The interaction between two droplets and the interaction between two solid spheres

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ABSTRACT

Although the phenomena related to the multiphase flow can be found in many kinds of industrial and engineering applications, the physical mechanism of the multiphase flow has not been investigated in detail. The major reason for the lack of data in the multiphase flow lies in the difficulties in measuring the flow quantities of the multiple phases simultaneously. The difference in the refractive indices makes the visualization in the vicinity of the boundary of the multiple phases almost impossible. In this study, the refractive index of the aqueous phase has been equalized to that of the oil phase by adjusting the concentration of the aqueous solution. Both phases are seeded with neutrally buoyant particles respectively. The aqueous droplets are lightly colored with fluorescent dye so that the invisible droplets can be identified. Thus, the difference in the background brightness in both phases helps PIV to distinguish the motions in each phase. The flow around and inside of two falling droplets interacting each other has been extensively measured by this index-matching technique and PIV. The results show the details of the flow structures about the two falling droplets. It has been shown that the flow between two droplets pulls pursuing droplets towards the preceding droplet. This causes the chasing motion of the pursuing droplet and finally it catches up the preceding droplet and overtakes it. The similar motion of two particles is well known as "Drafting, Kissing and Tumbling" motion. The effect of the initial relative positions of two droplets is investigated in detail and has proved that the condition that causes the DKT motion is shown. The pressure field and the vorticity field have been calculated from the velocity field obtained by PIV. Moreover, the interaction between two solid spheres is also investigated by PIV and the difference in the boundary condition that affects the interaction is discussed in detail.

INTRODUCTION

Multiphase flow has been one of the most difficult and, at the same time, one of the most practically important phenomena in the fluid mechanics. Many studies for the multiphase flow have been conducted in order to investigate the details about the momentum and material transfer at the interface. Numerical studies, such as Dandy and Leal (1989) [1], have revealed many kinds of features about the both phases. Even though the measurements about the surrounding fluid, such as Cieslinski et al. (2005) [2], have been extensively carried out, only a few results have been reported about the flow near the boundary and the flow inside of a bubble or a droplet. This is mainly because the discontinuity of the medium at the interface of the multiphase flow makes the measurement or even the visualization almost impossible.

Recent developments in the visualization technique and the improvements in the imaging devices make the great progress in the measurement techniques. Especially, the success by the particle image velocimetry (PIV) and by the particle tracking velocimetry (PTV) is outstanding. Nevertheless, the PIV or PTV measurements in the multiphase flow are still limited to the examination of outer phases. The reason of the lack of data for the inner phases is because the visualization itself is still very difficult with the refraction at the interface of the multiphase flow. Yamauchi et al. (2000) [3] have succeeded in measuring the flow field inside of the water droplet falling through the stationary oil by compensating the complex distortion caused by the refraction at the boundary of a droplet assuming that Eötvös number and Reynolds number are both small and the droplet is perfectly spherical. Ninomiya and Yasuda (2006) [4] have carried out the flow visualization and the PIV measurements of the flow around and inside of a falling droplet simultaneously under various flow conditions by using the index matching technique, as was used by Knapp and Bertrand (2005) [5].

Presently, the flow field around and inside of two falling droplets interacting each other has been extensively examined by PIV measurement with the moving camera. The pressure field and the vorticity field are also calculated from the

PIV results about the velocity field. As a result, many features about the interaction between two droplets and the interaction between two solid spheres have been investigated in detail.

EXPERIMENTS

In order to visualize the flow around and inside of a droplet simultaneously, the refractive indices of the inner and the outer phases should be matched. As the refractive index of silicon oil at the room temperature is 1.4026, whereas that of water is 1.3330, the refractive index of water phase might be matched by introducing some miscible substance of higher refractive index. In this study, the glycerol, whose refractive index is 1.4716 and is also immiscible to silicon oil, is chosen for the refractive index matching substance.

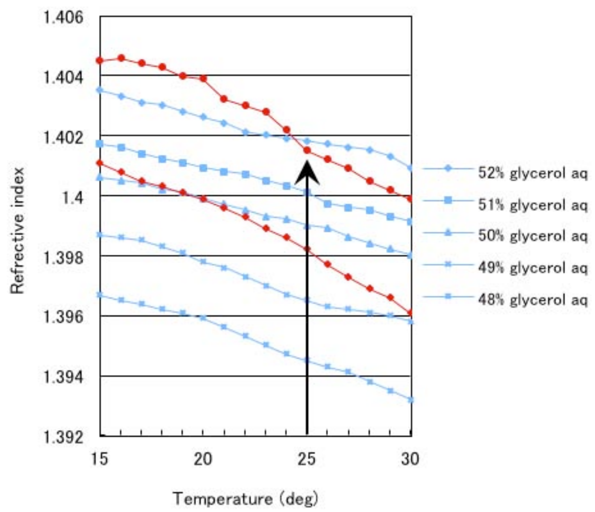


Figure 1 Refractive indices of fluids.

Table 1 Physical properties of fluids at 25 deg.

	Silicon Oil 20 cSt	52% Glycerol aq.
refractive index	1.4026	1.4026
viscosity	21.8 m Pa s	6.70 m Pa s
specific density	0.925	1.130
particle	ρ=0.95, d=15μm	ρ=1.13, d=20μm

Figure 1 shows the change of the refractive indices of two grades of the silicon oil and of the glycerol solution of various concentrations. It is obvious that the glycerol solution of higher concentration takes higher refractive index. The refractive index of ordinary liquid gets smaller with higher temperature, but its temperature sensitivity is different with liquid. Thus the refractive index of the silicon oil can be matched with that of glycerol solution of adequate concentration and temperature. Presently, 52 % glycerol solution is chosen so that its refractive index matches that of 20 cSt silicon oil, i.e., 1.4026, at room temperature of 25 deg.

The physical properties of the working fluids used in this study are summarized in Table 1. As for the oil phase, silicon oil of 20 cSt is chosen so that the terminal velocity of the falling droplets comes into the appropriate range for the PIV measurement. As shown in Table 1, the refractive indices of 52 % aqueous solution of glycerol and silicon oil of 20 cSt are exactly matched. As for the tracer particle for each phases, nylon 6 and polyethylene is selected whose specific densities are almost the same as those of fluids. Thus, the motions of each fluid can be visualized properly.

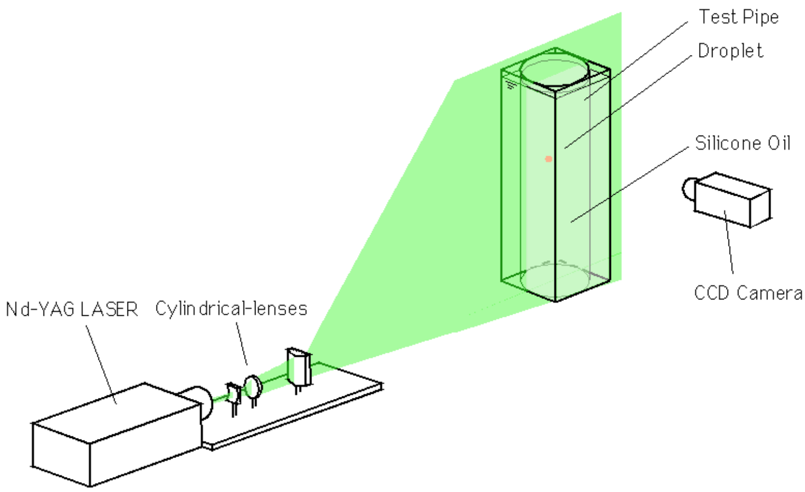


Figure 2 Experimental apparatus.

Figure 2 shows the schematic view of experimental apparatus. Silicon oil of 20 cSt is filled in the reservoir of 100 x 100 x 500 mm, inside of which thin cylindrical wall of Plexiglas is placed in order to avoid the effect of corner of the container. To illuminate the tracer particles, double-pulsed Nd-YAG laser is used and the beam is expanded by the cylindrical lens and then focused into thin sheet by the sheet forming optics as shown in Fig. 2. The positions of the droplet injecting nozzles are carefully aligned with the laser light sheet so that the exact center plane of the two droplets can be visualized.

As the refractive indices of both phases are perfectly matched, the boundary of the droplet is no more visible. Thus, in this study, the droplet is slightly colored by Rhodamine B so that the shape of the droplet can be distinguished by the laser-induced fluorescence (LIF).

The image of the droplet is captured by moving CMOS camera that has the resolution of 1024 x 1024 at the frame rate of 60 fps and then the images are directly transferred to PC. The CMOS camera is mounted on the slider that travels at the constant speed in order to capture the images of the flow field around and inside of the falling droplets as long as possible. The terminal velocities of the two falling droplets have been measured in the preliminary experiment to determine the traveling speed of the slider.

Before measuring the velocity field around and inside of a falling droplet, the size and the position of the droplet are calculated from the images. As the droplet is slightly colored by the fluorescent dye, the droplet can be identified as the slightly bright region. In order to eliminate the images of the tracer particles, the smoothing is applied to the original image. Then the derivative of the brightness is taken in order to enhance the outline of the droplet. Finally, by fitting the equation of ellipse to the outline by the least square method, the center and the radii in major and minor axis of the droplet are obtained.

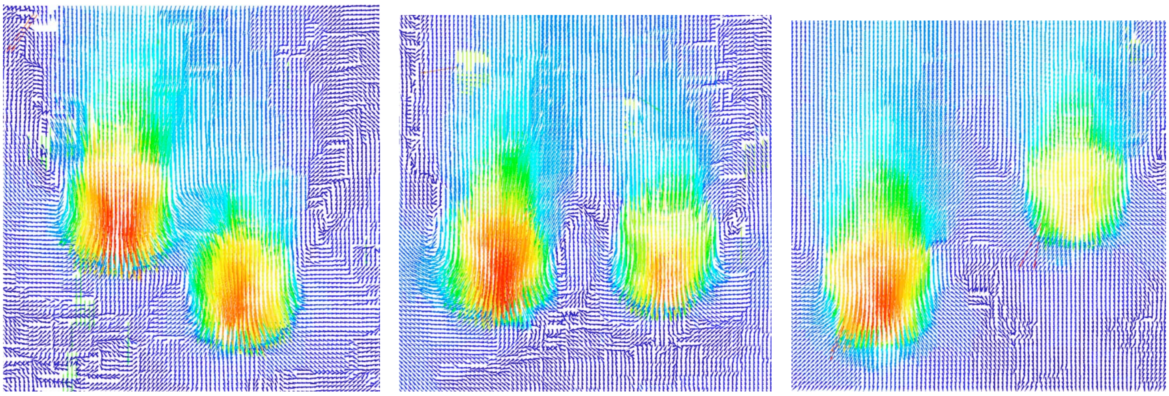
The typical size of a droplet, which is almost spherical under the condition of present study, is about 4.5 mm in diameter. The terminal velocity is calculated from the displacement and the time interval and then the non-dimensional parameters, such as the aspect ratio of the droplet, drag coefficient C_D, Reynolds number Re, Morton number Mo and Eötvös number Eo or Bond number Bo. The typical terminal velocity of a droplet is 66 mm/s and this value ends up with Re = 12.9 and C_D = 2.56. According to the Grace's diagram, excerpted from Clift et al. (1978) [6], the present droplet is plotted in "spherical" zone and the measured aspect ratio of 0.95 agrees well with the diagram.

PIV RESULTS

Even though many kinds of feature about the two-phase flow can be examined by the index matching technique, firstly the attention has been paid upon the interaction between two falling droplets. Similar works have been done by Kitagawa et al. (2004) [7] and by Murai et al. (2006) [8], but the flow field inside of the dispersed phase has not been investigated in the previous studies. In this study, two water droplets have been simultaneously injected into Silicone oil from two nozzles of some distances. This distance has been changed to investigate the details of the effect of the initial distance to the interaction between two droplets. In order to investigate the details of the interaction between two droplets, the terminal velocities of two droplets have been measured in the preliminary tests so that the CCD camera mounted on a slider can capture the motions of two droplets as long as possible.

The typical results for the interaction between two falling droplets are shown in Figs. 3 and 4. These results are for the cases of the initial vertical distance of 12mm. Figures 3(a) and 4(a) designate the flow field around and inside of two falling droplets at their early stage. The horizontal distance between two droplets at this location is 4.56 mm, which is a little bit smaller than the distance at which they were injected. Figure 3(a) shows the flow field at the fixed coordinates and the color of the vector indicates the magnitude of velocity. The strong downward motions of two droplets are evident and it is obvious that the fluids behind the droplets are drawn by the droplets. It is also seen that the fluids in front of the droplets are pushed aside by the droplets. Figure 4(a) is the plot of the flow relative to the droplets. The mean terminal velocity of two droplets is subtracted from the results in Fig. 3(a). It is obvious that the counter-rotating vortices in two droplets are anti-symmetric, which result from the interaction between two droplets. The flows in front of two droplets make their way around the droplets, whereas two droplets suppress the flow between two droplets. The most interesting feature is that the flow between two droplets pulls the pursuing droplet toward the preceding one and thus the pursuing one is faster than the preceding one.

Figures 3(b) and 4(b) show the flow field around and inside of two droplets at the timing of the overtaking. Here again, Fig. 3(b) is the result at the fixed coordinates and Fig. 4(b) is that in the moving coordinates. In this case, the horizontal distance at this location is 7.11 mm, which is bigger than the original separation and is the consequence of the interaction between two droplets. The latter droplet is overtaking the former one and is faster than it. As for the counter-rotating flows in the droplets, the preceding droplet is less anti-symmetric than those in Fig. 4(a), but the



(a) drafting (b) kissing (c) tumbling

Figure 3 PIV results (flow at fixed coordinates).

(a) drafting (b) kissing (c) tumbling

Figure 4 PIV results (flow relative to droplets).

pursuing one is more. This means that the flow field around the preceding droplet is no more affected by the interaction between two droplets. It is interesting that the fluid between two droplets breaks into the gap between them and thus the two droplets are pushed away in the horizontal direction. Another evidence found by these figures is that the horizontal displacement of the preceding droplet is much bigger than that of the pursuing one.

In Figs. 3(c) and 4(c), the flow fields around and inside of two droplets after the overtaking are shown. Here again, Fig. 3(c) is the result at the fixed coordinates and Fig. 4(c) is that in the moving coordinates. The horizontal distance at this location is 8.16 mm, which is a little bit bigger than that in Figs. 3(b) and 4(b), but the increase is not so bigger than before. Now the preceded droplet travels as if it goes by itself and it cannot chase the other droplets again. This is because the horizontal distance between the two droplets is now much larger than to make another interaction. As for the counter-rotating flows in the droplets, there still remains a little bit anti-symmetry in the pursued droplet, but the two droplets travel as if they go by themselves.

Even thought the figure cannot be shown because of the space, the trajectories of two droplets have been traced. This can be done with the use of moving camera. First, the pursuing droplet is pulled toward the preceding droplet vertically and horizontally. The preceding droplet is pushed aside horizontally when the pursuing droplet overtakes. After the overtaking, the pursuing droplet travels a little bit away horizontally. As a result, two droplets have been separated much more in horizontal direction after the overtaking and thus the reciprocal chasing does not occur.

Figure 5 designates the map of the initial relative positions between two droplets. The symbols by blue diamond represent the condition that the overtaking occurs. The green triangles show the condition for slight interaction, by which the two droplets do not catch up but depart in the horizontal direction. The red squares mean that there is almost no interaction observed. It can be concluded that the two droplets have to be closely located in the horizontal direction to make the overtake occur, but it is quite tolerant for the initial vertical distance.

As the velocity field around and inside of the two falling droplets interacting each other has been obtained in detail, many fluid dynamic characteristics, such as vorticity field and pressure field, about the droplets can be calculated from the velocity field. The typical example is shown in Figure 6, which represents the pressure field about the interaction. This pressure field is calculated by solving the Poisson equation under the assumption that the flow field is two-dimensional and the boundary condition around the droplets is negligible. It is obviously seen that the pressure in front of the preceding droplet is much higher than that of the pursuing droplets. As the pursuing droplet suffers the wake of the preceding droplet where the pressure is lower than the surroundings, the pursuing droplet is pulled by this low-pressure region. This might be the mechanism of the overtaking interaction between two falling droplets. Other results are omitted because of the space.

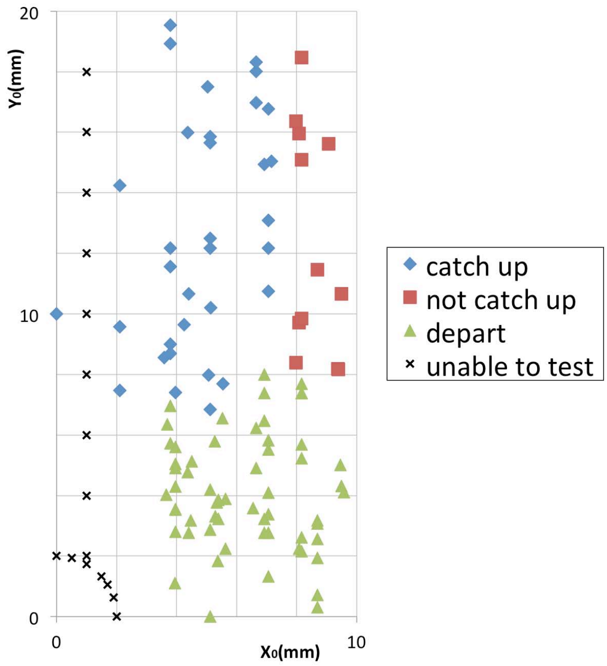


Figure 5 Map of initial position to catch up

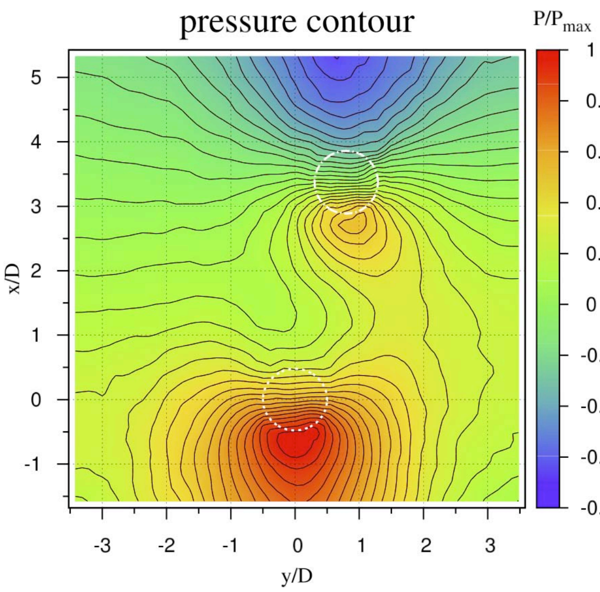


Figure 6 Pressure field around two droplets

As for the interaction between two solid spheres, "Drafting-Kissing-Tumbling" motion named by Fortes et al. (1987) [9] is well known. Even though the various initial separations between two droplets have been tested in this study, "Kissing" was not seen in any condition while "Drafting" and "Tumbling" are very similar to those in the previous study. The boundary condition around the solid spheres is non-slip and that around liquid droplets allows the fluid to travel along the surface of the droplets. This difference in the boundary condition may be the major reason for the lack of "Kissing". In order to investigate the effect of the boundary condition, similar interaction between two solid spheres have also been measured in this study. The solid spheres used in this study is made of Nylon-66 and thus their specific density is 1.13, which is exactly same as those of the droplets used in this study, and their size is 4.0mm, which is a little bit smaller than them. In order to illuminate both side of the droplets, the oblique mirror was used in the rear side.

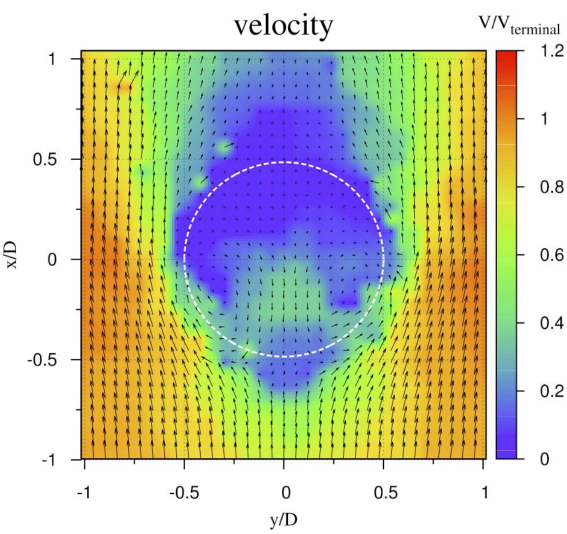


Figure 7 Flow around droplet

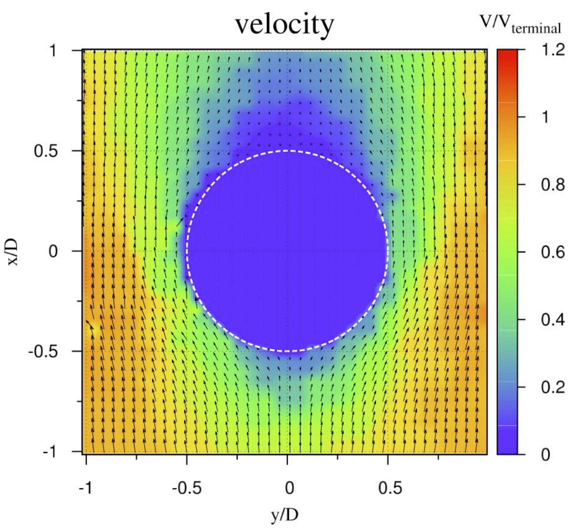


Figure 8 Flow around solid sphere

Even though the details of the flow field around the two solid spheres interacting each other have been obtained, the figures have to be omitted because of the space. Nevertheless, quite similar DTK motion is also found for the interaction between two solid spheres. The "Drafting" and "Tumbling" is also seen but the "Kissing" did not occur. The major reason for the lack of "Kissing" in this study may be the smallness of the Reynolds number, as that by Fortes et al. is 730 and their inertia force is much higher compared to our cases.

As for the difference in the boundary conditions, it is found that the initial separation between two solid spheres is a little bit limited for the overtake to occur than that for two liquid droplets. Figures 7 and 8 show the velocity field in the vicinity of droplet and solid sphere. It can be seen from these figures that the velocity gradient near the boundary is steeper for solid sphere than for droplet. This is because of the non-slip boundary condition at the solid surface and thus the boundary layer thickness gets thicker for solid sphere. Consequently, the fluid between two solid sphere cannot penetrate into the gap of two solid sphere and the overtake motion is limited compared to the interaction between two droplets.

CONCLUSIONS

In order to investigate the details of the flow around and inside of the falling droplets simultaneously, the refractive index of the water phase is perfectly matched to that of the oil phase and thus the refraction at the boundary of water droplets falling in oil is completely avoided. By introducing the tracer particles, which are neutrally buoyant to each phases, and by slightly coloring the droplet by the fluorescent dye, the flow around and inside of the falling droplets and the positions of the droplets are clearly visualized. As a result of the PIV measurement using this index matching technique, the details of the flow fields around and inside of the two falling droplets have been investigated in detail. Moreover, the interaction between two solid spheres is also examined. The followings are the conclusions of this study:

1) The velocity field around and inside of two falling droplets interacting each other has been intensively measured by PIV. The vorticity and the pressure field calculated from the velocity data are very helpful for understanding the mechanism of the overtake motion.

2) The effect of the relative initial position between two droplets is investigated in detail. The "Drafting" motion and the "Tumbling" motion are found to occur for the wide range of initial position during the overtake, but the "Kissing" motion has not been observed under experimental condition of this study.

3) By comparing the interaction between two droplets and the interaction between two solid spheres, it is found that the thicker boundary layer for the solid spheres prevents the overtake motion than the liquid droplets.

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