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The Motion of Individual Bubbles in a Bubble Swarm and the Structure of the Liquid Motion

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Abstract: - This study describes experimental results on the wake structure generated by a bubble swarm using LDV. The authors have considered the individual bubble motion of a bubble swarm and the liquid-phase motion driven by the buoyancy. The bubbles were simultaneously released from 19 needles under precise control; two bubbles were released from each needle at a short interval; as a result a total of 38 bubbles composed the bubble swarm. The 38 bubbles were almost uniform and 2.6mm in equivalent diameter. The center-gravity motion of the each bubble was obtained from high-speed visualization. The liquid-phase motion induced by the dispersed bubble buoyancy was measured via LDV. The following results were obtained: in the frontal region of the bubble swarm, the liquid-phase motion induced by the individual bubbles of the swarm did not interact with each other; in the rear region of the bubble swarm, the liquid-phase motion intensively interacts with each other through the wakes; inside of the bubble swarm, the liquid-phase motion was affected by the center-gravity motion of each bubble.

Key-Words: Multiphase flow, LDV, Bubble swarm, Wake, FFT, Bubble trajectory, Bubble velocity

1 INTRODUCTION

Gas-liquid multiphase systems are frequently observed in natural phenomena and in various areas of engineering, e.g. chemical reactor, heat exchanger, and so on. In order to improve these devices/plants, mass, momentum and energy transfer between the gas and liquid-phases in the turbulent bubbly flow must be completely controlled. To deeply understand the multiphase flow, the detailed studies on a single bubble and/or a bubble swarm are necessary, because the flows have multi-scale ranging phenomena. We need a detailed understanding and modeling regarding the local- and global-scale structure of the flows [1] as well as the coupling mechanism between the bubble motion and the surrounding-liquid motion [2]. In the other words, the momentum transfer between gas and liquid phases should be elucidated in careful consideration of the coupling mechanism among multi-scale ranges. Furthermore, the mass transfer between gas and liquid phases depends on the local- and global-scale structure of the flow; the mass transfer coefficient for a single bubble depends on the bubble diameter [3]; the overall mass transfer is enhanced by the large-scale structure of the flows [4].

Laser devices such as YAG laser, high-speed video camera, Laser Doppler Velocimetry (LDV), Particle Image Velocimetry (PIV) and so on have enabled researchers to obtain the more detailed data of the bubble motion and the flow structure of the surrounding liquid. Ellingsen and Risso used LDV combined with two sets of video camera to provide simultaneous measurements for the bubble motion and the flow structure of surrounding liquid [5]. Both the gas and liquid phases had been accurately investigated, however the description about interface motion of the bubble might be insufficient. Brücker implemented PIV [6]; he mentioned the bubble shape and the liquid-phase velocity field. Recently, Fujiwara et al. investigated the flow structure in the vicinity of a bubble moving in a shear flow via combination of PIV-LIF and shadow image technique [7]. Tomiyama et al. reported that a terminal velocity of an isolated single bubble depends on the initial shape deformation [8]. Wu and Gharib obtained the similar knowledge [9]. Although many researches have been discussing the motion of a single bubble and its surrounding liquid flow, the knowledge about the bubble-swarm motion and the liquid-phase motion, in particular coupling mechanism between liquid-phase motion driven by dispersed buoyancy of the individual bubbles and large-scale liquid-phase motion driven by the bubble swarm, is still insufficient.

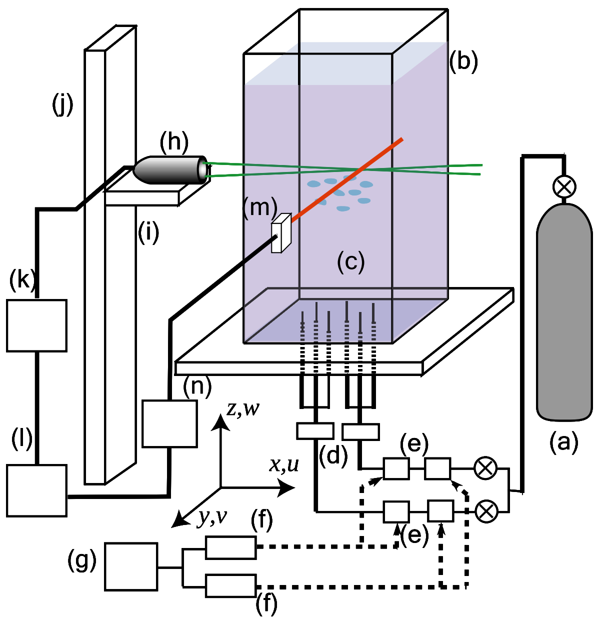
In the present study, the authors focus the motion of the individual bubbles of the bubble swarm and the large-scale liquid-phase motion induced by the swarm buoyancy as well as the local-scale motion induced by the individual buoyancy of the bubbles.

The bubbles in the range from 2 to 5 mm in equivalent diameter, it is well known that the bubbles rise zigzagging and/or helically [10], were examined. The following results were obtained: in the frontal region of the bubble swarm, the liquid-phase motion induced by the individual bubbles of the swarm did not interact with each other; in the rear region of the bubble swarm, the liquid-phase motion intensively interacts with each other through the wakes; inside of the bubble swarm, the liquid-phase motion was affected by the center-gravity motion of each bubble. On the basis of these results, a coupling model between the liquid-phase motion induced by individual dispersed bubbles and the liquid-phase motion induced by the bubble swarm.

2 Experimental Set-Up

2.1 Method of bubble swarm injection

In this experiment, we measured the motion of individual bubbles in the bubble swarm and the liquid-phase motion induced by the bubbles. Fig.1 shows schematic of the experimental setup for this study. The experiments have been performed using an acrylic water vessel of 149mm-by-149mm square section and 520mm in height.



(a) Cylinder, (b) Acrylic water vessel, (c) 19 needles, (d) Air distributer, (e) Electromagnetic valve, (f) Digital timer, (g) DC power source, (h) LDV probe, (i) LDV stage, (j) Lift, (k) LDV system, (l) PC, (m) Laser optic sensor, (n) A/D converter

Fig.1 Schematic experimental setup

The vessel was filled up with distilled water. Pure air was injected into the water through 19 needles (0.26mm ID) located at the vessel bottom. The interval of each needle was 9.58mm. The air from the cylinder was pumped into two lines. The bubbles were released from 19 needles, when the two electromagnetic valves were opened. Two bubbles were released from each needle at a short interval; consequently the bubble swarm consisted of 38 uniform bubbles. The timer controlled the electromagnetic valves to adjust the bubble injection rate. In order to make uniform bubble swarms, the period of the valve opening had to be shorter. For this purpose we used two electromagnetic valves set in tandem arrangement. The part time of each period of the valve open was crossover. The interval of bubble swarm injection was kept in an interval of 10s. In this period, the wake of former bubble swarm was almost disappeared.

2.2 Visualization

Two set of high-speed digital video camera (NAC HSV-500C3, 250frames/s) were employed to obtain three-dimensional trajectories of the bubbles and the instantaneous bubble velocities. The axes of the cameras were at right angles to each other. Robots lift the cameras up as the bubble swarm is taken in frame. The pictures of bubble swarm are taken as shadow image. The origin of coordinates is the nib ofthe center needle. The ruler is in water vessel and is taken image with the bubble swarm. The cameras lifts are considered to calculation of the bubble motions.

2.3 LDV Measurement

The liquid-phase motions of x and z direction influenced by bubbles swarm are measured via LDV. We measured from y = -60.0mm ~ 60.0mm at intervals of 6.0mm at z = 100mm, 200mm, 300mm. Laser-beam passing sensor crosses x = 0.0mm, y = 0.0mm at each height. The signals of laser-beam passing sensor were stored in PC through a high-speed A/D converter (20MHz/ch). The laser-beam passing sensor was used to detect the bubble swarm passage and to give the system a reference signal of TTL. Start times of the sensor reaction are different each time of bubble swarm passing. Therefore we examined the averaged positional relation between the bubble swarms and the laser-beam passing sensor.

In order to reverse the effect of scattering noises

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from the bubbles surfaces, we employ the same technique of Mudde & Saito [11]. First, from velocity data with scattering noises, we calculated the averaged velocities (u, w) standard deviations (σ). Second, we set thresholds as u, $w \pm 3\sigma$ and remove the velocities data beyond threshold area. Third, we calculated averaged velocities again.

3 Bubble Motion

Fig. 2 shows a typical time evolution of the bubble swarm. When the bubbles are released from the needles (see (a)), the bubbles are formed into two-groups lining on two-plane: i.e., leading bubbles and following bubbles. Then at about 170mm height (see (c)), the following bubbles catch up with the leading bubble group, and are mixed up with the leading bubbles. The case that two bubbles or some bubbles rise up the same axis, the following bubble catches up with leading bubble [12], [13]. It seems that the same phenomenon was observed in this case. Fig.3 (a), (b) show the center-gravity motion of the leading bubbles and following bubbles. The trajectories of the leading bubbles extend to radial direction after bubbles injection. On the other hand, the trajectories of the following bubbles extend after catching up with the leading bubbles. From these results, the following bubbles were affected strongly by the wake influenced by the leading bubbles. Fig.4 shows the result of frequency analysis of the bubbles trajectories. The individual bubbles have the spiral motion with 7.2Hz. Too an isolated bubble rises with zigzag or spiral motion with about 7Hz [14], [15].

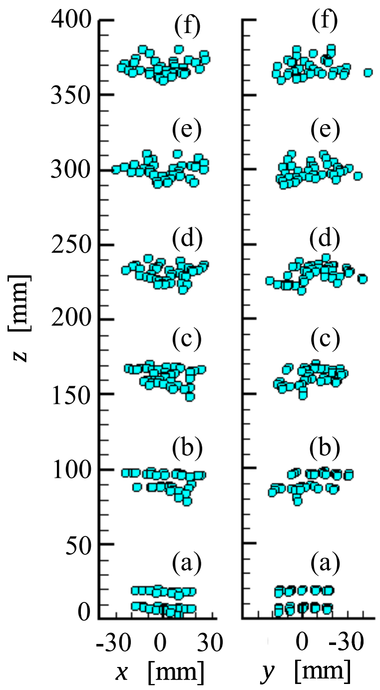
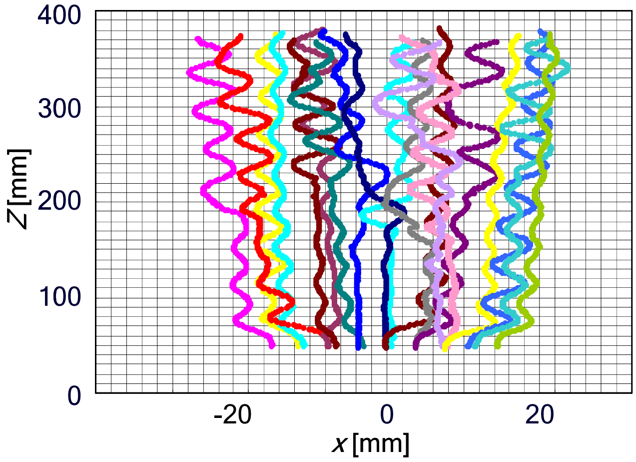
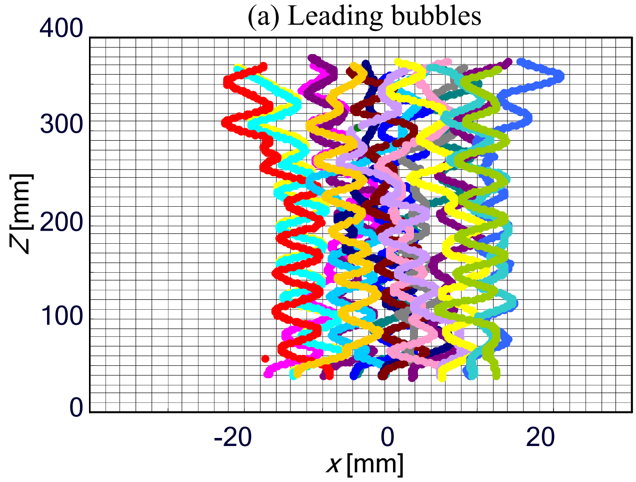


Fig.2 Bubble trajectory



(a) Leading bubbles



(b) Following bubbles

Fig.3 bubble trajectory

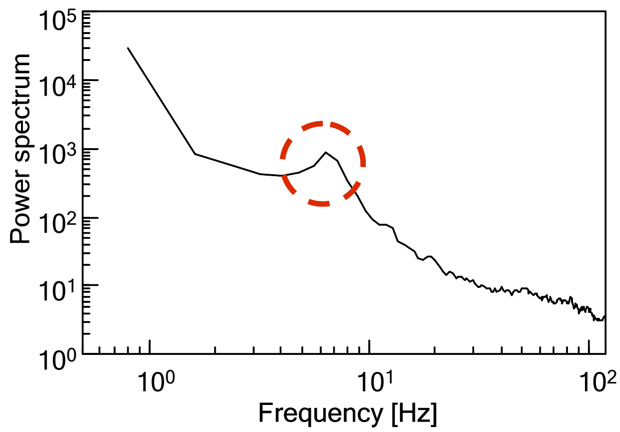


Fig.4 Frequency analysis of bubble motion

4 Liquid Motion

Fig. 5 shows the time transitions of u and w measured on the central axis of the frontal and rear regions of the bubble swarm at z = 300mm, where u is the time section average of the x-direction velocity component u, and w is the time section average of the z-direction velocity component w.

The bubble swarm passes the measuring point during the time interval of 0_- to 0_+. From the results on *u*, before the bubble swarm passes the measuring point, the values of *u* are distributed round 0m/s. After the bubble swarm passes the measuring point, in particular from 0_+ to 1.0s, *u* shows widely fluctuating.

Then the values of *u* are attenuated. From the results on *w*, just before the bubble swarm passes the point, a weak upward flow is observed. After the bubble swarm passes over, a significant upward flow is observed; and then *w* are attenuated. These phenomena can be explained as follows: the upward flows are separately generated in the nearly frontal region of individual bubbles; the wakes of the bubbles are interfered with each other.

Fig. 6 shows the profiles of *u* and *w* in the frontal region of the bubble swarm on *y*-axis at *z* = 300mm as well as those in the rear region. Fig. 7 shows the profiles of standard deviations *u* and *w* in the frontal and rear regions.

In these figures, dashed lines indicate the estimated edge of bubble swarm. From the distribution pattern of u_{front}, u_{front} is distributed almost round 0m/s. However, from the distribution pattern of $\sigma_{u\text{-}front}$, the values are high at the frontal region. From the distribution pattern of w_{front}, equable upward flow is observed at frontal region. On the other hand, after the bubble swarm passes, the pattern intends to have a center peak, in particular the center-peak patterns w_{rear} are very clear.

In order to obtain a frequency characteristic of the liquid-phase motion influenced by the bubble swarm buoyancy, we analyzed the frequency. Here, LDV probe is lifted up to chase the bubble swarm and measure the liquid motion inside the bubble swarm. Because LDV probe is moved, there are noises from the vibration and relative velocity. Therefore, we measured the stagnant water without the bubble swarm in the same method, and we subtract the spectrum of the frequency analysis result without the bubble swarm from the result with the bubble swarm.

Figs. 8 (a) and (b) show the frequency analysis result. (a) is the result from *u*, (b) is the result from *w*. From these figures, a low frequency component (about 7Hz) stands out. From fig. 4, center-of-gravity motion of the bubbles of the bubble swarm has spiral motion with 7.2Hz. Therefore inside of bubble swarm, liquid-phase motion is related to bubble spiral motion.

To sum up, in the upper-side region of the bubble swarm, the liquid-phase motion induced by the individual bubbles of the swarm did not interfere with each other. In the lower-side region of the bubble swarm, the liquid-phase motions interfere with each other through the wakes. Inside of the bubble swarm, the liquid-phase motion was affected by the center-gravity motion of each bubble.

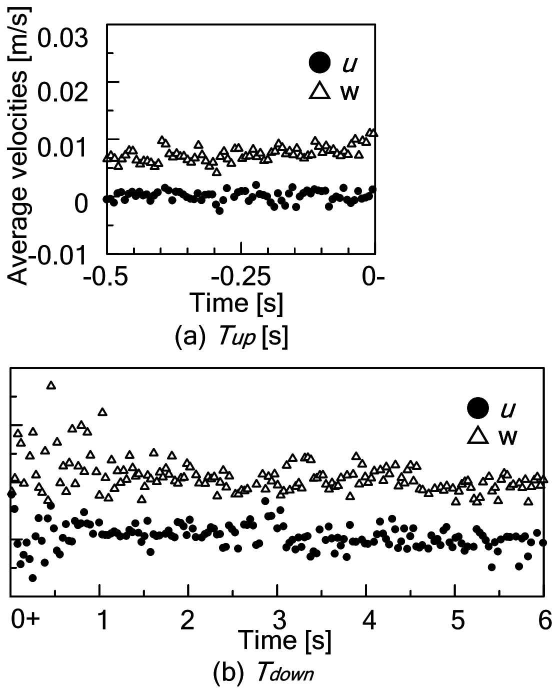


Fig.5 Time Transition of liquid motion

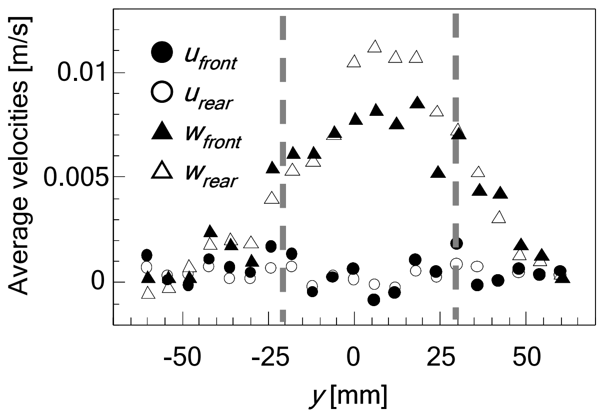


Fig.6 Profile of average velocity

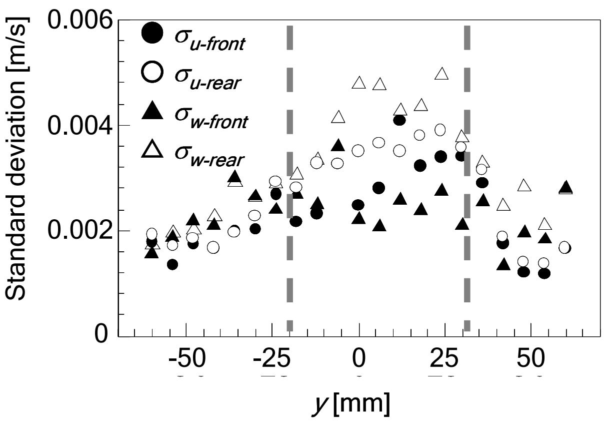


Fig.7 Profile of standard deviation

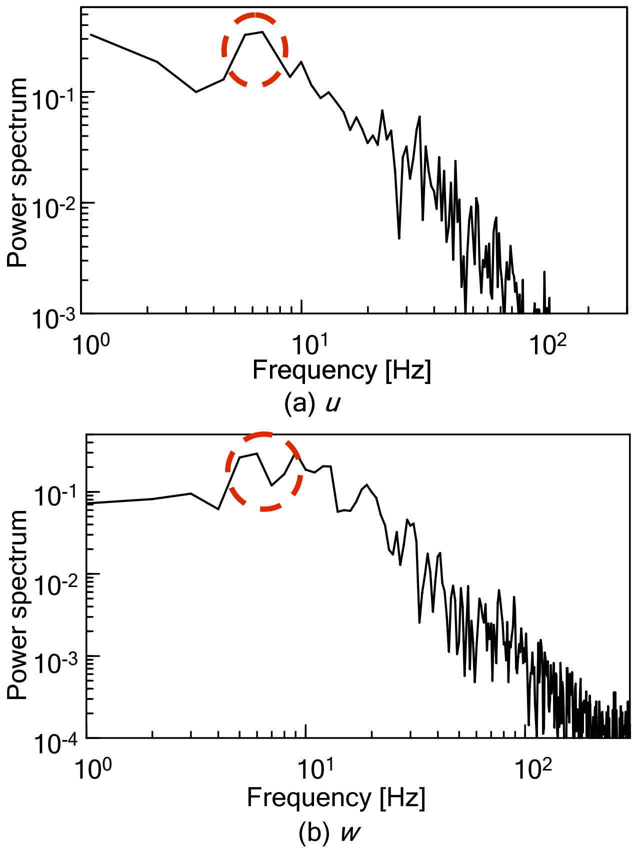


Fig.8 Frequency analysis of liquid motion

5 Conclusion

The structure of gas-liquid motion in the bubble swarm consisting of 38 almost uniform bubbles of 2.6mm equivalent diameter was investigated via two-set high-speed digital video cameras and LDV. The following bubbles catch up with the leading the following bubbles catch up with the leading bubble group, and are mixed up with the leading bubbles. Individual bubbles trajectories have the spiral motion with 7.2Hz.

The liquid-phase motion induced by the bubble swarm, the upward flows are separately generated in the nearly frontal region of individual bubbles. The wakes of the bubbles are interfered with each other. Inside of the bubble swarm, the center-gravity motion of each bubble affected the liquid-phase motion.

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