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Effects of surfactant on quasi-static bubble growth from an orifice

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ABSTRACT

The effects of surfactant on quasi-static bubble growth from an orifice of 2.0 mm in diameter were investigated by using a high-speed video camera and an image processing method. Triton X-100 was used for surfactant and its concentrations were set at 0.0, 0.1, 0.3, 0.5 and 1.0 mol/m^3. To obtain further knowledge of the bubble growth in the clean and contaminated systems, the flow fields around the bubbles were measured by using particle image velocimetry (PIV). The conclusions obtained are as follows: (1) the increase rate of the bubble aspect ratio in the contaminated system almost agrees with that in the clean system before reaching a specific bubble volume, and becomes larger after that, (2) as the surfactant concentration increases, the smallest contact angle increases and the bubble volume at the smallest contact angle decreases; furthermore, the bubble volume at the branch point of the contact angle between the clean and contaminated systems nearly agrees with that at the branch point of the aspect ratio, (3) the surfactant does not affect the flow fields around the growing bubbles in the experiment.

1. Introduction

Bubbly flow is widely utilized in many industrial systems such as chemical reactors and bioreactors. The liquid phase is often contaminated by surfactants, hence, many studies about bubble and drop motion in contaminated systems, e.g., rising velocities of bubbles and drops in infinite stagnant liquids [6,18,21,29], in vertical pipes [2,13,17,22], and bubbly flow structure [24,26] have been carried out.

Bubble diameter is the characteristic length of bubble motion. Bubbles are often dispersed in the liquid from submerged orifices; thus, many theoretical and experimental studies about bubble growth and the detachment of bubbles from orifices in clean systems have been carried out and subsequently were reviewed by several authors [5,15,16,30]. Moreover, interface tracking simulations are recently useful to estimate the detachment bubble diameter and discuss the detachment mechanism for wide ranges of parameters [1,3,4,8,10,12]. However, only a few studies about bubble growth and detachment from an orifice in contaminated systems have been carried out. Hsu et al. [14] investigated the bubble detachment from orifices for a wide range of gas flow rate in aqueous surfactant solutions. They found that the detachment bubble diameter at low gas flow rate in contaminated systems is smaller than that in clean system, and the difference of the detachment diameter decreases with increasing gas flow rate, i.e., the detachment diameter in both clean and contaminated systems is the same as that at high gas flow rate. They also attempted to predict the detachment bubble diameter in the contaminated systems by using theoretical model proposed by Ruff [23] with dynamic surface tension. However, the model is insufficient to predict the detachment bubble diameter in the contaminated systems. Yang et al. [31] investigated the effects of two catanionic surfactants, i.e., mixture of cationic and anionic surfactants, on bubble detachment. Since it takes a long time to reach equilibrium surface tension compared with the time scale of bubble growth, the catanionic surfactants did not affect the detachment bubble diameter. Loubière and Hébrard [19] investigated the effects of cationic, nonionic, and anionic surfactants, as well as orifice types, i.e., rigid and flexible orifices, on the bubble detachment diameter. Regardless of the surfactant and orifice types, the detachment diameter in contaminated systems is smaller than that in clean systems.

The above-mentioned studies mainly focused on the effects of surfactants on the bubble detachment diameter. However, it is necessary to discuss the growing process of bubbles in contaminated systems to understand the causes of the decrease in the detachment bubble diameter. In this study, quasi-static bubble growth, i.e., bubble growth and detachment diameter are not affected by the gas flow rate from the orifice, in clean and contaminated systems was investigated by using a high-speed video camera and an image processing method. The orifice diameter was 2.0 mm. The surfactant was Triton X-100 at

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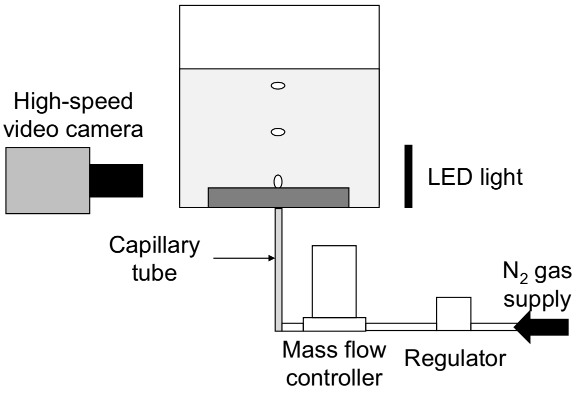

Fig. 1. Experimental apparatus.

concentrations of 0.0, 0.1, 0.3, 0.5 and 1.0 mol/m^3. It is well known that Marangoni stress, which is the gradient of the surface tension caused by the surfactant concentration at the interface, affects the flow field around and inside the bubbles and drops [6,18]. Hence, to obtain further knowledge of the bubble growth in the clean and contaminated systems, the flow fields around the growing bubbles were measured by using particle image velocimetry (PIV).

2. Experimental method

2.1. Bubble growth and detachment

The experimental apparatus is shown in Fig. 1. The height, width and depth of the tank were 100, 100 and 100 mm, respectively. The tank was made of transparent acrylic resin. A flat stainless steel plate with a circular orifice of 2.0 mm in diameter was placed at the bottom of the tank. The tank was filled with water up to 70.0 mm above the orifice. Experiments were carried out at atmospheric pressure and room temperature. The temperature of the liquid and gas was kept at 293 ± 2.0 K.

Nitrogen gas was supplied from gas refining equipment installed in our university. The flow rate of the gas was controlled by a mass flow controller (FUJIKIN Inc., FCST 1005(M)L) and it can control the flow rate up to about 180 mm^3/s. Di Marco [9] reported that quasi-static bubble growth regime can be defined by the following condition

$$\frac{\rho_L u_o d_o^{1.5} g^{0.5}}{\sigma} = EoFr^{0.5} < 1 \tag{1}$$

where ρ_L is the liquid density, u_o the gas velocity at the orifice, d_o the orifice diameter, g the magnitude of acceleration of gravity, σ the surface tension, Eo the Eötvös number, Fr the Froude number, respectively. The present experiments in both clean and contaminated systems implement Eq. (1) in consideration of reduction in the surface tension by the surfactant.

A capillary tube with 0.5 mm internal diameter d_c and 1.0 m length l_c was connected to the bottom orifice. Takahashi and Miyahara [27] showed that l_c/d_c^4 must be larger than 1.0×10^{12} m^{-3} for constant bubble growth. Furthermore, Terasaka and Tsuge [28] pointed out that Miyahara and Takahashi's constant flow condition cannot sustain constant bubble growth at low gas flow rate. They proposed the condition $\Delta P/(4\sigma/d_c) > 1$ for constant bubble growth, where ΔP is the pressure drop in a capillary. These conditions were sufficiently implemented in the present study.

Purified water made by purification device (TOKYO RIKA KIKAI Co., Ltd., SA-2000E1) was used for the liquid phase in the clean system. In the contaminated system, surfactant was added to the purified water. Triton X-100 ($C_8H_{17}C_6H_4(OCH_2CH_2)_{10}OH$) was used for the surfactant. The surfactant concentrations were 0.0, 0.1, 0.3, 0.5 and 1.0 mol/m^3. Stebe et al. [25] reported that the critical micelle concentration (CMC) of Triton X-100 is 0.23 mol/m^3. Hence, the concentrations of 0.3, 0.5 and 1.0 mol/m^3 are larger than CMC. Since the surfactant concentration was less than 0.1 wt% at 1.0 mol/m^3, the change in density and viscosity of the liquid due to the surfactant was negligible.

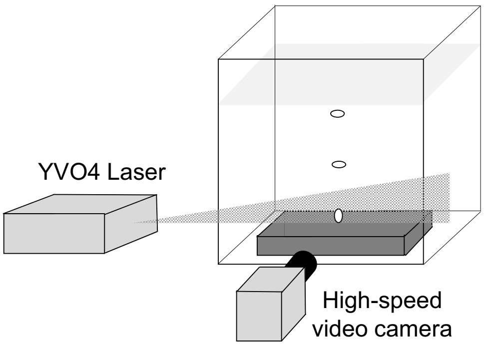

Fig. 2. PIV measurement setup.

Bubble images were taken by using a high speed video camera (PHOTRON Ltd., FASTCAM Mini UX50, frame rate = 1000 frame/s, spatial resolution ~ 0.01 mm/pixel). LED light source was used for back illumination. Instantaneous bubble volume, diameter, aspect ratio and contact angle were calculated from the bubble images using an image processing method [17,29]. The smallest calculated instantaneous bubble volume was 1.8 mm^3. For spatial resolution of 0.01 mm/pixel, the relative error in the measured bubble volume and aspect ratio was, therefore, less than ±2.0% and ±1.3% for this bubble, respectively. The errors can be decreased with increasing bubble volume. The contact angle was calculated by using least squares method, and 15 pixels above the bottom of the bubbles were adopted in the calculation. To check the effects of the number of pixels in the calculation, the contact angle was also calculated for 10 pixels above the bottom. The differences between the calculations for the 10 and 15 pixels were less than 5%.

2.2. PIV measurement

Fig. 2 shows the relation of the laser sheet and high-speed camera on a growing bubble from an orifice. The light sheet was generated by an YVO4 laser (KATOKOKEN Co., Ltd., G2000, 2W). Silicon carbide (SiC) particles of 15 µm in mean diameter were

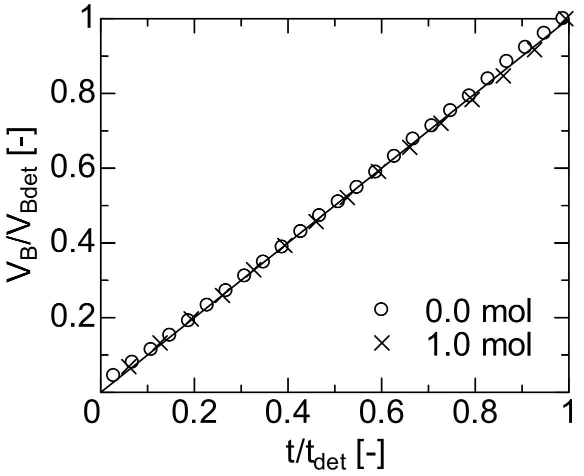

Fig. 3. Evolution of bubble volume at $Q \sim 170$ mm^3/s in 0.0 and 1.0 mol/m^3.