Visualization and PTV Study of Natural Convection in Particle Suspensions*

(Simultaneous Measurements of Velocity, Temperature and Interface between Particle-Free Fluid and Suspension)

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Natural convection in a suspension was studied experimentally using both refractive index matching and laser induced fluorescence (LIF) techniques. A rectangular test section was filled with particle suspension and was heated from a horizontal bottom, and two facing vertical walls were kept at a constant temperature. The images of the fluorescent particles were captured by a CCD camera through a sharp cut filter which separates emitted fluorescence from scattered excitation light. The flow velocity fields were analyzed quantitatively using Particle Tracking Velocimetry (PTV). Interface between particle-free fluid and suspension as well as temperature fields was visualized simultaneously with the velocity fields. It was suggested that two-layer convection cells were driven by both heating and sedimentation of particles which drives convection in the overlying layer due to the release of the heated clear fluid at the interface.

Key Words: Natural Convection, Flow Visualization, Digital Image Processing, Laser Induced Fluorescence, Suspension, Particle Tracking Velocimetry, Double Diffusive Convection, Refractive Index Matching

1. Introduction

Natural convection in a suspension of small particles occurs in a wide variety of industrial and natural settings, such as a solar collector, a thermal storage system, and material processing with solidification of a binary mixture^{(1),(2)}. In these suspensions, the suspended particles sediment due to the gravity forming a concentration gradient or a gradient of bulk density in a suspension. This gradient of bulk density plays an important role in peculiar flow motions of suspensions interacting with the temperature fields.

It was noticed by Suzuki-Okada⁽¹⁾ and Okada-

Suzuki⁽²⁾ that the formation and the vanishing of multi-layered convection cells which were similar to the ones in a double-diffusive convection were observed in a fine particle suspension in a rectangular enclosure in which a portion of the bottom surface is heated and the two vertical walls are cooled. In this case, however, the flow fields in the suspension were not obtained due to the turbidity of the suspension.

The authors⁽³⁾ succeeded in visualizing the flow structures of natural convection in suspensions by making the suspensions nearly transparent using refractive index matching technique, where the formation and the vanishing of two-layer convection cells were observed. This technique, however, has the problem that the background scattering noise from suspended particles makes it difficult to separate tracer particle image from the background, and consequently the Particle Tracking Velocimetry (PTV) measurements generate many spurious vectors. To overcome this difficulty, we employed the technique using fluorescent tracer particles which are Argon-ion laser excitable. The removal of the scattering noise

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was achieved using an optical filter which separates fluorescence image of small tracer particles from any scattered excitation light. In order to reveal the mechanisms for the formation and the vanishing of two-layer convection cells, which are distinct from those in a particle-free fluid, we visualized velocity fields, particle distributions and the temperature fields simultaneously.

2. Nomenclature

- a : thermal diffusivity
 $\Delta T = T_h - T_c$
 g : gravity
 Gr : Grashof number $= g\beta\Delta TL^3/\nu^2$
 L : width of the enclosure
 Pr : Prandtl number
 Ra : Rayleigh number
 T_c : cold wall temperature
 T_h : hot wall temperature
 u, v : x and y component of velocity
 β : thermal expansion coefficient of suspending fluid
 ν : kinematic viscosity of suspending fluid
 ρ : density of suspending fluid
 ϕ : concentration of suspending particles [= (weight of suspended particles)/(weight of suspending fluid)]

3. Experiments

3.1 Fluorescent particles

The unique feature of the approach in this study is the use of fluorescent tracer particles. Polyethylene beads of 150 ~ 200 μm diameter (Sumitomo Seika Chemicals, HE-3008; density 0.975) were coated with acrylic polymer emulsion color (Turner Colour Works Ltd., Acryl Gouache No.206 luminous red). We have found that these tracer particles coated with luminous color paints have the favorable properties that they are Argon-ion laser excitable. Acrylic

polymer emulsion color was found to be the best paint for coating polyethylene beads, because of its strong adhesiveness and water-resistance properties. It is also resistant to the fluid used in this study and never contaminates fluid, which yields clear fluorescent particle image without background fluorescence.

The removal of the scattering noise was achieved using these fluorescent tracer particles and an optical filter. The fluorescence images of tracer particles were captured by a CCD camera with a sharp cut filter (Kenko O-56; $\lambda > 560 \text{ nm}$) under Argon-ion laser light in the multi-line operation. Since the wavelength of emitted fluorescence (λ_2) is longer than that of excitation light (λ_1), fluorescence image of the tracer particles can be separated from any scattered excitation light with the sharp cut filter (Fig. 1).

3.2 Material

The particles of the suspension are glass beads with index of refraction 1.5, density 2.5 g/cm^3 (Toshin, No. 0.05). Measurements by a microscope gave a particle diameter 57.5 μm with a standard deviation 6.4 μm . The distribution of the glass beads is shown in Fig. 2. Glass beads were dispersed in a mixture of tetralin (refractive index: 1.54) and silicone oil (refractive index: 1.40; Toshiba Silicone, TSF 451-1000) in proportion (1:2.57, by weight) chosen to nearly match the particle refractive index. Physical properties of the suspension and the tracer particles are listed in Table 1.

3.3 Apparatus

Figure 3 shows the scheme of the experimental setup. Experiments were performed in a cubic cavity of dimension $L=60 \text{ mm}$ ($60 \times 60 \text{ mm}$ square base and 60 mm height). Two vertical cold walls are made of 1 mm copper sheet and held at a constant temperature $T_c=28^\circ\text{C}$ by circulating the water from a cold bath with a thermostat. The bottom surface of the test cell was divided into three segments with the middle $60 \times 30 \text{ mm}$ heated section separating two adiabatic

Fig. 1 Laser Induced Fluorescence (LIF) particles and functions of the optical filter

Fig. 2 Distribution of glass beads diameter

Table 1 Physical properties of the particles, suspending fluid and tracer particles used in experiments

Glass beads		
Density		2.5 g/cm ³
Average diameter		57.5 ± 6.4 μm
Refractive index		1.5
Suspending fluid		
Density		0.975 g/cm ³
Viscosity(at 30°C)		20.12 cSt
Refractive index		1.50
Thermal diffusivity		5.35 × 10 ⁻⁸ m ² /s
Coefficient of thermal expansion		0.7996 × 10 ⁻³ 1/K
Tracer particles		
Density		0.975 g/cm ³
Average diameter		161.5 ± 17.9 μm

Fig. 3 Scheme of the experimental setup

sections.

A 10 mm Plexiglas sheet served as the bottom of the test cell. The heated section was installed in a milled groove on the upper face of the sheet so that the top of the heated section was flush with the upper surface of the Plexiglas sheet. The heater was consisted of a 1 mm copper top plate and an electric sheet heater (SAMICON 230 N, 20 V-30 W). A thermocouple was installed below the copper plate, and its output was monitored by an electronic control circuit which adjusted the power to the heater so as to maintain temperature of the copper plate to $T_h = 43 \pm 0.1^\circ\text{C}$.

The test section was filled with a suspension held at the uniform temperature T_c prior to application of bottom heating. The suspension was mixed well by a rod and kept still for 30 seconds to minimize perturbation when it was judged to be uniformly mixed. Transient flow is initiated by impulsively increasing the temperature of the hot wall to T_h .

3.4 Measurements

Figure 4 shows the visualization system. Two

Fig. 4 Visualization system

CCD-Cameras were set in front of the test section; the CCD-Camera #1 detects the tracer particle image using LIF technique described in section 3.1, while the CCD-Camera #2 detects the interface between particle-free fluid and suspension layers which appears with the sedimentation of particles. The camera #3 was set at the opposite side and detects the temperature distributions on the backside wall using thermo-sensitive liquid-crystal sheet film.

The suspension was seeded with the small amount of fluorescent tracer particles (0.37 g/l), and the fluorescence emissions from these particles were captured by the CCD-Camera #1 (SONY, XC-77RR) with the optical filter under a vertical Argon-ion laser light sheet (approximately 1.5 mm thick). The CCD camera was in frame mode and the laser light sheet was synchronized with the TV signal with 10 ms emission period using a synchronizing signal generator, an odd/even field index generator, a digital retarder, a function generator, and an AOM so that obtain an instant image within a frame. The captured images were recorded on a VCR (SONY, SVO-5800) and processed with the digital image processor (Nexus Qube). The triple pattern matching method⁽⁴⁾ was used here for particle tracking between video frames. The slow nature of convective flows makes it difficult to obtain velocity vectors from contiguous video frames. The following results were based on the video sampling at a rate of 1 frame per second. The PTV system is shown in Fig. 5.

The CCD-Camera #2 without the optical filter detects the scattering light image of suspended particles under the same laser light sheet which yields the information about the distribution of suspended particles in the plane. The captured images were recorded on a VCR #2 (MITSUBISHI, HV-S700) and processed by a personal computer to make binary image using image-processing software (Adobe Photoshop

Fig. 5 Test section and PTV system

Fig. 6 Example of a captured video image of glass beads suspension with $\phi=3$ wt%

LE-J). The suspension layer and the particle-free layer were estimated based on the difference of light intensity, and the sharp interface between these layers was determined.

Figures 6(a) and (b) show the video images captured at the same time by the CCD-Camera #1 and #2, respectively. Clear tracer particle images without scattering noise were obtained by the CCD-Camera #1 with the sharp cut filter. On the contrary, it is difficult in the video images from the CCD-Camera #2 without a filter to separate tracer particles from scattering noise of suspended particles.

The wall temperature fields were visualized with the thermo-sensitive liquid-crystal sheet film having the working ranges from 30 to 35°C. The reaction of the sheet to the environment temperature yields color maps which were photographed by a Camera #3 under lighting of a halogen lamp (150 W) when typical flow patterns appeared.

Velocity and particle distributions were measured at a plane $z=5L/6$ in the suspension. The two dimensionality of the convective flows has been checked in the preliminary study.

Table 2 The parameters in experiments

$\Delta T(^{\circ}\text{C})$	Gr	Pr	Ra	ϕ (wt%)	
15	5.81×10^4	2.40×10^2	1.42×10^7	0	3

4. Results and Discussion

4.1 Experimental conditions

Table 2 lists the parameters of the experiments. In this study, temperature difference ΔT was kept constant and concentration ϕ was varied. Since the suspending fluid is the mixture of tetralin and silicone oil, the kinematic viscosity of the suspending fluid was measured with Ubbelohde viscometer and other fluid properties were calculated based on the Ref. (5). The fluid properties at cold wall temperature T_c was used for the calculation of nondimensional parameters in the Table 2.

Since the concentration of suspended particles is dilute (3 wt%, or 1.2% volume fraction) and the sedimentation velocity of particles ($\approx$ sedimentation velocity of the interface) is small (0.2 mm/s), the heat transfer associated with the sedimentation of particles is thought to be negligible and the effect of the particles except for the buoyant force associated with the change of bulk density is thought to be negligible.

4.2 Transient change of flow patterns, interface shapes, and temperature distributions

Typical flow visualization results are shown in Fig. 7 for 3 wt% suspension. Velocity vectors obtained by PTV were grid interpolated from which flow structures can be visualized. In Figs. 7(a-1)–7(a-7), velocity vectors and particle distributions were synthesized, where gray and white regions represent the suspension layer and the particle-free fluid, respectively. The temperature front which separates the heated region (at least 2°C above T_c) from the other cold region was visualized as the white region in Figs. 7(b-1)–7(b-7) by thermo-sensitive liquid-crystal sheet film.

Peculiar flow patterns which were distinct from those in a particle free fluid were observed as shown in Fig. 7, where convective flow patterns change with time accompanied by the formation and vanishing of the two-layer convection cells.

Strong convective motion was induced by bottom heating and the vertical propagation of the convection cell was suppressed by the formation of a particle-free layer at the top whose density is smaller than that of heated suspension [Fig. 7(a-1)]. The high temperature region was propagated within the convection cells at the bottom [Fig. 7(b-1)].

This convective motion at bottom became weaker with time as shown in Fig. 7(a-2). The interface

Fig. 7 The velocity distributions, temperature distributions, and interface shapes at various times after initiation with $\phi=3$ wt%, $\Delta T=15^\circ\text{C}$

moved from $y/L=0.7$ [Fig. 7(a-1)] to $y/L=0.6$ [Fig. 7(a-2)] during this period due to the sedimentation of suspended particles. This implies that the concentration or the bulk density of the lower suspension becomes higher, while the light particle-free fluid region spreads toward the bottom. The balance of the buoyant force by heating and the negative buoyant force by bulk density is thought to be important to the suppression of the lower convective motion.

The locations of the temperature fronts were almost the same in Figs. 7(a-2) and 7(a-3), while the location of the interface in Fig. 7(a-3) is lower than

that in Fig. 7(a-2) due to the sedimentation of the particles. In Fig. 7(a-3), the interface had been passed through the top of the heated region, and upper-layer convection started at this time. At the same time, small convection cell existed at the bottom, and consequently the two-layer convection cells were formed in the cavity [Fig. 7(a-3)].

After the initiation of upper-layer convection, heated region propagated towards the top wall [Fig. 7(b-4)] and large deformation of the interface due to the upper-layer convective motion was observed, where the interface shape was corresponding

Fig. 8 The velocity and temperature distribution at 1 minute after initiation with $\phi=0$ wt%, $\Delta T=15^\circ\text{C}$

geometrically to the upper-layer convection cell [Fig. 7(a-4)].

Upper-layer convection cell developed in size with the deformation of the interface. The temperature front reached the top wall [Fig. 7(b-5)] and the particle-free layer reached the bottom surface at the left and right walls accompanied by the transition to single-layer convection cell [Fig. 7(a-5)] producing a suspension column [Fig. 7(a-6)]. The lifted heavy suspension became unstable and interfacial breakdown occurred accompanied by the chaotic motion of the fluid without remaking the suspension layer. After the breakdown, most of the particles sedimented and steady single convection cell was formed in the cavity [Fig. 7(a-7)]. The temperature was also in steady state, and all over the cavity was heated [Fig. 7(b-7)].

Figure 8 shows the velocity fields and temperature distributions for $\phi=0$ wt% (particle free fluid) case at 1 min after initiation. Comparing the temperature distributions for the particle-free fluid to that for suspension case at 1 min 47 s after initiation [Fig. 7(b-2)], the temperature front reaches much faster to the top wall. Single cell convection was observed all the time for 0 wt% case from the initiation to the steady state.

4.3 Explanation of the occurrence of two-layer convection cells

Here we discuss some attempts to make explanation of the formation of two-layer double convection cells from our visualization results.

The two-layer convection cells observed here is similar to the ones observed in double-diffusive convection, where concentration interface in double-diffusive convection seems to correspond to the interface between suspension and particle-free layer. In suspensions, however, it should be taken into account that the interface moves downwards with time due to the sedimentation of particles.

As described in section 4.2, the relation between the location of the interface and the temperature front seems to play an important role in the formation of

Fig. 9 Time courses of the height of the profile of temperature distribution and interface from the base

two-layer convection cells. Figure 9 shows the transient change of the location of the top surfaces of the suspension layer and the temperature front. The sedimentation curves in Fig. 9 show the time courses of the vertical location of the interface between particle-free layer and suspension at the center ($y_{I\text{ center}}$), at the left wall ($y_{I\text{ left}}$), and at the right wall ($y_{I\text{ right}}$). While the rising curves in Fig. 9 show the temperature front for the 3 wt% suspension (y_T) and particle-free fluid ($y_{T0\text{ wt}\%}$), which separates the upper cold region and the lower heated region.

The temperature front curve for 3 wt% suspension has a plateau ($y/L=0.55$) beginning at about 100 s and ending at about 220 s after initiation showing the suppression of the vertical heat transfer associated with the convective flow patterns. In contrast, any plateau did not appear in the particle-free fluid.

On the other hand, the interface location moves downwards with time due to the sedimentation of suspended particles. The change of the sedimentation curve at the center is smaller than that at the walls because the scattering from some particles carried with the upper-layer convection lasting for a long time. This implies that the interface location at walls represents the substantial interface.

It must be noticed that the time at which upper-layer convective motion started coincides with the time when the sedimentation curve at walls crosses the temperature front curve at 140 s after initiation. After the upper-layer convection started, the temperature front curve begins to rise again. The passing of the interface through the temperature front implies that the particles were removed from the heated suspension near the interface where the buoyant force by temperature was balancing with the negative buoyant force by particles.

It is possible at this point to make a comparison of the above observations of the condition for the

formation of the upper-layer convection cell with the study of Huppert et al.⁽⁶⁾, Kerr-Lister⁽⁷⁾ and Cardoso-Woods⁽⁸⁾ on systems for a suspension of small particles overlain by a clear fluid whose density is greater than that of the interstitial fluid, but less than that of the bulk suspension. They reported that the settling of the suspended particles in the lower layer can lead to convection in the overlying particle-free fluid releasing light fluid convecting into the upper layer. It is likely that the same situation occurs in this study; the overlying particle-free layer convection is initiated by the release of the heated clear fluid at the interface. It may be admitted now that this fundamental mechanism, 'sedimentation driven convection' can be attributed to the formation of two-layer convection cells.

5. Uncertainty Analysis

In the PTV measurement, uncertainty of measurement comes from measurement accuracy and particle traceability.

The velocity of a particle is calculated from the particle-image displacement dl , the time interval dt and the magnification factor f as follows.

$$u_i = (dl_i/dt)f. \quad (1)$$

The uncertainty of an instantaneous velocity component is estimated at 95% coverage by the following equation⁽⁹⁾,

$$\Delta u_i^2 = (f\Delta dl_i/dt)^2 + (dl_i f \Delta dt/dt^2)^2 + (dl_i \Delta f/dt)^2, \quad (2)$$

where the first term on the right hand side comes from the limit of the spatial resolution of an optical system, the second term represents the influence of the time jitter in digital retarder, and the third term is the uncertainty in the overall magnification factor of image.

The error source from digital retarder Δdt can be described as $(\Delta dt) = \pm (\text{delay time} \times \text{quarts accuracy}) + (\text{signal transfer delay})$. In this study, the delay time is set to 1/50 s, the accuracy of quarts is $\pm 1 \times 10^{-5}$, and the transfer delay is 0.5 μ s. The calculated Δdt is so small ($0.5 \pm 0.2 \mu$ s) that the error source due to the digital retarder can be omitted. Table 3 summarizes the values of the quantities appearing in Eq. (2). The value of dl_x and dl_y are determined as the maximum displacement at steady state convection. Δdl_x and Δdl_y are calculated from the fact that typical particle images occupy about 1 pixel². Then, the uncertainties of the instantaneous velocity components u , v , are evaluated at 95% coverage as follows.

$$\Delta u = \pm 0.017 \text{ mm/s}, \quad \Delta v = \pm 0.017 \text{ mm/s}.$$

The error due to the particle traceability is evaluated by particle relaxation time. The estimated relaxation time of the tracer particle is 75 μ s, which is

Table 3 Uncertainties and typical values of quantities in Eq. (2)

dl_x	7.98 pixel
dl_y	6.90 pixel
Δdl_x	± 0.08 pixel
Δdl_y	± 0.08 pixel
dt	1 s
f	194.17 μ m/pixel
Δf	$\pm 0.91 \mu$ m/pixel
Δu	$\pm 17.15 \mu$ m/s
Δv	$\pm 16.75 \mu$ m/s

thought to be enough for the measurements in this study.

6. Conclusions

Transient change of natural convection of particle suspensions in a square cavity was studied. The suspension was heated from the bottom wall while the two facing vertical walls were kept at a constant temperature. The two dimensional velocity fields, particle distributions in a plane, and the wall temperature fields were visualized simultaneously using three cameras in order to explain the mechanisms for peculiar flow patterns in suspensions. The following conclusions were obtained from the experiments.

(1) The visualization method with the refractive index matching technique and the laser induced fluorescent tracer particles has been shown to provide sufficient tracer particle images without scattering noise from suspended particles for the problems of natural convection in particle suspensions. The PTV, in conjunction with these techniques, has enabled the quantitative velocity measurements in a suspension.

(2) After the initiation, vertical propagation of the convection and temperature was suppressed by the upper particle-free layer for 3 wt% suspension in contrast to the 0 wt% case. The heated region is consequently limited to certain height from the bottom wall in 3 wt% suspension.

(3) When the interface between particle-free fluid and suspension passes through this heated region, the upper-layer convection starts. It was suggested that two-layer convection cells were driven by both heating and sedimentation of particles which drives convection in the overlying layer due to the release of the heated clear fluid at the interface.

(4) The lifted heavy suspension carried by the convective flows become unstable and interfacial breakdown occurs accompanied by the transition from two-layer convection to single layer convection without remaking the suspension layer.

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References

- (1) Suzuki, T. and Okada, M., Natural Convection of Water-Fine Particle Suspension in a Rectangular Cell, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 62, No. 593, B (1996), pp. 241-247.
- (2) Okada, M. and Suzuki, T., Natural Convection of Water-Fine Particle Suspension in a Rectangular Cell, *Int. J. Heat Mass Transf.*, Vol. 40, No. 13 (1997), pp. 3201-3208.
- (3) Mikami, F., Chen, B. and Nishikawa, N., Visualization of the Flow Features of Natural Convection in Particle Suspensions, *Theoret. Appl. Mech.*, Vol. 46 (1997), pp. 341-348.
- (4) Nishino, K. and Torii, K., A Fluid-Dynamically Optimum Particle Tracking Method for 2-D PTV : Triple Pattern Matching Algorithm, *Proc. ISTP-6 Thermal Eng.*, III (1993), pp. 339-344.
- (5) Ohe, S., *Sekkeisha no Tameno Busseichi Suisanhou*, (in Japanese), (1985), Chap. 6, 8, 9. Nikkan-Kogyo Shinbun.
- (6) Huppert, H.E., Kerr, R.C., Lister, J.R. and Turner, J.S., Convection and Particle Entrainment Driven by Differential Sedimentation, *J. Fluid Mech.*, Vol. 226 (1991), pp. 349-369.
- (7) Kerr, R.C. and Lister, J.R., Further Results for Convection Driven by the Differential Sedimentation of Particles, *J. Fluid Mech.*, Vol. 243 (1992), pp. 227-245.
- (8) Cardoso, S.S.S. and Woods, A.W., On Convection and Mixing Driven by Sedimentation, *J. Fluid Mech.*, Vol. 285 (1995), pp. 165-180.
- (9) Adachi, T., Nishino, K. and Torii, K., Digital PTV Measurements of a Separated Air Flow behind a Backward-Facing Step, *J. Flow Visualization and Image Processing*, Vol. 1 (1993), pp. 165-180. or *Proc. ISROMAC-5*, Hawaii, USA, (1994-5), pp. 441-460.
- (10) Jinbo, G., Ozawa, E., Sakisaka, Y., Komiyama, H., Sadakata, M. and Yoshizawa, A., (ed.), *Biryuushi Handobukku*, (in Japanese), (1991), pp. 115-116, Asakura.