Experimental Clarification of Gas-Liquid Interaction in Turbulence Generated by Using an Oscillating-Grid

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1 Introduction

Owing to the complicated structures and mechanisms of the multiphase flows, particularly in the bubbly turbulent flows, which are frequently encountered in industrial plants and environmental engineering (e.g., Boden et al., 2008, Vlasogiannis et al., 2002, Saito et al. 2000, 2011), understanding the dynamical interaction between the gas-phase and liquid-phase is indispensable for the elucidation of the gas-liquid two-phase flows. Because the gas-liquid interaction is strongly related to the modulations of both the bubble and liquid-phase motion (Nagami and Saito, 2014), and dominates the mass/heat transfer (Saito et al, 2005, Tsuchiya et al, 2001).

Many numerical simulations for the bubbly flows were published (e.g. Patricia Ern et al., 2012). However, owing to limited information of complicated interaction between the bubbles and the liquid-phase turbulence, therefore, the reliable measurement techniques in the complex gas-liquid two-phase flows are strongly required.

In an air–water flow of uniformly dispersed bubbles, Lance and Batile (1991) measured the modulation (induced by the interaction of the bubbles and the ambient grid-generated turbulence) of the liquid-phase turbulence, by using laser-Doppler and hot-film anemometry. Rensen et al. (2005) investigated the influence of bubbles on a fully developed turbulent flow by performing hot-film anemometry measurements in Twente water tunnel. The structure functions and the power spectral density functions show an increase of the energy for two-phase flow compared to single-phase flow.

To precisely extract dynamic gas–liquid interactions, experiments should be conducted under comprehensible turbulence and fully controlled bubble. In the present study, we employed the turbulence formed by using an oscillating-grid that can provide conditioned homogeneous isotropic turbulence without a mean flow ((Hopfringer et al., 1982)). Morikawa and Saito (2008) described the turbulence modulation induced by the interactions between the flow induced by a single bubble swarm and liquid-phase ambient isotropic turbulence, based on the results of laser Doppler anemometry (LDA) measurements. Imaizumi and Saito (2010) reported that the differences between the bubble motion in oscillating-grid turbulence and that in rest water. The bubbles examined in the present research were 2.9 mm in equivalent diameter, categorized into an oblate ellipsoid. A rising bubble with a diameter of 2-3 mm takes the highest value of a mass transfer coefficient (Motarjemi and Jameson, 2001), and ascends zigzag or spirally, in association with the surface oscillation (Fan and Tsuchiya, 1990).

In our previous studies (Nagami Y. and Saito T. 2013, 2014), we quantitatively discussed the modulations of the bubble motion (bubble gravity-center and surface oscillation). Firstly, we confirmed the homogeneous isotropic ratio depended on the distance from the neutral oscillation position of the grid to the measurement area in the center area of a water vessel. Secondly, we precisely visualized the bubble motion (the gravity-center motion and the surface oscillation) in close-up from the rectilinear, zigzag and spiral motion with highly reproducibility. Thirdly, we mainly discussed the modulation of bubble motion induced by the gas-liquid interaction in the oscillating-grid turbulence.

Based on the experimentally-verified measurement techniques and reliable data, in the present paper, in order to clarify gas-liquid interaction from particular modulations of both the bubble and liquid-phase motion the gas-liquid interaction more deeply, we mainly investigated the modulation of the surrounding liquid-phase motion and the anisotropic interaction between the bubble-oriented flow and the ambient turbulence on the bubble motion.

2 Experimental apparatus

As shown in Figure 1, the experimental apparatus used in the present research mainly consisted of an oscillating-grid turbulence system, an in-house bubble launch device equipped with a hypodermic needle, and a laser system with a set of optics. The oscillating-grid turbulence was formed in a cylindrical vessel (a) which was made of an acrylic pipe (inner diameter: 149 mm) covered with a rectangular acrylic water jacket (b) in order to remove the influences of refraction and deformation during the images recording. The origin of the coordinate system (x, y, z) was set at center of the bottom of the vessel. The vessel was
In order to discuss the dynamical interaction between the bubble and surrounding decaying turbulence, the bubble size, trajectory, shape, orientation and surface oscillation should be controlled fully and completely. For this specific purpose, we employed an in-house bubble launch device (Nagami and Saito, 2013), which consisted of a coarse-pressure controller, #1 (l), a fine-pressure controller, #2 (m), a function generator (o), a power amplifier (n), an audio speaker (p). By using this device equipped with a specially-manufactured hypodermic needle (q) (outer diameter: 0.65 mm, inner diameter: 0.40 mm, and cutting angle: 30 degree) with the needle tip which was precisely ground in the shape of a two-stage wedge. Thus, extremely uniform single bubbles were launched into the water and an optional interval from the hypodermic needle.

Because the examined bubbles in the present research were 2.9 mm in equivalent diameter, therefore, the bubble surface oscillation is an important factor that affects the gravity-center motion. Saito et al. (2010) evaluated the shape oscillation of a bubble using its right and left curvatures. Figure 2 shows the bubble shape characterization and the dimensionless curvatures $\kappa_R$ (the right side) and $\kappa_L$ (the left side) calculated by equations (1) and (2).

The properties of the bubbles are listed in Table 1. The Reynolds number $Re$, Weber number $We$, Eotvos number $Eo$ and Morton number $Mo$ were calculated from the following equations, respectively.

$$D_{eq} = \text{Major}^2 \cdot \text{Minor}$$

(1)

$$\kappa_{R,L} = \frac{D_{eq}}{2r_{right,left}}$$

(2)

### Table 1: The properties of the bubbles

<table>
<thead>
<tr>
<th>Condition</th>
<th>$Deq$ [mm]</th>
<th>$Re$ [-]</th>
<th>$We$ [-]</th>
<th>$Eo$ [-]</th>
<th>$Mo$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>2.9</td>
<td>765</td>
<td>3.12</td>
<td>0.96</td>
<td>2.73x10$^{11}$</td>
</tr>
<tr>
<td>OB</td>
<td>2.9</td>
<td>775</td>
<td>3.21</td>
<td>0.96</td>
<td>2.73x10$^{11}$</td>
</tr>
</tbody>
</table>

$$Re = \frac{w_{in}D_{eq}}{\mu_L/\rho_L}$$

(3)
We \approx \frac{\rho_l D_{eq} w_{av}^2}{\sigma} \quad (4)

E_0 = \frac{g D_{eq}^2 (\rho_L - \rho_B)}{\sigma} \quad (5)

Mo = \frac{g \mu_L (\rho_L - \rho_B)}{\rho_L^2 \sigma} \quad (6)

3 Measurement and analysis method

In an interrogation area, in order to obtain the liquid-phase motion and visualize the bubble motion simultaneously, we conducted PIV/LIF measurement and IST with a high-speed video camera. An Nd:YAG laser (wavelength: 532 nm) (f) and laser fluorescence particles (avg. dia.: 8 μm; excitation wavelength: 532 nm; emission wavelength: 612 nm) completely dispersed in the water were used. The interrogation area was illuminated with the laser sheet (sheet thickness: 2 mm) through a rod lens (g). In order to extract the contour of the bubbles for calculating the gravity-center motion and surface oscillation, a ring-shaped continuous red-LED array (j) (wavelength: 660 nm) was placed at the opposite side of the camera. The scattering light from the bubble surface was removed through a sharp cut filter (i) (threshold processing called “3σ processing” (the deviations larger than positive and negative three times of the standard deviation were removed from the liquid-phase velocity result), which is usually employed in LDA measurement of gas–liquid turbulent flows (Mudde and Saito, 2001; Higuchi and Saito, 2010). The present PIV measurements were carried out ten times in each experimental condition. We calculated the ensemble average of the liquid-phase velocity field, and the standard deviation of the liquid-phase velocity (hereafter rms velocity) was calculated from these PIV datasets. Therefore, we were able to reject error vectors due to the nonuniform distribution of the tracer particles, and as a result, we obtained correct vectors in the whole measurement area.

In PIV/LIF measurements, the number density of the seeding tracer particles and the most appropriate algorithm corresponding to the dynamic range of the target flow are extremely important. In the present experiment, for the particular purpose of prevention of the PIV tracer particles from influencing the original gravity-center motion and surface oscillation of the bubble, we carefully determined the number density (average 8000 particles/cm²) of the tracer particles. In the PIV/LIF analysis, first, the bubble was removed from the original images (including the bubble and tracer particles) in order to extract only the tracer particles. Second, we applied the PIV algorithm with the fast Fourier transform FFT-based recursive cross-correlation method to analyze the processed images (including only the tracer particles). The primary interrogation area was 32 × 32 pixels, the final interrogation area was downsized to 16 × 16 pixels, and every overlap was 50%. The recursive cross-correlation method (Hart, 2000) not only increased the spatial resolution but also prevented the generation of incorrect vectors. From the PIV/LIF results, the average cross-correlation coefficient was higher than 0.7, as was the percentage of the average signal-to-noise (S/N) ratio. The uncertainty of the measured velocities was less than 0.006 m/s (2% of full-scale range of 0.3 m/s). The uncertainty accorded with our results of the previous experiments in which one of the authors applied the FFT-based recursive cross-correlation method to measure liquid motion around a zigzagging single bubble in stagnant water (Saito et al., 2010). In addition, we employed the threshold processing called “3σ processing” (the deviations larger than positive and negative three times of the standard deviation were removed from the liquid-phase velocity result), which is usually employed in LDA measurement of gas–liquid turbulent flows (Mudde and Saito, 2001; Higuchi and Saito, 2010). In area 1 (the bubble was rising rectilinear and 2D zigzag motion), in the both of x-z and y-z planes as shown in Figure 3, the bubble gravity-center motions were almost the same under Conditions B and OB. In the y-z plane, the curvatures of the bubble on the right side and left side were symmetric and were almost the same under Conditions B and OB. These results indicate that the initial bubble conditions were not influenced by the ambient decaying turbulence. By comparing the curvature under Conditions B and OB in the x-z plane (i.e., just after the bubble launched into the water phase), the short-lasting phase differences appeared. In the present research, to fully control not only the bubble trajectory but also the plane of the zigzag bubble, we employed the hypodermic needle, not the capillary tube or nozzle that is usually used to launch the bubble. In this case, since the hypodermic needle was set to the positive direction of the x-axis, a ripple with high curvature propagated in a counterclockwise direction (Nagami and Saito, 2013). We consider this phenomenon became relatively weak in decaying turbulence, and which induced the phase difference of curvature under Conditions B and OB in the x-z plane.
In area 2, as shown in Figure 4, we found that not only the bubble gravity-center motion but also the bubble surface motion were modulated in the decaying turbulence. In both the $x$-$z$ and $y$-$z$ planes, the gravity-center motions were modulated in the area between $z = 100$ mm and $z = 115$ mm, indicating that this is the area at which the transition from the 2D motion to the 3D motion started. In the transition area, the amplitudes of the right side and left side curvature fluctuations under Condition OB were almost the same as those under Condition B. However, the phase difference in the curvatures between Condition B and Condition OB became larger along with the bubble rising. The area 2 in which the phase difference in the curvatures was clearly observed corresponded well with the transition area in which the bubble motion was modulated. Yoshimoto and Saito (2010) conducted a stereo PIV measurement in order to discuss the bubble motion and the surrounding liquid motion in stagnant water. They reported that the bubble changed its own path direction induced by the difference of the right- and left-side liquid-phase velocities surrounding the bubble. In the present experiment, when the bubble rose in a zigzag motion in the $x$-$z$ plane under Condition B, the surrounding liquid-phase motions on the right and left side were asymmetric. Under Condition OB, taking the decaying turbulence into account, we considered the difference of the liquid-phase motion of the right and left sides of the bubble affected the ascent direction of the zigzag motion. In contrast, in the $y$-$z$ plane, the liquid-phase motion was symmetric since the bubble rose in a rectilinear motion under Condition B. Under Condition OB, the liquid-phase motions on the right and left sides were unbalanced. These results indicate that the rapid increases in the liquid-phase fluctuations,
induced when the bubble passed the interrogation area, were broken by the ambient decaying turbulence.

Vertical velocity components enhanced the bubble gravity-center motion to the positive $x$ direction. In the $y$-$z$ plane, the bubble motion was two-dimensional under Condition OB. The right-side and left-side curvatures were symmetric under Condition B, in contrast, especially between $z = 118$ mm and $z = 133$ mm under Condition OB, in two areas the distinguished asymmetry of the curvatures appeared. This result indicated that the bubble changed its ascent direction in this section of $z$ direction. Comparing the contour map under Condition B with that under OB, it is seen that the symmetric liquid-phase motions surrounding the bubble were almost collapsed by the ambient decaying turbulence. The strongly positive horizontal velocity components under Condition OB enhanced the bubble motion to the positive $y$ direction.

![Image](attachment:image.png)

Figure 5: Results of gravity-center motion and surface oscillation, and the standard deviation of the liquid-phase velocity in the both $x$-$z$ and $y$-$z$ plane in area 3 (the bubble rising 2D or 3D motion).

In the $x$-$z$ plane in area h3 as shown in Figure 5, just after the transition area, the bubble trajectory under Condition OB was expanded in the $x$-direction compared with that under Condition B, and the two bubble trajectories were almost parallel. Therefore, under Conditions B and OB, the right- and left-side curvatures’ amplitudes were almost the same, and the phase differences fluctuated in almost the same period. From the results of liquid-phase motion, the liquid-phase velocities surrounding the bubble were mixed with decaying turbulence which can be confirmed by comparing the results obtained under Condition B and those under Condition OB. Under Condition OB, the decrement of the negative horizontal velocity components and the increment of the positive vertical velocity components enhanced the bubble gravity-center motion to the positive $x$ direction.

![Image](attachment:image2.png)

Figure 6: The standard deviations of the liquid-phase and comparison between time evolution of the normalized rms velocities ($u^*_{rms}$ and $w^*_{rms}$) and that of rms velocities ($u_{rms}$ and $w_{rms}$).

Based on the quantitative consideration of the bubble motion, in order to confirm the modulation of the surrounding liquid-phase motion and the anisot-
ropic interaction between the bubble-oriented flow and the ambient turbulence on the bubble motion, we conducted the experiments with a single bubble swarm (3 bubbles) and bubble swarms (3 bubbles × 3 times with 8 Hz) in the homogeneous isotropy which was satisfactorily the liquid-phase rms velocity ratio \( (w_{rms}/u_{rms}) \) formed in of 0.7 ~ 1.3. The peak intensity under Condition OB(3×3) was much larger than that of the single bubble swarm. We reconsidered the time evolution of rms velocities normalized by the maximum rms velocities. \( w_{rms} \) was larger than \( u_{rms} \) during the examined time range. However, before the bubble launch, \( u_{rms}^{*} \) was almost the same as \( w_{rms}^{*} \). Just after the bubble launch (i.e. the bubble rose in the ambient turbulence), \( u_{rms}^{*} \) immediately became larger than \( w_{rms}^{*} \). Furthermore, increase rate of \( u_{rms}^{*} \) was larger than that of \( w_{rms}^{*} \). This phenomenon suggests an anisotropic interaction between the bubble-oriented flow and the ambient turbulence.

5 Conclusions

In order to clarify the dynamical gas-liquid interaction in the multiphase flows, by using the ideal experimental apparatus and reliable measurement techniques, the modulation of the bubble motion in the decaying turbulence and the dynamic interaction between the bubble and the liquid-phase motion were carefully investigated. For this purpose, we employed a computationally controlled oscillating-grid which generates comprehensible grid-turbulence and an in-house bubble launch device equipped with a specially-manufactured hypodermic needle that enabled us to completely control the bubble motion.

We discussed the relationship between the 2D-zigzag/3D bubble motion captured by IST and the liquid-phase motion of stagnant water/decaying turbulence obtained by PIV/LIF measurement. Based on all of the results, we found out that the relations between the bubble motions and the surrounding liquid-phase motions are different in the zigzag plane and the plane orthogonal to the zigzag plane. A bubble with 2.9 mm in equivalent diameter, in the stagnant water, rose zigzagging in the zigzag plane and rose rectilinearly in the plane orthogonal to the zigzag plane. In the anisotropic oscillating-grid decaying turbulence, with increasing intensity of the background turbulence, the modulation of the bubble motion was induced mainly by the vertical fluctuation of liquid-phase motion in the \( x-z \) plane, and was dominantly induced by the asymmetric surface oscillation of the bubble in the \( y-z \) plane.

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