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Natural convection of water–fine particle suspension in a rectangular cell

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Abstract—A water–fine particle suspension with a uniform initial temperature and concentration in a rectangular cell is heated from a central part of the horizontal bottom wall and temperatures at both the vertical side walls of the cell are kept at the initial temperature. This transient natural convection is experimentally studied. During the fall of particles, the suspension forms layers. Concentration of particles, average diameters of particles, temperatures in each layer and time-dependent heat transfer coefficients on the heated bottom wall are measured. The mechanisms of formation and vanishment of the layers are clarified. © 1997 Elsevier Science Ltd.

1. INTRODUCTION

Clathrate is one of the attractive materials for latent heat of fusion thermal energy storage. When clathrate is melted, it separates into organic liquid and emulsion which is a mixture of water and a number of small drops of the organic liquid dispersed in it. Chiba *et al.* [1] showed that natural convection of the emulsion, which has significant effects on the melting process of clathrate, is different from natural convection of pure substance. The natural convection of suspension which is a mixture of water and small particles has applications in the chemical industry and the food industry and also in a solar collector where a suspension is used as a working fluid in order to enhance absorption of solar radiation [2]. The natural convection of both emulsion and suspension has the following common characteristics. If density of particles (or drops) is larger than that of water, the particles fall down in flowing suspension (or emulsion) and the movement of particles distributes the density of suspension. The natural convection of suspension is driven by the density distribution which is caused by both the temperature distribution and the concentration distribution of particles. Previous studies on suspensions focused on hydrodynamics and many books on them have been published [3] and also, hydrodynamics of sedimenting particles are recently reported [4–6]. Concerning the forced convection heat transfer of suspension, Self *et al.* studied the rheological and heat transfer characteristics of potato based starch-water suspension flowing in pipe [7]. Concerning the natural convection of suspension, Akagi and Yoshitani studied a natural convection of coal oil mixture around a horizontal cylinder experimentally and analytically and showed effects of the non-Newtonian fluid and the convection in a partial region on the heat transfer process [8]. Studies on the natural convection of suspension with sedimenting particles are hardly found except that the stability condition of double-diffusive convection with fine dust has been obtained theoretically [9].

In the present paper, the natural convection of water–fine particle suspension in a rectangular cell is experimentally studied. The central part of the horizontal bottom wall of the rectangular cell is heated and both the vertical side walls are cooled. Effects of sedimenting particles on the natural convection, temperature distribution, concentration distribution and heat transfer coefficient on the heated wall, are made clear. Characteristics of the natural convection which are peculiar to suspension are shown.

2. PROPERTIES OF SUSPENSION AND EXPERIMENTAL APPARATUS AND PROCEDURE

In the present experiment, micro beads made of soda glass of which specific gravity was 2.5 were dispersed in water. Two kinds of micro beads (MB-10 and MB-20) were used and their cumulative curves of particle size obtained by measuring 400 samples are

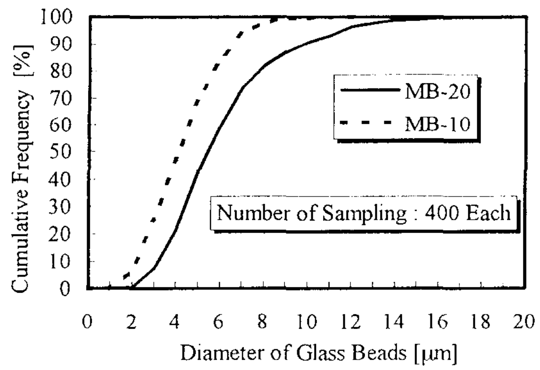

Fig. 1. Cumulative curves of glass beads.

shown in Fig. 1. The sizes are comparable to the drop size in the emulsion formed by melting clathrate. Average diameters of the particles are 4.75 μm for MB-10 and 6.51 μm for MB-20. Standard deviations for MB-10 and MB-20 are 1.74 and 2.74 μm, respectively. Because the concentration of the suspension is less than 5 wt%, the suspension can be treated as Newtonian fluid though the viscosity of the suspension is a little bit larger than that of pure water [10].

Schematic of test cell is shown in Fig. 2. Two test cells which were similar to each other were used. One of them called Test Cell ① is 80 mm wide, 120 mm high and 200 mm deep. The other cell called Test Cell ② is the half size of Test Cell ① (namely 40 by 60 by 100 mm). In Fig. 2 both the vertical side walls made of copper are the cold surfaces and a central part of bottom wall which is 40 mm wide and also made of copper is the hot surface. Other walls are made of acrylic plates so that natural convection inside the cell can be visualized from the front wall. Both sides of the hot wall and the top wall of the cell are insulated with a styrene foam. The hot wall is heated and kept at a constant temperature by letting hot water flow into channel behind the wall from a constant temperature bath. The cold walls also have channels and are kept at a constant temperature by using the other constant temperature bath. The temperatures on the hot and cold walls were measured by T-type thermocouples and the temperature distribution in the suspension was measured by moving a thermocouple vertically and horizontally. Still more, the temperature distribution in Test Cell ① was measured by 81 thermocouples arranged in a lattice in the cell. Average heat flux on the hot wall was measured by a heat sensor (80 by 20 by 1.7 mm) installed behind the hot wall. The heat sensor was made of polyester and adhered between the hot wall and a copper plate with channel. The space between the hot wall and the plate with channel was filled up with silicone of which thermal conductivity is approximately the same as that of the heat sensor. In order to obtain the average heat flux on the hot wall, the heat flux indicated by the heat sensor was corrected by assuming that heat flows through the heat sensor and the space filled with silicone in parallel. The hot and cold constant temperature bathes were respectively at 50 and 10°C in all the experiments. The cold wall was kept at $Tc = 10$°C but the hot wall temperature was $Th = 21$–26°C because of thermal resistance of the heat sensor.

	H	W1	W2
Test Cell ①	120mm	80mm	40mm
Test Cell ②	60mm	40mm	20mm

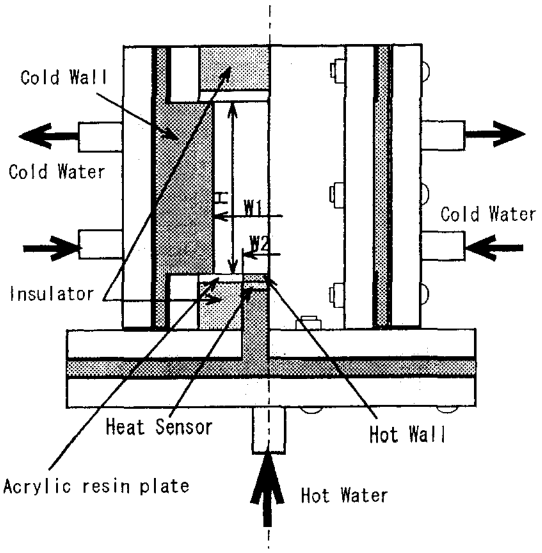

Fig. 2. Schematic of test cell.

The suspension with a predetermined concentration was filled in the test cell. By letting cold water flow from the constant temperature bath into the channels behind the side walls and the bottom wall (hot wall), the initial temperature of suspension was set at 10.0±0.1°C. After the initial condition was established, the suspension was stirred well so that all sedimental particles might float in water. After 5 min to settle down the flow caused by stirring, experiments were initiated by letting hot water flow from the other constant temperature bath into the channel behind the hot wall. During the experiments, temperature was measured and a small amount of suspension was collected to measure concentration and mean diameter of particles and photographs of suspension were taken.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1. *Visualized natural convection*

Based on knowledge of natural convection of usual liquid, the natural convection of suspension in the present experiment was predicted as shown in Fig. 3. However, the experiments made it clear that several layers were formed in the cell. Figure 4 shows the shape of layer and the change of layers, in this case the suspension with 3 wt% initial concentrations of MB-20 particle was filled in Test Cell ①. Time printed

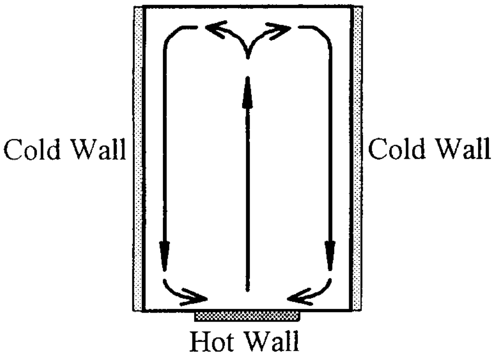

Fig. 3. Schematic of predicted flow.

in Fig. 4 shows an elapse time from the start of heating. Figure 4 shows that as time passes several thin layers are generated and then as the number of layers decreases, the thickness of layers becomes greater. The layers in Fig. 4 are numbered from the highest layer. Since particles in suspension are falling, the location of the highest interface of layers gradually goes down. Finally all the interfaces between the layers vanish and the single layer as shown by the photograph at 1365 min in Fig. 4 is present in the cell. Figure 5 shows how a layer vanishes. The photographs in Fig. 5 were taken in the same experiment as Fig. 4. Three layers are found in Fig. 5. Suspension in the intermediate layer falls down along the cold walls and flows into the lowest layer. The interface between the intermediate layer and the lowest layer becomes obscure near the cold walls and then both the layers mix to be a layer. In Fig. 5 the lowest layer vanished but in some cases it was observed that a middle layer also vanished. Figure 6 shows a flow of suspension visualized by using ink. In this case, suspension is separated into two layers and when ink was injected near the center of the lower layer, it flowed upward and turned right and left just before the interface of the layers and then flowed down along the cold walls. When ink was injected into the upper layer, circulation flows only in the upper layer were observed. These observations suggest that each layer has a couple of circular flows and each flow in a layer does not go into the neighboring layers.

3.2. *Temperature measurement*

The temperature distributions were obtained from measurement of 81 thermocouples. Figure 7 shows isothermal lines at 135 min, where four layers are formed. In this case the initial concentration is 3 wt% and MB-20 beads and Test Cell ① are used. Broken lines in Fig. 7 show the interfaces. The temperature in the lowest layer is higher than 15°C. The temperatures in the upper layers decrease stepwise. The isothermal lines changed slowly with time. In order to make the temperature distributions in each layer clearer, the temperature distributions in vertical and horizontal directions were measured at every 2 mm distance by a movable thermocouple. In Fig. 8 the temperature distributions in the vertical direction along the centerline of the cell are shown before and after the number of layers changes from four to three. The abscissa of Fig. 8 represents the distance from the top of the cell and the vertical lines (solid and dotted lines) show the locations of the interfaces obtained from photographs. The temperature increases rapidly at the interfaces as the distance increases. The lower layer has the higher temperature. The temperatures of each layer are almost uniform. When the layers are numbered from the top of the cell, in Fig. 8 the third layer and the fourth layer mixed into one layer. The temperature of the third layer at 277 min is approximately equal to the average of the temperatures of the third layer and the fourth layer at 260 min. The temperatures of the first and second layer are hardly affected by the mixing.

3.3. *Measurements of concentration and mean diameter of particles*

Weight concentrations of glass beads in each layer were measured as follows. About 10 g of suspension was collected, respectively, from the central areas of each layer and poured into a small bottle of which weight had been measured. After the weight of the bottle with suspension was measured, water of suspension in the bottle was sufficiently evaporated and then the weight of the bottle with glass beads was measured. The concentration of suspension was calculated from these weight measurements. For the above measurements of weight an electric balance with the minimum scale of 0.1 mg was used. Mean diameter of beads in the suspension was measured as follows. Water was poured into the bottle with glass beads which was dried up to get the concentration. A small amount of suspension in the bottle was collected and particles in the suspension were observed by a laser microscope. Diameters of two hundred beads selected at random were measured. Two kinds of beads were used and suspensions with various initial concentrations were examined in Test Cell ①. When three layers were formed in the cell, the concentrations and the mean diameters of beads in each layer were measured and shown in Figs 9 and 10, respectively. The abscissa is the layer number counted from the top of the cell. In Fig. 10, the average concentration of the suspension in the cell is less than the initial concentration because of sediment on the bottom wall. Figures 9 and 10 show clearly that the lower layer has the greater concentration and the greater diameter, though a couple of data deviate somewhat from the other data. As one example of experiments, particle size distributions of each layer are shown in Fig. 11. The cumulative curve shifts to right as the depth of layer increases. From this experiment, it is found that beads with 1–7 μm diameter are dispersing in the layers and since the larger beads shown in Fig. 1 have sedimented in the initial stage of the experiment, they do not affect the natural convection. In order to clarify time dependency of the concentrations of each layer,

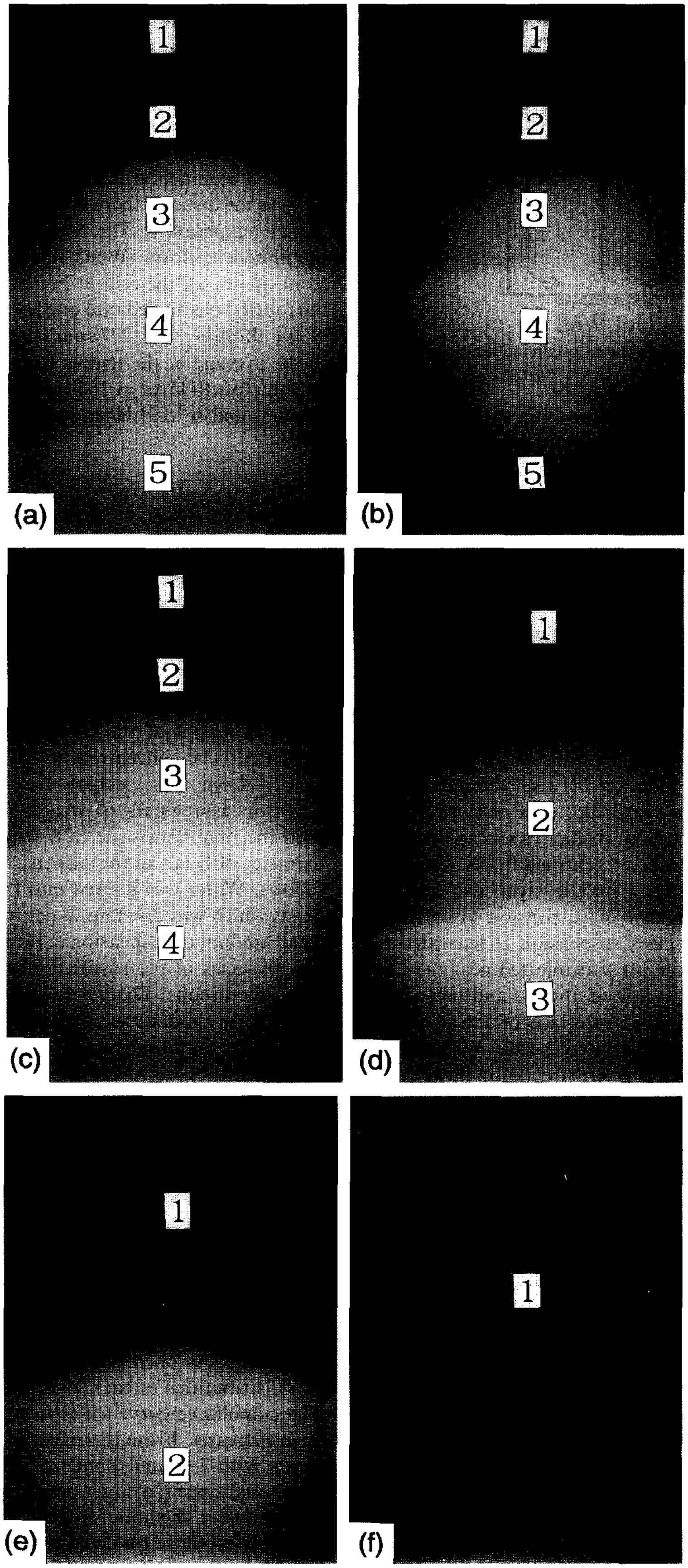

Fig. 4. Change of layers in the test cell (MB-20, 3wt%, Test cell ①, $Th = 25.1^{\circ}C$): (a) 390 min; (b) 417 min; (c) 421 min; (d) 500 min; (e) 690 min; (f) 1363 min.

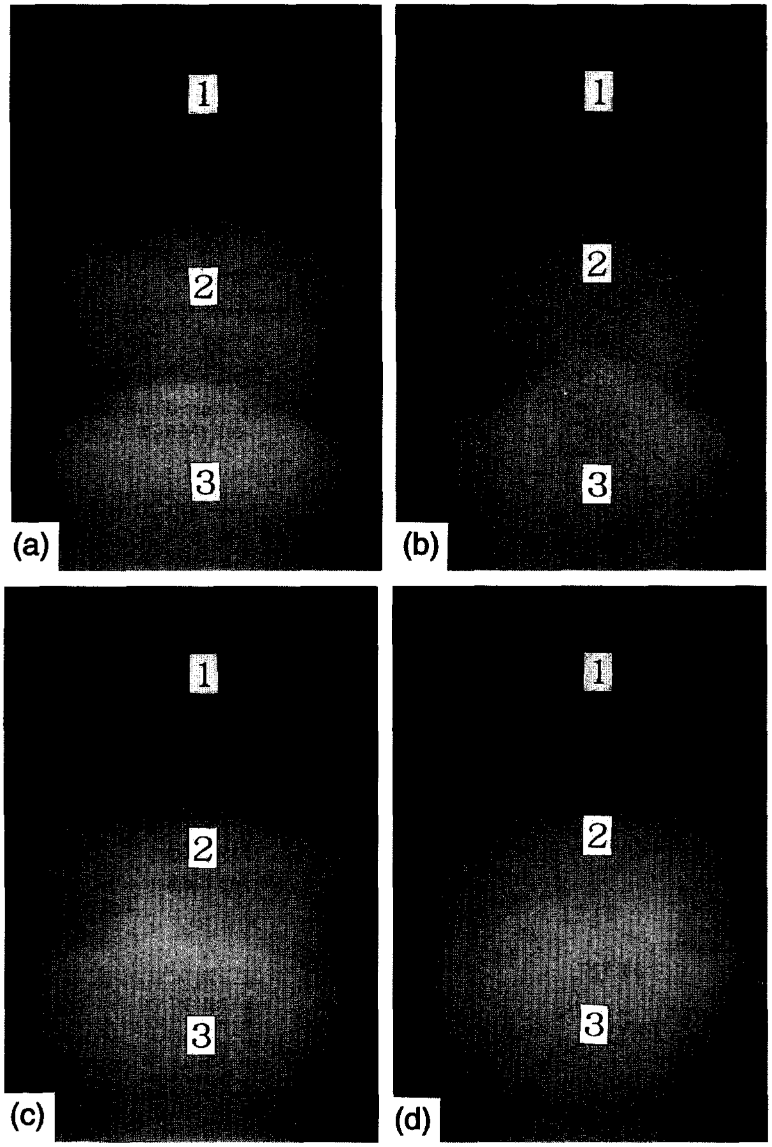

Fig. 5. Vanishment of a layer (the same experiment as Fig. 4) : (a) 560 min ; (b) 563 min ; (c) 565 min ; (d) 567 min.

the concentrations of each layer were measured while three layers change to two layers. The results are shown in Fig. 12. Vertical lines in Fig. 12 show the time when a layer vanished. The concentrations of each layer decrease gradually after three layers appeared in the cell. The second layer and the third layer mixed at 265 min. The average concentration calculated from the volumes and concentrations of the second layer and the third layer just before the mixing was 0.092% and the measured concentration of the second layer just after the mixing was 0.088%. Both the concentrations agree well with each other.

3.4. *Measurement of heat transfer coefficient on the hot wall*

Heat transfer coefficient on the hot wall was obtained from the heat flux measured by the heat sensor and from the difference between the hot and cold wall temperatures. Time-dependent heat transfer coefficients are shown in Figs 13 and 14. The results in the case of using different kinds of beads are shown in Fig. 13 and the results in the case of using different test cells are in Fig. 14. To be exact, the heat transfer coefficient obtained here means an overall heat transfer coefficient which includes a thermal resistance of sediment. The heat transfer coefficient in an initial stage after heating decreases rapidly. This phenomenon is common to a transient natural convection. After the end of the transient heat transfer, a variation of the heat transfer coefficient which is peculiar to the suspension was observed. As shown in Figs 13 and 14, the heat transfer coefficient after the initial stage increases gradually with saw-toothed oscillation. It was observed that the rapid increase of the heat trans-

Fig. 6. Flow visualization by ink (MB-20, 3wt%, Test cell ①, $Th = 26.5$°C).

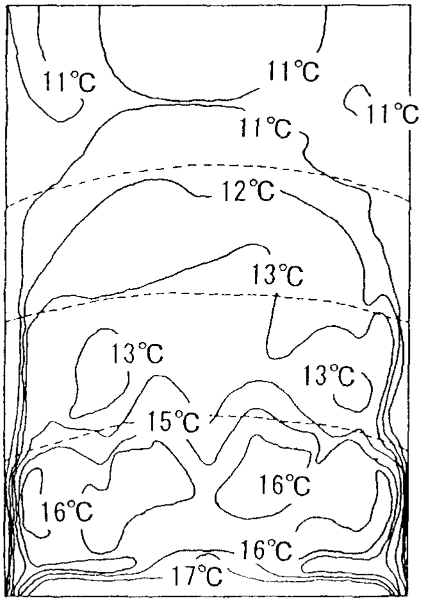

Fig. 7. Isotherm at 135 minutes in the case of four layers (MB-20, 3wt%, Test cell ①, $Th = 28.8$°C).

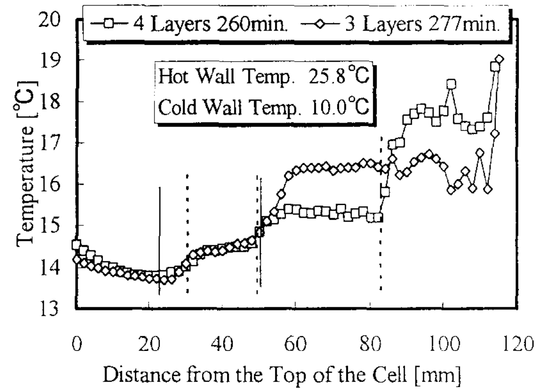

Fig. 8. Temperature distribution along the center line of the cell (MB-20, 3wt%, Test cell ①).

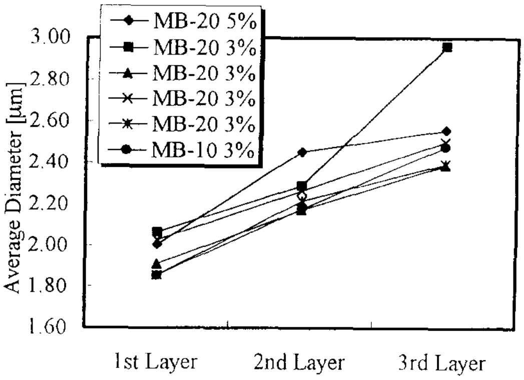

Fig. 9. Average diameters of particles in each layer (Test cell ①).

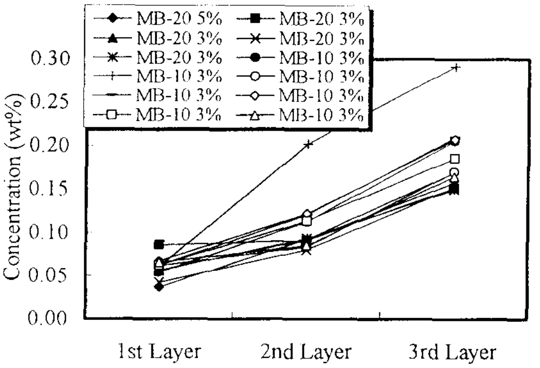

Fig. 10. Concentrations of particles in each layer (Test cell ①).

fer coefficient corresponded to the mixing of the lowest layer with the upper layer. After all the interfaces vanished and almost all the particles sedimented, the heat transfer coefficient becomes constant. Mechanism of the cyclic oscillation of the heat transfer coefficient can be explained by the mixing of layers. When the lowest layer mixes with the neighboring layer with a lower temperature, the temperature of the renewal lowest layer decreases rapidly. Therefore, the heat transfer coefficient on the hot wall increases rapidly. From one mixing till the next mixing, it decreases gradually as the temperature of the renewal lowest layer increases gradually. The interval from one mixing till the next becomes long as the mixing repeats, because increase of thickness of the lowest layer depresses a rate of temperature rise of the lowest layer. After the last two layers mixed, almost all the particles sedimented except that a few very small par-

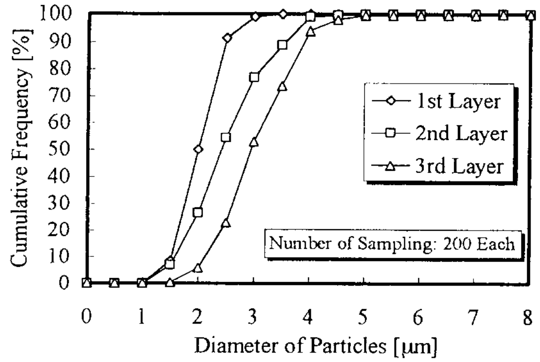

Fig. 11. Cumulative curves of particles for each layer in the case of three layers (MB-20, 3wt%, Test cell ①).

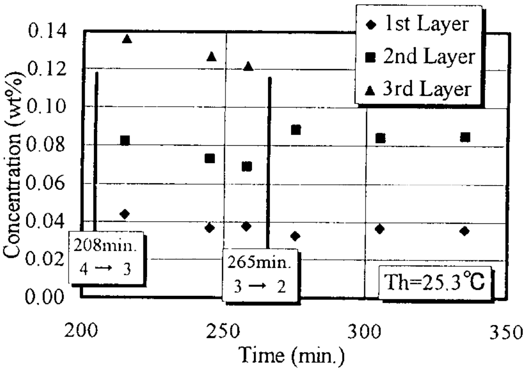

Fig. 12. Variation of concentrations of particles of each layer with time.

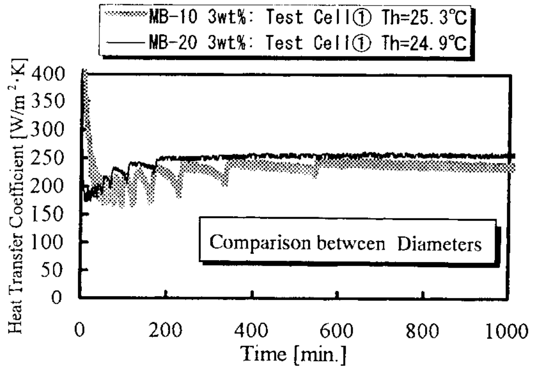

Fig. 13. Variation of heat transfer coefficient with time (comparison between the results obtained from the different beads diameters).

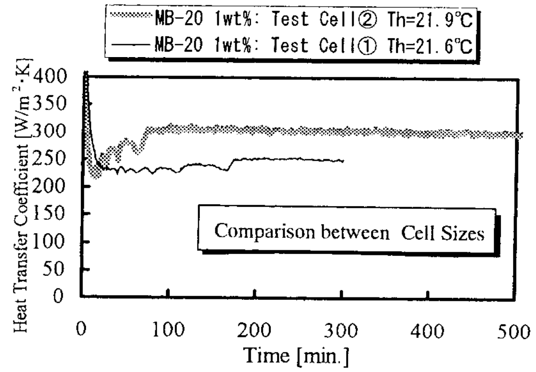

Fig. 14. Variation of heat transfer coefficient with time (comparison between the results of experiments with the different cell sizes).

ticles were floating. Then a convection occurs in the whole cell and the heat transfer coefficient becomes constant. Figures 13 and 14 show that in the case of the larger particle size or the smaller test cell the layers appear and vanish earlier.

3.5. *Mechanism of vanishment of layers*

Concerning the phenomenon of layer formation, the natural convection of suspension is similar to the double diffusive natural convection. In the present experiment, initially the suspension has a uniform temperature distribution and a uniform concentration distribution. During the period to settle down the flow caused by stirring, the particles have been sedimenting. According to the Stokes' law, the particles with the larger size have the larger falling velocity. Therefore, the distribution of particle concentration has a positive gradient in the downward direction. This density distribution is stable. On the other had, since the suspension is heated at a part of the bottom wall of the cell, the temperature at a location in the cell is greater than that at the higher location. This temperature distribution is unstable because heavier fluid is located over lighter fluid. But the thermal diffusivity of suspension is larger than the diffusion coefficient of particle in suspension. Therefore, a stable density distribution is maintained. The condition mentioned above corresponds to the condition on which the double diffusive convection mode is realized [11]. Therefore, we consider that the appearance of layers is caused by the double diffusive convection.

The density of suspension is determined from the temperature and concentration. When the layers are maintained, unstableness caused by the temperature distribution must be cancelled by the concentration distribution and the density must satisfy stably. The densities of each layer are shown in Figs 15 and 16 during transition process from three layers to two layers. The experiment in Figs 15 and 16 is the same as Fig. 12. The ordinate of Fig. 15 is the density of suspension in each layer and the abscissa is the temperature of the layer and the oblique lines show constant concentration lines. In Figs 15 and 16 the densities in the central core of each layer are plotted. Figure 15 shows that the density stratification is stable and the density decreases with time according to temperature rise and concentration drop. Though the rate of concentration drop in the second layer is almost equal to that in the third layer, the rate of temperature rise in the third layer is greater than that in the second layer. Therefore, the density difference between the second layer and the third layer decreases with time until 265 min as shown in Fig. 16. In a well-known double diffusive convection, both the directions of

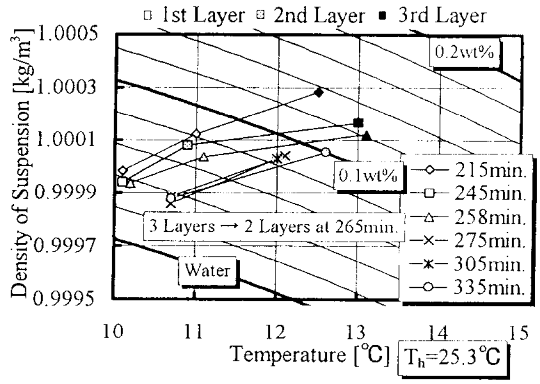

Fig. 15. Density of suspension obtained from the temperatures and the particle concentrations of each layer (MB-20, 3wt%, Test cell ①).

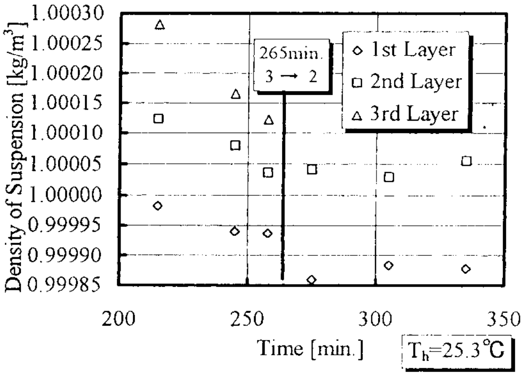

Fig. 16. Variation of density of suspension with time (MB-20, 3wt%, Test cell ①).

heat flux and mass flux at an interface between layers are upward and density flux is in downward direction. Because the difference of the density in the lower side of interface from that in the upper side tends to increase, the interface should be kept stable, but in the case of suspension, the mass flux at each interface is in downward direction because of sedimentation. The density in a layer varies owing to net heat flow rate and net mass flow rate of the layer. Difference between the variation rates of density in each layer breaks stability of layer. As mentioned in Section 3.1, the suspension in the upper layer flowed down along both the side walls and pushed down the interface of the layers and then the lower layer vanished. Because of cooling from the side wall and sedimentation, the local density over an interface near the side wall becomes equal to and then greater than the local density under the interface which can be assumed to be equal to the density in the central core of the layer under the interface. This is the reason why a layer mixes with the lower layer.

4. CONCLUSIONS

Natural convection of suspension with sedimenting particles in a rectangular cell was studied. The suspension was heated from a part of bottom wall and cooled from both the side walls. From the experiments of this system, the following conclusions were obtained.

(1) During the sedimentation of particles, the suspension forms layers.

(2) The number of layers decreases with time and finally all the interfaces between the layers vanish and the convection of single layer is left in the cell.

(3) The formation of layer is caused by the double diffusive convection based on the temperature and concentration gradients in suspension.

(4) The heat transfer coefficient on the heated wall varies with cyclic oscillation because of vanishment of layers. This variation is peculiar to suspension.

(5) The time interval of vanishment of layers becomes shorter in the case of the smaller cell or the larger particle size.

(6) Mechanism of the vanishment of layers is explained by the double diffusive convection and the sedimentation of particles.

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