3-dimensional liquid motion around a zigzagging ascent bubble measured using tomographic Stereo PIV

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Abstract
In the present study, our aim is to quantitatively elucidate the 3-D structure of the liquid motion surrounding a bubble via Stereo PIV and to discuss the relationship between the bubble wake motion (obtained from LIF/HPTS visualization) and its surrounding liquid motion (obtained from Stereo PIV). We focused on a zigzagging ascent bubble of 2.9 mm in equivalent diameter.

First, the surrounding liquid motion of the bubble was obtained via the Stereo PIV. The recursive cross correlation algorithm was employed in order to accurately measure the liquid motion. Based on the results, we clearly extracted the wakes which were shed from the rear of the ascent bubble. Basically, the Stereo PIV is 2-dimension-3-component measurement; therefore, in order to reconstruct the 3-D structure of the liquid motion around the bubble, the measurement volume was sliced by laser sheet at several depth positions. We carried out the Stereo PIV measurements along the zigzag trajectory of the bubble. To exactly extract the liquid motion and bubble motion, we used the special bubble launch device which consists of a hypodermic needle and pressure oscillation device. This device enabled us to reproduce and synchronize the formation of a bubble precisely.

Second, the wake of a CO₂ bubble was visualized via LIF/HPTS method. LIF/HPTS are quite useful for visualizing the dynamical structure of the bubble wake. Based on the results, we obtained the dynamical growth of the bubble wake and the process of the wake shedding. By combining the results of the Stereo PIV and LIF/HPTS, the relationship between wake motion of the single rising bubble and the 3-D flow structure of the surrounding liquid motion is discussed.

Finally, from the results of the Stereo PIV, the relationship between the bubble motion (zigzag motion and shape oscillation) and the surrounding liquid motion is discussed.

1. Introduction

Bubbles are found in natural and industrial flows, and they play an important role in process of heat and mass transfer. In industrial equipment, bubbles are encountered in chemical reactors, heat exchangers, GLAD (Gas Lift Advanced Dissolution) system (e.g. Saito et al., 1999, 2000 and 2001) and so on. Especially, GLAD system is a potential global warming countermeasure technology. In order to optimally design and control those plants and systems, deep understanding of the structure and mechanism of the bubbly flows is needed.

The bubble diameters are a dominant factor characterizing the bubbly flows. In the above-stated systems, the bubbles with diameters in a range from 2 to 3 mm are used. These bubbles ascend zigzag or spirally (Clift et al., 1978) accompanying with the drift motion (Brücker, 1999), and their shapes are oblate ellipsoids with surface oscillation (Fan and Tsuchiya., 1990). Many researches were conducted in order to elucidate these mechanisms. The relationship between the bubble motion (zigzag or spiral motion, drift motion and shape oscillation) and the surrounding liquid motion is essential. To clarify the relationship, Particle Image Velocimetry (PIV) is the one of practical tools. Brücker (1999) used the PIV; he described the bubble shape and liquid velocity field. Fujiwara et al. (2004) investigated the flow structure in the vicinity of a bubble moving in a shear flow via combination of PIV-LIF and shadow image technique. Hassan et al. (2001) carried out 3-dimensional measurement of the flow field induced by a small air bubble rising in stagnant water by
using Stereo PTV. Although many researches have been discussing the relationship, the knowledge of the motions is still insufficient.

In this study, we focused on a zigzagging ascent bubble 2.9 mm in equivalent diameter. We discuss the relationship between the bubble motion (zigzag motion and shape oscillation) and the surrounding liquid motion. In order to obtain the information of the surrounding liquid motion, we carried out Stereo PIV measurements.

2. Experimental setup.

2.1 Experimental setup.

Figure 1 shows a schematic diagram of an experimental setup for the Stereo PIV measurements. An acrylic water vessel (a) (160 mm × 160 mm × 300 mm) was filled with purified water to a depth of 230 mm. The origin of the coordinate system (x, y, z) was set at the center of the bottom of the vessel. A single pure-air bubble was launched from a hypodermic needle (b) fixed on the bottom of the acrylic vessel. We used the hypodermic needle (0.65 mm in outer diameter, 0.40 mm in inner diameter and 30 degrees in cutting angle) to form a uniform bubble in diameter, orientation, initial deformation and trajectory with high reproduction. To control the bubble launch, we used a bubble launch device (c) composed of an audio speaker and pressure controllers. The pressure controllers hold the balance between the water and air pressure at the edge of the hypodermic needle. The audio speaker highly reproduces the bubble formation and the launch of a bubble by utilizing a well controlled pressure oscillation (Saito et al., 2010; Sanada et al., 2006). A function generator (d) sends a pulse signal
into the audio speaker through a power amplifier. The oscillation of the audio speaker was controlled by this pulse signal. Bubble properties are listed in Table 1. Reynolds number $Re$, Weber number $We$, Eotvos number $Eo$ and Morton number $Mo$ were calculated from the following equations, respectively.

<table>
<thead>
<tr>
<th>$D_{eq}$ [mm]</th>
<th>$V_b$ [mm/s]</th>
<th>$Re$</th>
<th>$We$ [-]</th>
<th>$Eo$ [-]</th>
<th>$Mo$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.9</td>
<td>290</td>
<td>833</td>
<td>3.34</td>
<td>1.11</td>
<td>$3.00 \times 10^{-11}$</td>
</tr>
</tbody>
</table>

\[
Re = \frac{V_b D_{eq}}{\nu}
\]

\[
We = \frac{\rho_L D_{eq} V_b^2}{\sigma}
\]

\[
Eo = \frac{g D_{eq}^2 (\rho_L - \rho_B)}{\sigma}
\]

\[
Mo = \frac{g \mu_L^4 (\rho_L - \rho_B)}{\rho_L^2 \sigma^3}
\]

2.2 Stereo PIV measurement.

2.2.1 Image recording and Illumination systems.

In the PIV measurement, Nd: YAG Laser (wavelength 532nm) (e) and PIV particles (fluorescence reagent: rhodamine B, average diameter: 8 μm, maximum excitation wavelength: 542 nm and maximum emission wavelength: 612 nm) (f) were employed. The laser beam was formed into a thin laser sheet (sheet thickness: 1 mm) through rod lenses (g), and a measurement area was illuminated from two directions uniformly.

Two sets of high-speed video cameras (Photron, FASTCAM SA1.1) (h) were employed in the stereo PIV. The angle between optical axes of cameras was 45 degrees. The spatial resolution was $1024 \times 1024$ pixel$^2$ (12.8 μm/pixel). The frame rate was 2000 frame/sec. The scattering light from the bubble surface was removed through a sharp cut filter (i) (threshold of transparent wavelength 560 nm). Furthermore, the bubble motion was also visualized by LED light (j) (wavelength 660 nm) and another high-speed video camera (Phantom V9) (h).

In the stereo PIV measurement, the angular displacement method was used. In order to obtain the well-focused particle image at whole the image plane, each camera image plane was tilted to satisfy the Schiempflug condition. The lens axis and image plane intersect the object plane at one point.

Basically, the Stereo PIV is 2-dimension-3-component measurement. In order to reconstruct the 3-D structure of the liquid motion around the bubble, the measurement volume was sliced at several depth positions. In this study, the bubble launch device was used, which can launch the uniform bubble with the extremely high reproducibility (Saito et al., 2010). Therefore, the slice
measurement was achieved by shifting the hypodermic needle at depth position. The hypodermic needle which was set on the bottom of the acrylic vessel was shifted at 0.5 mm intervals in a depth. In order to shift and align the needle precisely, the precision translation stages were used. The Stereo PIV measurement was carried out at each cross-section.

2.2.2 Data processing for Stereo PIV.

In order to obtain the mapping function between the image planes and object planes, a calibration procedure is needed. In this study, a calibration target (Edmund Optics) with dots of 250 μm in diameter and 500 μm in the dot pitch was used. The front surface of the calibration target was aligned with the center plane of the laser sheet. The calibration images were obtained at nine locations in depth. The interval was 500 μm.

As the mapping function, the following multidimensional polynomials were used;

\[
x = a_0 + a_1X + a_2Z + a_3X^2 + a_4XZ + a_5Z^2 + a_6X^3 + a_7X^2Z + a_8XZ^2 + a_9Z^3,
\]

\[
z = b_0 + b_1X + b_2Z + b_3X^2 + b_4XZ + b_5Z^2 + b_6Z^3 + b_7X^2Z + b_8XZ^2 + b_9Z^3,
\]

here, \(x, z\) show the three-dimensional physical coordinate. \(X, Z\) shows the two-dimensional coordinates of the camera. The ten coefficients were calculated from the calibration image by using a least square method.

We obtained 2-dimensional-3-component-velocity field through the mapping function and the results of PIV data of each camera. In the PIV measurements, first, a single bubble was removed from the original images in order to extract only the tracer particles. Second, from the processed image (the tracer particles), we applied PIV algorithm with the FFT-based recursive cross-correlation method to calculate the velocity field of the liquid phase; the interrogation area was downsized from 32 × 32 pixels to 16 × 16 pixels, and the overlap was 50%. The recursive cross-correlation method (Hart D. P., 2000) not only increased the spatial resolution but also prevented the generation of incorrect vectors. In our previous study (Saito et al., 2010) have applied the FFT-based recursive cross-correlation method to measure liquid motion around a single zigzagging bubble. The present PIV measurements were carried out ten times at each case. We took ensemble average for the velocity field of the liquid phase. Therefore, we were able to avoid error vectors which are caused by the non uniform distribution of the tracer particles; as a result we finally obtained correct vectors in whole measurement area.

3. Results and Discussion.

3.1 Results of Stereo PIV measurement.

Figures 2 show the results of stereo PIV measurement at the second inversion point. In Figs. 2, the vectors show the composition of three-component velocities which were obtained from the stereo PIV. The measurement volume was sliced into three cross sections (\(y = -1, 0, 1\) mm). Fig. 2 (a) shows the distribution of velocity vectors of \(x-z\) plane and (b) shows that of \(y-z\) plane at the center of the bubble. In Fig. 2 (a), the flow which was dragged behind the ascent bubble is clearly observed. In Fig. 2 (b), at the \(y-z\) plane, it is shown that the surrounding liquid motion was almost
symmetric at the front of bubble as shown by the red dashed arrows. Figures 3 show the result of stereo PIV and the result of LIF/HPTS at the same time. Fig. 3 (a) shows the distribution of velocity vectors of liquid phase. Fig. 3 (b) shows the result of LIF/HPTS. LIF/HPTS are quite useful for visualizing the dynamical structure of the bubble wake (Yamamoto and Saito et al., 2008). In Fig. 3 (b), it is shown that the bubble wake induced by the ascent bubble developed and was shed from the rear of the bubble. By comparison between Fig.3 (a) and Fig.3 (b), as marked by the dashed circle, it was found that the liquid motion which was induced by a single ascent bubble corresponds with the bubble wake which was observed by LIF/HPTS. Therefore the liquid motion induced by the bubble wake is also observed through the stereo PIV measurement.

In the following section, we will discuss the relationship between the bubble motion (zigzag motion and shape oscillation) and the liquid motion around the bubble.

Fig.2: A typical result of the stereo PIV at the second inversion point.
3.2. Relationship between the surrounding liquid motion and bubble motion.

3.2.1 Bubble motion.

In order to discuss a relationship between the zigzag bubble motion and the surface oscillation, we calculated the curvatures at right and left side of the bubble. Saito et al. (2010) evaluated shape oscillation of a bubble using its curvatures. Figures 4 show the trajectory of the gravity center of the bubble and the dimensionless curvatures. $\kappa_R$ is the right one, and $\kappa_L$ the left one calculated by equation (7):

$$ \kappa = \frac{D_{eq}}{2r}, $$

here, $D_{eq}$ represents the equivalent diameter of the bubble, and $r$ the curvature radii at the left and right edges of the bubble. By calculating the curvatures of the bubble contour, we can discuss the time-series magnitude of the shape oscillations of the bubble, quantitatively.
From these figures, when the bubble linearly rises just above the needle, the magnitudes of $\kappa_R$ and $\kappa_L$ are almost the same. During this linear section the shape oscillation of both sides is symmetric. On the other hand, when the bubble changes its direction of the motion at the first inversion point, the left-side shape oscillation is larger than that of the right side as observed in Figs. 4 (b) and (c). After the first inversion point, the shape oscillation of the left edge increases, while that of the right edge decreases. At the second inversion point, $\kappa_L$ reaches the maximum value. Afterword, the magnitude of right-edge curvature increases with a decrease in the magnitude of the left-edge curvature.

### 3.2.2 The surrounding liquid motion of the bubble.

In order to discuss the relationship between the surrounding liquid motion and the bubble motion (the shape oscillation and the zigzag motion), we focused on the symmetry of the right- and left-side liquid motion and the symmetry of the right- and left-edge curvatures. We defined the following dimensionless number;
\[
\frac{V_{\text{x-left}}}{V_{\text{x-right}}},
\]

(8)

here, \( V_{\text{x-left}} \) represents the average velocity in \( x \)-direction at the left side of the bubble, \( V_{\text{x-right}} \) the average velocity in \( x \)-direction at the right side of the bubble.

Figures 5 show the surrounding liquid motion of the bubble at the first inversion point. Fig. 5 (a) shows the trajectory of the gravity center of the bubble. Fig. 5 (b) shows the time-series \( V_{\text{x-left}} / V_{\text{x-right}} \). Fig. 5 (c) shows the dimensionless curvature at the right and left edges of the bubble. In Fig. 5 (a), the bubble changes its direction of the motion gradually. In Fig. 5 (b), when the bubble linearly rises \((0.045 - 0.07 \text{ sec})\), \( V_{\text{x-left}} / V_{\text{x-right}} \) takes almost unity. The surrounding liquid motion of the right and left sides of the bubble is symmetric. \( V_{\text{x-left}} / V_{\text{x-right}} \) increases after 0.08 sec. The velocity in \( x \)-direction at the left side of the bubble is larger than that at the right side of the bubble. In Fig. 5 (c), the magnitude of \( \kappa_L \) is larger than that of \( \kappa_R \); in addition the fluctuation of the dimensionless curvature becomes large gradually. From Figs. 5 (a) and (b), it is found out that the bubble changes its direction of the motion to upper left direction significantly when the velocity at the left side increases. From Figs. 5 (b) and (c), it is found out that the velocity in \( x \)-direction at the left side increases with increase in the magnitude of the left-edge curvature.

Figs.5: Bubble trajectory, the dimensionless number \( V_{\text{x-left}} / V_{\text{x-right}} \) and dimensionless curvature \( \kappa_L / \kappa_R \) at first inversion point.
Figures 6 show the surrounding liquid motion of the bubble and the left-edge dimensionless curvature to that at right edge of the bubble at second inversion point. Fig. 6 (a) shows the trajectory of the gravity center of the bubble. Fig. 6 (b) shows the time-series $V_{x\text{-}left}/V_{x\text{-}right}$. Fig. 6 (c) shows the dimensionless curvature at left edge to that at right edge of the bubble.

From Figs. 6 (a) and (b), when the bubble rises to upper left before second inversion point, the value of $V_{x\text{-}left}/V_{x\text{-}right}$ decreases gradually. At the second inversion point (0.15 – 0.16 sec), the value of $V_{x\text{-}left}/V_{x\text{-}right}$ is almost one. It is considered that the velocity in $x$-direction at both sides is symmetry at the second inversion point. Afterword, the value of $V_{x\text{-}left}/V_{x\text{-}right}$ becomes less than one. In Figs. 6 (c), at the second inversion point, the magnitude of $\kappa_R$ is larger than $\kappa_L$. After the second inversion point, the magnitude of $\kappa_L$ becomes larger than $\kappa_R$. From Figs. 6 (b) and (c), it is shown that the velocity in $x$-direction at left side of bubble decreases with an increase of the magnitude of curvature at right edge of bubble before second inversion point. From Figs. 6 (a) and (c), the bubble changes its direction of the motion to upper right with an increase of the velocity in $x$-direction at right side.

From these results, it is considered that the asymmetry of shape oscillation resulted in the velocity difference between left side and right side of the bubble. Therefore, the bubble changes its direction of the motion resulting form the velocity difference.

Figs.6: Bubble trajectory, the dimensionless parameter $V_{x\text{-}left}/V_{x\text{-}right}$ and dimensionless curvature $\kappa_L/\kappa_R$ at second inversion point.
3. Conclusion

In this research, the relationship between a single bubble motion (shape oscillation and zigzag motion) and the surrounding liquid motion around the bubble was investigated. The surrounding liquid motion around a single ascent bubble was investigated by using Stereo PIV measurement. Furthermore, the measurement volume was sliced at depth in order to reconstruct the 3-D structure of the liquid motion around the bubble.

From the results of Stereo PIV, we could observe the flow which was dragged behind the ascent bubble clearly. By comparison between the result of Stereo PIV and the result of LIF/HPTS in the same time, it is found that the flow which was induced by a single ascent bubble corresponds with the bubble wake which was observed by LIF/HPTS.

We discuss the relationship between the surrounding liquid motion around the bubble and bubble motion. At the first inversion point, the velocity in \( x \)-direction at left side of bubble increases with an increase of the magnitude of curvature at left edge of bubble. At that time, the bubble changes its direction of the motion to upper left significantly. At the second inversion point, the velocity in \( x \)-direction at left side of bubble decreases with an increase of the magnitude of curvature at right edge of bubble before second inversion point. At that time, the bubble changes its direction of the motion to upper right significantly. From these results, it is considered that the asymmetry of shape oscillation resulted in the velocity difference between left side and right side of the bubble. Therefore, the bubble changes its direction of the motion resulting form the velocity difference between the left side and the right side of bubble.

References


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