh number, Ra_y , properties of gelatin suspension

413

were needed. Since gelatin particle loadings in this study were less than 1% by weight,

414

properties of deionized water were used for all fluid properties for gelatin particle suspension.

415

All physical properties of working fluid were evaluated at the film temperature,

416

$T_{\text{film}} = (\bar{T}_{\text{hot}} + \bar{T}_{\text{cold}})/2$, where $\bar{T}_{\text{hot}}$ and $\bar{T}_{\text{cold}}$ are the mean temperature of the hot and cold walls,

417

respectively. Fig. 7 shows the local Nusselt numbers for two-phase natural convection with

418

respect to local Rayleigh numbers. The trendlines were obtained from single-phase experiments

419

and are shown in the as a reference for the determination of enhancement/de-enhancement in the

420

local Nusselt number of the two-phase natural convection due to the presence of the gelatin

421

particles.

422

Fig. 7 shows the variation for bath temperature difference of 10°C and 20°C. (A) is for

423

the nominal particle size of 134 μm and (B) for 230 μm . (A) is for particle loading of 0.026

424

wt%, and (B) is for 0.26 wt%. The noted values of particle loading indicate the percentage of the

425

gelatin particles in suspension by weight. 0.026 corresponds to 5 grams of gelatin particle in the

426

cell, which contains approximately 19.2 kilograms (20 liters) of deionized water. The vertical

427

dash line at $Ra_y = 10^8$ indicates the boundary between laminar and transition region. The vertical

428

dash line at $Ra_y = 10^{10}$ indicates the boundary between transition and turbulent region. In each

figure, (II) is an enlargement of (I) from $10^9 \leq Ra_y \leq 10^{11}$ and $100 \leq Nu_y \leq 1000$. That is, the lowest measurement point influence by conduction heat transfer is discarded to effectively show the convection heat transfer results.

From Fig. 7 (A) to (B), there is a reduction in local Nusselt number, Nu_y , at lower Rayleigh number, $10^6 \leq Ra_y \leq 10^7$ for both cases of bath temperature difference of 10 and 20°C. In transition region, $10^9 \leq Ra_y \leq 10^{11}$, there is no significant change in Nu_y between single- and two-phase cases except for the case of nominal particle size of 230 μ m, particle loading of 0.260 wt%, and bath temperature difference of 20 °C. However, in turbulent region, $10^{10} \leq Ra_y$, the data plots for two-phase cases show both increase and decrease in Nu_y . As it is seen in Fig. 7 (A)(II), there is an increase in Nu_y , compared to the reference line of single-phase natural convection, for the case of bath temperature difference of 10°C. However there is a decrease in Nu_y for the case of bath temperature difference of 20 °C especially at Rayleigh number of 5×10^{10} and 6×10^{10} . In Fig. 7 (B)(II), there is no significant difference between single- and two-phase cases for the case of bath temperature difference of 10°C. For the case of bath temperature difference of 20°C, the plots of Nu_y are consistently below the reference line of single-phase case. This can be due to the thermal stratification within the natural convection cell. Introducing a scaling, or order of magnitude analysis, a heat transfer relationship incorporating the stratification parameter, S , with $S = 0$ for non-stratified case and $S > 0$ for stratified case. Fig. 8 shows a graph of stratified Nusselt number and the Rayleigh number. Fig. 8 also shows trendlines of ' sNu_y vs. Ra_y ' obtained for transition, and turbulent regime. The value of the stratification factor depended on each experimental run and ranged from 0.9 to 1.44. After

thermal stratification was taken into account, the data points can be shifted closer to conventional data points and in such a case would show less spread than when stratification is not factored.

Velocity profiles

Velocity measurements were made using Met-Flow ultrasonic velocity profiler (UVP). The vertical velocity components were obtained in the vicinity of the hot wall. Three transducers, each with casing diameter of 8 mm (active diameter is 5 mm) were used. The distance between the transducers was 12.7 mm. The transducers were installed 103 cm above the bottom of the cell and were moved in a transverse direction towards the center of the cell at 1 to 4 mm intervals. Since the transducer has a diameter of 8 mm, there is no data between 0 to 4 mm distances from the hot wall. The velocity measurements were taken in the range of $0.50 \leq y/H \leq 0.98$, where y/H is the dimensionless height from the bottom. Below $y/H = 0.50$, where the distance from the transducers were large, the profile has a lower measurement success rate than the higher value of y/H , since the echo is not sufficiently strong from the far side. Measurements made along the axis were spatially limited in range; this range is called the measurement window. The measurement window was 748 mm in this study. The window is divided into 128 measurement volumes. The length of each measuring volume along the axis of detection was chosen as 0.74 mm. The velocity profiles are plotted against the distance from the hot wall at $y/H = 0.944$ and 0.538 . At $y/H = 0.944$ the convective flow at the hot wall is turbulent, while at $y/H = 0.538$ the flow is in transition or turbulent region depending on conditions, such as, temperature distance between the hot wall and bulk temperature. The velocities obtained from UVP measurements were space and time averaged within the single measurement volume. The minimum velocity resolution used in this study was 0.72 mm/s. This

means that the velocity obtained from measurements were in multiples of 0.72 mm/s, such as 0.72, 1.44, and 2.16. The velocity difference smaller than 0.72 mm/s was not detectable. The maximum averaged velocity obtained in this study was 7.2 mm/s. Since velocity is very small in this study, the standard deviation is large. The standard deviation in velocity measurements ranges 40 % to 414 %. The error in the distance from the hot wall was taken as 1 millimeter. Figs. 8-9 (A) and (B) show the comparison of velocity profiles between single-phase and two-phase flows. For two-phase case, the particle loading is 0.260 wt% and particle size is 134 μm . (A) is the velocity profiles at dimensionless height, y/H , of 0.944 and (B) is for 0.538. In each figure, (I) is for bath temperature of 10°C and (II) is for 20°C. From Fig. 8-9 (A) there is no significant difference between single-phase and two-phase cases when error bars are taken into account. However, the plots for two-phase case in (II) are smaller in the range of $4 \text{ mm} \leq x \leq 11 \text{ mm}$. In Fig. 8-9 (B) the difference between single- and two-phase cases can be seen at $23 \text{ mm} \leq x \leq 32 \text{ mm}$. For the case of bath temperature difference of 10°C, the velocity of two-phase case is larger than single-phase case at $23 \text{ mm} \leq x$. However for the case of temperature difference of 20 °C, the velocity of two-phase case is smaller at $23 \text{ mm} \leq x \leq 25 \text{ mm}$.

Implications

Hoffman et al. [14, 15, 40] showed that temperature sensitive gels could be used to selectively or non-selectively remove undesirable toxins, to assay for specific substances, and to recover selected products of a biochemical process. This process may also be applied in a non-biochemical situation. The basis of the model proposed in this study is formulated from Hoffman et al. [14, 15, 40]. The schematic illustration of this study's proposed model entrapment process is as shown in Fig. 910(A). The entrapment process illustrated in Fig.

910(A) thus forms a foundation for a rudimentary filtering system. In this situation, the Dynamic Filtering System or DFS (see Fig. 910(B)), dried temperature sensitive gels are immersed into a natural convection cell (step 1), which may contain mixed waste effluents with targeted particles. Opposite walls of the enclosure are heated and cooled. The gels absorb wastewater and swell with increasing temperature (swollen state) denoted by step (2). If the wastewater contains radioactive materials, then a probable scene, is one in which the radioactive waste particles adhere to this low-cost gel-like material. The gels then undergo volumetric transition and collapse when they are cooled below the LCST (step 3). In this collapsed state, the gels will release only water and encapsulate the solid particulates. In step (4), gels, which captured solid particles, sink to the bottom of the convection cell as they become denser than the carrier fluid. Finally, the waste stream is drained and the gel-sediment mix, which trapped radioactive solid particles, are collected for eventually semi-dry storage or disposition. In order to realize this Dynamic Filtering System (DFS), a fundamental understanding of the nature of the temperature sensitive gel materials, as well as the natural convection of temperature sensitive gel would be needed.

Conclusions

Measurements of temperature and velocity were carried out in order to obtain a better understanding of heat transfer characteristics of gelatin particle as a surrogate to thermally transitioning polymer gel particles that would potentially aid in extraction of radioactive particles in mixed waste. Although the ultimate goal of this study was to evaluate dynamic filtering capability of mixed waste streams with thermally transitioning polymer gel particles, especially

radioactive particulates and potentially heavy metals, a fundamental understanding first of natural convection of a hydrophilic particle-laden suspension was investigated. In this study gelatin was used for experiments. Although hydrophilic, since the solid density of gelatin particles in the water was larger than that of water, the gelatin particles gradually settled out of suspension.

The heat transfer result comparing single-phase and two-phase natural convection revealed the effect of particles on natural convection heat transfer. Heat transfer results with and without particles showed both enhancement and de-enhancement in Nusselt number, depending on bath temperature difference and particle size as follows:

- 1) There was no significant change in heat transfer when particle loading was varied.
- 2) In general, for the case of bath temperature difference of 10°C and particle size of 134 μm , there was an enhancement in heat transfer whereas for bath temperature difference of 20°C, there was a de-enhancement in heat transfer.
- 3) For the case of particle size of 230 μm , there was more de-enhancement in heat transfer compared with the case of particle size of 134 μm .

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Symbol	Description
A	Aspect ratio $[H/L]$
c	Velocity of ultrasound in the two-phase flow
$\bar{d}$	Number-average particle diameter
d_p	Gelatin particle size (μm)
f_i	Fraction in the class range
f_d	Doppler frequency shift
f_0	Ultrasound frequency
g	Gravitational acceleration (m/s^2)
H	The distance between two horizontal walls
k	Thermal conductivity ($\text{W/m}\cdot\text{K}$)
L	The distance between hot and cold walls
L_1	Thickness of the aluminum tube wall
L_2	Thickness of the aluminum tape
n_i	Number of particles
Nu	Nusselt number $[hH/k]$
Nu_y	Local Nusselt number $[hy/k]$
Pr	Prandtl number $[\nu/\alpha]$
q_x''	Heat flux at x (W/m^2)
Ra	Rayleigh number $[g\beta\Delta TH^3/\nu\alpha]$
Ra_H	Rayleigh number based on the cell height H $[g\beta\Delta TH^3/\nu\alpha]$
Ra_y	Local Rayleigh number $[g\beta\Delta Ty^3/\nu\alpha]$
S	Stratification parameter $[(T_{\text{top}} - T_{\text{bottom}})/(T_{\text{wall,y}} - T_{\text{bulk,y}})]$
S_{ave}	Average stratification parameter
sNu_y	Local stratified Nusselt number $[Nu_y/(1+S)^{1/4}]$
t	Time lapse between the emission and reception of ultrasound pulses
T	Local temperature in $^{\circ}\text{C}$

T_{bottom}	Bulk temperature at the bottom of the cell (°C)
T_{bulk}	Bulk temperature (°C)
T_{cold}	Cold wall temperature (°C)
T_{film}	Film temperature, $[(\bar{T}_{\text{hot}} + \bar{T}_{\text{cold}})/2]$ (°C)
T_{hot}	Hot wall temperature (°C)
T_{inside}	Inside surface temperature of the aluminum tube (°C)
T_{surface}	Surface temperature of the aluminum tube (°C)
ΔT	Temperature difference $[T_{\text{hot}} - T_{\text{cold}}]$ (°C)
T_{top}	Bulk temperature at the top of the cell (°C)
T_{wall}	Wall temperature (°C)
$\bar{T}_{\text{bulk}}$	Average bulk temperature (°C)
$\bar{T}_{\text{cold}}$	Average cold wall temperature (°C)
$\bar{T}_{\text{hot}}$	Average hot wall temperature (°C)
u	Fluid velocity component perpendicular to the hot wall
u_p	Velocity of the particles within the convective cell

540

541

542 Greek letters

Symbol	Description
α	Thermal diffusivity (cm ² /s)
β	Thermal expansion coefficient (K ⁻¹)
σ	Standard deviation

543

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Figure 5: Temperature contours for single-phase flow and two-phase flow for particle size of 134 μm at $\Delta T_{\text{bath}} = 10^\circ\text{C}$ (top row) and $\Delta T_{\text{bath}} = 20^\circ\text{C}$ (bottom row) and for various particle loadings.

Figure 6: Temperature contours for gelatin particle size of, $d_2 = 230 \mu\text{m}$. at $\Delta T_{\text{Bath}} = 10^\circ\text{C}$ (top row) and $\Delta T_{\text{Bath}} = 20^\circ\text{C}$ (bottom row). For two-phase cases, the particle loadings are 0.026 wt% and 0.260 wt%.

Figure 7: Graph of Nusselt numbers against Rayleigh numbers for the two-phase flow. (A) (I) shows the variation for bath temperature difference of 10°C and 20°C for particle size of 134 μm . The particle loading is 0.026 wt%. (A) (II) is an enlargement of (A) (I) from $10^9 \leq Ra_y \leq 10^{11}$ and $100 \leq Nu_y \leq 1000$. The decrease in Nusselt number is seen at the lower Rayleigh number, $10^6 \leq Ra_y \leq 10^7$. The lower the bath water temperature difference, the higher the value of Nu_y . (B) (I) shows the variation for bath temperature difference of 10°C and 20°C for particle size of 230 μm . The particle loading is 0.26 wt%. (B) (II) is an enlargement of (B) (I) from $10^9 \leq Ra_y \leq 10^{11}$ and $100 \leq Nu_y \leq 1000$. The decrease in Nusselt number is seen at the lower Rayleigh number, $10^6 \leq Ra_y \leq 10^7$. The lower the bath water temperature difference, the higher the value of Nu_y .

Figure 8: Graph of stratified Nusselt numbers against Rayleigh numbers for two-phase natural convection. (I) and (II) show the variation for bath temperature difference of 10 °C and 20 °C for the nominal particle size of 134 μm and 230 μm . (I) is for particle loading of 0.026 wt% and (II) is for 0.260 wt%.

Figure 9: (A). Velocity profiles for single- and two-phase flows at $y/H = 0.944$. For two-phase case, particle size is 134 μm and particle loading is 0.26 wt%. (A)(I) is for bath temperature difference of 10°C and (A)(II) is for 20°C. (B). Velocity profiles for single- and two-phase flows at $y/H = 0.538$. For two-phase case, particle size is 134 μm and particle loading is 0.26 wt%. (B)(I) is for bath temperature difference of 10 °C and (B)(II) is for 20 °C.

Figure 10: (A) Schematic of gelatin particle with volumetric phase transition and interaction with solid particles. (B) Schematic of proposed Dynamic Filtering System (DFS). LCST denotes lower critical suspension temperature.

Figure 1: Schematic diagram of experimental setup for temperature measurement showing positioning of thermocouples and direction of water flow.

Figure 2: Diagram of temperature gradient between aluminum channel wall and aluminum tape.

Figure 3: Schematic picture of UVP velocity profile measurement on the hot wall of the natural convection cell.

Figure 4. Bulk temperature profiles. (A) is for single-phase and (B) is for two-phase. For (B), the bath temperature difference is 10°C and particle size is $134\mu\text{m}$. y/H is the dimensionless height from the bottom of the cell. ΔT is the difference in the mean values of the hot and cold wall temperatures obtained

from the relation $\Delta T = \bar{T}_{\text{hot}} - \bar{T}_{\text{cold}}$. S_{ave} is averaged stratification parameter and obtained from

$$(T_{\text{top}} - T_{\text{bottom}}) / (\bar{T}_{\text{hot,y}} - \bar{T}_{\text{bulk,y}}).$$

Figure 5: Temperature contours for single-phase flow and two-phase flow for particle size of $134\ \mu\text{m}$ at $\Delta T_{\text{bath}} = 10^\circ\text{C}$ (top row) and $\Delta T_{\text{bath}} = 20^\circ\text{C}$ (bottom row) and for various particle loadings.

Figure 6: Temperature contours for gelatin particle size of, $d_2 = 230 \mu\text{m}$. at $\Delta T_{\text{Bath}} = 10^\circ\text{C}$ (top row) and $\Delta T_{\text{Bath}} = 20^\circ\text{C}$ (bottom row). For two-phase cases, the particle loadings are 0.026 wt% and 0.260 wt%.

Figure 7: Graph of Nusselt numbers against Rayleigh numbers for the two-phase flow. (A) (I) shows the variation for bath temperature difference of 10°C and 20°C for particle size of 134μm. The particle loading is 0.026 wt%. (A)(II) is an enlargement of (A)(I) from $10^9 \leq Ra_y \leq 10^{11}$ and $100 \leq Nu_y \leq 1000$. The decrease in Nusselt number is seen at the lower Rayleigh number, $10^6 \leq Ra_y \leq 10^7$. The lower the bath water temperature difference, the higher the value of Nu_y . (B)(I) shows the variation for bath temperature difference of 10°C and 20°C for particle size of 230μm. The particle loading is 0.26 wt%. (B)(II) is an enlargement of (B)(I) from $10^9 \leq Ra_y \leq 10^{11}$ and $100 \leq Nu_y \leq 1000$. The decrease in Nusselt number is seen at the lower Rayleigh number, $10^6 \leq Ra_y \leq 10^7$. The lower the bath water temperature difference, the higher the value of Nu_y .

Figure 78: Graph of stratified Nusselt numbers, sNu_y , against Rayleigh numbers, Ra_y , for two-phase natural convection. (I) and (II) show the variation for bath temperature difference of 10 °C and 20 °C for the nominal particle size of 134 μm and 230 μm . (I) is for particle loading of 0.026 wt% and (II) is for 0.260 wt%.

(A)(I)

(B)(I)

(A)(II)

(B)(II)

Figure 89: (A). Velocity profiles for single- and two-phase flows at $y/H = 0.944$. For two-phase case, particle size is $134\mu\text{m}$ and particle loading is $0.26\text{ wt\%}$. (A)(I) is for bath temperature difference of 10°C and (A)(II) is for 20°C . (B). Velocity profiles for single- and two-phase flows at $y/H = 0.538$. For two-phase case, particle size is $134\mu\text{m}$ and particle loading is $0.26\text{ wt\%}$. (B)(I) is for bath temperature difference of 10°C and (B)(II) is for 20°C .

Fig. 910(A)

Fig. 910(B)

Figure 910: (A) Schematic of gelatin particle with volumetric phase transition and interaction with solid particles. (B) Schematic of proposed Dynamic Filtering System (DFS). LCST denotes lower critical suspension temperature.

Figure

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