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Effects of surface-active agents on bubble growth and detachment from submerged orifice

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HIGHLIGHTS

- High speed imaging and particle image velocimetry captured the quasi-static bubble growth from a submerged orifice.
- Effects of dynamic surface tension on the bubble growth and detachment have been investigated.
- Surface tension gradient has a significant effect on the bubble growth and detachment.

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ABSTRACT

Present study deals with the effects of surfactants on the dynamics of bubble growth and detachment from a submerged orifice. Experiments are conducted to study the quasi-static growth of air bubble in de-ionized (DI) water mixed with nonionic surfactant Triton X-100. For comparison, bubble growth in pure DI water is also studied. While high-speed imaging is used for flow visualization, instantaneous velocity field, at different stages of bubble growth, are captured via particle image velocimetry. The study also uses bubble pressure Tensiometer technique and Goniometer for measuring the surface tensions. Present investigation shows that the bubble detachment volume decreases with the increase in the surfactant concentration. Further, for low concentration of surfactant, the surface tension gradient influences the flow field significantly and aid the bubble detachment.

1. Introduction

Formation of gas bubbles in liquid and the interactions of the bubbles with submerged surfaces influence the performance of many engineering systems (Kulkarni and Joshi, 2005). For instance, in many electrochemical devices, bubbles, formed at the electrode/electrolyte interface, reduces the active electrode-area and thus limits the device performance. While designing electrochemical systems, special techniques are often employed to remove the bubbles from the electrode surfaces. Such techniques include the use of ultrasound field (Zadeh, 2014), magnetic field (Matsushima et al., 2009), as well as surface-active agents (Lee et al., 2005). Leong et al. (2011) studied the role of surfactant head group, chain length, and cavitation microstreaming on the growth of bubbles. Influence of acoustic fields on the growth and collapse of bubbles has been studied (Ashokkumar et al., 2007; Leong et al., 2010) in detail. Efficient implementation of the above techniques, however, requires careful investigation of bubble nucleation, growth and detachment on submerged surfaces.

Studies on bubble growth and detachment usually follows two distinct approaches. In the first approach, many bubbles grow on a submerged surface and diagnostics are focused on the collective behavior of the bubbles in liquid. Second method uses single or very few bubbles and focus on their evolution. Single bubble studies are particularly effective in isolating the influences of various factors impacting the gas bubble evolution in liquid. Among such influencing factors, use of surfactants has emerged as a useful means to control the bubble dynamics (Allen and Deutsch, 2014). In the present study, effects of surfactant are investigated on single bubble evolution from submerged orifice.

Growth and departure characteristics of single gas bubble in liquid has been studied using a variety of computational and experimental techniques. Computational analysis on bubble growth characteristics typically uses volume-of-fluid (Albadawi et al., 2013; Chakraborty et al., 2009; Valencia et al., 2002) or particle-based methods (Das and Das, 2009). Large number of computational studies have successfully captured the fluid dynamics of

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Nomenclature

V_b	gas bubble volume (mm^3)	t	instantaneous time (s)
r_o	submerged Orifice radius (mm)	V_p	volume of the particle (mm^3)
σ	surface tension (N/m)	A_p	surface area of the particle (mm^2)
ρ_g	density of gas (kg/m^3)	$V^{\cdot}_{pr}$	predicted volume (mm^3)
ρ_l	density of liquid (kg/m^3)	Bo	Bond number
g	acceleration due to gravity (m/s^2)	P_{max}	maximum pressure (N/m^2)
N_{Re}	Reynolds number	P_o	hydrostatic pressure (N/m^2)
Q	discharge rate (m^3/s)	CMC	critical micelle concentration
μ_g	viscosity of gas ($N\ s/m^2$)	t_l	life time of bubble (s)
t_d	detachment time (s)		

bubble motion in for a variety of gas-liquid environments (Chakraborty et al., 2009; Eshraghi et al., 2015). Deodhar (2012) simulated the influence of surfactant during bubble growth in aqueous solutions. It was observed that the dynamic surface tension influences the flow field due to non-uniform adsorption and desorption of surfactant molecules around the bubble interface.

Hsu et al. (2000) conducted a series of experiments to identify the variations in bubble shape and volume due to surfactant addition. Using high-speed imaging, Kalaikadal (2012) showed that the dynamic surface tension plays primary role in dictating the shape and volume of a gas bubble in a surfactant. Loubière and Hébrard (2004) studied the kinetics of adsorption and desorption of cationic, anionic and non-ionic surfactants and investigated the effects of the surfactants on bubble volume and frequency. The study emphasizes the role of dynamic surface tension and the need of further research for better understanding the interactions between the bubbles and the surfactants.

Using particle image velocimetry (PIV) as well as numerical techniques, King and Sadhal (2014) studied the effects of Sodium dodecyl sulfate on the growth of air bubble in water. The investigation shows that the surface tension gradient assists in detachment and formation time up to the critical micelle concentration (CMC) of the surfactant. The PIV results indicated enhanced liquid-velocity at the gas-liquid interface induced possibly by the surface tension gradient. In contrary, the PIV measurement by Kurimoto et al. (2016) showed that the surfactant Triton X-100 creates smaller bubbles while keeping the velocity field largely unaffected.

The above review of literature clearly indicates that, for the sub-micellar concentration of the surfactant, the dynamic surface tension and the surface tension gradient play vital role in bubble growth and detachment. Studies also show that, based on the flow rate, the bubble formation dynamics may be grouped under three different categories: static, dynamic and turbulent (McCann and Prince, 1971). In the quasi-static regime, the bubble detachment volume does not depend on the gas flow rate and the volume can be calculated using the bubble orifice and surface tension value as given by Tate's law (Kulkarni and Joshi, 2005):

$$V_b = \frac{2\pi r_o \sigma}{(\rho_l - \rho_g)g} \tag{1.1}$$

In the present experiments, the gas flow rates are controlled to maintain the constant-volume bubble growth regime. The constant-volume regime is ensured by limiting the Reynolds number, defined in Eq. (1.2), below 100 (Xiao, 2004).

$$N_{Re} = \frac{4\rho_g Q}{\pi d_o \mu_g} \tag{1.2}$$

where Q represents the discharge rate, d_o orifice diameter and μ_g, gas viscosity.

The effect of time dependant surfactant properties on the bubble detachment can be deciphered clearly in quasi static regime. Such observation necessitates the study of the combined effects of dynamic surface tension and surface tension gradient in quasi-static bubble growth regime. Different surfactant concentrations are used to ascertain the effects on detachment of bubble and the flow field around the growing bubble. The present work, therefore, focuses on the quantitative understanding of the bubble growth in the quasi static regime where only buoyancy and surface tension forces are dominant. Present study uses PIV and high-speed imaging techniques for careful measurement of the transient velocity field as well as the volume and shape of the quasi-static bubbles. The ensuing discussion outlines on the experimental setup design, parameters that are controlled and techniques that have been employed to study the characteristics of bubble growth.

2. Experimental

The schematic diagram of experimental set up is shown in Fig. 1. The bubble growth experiments are conducted on a water column fabricated of transparent Poly (methyl methacrylate) (PMMA) acrylic glass sheets of size $100\,mm \times 100\,mm \times 500$ mm. The size of the experimental setup is quite large compared to the bubble size such that the wall effects remain negligibly small. The orifices used are of 1 mm and 1.6 mm diameter and connected to a New Era (model number NE-300) syringe pump through a long capillary tube. The pump-capillary combination ensures constant volumetric flow rate. The orifice sizes are optimized to control the bubble size. Bubble-size optimizations are essential to avoid the reflection of the PIV laser as well as to minimize the loss of information due to the shadow of the bubble. For high speed imaging, Basler A504k F-mount, 500fps, colour CMOS camera has been used. The camera has a resolution of 1280×1024 pixels with a pixel size of $12 \times 12\ \mu m$. 22 W LED downlight act as light source for high speed imaging placed at the back of the water column with a filter sheet.

A MATLAB® program is developed to identify the boundary of the bubble and calculate the geometric characteristics of the bubble. The algorithm for finding the bubble characteristics starts with converting the raw bubble image into a binary image over a carefully chosen threshold value. The program then detects the coordinates of the boundary of the binary image to provide the bubble profile. Once the boundary is identified, the geometric characteristics such as, volume, height, center of gravity and sphericity were calculated from this profile. The bubble volume is calculated by using Pappus centroid theorem where the bubble profile was revolved around the central axis to give the volume of revolution.

$$\text{Volume } (V_b) = (\text{distance travelled by centroid}) \times (\text{Area}) \tag{2.1}$$