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# Comparison between single- and two-phase heat transfer in a thermally stratified enclosure

Izumi Hagiwara [a], A. Tokuhiro [b], P.G. Oduor [c,*]

[a] Formerly at University of Missouri-Rolla (Missouri University of Science and Technology), Nuclear Engineering Department, Missouri University of Science and Technology, 222 Fulton Hall, 301 W. 14th St., Rolla, MO 65409-0170, USA

[b] Akira Tokuhiro, Nuclear Engineering Dept., Idaho Falls Center for Higher Education, 1776 Science Center Drive, Ste 306, Idaho Falls, ID 83402, USA

[c] Dept. of Geosciences, North Dakota State University, Fargo, ND 58108, USA

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ABSTRACT

The ratio of local Nusselt number of two-phase natural convection, $Nu_{y,\ two}$, to local Nusselt, $Nu_{y,\ single}$, number of single-phase natural convection was empirically determined. Gelatin particles were immersed in a custom-built rectangular enclosure. With one end maintained at a thermal high, the particles settling and thermal enhancement characteristics were analyzed. The value of $\eta$ ($\eta = Nu_{y,\ two}/Nu_{y,\ single}$) decreased significantly at $y/H$ (dimensionless height) = 0.03 for all cases. The laminar-to-turbulent transition was in the range of $0.136 \le y/H \le 0.538$ for $\Delta T_{Bath} = 10$ °C, and $0.136 \le y/H \le 0.335$ for $\Delta T_{Bath} = 20$ °C. In general, for dual-phase flow, when $\Delta T_{Bath} = 10$ °C for particle size of 134 μm, there was a thermal enhancement as compared to when $\Delta T_{Bath} = 20$ °C, where there was a de-enhancement.



## 1. Introduction

The natural convection of single- and/or dual-phases offers essential elements in studies involving thermally-derived density gradients especially in enclosures. Natural convection is observed when density gradients are present in a fluid (e.g. Refs. [1–7]). In single-phase convective flows there exists only the fluid that flows owing to temperature gradient. A two-phase flow is one where the second phase has the chance of moving with the convective current and settling. Heat transfer for two-phase flows introduces a myriad of factors that have to be taken into account for an exhaustive analysis. These factors can be inherent properties of the particles, like physical form, rheology, particle–particle interaction, surface characteristics, yield stress, concentration, viscosity, and change in these properties after immersion in a fluid including permeability, porosity or compressibility of sediments generated (e.g. Refs. [8–10]).

Suspended particles contribute heat transfer enhancement in natural convection due to a local increase in turbulence brought about by the movement of particles through the boundary layer. This mechanism has been reported by Tamari and Nishikawa [11] and Wachowiak [12] for air bubble injection in natural convection and it is explained as follows. Since the rise velocity of air bubble in suspension is larger than the convective flow, as a bubble rises near the hot wall, the bubble not only drags liquid along with it parallel to the surface, but it also pumps some of the liquid in the direction perpendicular to the hot wall. The aim of this study was to obtain local heat transfer coefficients: (i) local Nusselt numbers, $Nu_y$, (ii) local Rayleigh numbers, $Ra_y$ across the natural convection cell as a precursor in determining the efficacy of gelatin particles as an essential matrix for a dynamic filtering system.

## 2. Methods

Gelatin, a hydrophilic particle, with a dry bulk density approximately 680 kg/m$^3$ (and a measured wet density of about 1390 kg/m$^3$) was sieved according to an order of particle sizes. Ordered sizes were reclassified with respect to their Martin's diameter (e.g. Refs. [13–15]) determined using a SMZ800 Nikon microscope fitted with a digital camera. An enclosure (Fig. 1) made of Plexiglas, and insulated with polystyrene, was filled with approximately 20 L of deionized/deaired water and thereafter a set volume of gelatin particles was immersed and stirred within the cell for homogeneity.

Suspensions of gelatin particles were prepared of average particle sizes $d_1 = 134$ μm and $d_2 = 230$ μm with weight percent

* Corresponding author.
*E-mail addresses:* h19_izumi@hotmail.com (I. Hagiwara), tokuhiro@uidaho.edu (A. Tokuhiro), Peter.Oduor@ndsu.edu (P.G. Oduor).

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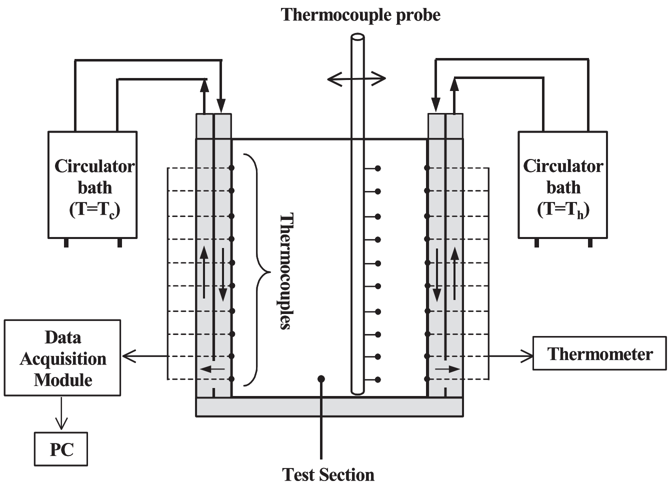


**Fig. 1.** Schematic diagram of experimental setup (redrawn from Ref. [16]).

loading equal to: (a) $\phi_1 = 0.026$ wt%, (b) $\phi_2 = 0.104$ wt%, (c) $\phi_3 = 0.26$ wt%, and (d) $\phi_4 = 0.518$ wt%. To enable visibility, 18–24 μm sized nylon seeding particles (Expancel microspheres, 091 DU 80, Akzo Nobel) were added after temperature measurements were recorded. An aluminum square channel maintained at a thermal high was connected to a LAUDA RM6 Brinkman Instruments refrigerator-heater water bath. A second setup with a PVC square channel was similarly connected to another LAUDA RM6 Brinkman Instruments refrigerator-heater system but maintained at a thermal low. At the hot (20 °C) end channel, were 32 AGW Chromel–Alumel thermocouples, while for the cold (10 °C) end, 20 AGW Chromel–Alumel thermocouples were used. All thermocouples were calibrated using a CL-307 (Omega Engineering, INC.) thermocouple calibrator. Water cycled from the aluminum channel into the PVC one in the first loop and vice versa for the second loop. Temperature was determined by measuring temperature difference between the inside and surface of the transfer tubes every quarter of an hour (cold) and every half hour (hot) until attainment of steady state (~6 h when differential temperature ≤0.2 °C). All temperature measurements were recorded using a data logger (Data Acquisition System – Personal Daq, IOtech). At the end of each experimental run, the sediment layer morphology and kinematics, for example, settling velocity were determined.

## 3. Results and discussion

### 3.1. Single- and two-phase heat transfer

In order to determine the fraction of enhancement/de-enhancement in the local Nusselt number of the natural convection due to addition of solid particles to water, the ratio of local Nusselt number of two-phase natural convection to local Nusselt number of single-phase natural convection, $\eta = Nu_{y,\ \mathrm{two}}/Nu_{y,\ \mathrm{single}}$, were plotted against the dimensionless height from the bottom, $y/H$ (Figs. 2–4). The local Nusselt numbers for single-phase case were calculated from trendlines, which were obtained from single-phase experiments. Heat transfer across the convection cell is enhanced when the value of $\eta$ is greater than one or de-enhanced when $\eta$ is less than one. The laminar-to-turbulent transition is in the range of $0.136 \le y/H \le 0.538$ for case of bath temperature difference of 10 °C, and $0.136 \le y/H \le 0.335$ for 20 °C. This laminar-to-turbulent transition range is shown in the figures as vertical dotted lines. Since the upper limit of the transition depends on bath temperature difference, the upper limit of transition in figures is taken as the average of the two cases.

Fig. 2 shows the ratio of local Nusselt number of two-phase natural convection to local Nusselt number of single-phase natural convection with the variation for bath temperature difference of 10 °C and 20 °C for particle size of 134 μm. The horizontal axis indicates the dimensionless height from bottom of the cell; that is, the data at left give the value of $Nu_y$ along the lower section of the cell. (I) is for particle loading of 0.026 wt%, (II) is for 0.104 wt%, (III) is for 0.26 wt%, and (IV) is for 0.518 wt%.

From Fig. 2, it can be seen that the lower the bath temperature difference, the higher the value of $\eta$ for all particle loadings. The value of $\eta$ decreased significantly at $y/H = 0.03$ for all cases. These reductions in local Nusselt number would be due to sediment layer of the particles. For the case of particle loading of 0.026 wt% (Fig. 2(I)), the sediment layer depth, divided by cell height $H$, along the center plane of the cell is $y/H = 0.03$ for both cases of bath temperature difference of 10 °C and 20 °C. For the case of particle loading of 0.104 wt% (Fig. 2(II)), the mean sediment layer depth, which is divided by cell height $H$, is 0.031 for bath temperature of 10 °C and 0.020 for 20 °C. For case of particle loading of 0.260 wt% (Fig. 2(III)), the mean sediment layer depth, divided by cell height $H$, is $y/H = 0.060$ for bath temperature of 10 °C and 0.029 for 20 °C. For the case of particle loading of 0.518 wt% (Fig. 2(IV)), the mean sediment layer depth, divided by cell height $H$, is $y/H = 0.113$ for bath temperature of 10 °C and 0.037 for 20 °C. A large increase in the value of $\eta$ is seen for case of particle loading of 0.026 wt% and bath temperature difference of 10 °C in the range of $0.5 < y/H < 0.9$. Also there is an enhancement in $\eta$ for the case of particle loading of 0.518 wt% with bath temperature difference of 10 °C at $y/H > 0.136$. For bath temperature difference of 20 °C, it can be seen that the decrement in the value of $\eta$ is relatively larger in turbulent region than that in transition region.

Fig. 3 shows the ratio of local Nusselt number of two-phase natural convection single-phase natural convection with the variation for bath temperature difference of 10 °C and 20 °C for particle size of 230 μm. (I) is for particle loading of 0.026 wt% and (II) is for 0.26 wt%. From Fig. 3, the lower the bath temperature difference, the higher the value of $\eta$. In (II), the value of $\eta$ was decreased significantly at $y/H = 0.03$, but not in (I). For the case of particle loading of 0.026 wt% (Fig. 3(I)), the mean sediment layer depth, divided by cell height $H$, is $y/H = 0.016$ for bath temperature of 10 °C and $y/H = 0.012$ for 20 °C. In these cases, the sediment layer lies below measurement point at $y/H = 0.03$. For the case of particle loading of 0.260 wt% (Fig. 3(II)), however, the mean sediment layer depth, divided by cell height $H$, is $y/H = 0.094$ for bath temperature of 10 °C and 0.105 for 20 °C. There is a reduction in $\eta$ in turbulent region of $0.5 < y/H < 0.9$ for the case of particle loading of 0.026 wt% and bath temperature difference of 10 °C. There is a large reduction in the value of $\eta$ in case of particle loading of 0.26 wt% and bath temperature difference of 20 °C at almost all values of $y/H$.

Fig. 4 shows the ratio of local Nusselt number of two-phase natural convection to local Nusselt number of single-phase natural convection with variation in particle size, 134 μm and 230 μm. (I) and (III) are for bath temperature difference of 10 °C, and (II) and (IV) are for 20 °C. (I) and (II) are for the particle loading of 0.026 wt% and (III) and (IV) are for 0.26 wt%.

From Fig. 4, it can be seen that larger the size of gelatin particles, the lower the value of $\eta$. In the case of particle loading of 0.026 wt%, particle size of 134 μm, and bath temperature difference of 10 °C (Fig. 4(I)), there is a large increase in the value of $\eta$ when the value of $y/H$ is greater than 0.4 whereas for other particle loadings with same particle size and bath temperature difference, there is no increase in the value of $\eta$. In Fig. 4(II) and (IV) there is a consistently