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Discussion about the differences in mass transfer, bubble motion and surrounding liquid motion between a contaminated system and a clean system based on consideration of three-dimensional wake structure obtained from LIF visualization

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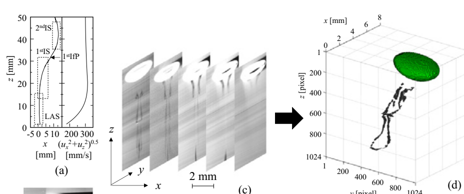
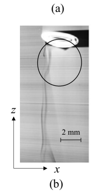
HIGHLIGHTS

- A deep understanding of a zigzagging bubble's mass transfer mechanism was gained.
- Bubble launch device with high reproducibility of bubbles and wakes was applied.
- Series cross-section images of a bubble and its wakes were captured via LIF.
- 3D bubble wakes were reconstructed via LIF results and image processing.
- Influences of the Marangoni convection on the mass transfer was discussed.

GRAPHICAL ABSTRACT





Construction of typical 3D bubble wakes at the 1stIS in the purified water.
(a) Bubble's trajectory and travelling velocity;
(b) Visualization image of typical bubble wakes from x-z view;
(c) Series equidistant cross-section images of bubble wakes from y-z plane;
(d) Construction of the 3D bubble wake;
LAS: Linear ascent section; 1stIS: First inversion section;
1stIfP: First inflection point; 2ndIS: Second inversion section;
Spatial resolution: 12.59 [μm/pixel].

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ABSTRACT

Mass transfer from a bubble to the surrounding liquid plays an important role in industry processes. To improve the efficiency of the industrial processes, a deep understanding of the mass transfer mechanism is essential. In the present study, the relationship between the instantaneous mass transfer and the motions of the bubble and three-dimensional bubble wakes is discussed, on the basis of precise measurement. Moreover, since some industrial applications are contaminated system, the authors consider influences of bubble-surface contamination on the above. In the present experiments, purified water, and water contaminated with a very small amount of surfactant (1-pentanol) were employed. LIF (Laser Induced Fluorescence) technique and HPTS (a pH-sensitive dye) that was calibrated through a photoelectric optical fiber probe in advance were employed to visualize the mass transfer of the bubble and the wake structure of the bubble. The authors investigated highly reproducible single bubbles (considered to be almost the same bubble) launched from a special bubble-launch device; successfully they acquired pseudo-time-series sliced bubble wakes' images from every y-z plane at an equidistant interval. By processing the pseudo-time-series images through their own new image-processing, they challengingly reconstructed three-dimensional bubble wakes. From careful observations on the three-dimensional bubble wakes' structure, they indirectly found out that the Marangoni convection, which was induced by the non-uniform distribution of surfactants desorption on the bubble surface, raised changes in the

Abbreviations: 1stIP, the first inversion point; 1stIfP, the first inflection point; 1stIS, the first inversion section; 2ndIP, the second inversion point; 2ndIS, the second inversion section; BLD, bubble launch device; HTPS, 8-hydroxypyrene-1,3,6-trisulfonic acid; LAS, linear ascent section; LED, light-emitting diode; LIF, laser-induced fluorescence; POFP, photoelectric optical fiber probe.

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boundary layers in the contaminated water. The authors discussed the influences of gas-liquid interface contamination on the bubble motions, bubble wakes, and mass transfer process based on the reconstruction of three-dimensional bubble wakes in the purified water and contaminated water.

Nomenclature

D_{eq}	equivalent diameter of the bubble [mm]
Eo	Eotvos number, $= g(\rho_L - \rho_B)D_{eq}^2/\sigma$ [–]
Mo	Morton number, $= g\mu^4/\rho_L\sigma^3$ [–]
Re	Reynolds number, $= \rho_L D_{eq} U_t/\mu$ [–]
u_x	the horizontal component of the bubble's travelling velocity [mm/s]
$k_L{}^*$	the average instantaneous mass transfer coefficient [m/s]
U_t	terminal velocity of the bubble [mm/s]
u_x	the horizontal component of the bubble's travelling velocity [mm/s]
u_z	the vertical component of the bubble's travelling velocity [mm/s]
We	Weber number, $= \rho_L D_{eq} U_t^2/\sigma$ [–]
x	coordinate [mm]
y	coordinate [mm]
z	coordinate [mm]
μ	viscosity [Pa s]
ρ_B	density of the bubble [kg/m^3]
ρ_L	density of the liquid [kg/m^3]
σ	surface tension [N/m]

1. Introduction

Gas-liquid two-phase flows are widely used in industrial processes such as a bioreactor, chemical reactor and wastewater treatment. In order to improve the efficiency and safety of these processes, a deep understanding of the relationship among mass transfer mechanism, bubble motion and the bubble-induced surrounding liquid motion (in particular the bubble wake) is essential. Furthermore, the above processes are usually contaminated systems. Hence the influences of bubble-surface contamination on the three-dimensional bubble motions (gravity-center motion and surface oscillation) and three-dimensional bubble-wake structure, and their effects on mass transfer were quantitatively and experimentally discussed compared with those of purified system in this paper.

The mechanism of gas-liquid mass transfer have been studied for several decades (Danckwerts, 1970; Jähne and Haußecker, 1998; Turney and Banerjee, 2008), however, the detailed mechanism are still unknown. Motarjemi and Jameson (1978) reported that a bubble with 2–3 mm in equivalent diameter took the maximum mass transfer coefficient. Bubbles of this size possess the following properties: shape of an oblate ellipsoid, zigzag or helical centroid motion, surface oscillation, and periodical vortex shedding. The surface oscillation was investigated by many researchers (Lunde and Perkins, 1998; Miyamoto and Saito, 2005; Moore, 1965; Saffman, 1956; Fan and Tsuchiya, 1990; Brücker, 1999). However, most of these researches were conducted only on the basis of two-dimensional experimental results. To understand the influences of the surface contamination on the mass transfer process comprehensively, the mass transfer process has to be discussed on the basis of three-dimensional structure of the bubble wake, because the relationship between the boundary layers and the bubble wake is a relationship of cause and effect.

In the present research, we focused on a single CO_2 bubble of about 3 mm in equivalent diameter, which ascends zigzag in clean water and in water contaminated with a very small amount of a surfactant (1-pentanol). In addition, bubbles of this size are often encountered in industrial processes. A lot of researchers have been investigating the mass transfer from a bubble to the surrounding liquid under the above both conditions; however most of their experimental researches discussed it only on the basis of two-dimensional and time average results. To understand the influences of the surface contamination on the mass transfer process comprehensively, the mass transfer process has to be discussed from time-evolution of the three-dimensional structure of the bubble wake, because the relationship between the boundary layers and the bubble wake is a relationship of cause and effect. Hence, the authors measured the bubble centroid and surface motions, and the CO_2 dissolution process via a LIF/HPTS (Laser Induced Fluorescence) method (Coppeta and Rogers, 1998) by using high speed video cameras. The authors captured slice images of the bubble wake from front and side views by using a bubble-launch device (Saito et al., 2010; Saito and Toriu, 2015) that precisely launched uniform single bubbles at an optional interval. Since the reproducibility of the single bubbles' size, shape, orientation, trajectory, surface oscillation was very high, the wakes of every single bubble were considered to be almost the same. By reconstructing three-dimensional bubble from precise experimental results challengingly and integrating all results obtained in the clean water and the contaminated water, the authors will present deep understanding of the influences of gas-liquid interface contamination on the bubble motions, bubble and mass transfer process.

From these experimental results, the effects of Marangoni convection on three-dimensional structure of the surface-contaminated-bubble wakes were experimentally elucidated. The Marangoni convection on the bubble surface indicated changes in the boundary layers in the contaminated water. These led the mass transfer coefficient of the single CO_2 bubble to decreasing in the contaminated water.

2. Experiments

2.1. Experimental setup for CO_2 dissolution process

Fig. 1 (based on the reference Huang and Saito (2017): Fig. 1 because they used the same experimental setup) shows schematic diagram of the experimental setup for LIF/HPTS experiments. An acrylic vessel (a) was 150 mm-square in cross section and 300 mm in height. Ion-exchange and boiled water for the specific purpose of avoiding generation and adhesion of bubbles on the