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Application of laser image technique for detection of detached volume of twin-bubble in semitransparent fluids

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ABSTRACT

A laser image measurement has been employed to quantify the volume and shape of twin-bubble generated in semitransparent glycerol aqueous solutions with high viscosity. The bubble generation regime was investigated by analyzing the shape evolution process of captured bubble, and the influences of solution mass concentration, orifice diameter and orifice interval on bubble's detached volume were discussed, respectively. The results show that twin bubbles formation experiences three stages of radial expansion, axial elongation and vertical detachment. Bubble detachment volume increases with the solutions concentration but decreases with orifice diameter. The detached volume climbs with the orifice interval, however smaller than that formed at single orifice.

1. Introduction

Bubble formation behavior is common in many industrial processes and technologies owing to its advantages of high effective inter-phase contact such as bubble columns, sieve plate columns and airlift bioreactors [1,2]. In these typical equipments, bubble formation plays a key role in determining the mass transfer, heat transfer and chemical reactions between gas and liquid phases, since it directly quantifies the bubble shape, the rate of bubble growth, the bubble detached volume, and the even the velocity of departing bubbles. Therefore, as a fundamental phenomenon, the dynamics behavior of twin bubbles formation is a vital issue in taking overall insight into the complex behavior of bubble swarm under industrial condition.

Single bubble formation and ascension from a submerged orifice has been received considerable attention for many decades, which is reviewed well by Kulkarni and Joshi [3]. The preponderance of the work in the open literatures relate to mechanistic models to predict the bubble growth and detachment characteristics such as bubble volume, frequency and shape, and have provided detailed information for the complex interaction between two phases as the interface deforms. Titomanlio et al. [4] indicated that the volume of twin bubble approximates that of single bubble with double the gas chamber volume and double the gas flow rate. Miyahara et al. [5] found that the effect of gas chamber volume on bubble volumes and frequencies decreases with the number of orifices. Ruzicka et al. [6,7] proposed two types of bubbling modes of bubble formation by means of analysis of pressure fluctuations in the gas chamber. McCann and Prince [8] proposed a bubble interaction model to predict bubble frequency. Dempster and Arebi [9] developed a nondimensional correlation for the bubble detachment volume. Xie and Tan [10] identified three regimes of synchronous, alternative and unsteady bubbling in studying multi-orifices bubble formation. Recently, A few researchers extended coverage to the interaction as well as coalescence behavior during twin bubbles formation at two neighboring orifices [11,12]. However, few studies have addressed the case of multiple orifices, and multi-bubbles formation mechanism remains still far from fully understood. For example, even for the influence of the fluid properties on the bubble detachment volume, it is quite difficult to modify one fluid property without affecting another or even. Furthermore, Duo to the complex interaction of neighboring bubble, much less is known about the difference between bubble formed at single orifice and that at multi-orifices.

Nevertheless, two types of experimental methods, i.e. intrusive and non-intrusive techniques, were employed in these investigations on bubble generation behavior [13]. However, intrusive technique disturbs inevitably the flow field and becomes invalid for the small difference of the measured indexes between the gas–liquid phases despite for any kind of device [14–18]. By contrast, non-intrusive technique overcomes the disadvantage interfering flow field and is applied widely in various specific forms [19–21]. Among these non-intrusive techniques, high-speed photography is used extensively due to its capability of catching

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Table 1
Physical properties of glycerol aqueous solutions.

Fluid	Density ρ_l $\left(\text{kg/m}^3\right)$	Surface tension σ $\left(\text{mN/m}\right)$	Viscosity μ (Pa s)
97.0% GL	1249.5	64.60	0.764
98.5% GL	1254.7	63.30	1.045
99.7% GL	1260.2	62.70	1.420

instantaneous bubble behavior and continuously recording [22]. Obviously, this method requires liquids transparent and having relatively low gas holdup in the near wall region.

In this paper, a laser image system was applied for visualization and determination of the process of twin bubbles formation from two identical submerged orifices. Based on application of beam expanding and light amplification, the minute bubble in semitransparent fluid can be real-time visualized and meanwhile recorded by CCD camera without distortion. By this means, twin bubbles formation mechanism in high viscosity glycerol aqueous solutions was investigated through the analysis of bubble shape evolution, and the influence factors on detachment volume of bubble were discussed within this experimental condition.

2. Experiment methods

The experimental apparatus included bubble generating system and laser image system, which is described in detailed in our previous work [23]. The experiments were conducted under following conditions: orifice diameters (D_o) 1.0×10^{-3} m, 1.6×10^{-3} m, 2.4×10^{-3} m; gas flowrate (Q_g) from 0.1×10^{-6} m^3/s to 1.0×10^{-6} m^3/s; glycerol aqueous solutions 97.0% (by mass, the same below), 98.5%, 99.7%, respectively; orifice interval (S) $1D_o$, $2D_o$, $3D_o$; The experimental temperature was 293 ± 0.1 K. The physical properties, including viscosity, surface tension and density, were, respectively, measured by Rheometer of StressTech (REOLOGICA Instruments AB, Sweden), dynamic surface tension apparatus (DCAT21, dataphysics, Germany) and pycnometer. The results are shown in Table 1.

3. Results and discussion

3.1. Bubble shape evolution and formation regime

Fig. 1 presents the bubble shape evolution with the growing time in glycerol aqueous solutions with mass concentration of 97.0%. It is clearly indicated that bubble formation experiences three stages: expansion stage, elongation stage and departure stage. In the expansion stage (e.g. 0–40 ms), both bubbles initially grow spherically owing to dominant effect of surface tension, however, bubble surface faced deforms obviously owing to the intensive compression between bubbles in spite of no contact. While during the elongation stage (40–120 ms), bubbles start to collides with each other, are then stretched as a results of the joint effect of increasing buoyancy and resistance, and consequently deviate symmetrically from vertical direction to the their own ones, which have the slim shape and hemispherical shape at the upper and lower ends, respectively. It is noteworthy that as the interaction of neighboring bubble gets significant with the increase of its

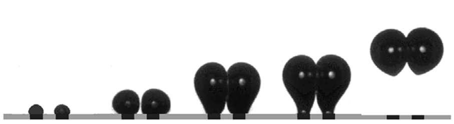

Fig. 1. Bubble shapes in 97.0% glycerin solutions at different time (D_o = 2.4 mm; S = 1D_o; Q_g = 0.2 ml/s).

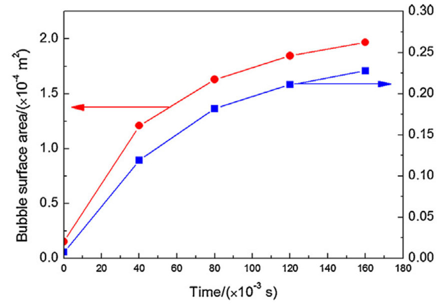

Fig. 2. Variations of bubble surface area and volume with time (97.0% GL; D_o = 2.4 mm; S = 1D_o; Q_g = 0.2 ml/s).

volume, the orientations of the bubble pairs start to deviate from the vertical axis crossing the middle point of the line joining the two centers of orifices. Consequently, the interface between twin bubbles is pressed heavily and getting flat with the development of stretching process. However, in the departure stage (120–160 ms), since the buoyancy exceed the resistance acted on bubble, bubbles begin to detach from the orifices and then rise, and bubble surfaces recover spherical shapes because of none draw effect of the orifices.

Moreover, the instantaneous volume and surface area of the one of two bubbles during forming process under same condition were calculated and the result is shown in Fig. 2. The result indicates that both volume and surface area in Newtonian fluids increase with growing time, but compared with linear growth of single bubble formation [24], their growth rates of twin bubbles reduce gradually although constant gas flow condition. This is because that neighboring generating bubble hinders to some extent the other bubble growth in glycerin aqueous solution, and this hindrance is strengthened with the increase of bubble volume for experimental orifice interval.

3.2. Effect of solution concentration on the detachment volume

The bubble detached volumes acquired in three kinds of glycerol aqueous solutions with mass concentration of 97.0%, 98.5% and 99.7%, vary with the gas volumetric flow rate, as shown in Fig. 3. It is demonstrated that bubble detached volume formed in Newtonian glycerol solutions increases with the solution concentration. This can be attributed following two aspects: First, the solution viscosity enhances with the rise of the concentration, which causes the growth of the drag force acted on bubble, and meanwhile the buoyancy on the bubble goes up thanks to the rise of the solution density. Consequently, the bubble formation time is delayed and hence the bubble becomes larger. Second, the surface tension decreases with the solution concentration, which, however, promotes bubble surface expansion and leads to larger detached volume.

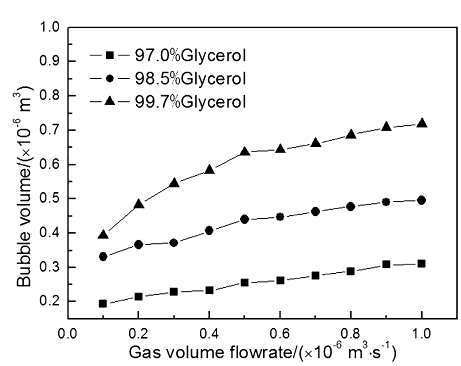

Fig. 3. Effect of solution concentration on twin bubble detached volume (D_o = 1.6 mm; S = 1D_o; Q_g = 0.25 ml/s)).