Measurement about the Interaction between Two Falling Droplets

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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 aqueous solution. Presently, the simultaneous visualization and the PIV measurement have been carried out about the both phases of the liquid-liquid two-phase flow. The measurement has been carried out for the flow field around and inside of two falling droplets interacting each other while they travel.

1. 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), have revealed many kinds of features about the both phases. Even though the measurements about the surrounding fluid, such as Cieslinski et al. (2005), 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) 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 the droplet is perfectly spherical and Eötvös number and Reynolds number are both small. Ninomiya and Yasuda (2006) 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). 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. As a result, many features about the flow related to the two falling droplets have been investigated by the results of the PIV measurements.

2. MEASUREMENT PROCEDURE

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 1.3999, 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 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.

![Fig. 1 Refractive indices of fluids](image)

**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             |
| tracer particle  | Polyethylene \(\rho=0.95,15\mu m\) | Nylon 6 \(\rho=1.13, 20\mu m\) |
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 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 CCD camera that has the resolution of 1376 x 1040 at the frame rate of 30 fps and then the images are directly transferred to PC. The CCD 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), the present droplet is plotted in “spherical” zone and the measured aspect ratio of 0.95 agrees well with the diagram.
3. PIV RESULTS

Even though many kinds of feature about the two-phase flow can be examined by the index matching technique, presently the attention has been paid upon the interaction between two falling droplets at the same height. Similar works have been done by Kitagawa et al. (2004) and by Murai et al. (2006), but the flow field inside of the dispersed phase has not been investigated. In this study, two water droplets have been simultaneously injected into Silicone oil from two nozzles of some horizontal 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 at the same height, 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.

![Fig. 3 PIV results (flow at fixed coordinates)](image)

![Fig. 4 PIV results (flow relative to droplets)](image)

The typical results of the PIV measurements in this study are shown in Figs. 3 to 6. These results are for the cases that the initial horizontal distance between two droplets is Lx = 4 mm for case (a) and is Lx = 9 mm for case (b). Figures 3 and 4 designate the flow field around and inside of two falling droplets at their early stage, which is just after the injection of the droplets. Figures 3(a) and 3(b) show the flow field at the fixed coordinates. The strong downward motions of two droplets are evident and 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 when they penetrate the surrounding fluid. As for the case (b) of large initial distance, the two droplets seem to travel almost independently and the upward motion, which may be the result of superposition of the effects of two droplets, is found in the
midst of the two droplets. On the contrary, as for the case (a) of small initial distance, the fluid between two droplets is drawn by the two droplets and moves downward.

Figures 4 are the plot of the flow relative to the droplets. The average of the terminal velocities of two droplets is subtracted from the results in Figs. 3 to highlight the motion inside of the droplets. As for the case (b), the almost symmetric two counter-rotating vortices are seen inside of both of the two droplets. This implies that there is only very little interaction between two droplets for the case (b) of large initial distance. But for the case (a) of small initial distance, as the fluid between two droplets is pulled by two droplets and travels with them, the shear on the facing side of the droplet gets very weak and thus rotating motion inside of the droplet is not seen on this side of two droplets. It is also seen that the wakes of two droplets merge into single motion, which may look like a wake of a single object. But it should be noticed that the two droplets themselves do not merge into single under this condition.

![Fig. 5 PIV results (flow relative to droplets)](image)

Figures 5 shows the flow fields at the vertical position of 90 mm from the nozzle. Beyond the vertical position of 50 mm from the nozzle, the velocities of the falling droplets reach their terminal velocities of 66 mm/s. Here again, Figs. 5 are the results in the moving coordinates. The horizontal distances between two droplets have been increased to 10.4 mm for case (a) and 13.6 mm for case (b). The increase for the small initial distance case (a) is much larger as the interaction between two droplets is very strong in the early stage. Now the surrounding fluid flows into the gap of two droplets and the shear on the both side of the droplets produces the counter-rotating vortices inside of the droplets. Even though that a slight asymmetry is seen for the counter-rotating vortices and a little outward motions inside of the droplets are found for case (a), now the flow fields inside of two droplets are almost symmetric for case (b).

![Fig. 6 PIV results (flow relative to droplets)](image)

In Figs. 6, the flow fields around and inside of two falling droplets when the two droplets travel far downstream to 200 mm are shown. The horizontal distances are 12.8 mm for case (a) and 14.4 mm for case (b). Though there still are a little bit of increases in horizontal distances for both cases, the
flow field looks like a superposition of two flow fields of single falling droplet. This is evident from the facts that the counter-rotating vortices inside of a droplet is symmetric and two shear layers around a droplet on the facing side of each droplets do not collapse and flows almost independently.

Figure 7 shows the plots of the horizontal distances between two droplets while they travel for the cases of different initial distances between two droplets. For any initial distance between two droplets, the distances between two droplets increase monotonously. It is also obvious that the smaller the initial distance, the faster two droplets separate. The rate of increase of the distance between two droplets is very large before they reach their terminal velocities at 50 mm downstream and gets quite small after the distance between droplets is larger than 14 mm. It is quite straightforward to conclude that the closer the initial distances, the stronger the interaction between two falling droplets.

3. 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 injected at the same height have been investigated in detail.

Thus, the followings are the conclusions of this study:

1) The index matching technique is very effective in visualizing the both phases of the multiphase flow. As for the PIV measurement, the difference in the background brightness of the slightly LIF-colored droplets and the non-colored surrounding fluid helps in distinguishing flow fields in each phases.

2) When the droplets fall, the fluids in front of the droplets are pushed aside and then coincide in the midst of two droplets. This may be the driving force of the separating motions of two droplets. But, for the case of small initial distance 4 mm, at the early stage after injection the fluid cannot penetrates
into the gap of two droplets and thus the two droplets fall as though the lump of two droplets is a single object.

3) When the falling speeds of droplets reach their terminal velocities at the vertical distance beyond 50 mm, even though slight asymmetry is still observed for the counter-rotating vortices inside of droplets and the droplets keep on leaving from each other, the interaction between two droplets gets very weak and the flow field looks like a superposition of two flow fields of single falling droplet.

4) According to the plots of the horizontal distances between two droplets, the smaller the initial distance between two droplets, the faster the two droplets separate. The rates of increase of the distances between two droplets are larger before they reach their terminal velocities.

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