Influences of bubble-surface contamination on the mass transfer and the bubble-induced surrounding liquid motions

Yuki Iburi¹, Takayuki saito²*
1: Graduate School of Integrated Science and Technology, Shizuoka University, Japan
2: Research Institute of Green Science and Technology, Shizuoka University, Japan
* Correspondent author: saito.takayuki@shizuoka.ac.jp

Keywords: Stereo PIV, LIF, Vortex, Mass transfer

ABSTRACT
Bubble flows are frequently used in various industrial plants such as a waste water treatment system, heat exchanger and bioreactor. In these plants, the flows’ structures are extremely complex due to various interactions between the bubbles and the surrounding liquid and between the bubbles themselves. A detailed relationship between the bubble motions and the mass transfer is discussed insufficiently even for a single bubble, which is the minimum number scale of the bubble flows. The behavior of the boundary layers (concentration boundary layer and velocity boundary layer) in the gas-liquid interface is an important factor in the mass transfer. It is still difficult to measure them directly, however a piece of indirect evidence of the behavior might be obtained from careful observation of three-dimensional structure of the bubble wake or the surrounding liquid motion. The authors visualized the bubble-induced surrounding liquid motion and the CO₂ dissolution process of a single CO₂ bubble (equivalent diameter: 2.9mm) in purified and contaminated (500ppm 1-pentanol solution) systems. In particular, the bubble in this size takes the zigzagging trajectory and the highest mass transfer coefficient. The bubble-induced surrounding liquid motion was measured by stereo PIV, and the dissolution process of the single CO₂ bubble was visualized by using LIF/HPTS. By comparison of the experimental results in the contaminated system with those in the purified system, their 3-D structures obtained from visualization results were quite different. This difference was considered to result from the effects of non-uniform concentration distribution at the bubble surface. The behavior of the boundary layers of the bubble is closely related to the mass transfer and the bubble-induced surrounding liquid motions. Moreover, the condition of the boundary layers might be inferred from the bubble motions (the bubble’s trajectory, the CO₂ dissolution process and the bubble-induced surrounding liquid motions).

1. Introduction
Bubble flows are frequently used in industrial plants such as bubble columns, heat exchangers and bioreactors. For example, a bubble column brings contact between a gas and liquid for a process of the gas-liquid reaction and gas absorption. The performance of these plants are essentially influenced by the behavior of bubbles. However, the liquid phase motion and bubbles’ motion and behavior are still unknown in these plants. Therefore, optimization of the plants and operation is not sufficient. In addition, Marangoni convection occurs at a bubble surface when a surfactant substance contaminates its interface (Takagi S and Matsumoto Y. 2011). In the present study, the authors focus on the bubble motions, mass transfer and bubble-induced surrounding liquid
motions of a single zigzag ascent CO₂ bubble (equivalent diameter: 2.9mm). A bubble with an equivalent diameter of 2 – 4 mm takes the zigzag or spiral motion, and a large mass transfer coefficient and characteristic wake structure. A relationship between the bubble motions and the behavior of bubble’s boundary layers (concentration boundary layer and velocity boundary layer) in the gas-liquid interface should be elucidated. Saito et al. reported the bubble-induced surrounding liquid motions of a zigzag ascent bubble in purified water and contaminated water, through PIV. Saito and Toriu calculated an instantaneous mass transfer coefficient of a zigzag CO₂ bubble from the measured bubble volume, and discussed enhancement mechanism of the mass transfer. Huang and Saito discussed a relationship between the direction of Marangoni convection and the zigzag motion of the bubble. In the present study, the authors visualized bubble motions, the CO₂ dissolution process and bubble-induced surrounding liquid motions of the zigzag ascent CO₂ bubble (equivalent diameter: 2.9mm) in purified water and contaminated water (500ppm 1-pentanol solution), via LIF/HPTS and stereo PIV measurement by using high-speed camera. The effects of the bubble surface contamination on the bubble motions, the CO₂ dissolution process and bubble-induced surrounding liquid motions were discussed from the experimental results.

2. Experiment set up

Figure 1 shows an outline of the experimental setup used in the present stereo PIV and LIF measurements. Ion-exchange and degassed water or 500ppm-1-pentanol solution was put in an octagon acrylic vessel (a). A hypodermic needle (b) was placed on the vessel’s bottom. Single bubbles were launched from the tip of the hypodermic needle into the examined water at an arbitrary interval by using a bubble-launching device (c) and function generator (d). The single bubbles from the needle were high reproducible. A ring-shaped LED (wavelength 630 nm) (e) enabled us to capture the bubble contour as high contrast images. In the stereo PIV measurement, PIV particles (diameter: 8µm, excitation wavelength: 532nm, emission wavelength: 570nm) were seeded in the water or solution. ND: YAG laser (532nm, LEE LASER) beems (f) sheeted by rod lenses (h) illuminated a plane including the bubble’s zigzag path, through mirrors (g). Three high-speed cameras (camera settings; frame rate: 3000fps, resolution: 1024×1024 pixels, spatial resolution 20.5 µm/pixel) (i) were employed to clarify positional relations between the bubble and the vector distribution obtained by stereo PIV. The center camera captured the bubble’s counter and trajectory. The right and left cameras were arranged in order to fulfill a scheimpflug configuration for stereo PIV measurement. In order to remove the scattering light from the bubble surface, a sharp cut filter (cut-off wavelength: LIF: 500 nm, PIV: 560 nm) (j) was inserted at the front of every camera lense. To reconstruct the 3-D structure of the liquid motion around the bubble, the hypodermic needle was shifted at 1.0 mm intervals in a depth (-5.0 mm ~ +5.0mm). Vortex region was calculated from the 3-D vector distribution of the liquid motion. In order to smoothly estimate the vorticity distributions from the stereo PIV results, post-processing
algorithm (Ido T et al. 2002) was applied. The interpolated velocity field possessed third-order spatial continuity and satisfied the equation of continuity by applying this algorithm. In the LIF/HPTS measurement, a fluorescent substance of HPTS (Coppeta J and Rogers C. 1998) (8-hydroxypyrene-1, 3, 6-trisulfonic acid, excitation wavelength: 455 nm, emission wavelength: 520 nm, concentration: \(1\times10^{-5}\) mol/l) was used to visualize the CO\(_2\) dissolution process from the bubble to the liquid phase. The emission intensity of HPTS depends on a pH level. Namely, the low pH regions were obtained as the low-brightness regions on an image. An Ar-ion laser system (458 nm, INNOVA 70C-3, COHERENT) (f) was used as excitation light source for HPTS.

![Diagram](image)

(a) Water Vessel; (b) Hypodermic needle; (c) Bubble-launching device; (d) Function generator; (e) Ring-shaped LED; (f) YAG LASER/Ar ion LASER; (g) Mirror; (h) Rod lens; (i) High-speed camera; (j) Sharp-cut filter

Fig. 1 Experiment set up for stereo PIV and LIF/HPTS.

3. Results and discussion

Figure 2 shows visualization results of CO\(_2\) dissolution process at the second inversion section in purified water (a) and contaminated water (b); hence they correspond with parts of the bubble wakes. As shown in these figures, the brightness and the shape of the dark regions are different between purified water and contaminated water. It can be seen that the CO\(_2\) dissolution process and the mass transport process from the bubble into the liquid phase has changed. Takagi described that on the basis of numerical simulation the flow structure was changed by the non-uniform distribution of adsorbed contamination at the interface. A very small amount of surfactant affects both molecular diffusion and convective transportation. Figures 2 show visualization results of vortex structure at the second inversion section in the purified water (a.2-4) and the
contaminated water (b.2-4). Iso-surfaces in Figures 2 are vortex regions calculated from the second invariant of velocity gradient calculated from the 3-D vector distribution. The second invariant of velocity gradient was normalized by the maximum value in every condition, and its threshold was 0.03. The 3-D shape of the vortexes in the contaminated water is different from that of the purified water. Change in the slip condition at the gas-liquid interface is considered to bring the change in the 3-D flow structure. Considering how the vortexes were formed, we are able to understand the change in the boundary layers, indirectly. In the contaminated water, a slip condition is considered to become a non-slip condition due to Marangoni convection occurring on the bubble-interface. Under the non-slip condition at the gas-liquid interface, the velocity boundary layer was changed and the concentration boundary layer was also affected along with it. Compared with the purified water, the vortex region formed at the bubble rear was wide. In the contaminated water, a separation point was moved to the bubble’s frontal area and a separation region increased (Takagi S and Matsumoto Y. 2011) results from the change of the velocity boundary layer. Furthermore, the concentration boundary layer thickness increased. Thus, mass transfer was suppressed. The Marangoni convection at the bubble surface affected the boundary layers. As a result, the bubble-induced surrounding liquid motions and the mass transfer were greatly changed.

(a): Purified water  
(b): 500 ppm 1-pentanol solution

**Fig. 2** Visualization of CO₂ dissolution process (1) and vortex structure (2: front) (3: side) (4: Oblique).
4. Conclusion
The influences of the bubble-surface contamination on the bubble-induced surrounding liquid motions and mass transfer in zigzag motion were investigated by using LIF/HPTS and stereo PIV measurement. In the contaminated water, the surrounding-liquid motions and the mass transfer were changed by Marangoni convection on the bubble-interface. In order to elucidate the behavior of the boundary layers of a zigzag ascent CO\textsubscript{2} bubble, we focused on its vortex structure and CO\textsubscript{2} dissolution process. The velocity boundary layer was considered to be changed by Marangoni convection on the bubble interface that affects the separation point and the concentration boundary layer. Therefore, the vortex region was changed and the mass transfer was suppressed. The behavior of the boundary layers was considered from the bubble motions (the bubble's trajectory, the CO\textsubscript{2} dissolution process and the bubble-induced surrounding liquid motions).

References
Huang J and Saito T (In press) Influences of gas-liquid interface contamination on bubble motions, bubble wakes, and instantaneous mass transfer. Chemical Engineering Science