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Laser image measurement of twin bubbles formation in shear-thinning fluids

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ABSTRACT

A laser image system for investigating twin bubbles formation in shear-thinning fluid was established. The process of twin-bubble formation could be directly visualized and real-time recorded through computer by means of He–Ne laser as light source using the beam expanding and light amplification technology. The shape and size of bubbles generating in carboxymethylcellulose (CMC) aqueous solutions were studied experimentally at orifice diameter 1 mm, 1.6 mm and 2.4 mm, the orifices interval $1D_o$, $2D_o$ and $3D_o$ (D_o: orifice diameter) and the gas flow rate from 0.1 to 1.0 ml/s, respectively. The effects of solution mass concentration, orifice diameter and orifice interval on bubble detachment volume were investigated. The results reveals that twin bubbles gradually touch each other and then deviate from the vertical axis crossing the middle point of the line joining the two orifice during the formation process. However compared with the perfect teardrop terminal shapes in glycerol solution, the bubbles formed in CMC solutions are stretched vertically due to the shear-thinning effect of fluids. The bubble detachment volume increases with the solution mass concentration, whereas decreases with orifice diameter. The detachment volume generated at twin orifices is less affected by orifices interval, but still smaller than that at single orifice.

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1. Introduction

The formation processes of bubbles in non-Newtonian fluids are frequently encountered in a wide variety of industrial fields such as chemical biochemical, environmental and food industries. Such process is important for the sparger design of gas–liquid contractors which have plentiful applications in bubble columns, sieve plate columns and kinds of airlift bioreactor. The information regarding the bubble shape, the rate of bubble growth, the volume of bubble detached, and even the velocity of departing bubble influence markedly its dynamics and the transport processes in gas–liquid two phases. As a fundamental phenomenon, the dynamics behavior of twin bubble formed from two uniform orifices plays a key role to taking overall insight into the complex behavior of bubbles swarm in non-Newtonian fluid under industrial condition.

Considering the importance of two-phase bubbly flow, as a prerequisite and necessary basis, a single bubble formation has been extensively reported in the literature [1]. Few studies have addressed the case of multiple orifices as an extension of single orifice bubble formation. Titomanlio et al. [2] found 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. [3] indicated that the effect of gas chamber volume on bubble volumes and frequencies weakens when the number of orifices is increased. Ruzicka et al. [4,5] found two types of bubbling modes of bubble formation at two orifices by means of analysis of pressure fluctuations in the gas chamber. McCann and Prince [6] proposed a bubble interaction model to predict bubble frequency as orifices were placed in a line of five orifices. Dempster and Arebi [7] developed a nondimensional correlation for the detachment volume of bubbles generated at three orifices in sub-cooled water. Xie and Tan [8] investigated bubble formation at symmetrical multi-orifices by both high-speed photography and analysis of chamber pressure fluctuations, and then identified three regimes of synchronous, alternative and unsteady bubbling. Moreover, many investigators focused on the formation of an ensemble of bubbles on perforated plates and sieve plates, and developed various models on mean bubble diameter or volume [9–13]. Recently, A few researchers extended coverage to the interaction as well as coalescence behavior during twin bubbles formation at two neighboring orifices [14,15]. However, mechanism of twin bubbles formation and detachment remains still far from fully understood up to now. For example, even for twin-orifice simultaneous bubbling, there exists obviously such two different behaviors as repulsion and attraction even coalescence at whiles. Furthermore, Duo to the inherent complex nature of non-Newtonian fluids and the interaction of neighboring bubbles, much less is known about multi-bubble formed in these fluids compared with that in Newtonian fluids.

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Nevertheless, in these investigations on bubbling flow, lots of experimental investigations were performed in various measurement methods [16], including mainly intrusive and non-intrusive techniques. In intrusive method, the needles or probes are set into flow field and the bubble characteristics can be acquired in terms of the signals transmitted from conductivity probes [17], optical fiber probes [18], ultrasound probes [19], endoscopic probes [20] and hot film anemometry [21]. However, the intrusive technique interferes inevitably the flow field and becomes noneffective for the small difference of the conductivity or refraction index between the gas–liquid phases. Non-intrusive technique overcomes the disadvantage disturbing flow field and many methods have been developed to study bubble behavior so far, including image technique, X-ray radiography [22], γ-ray radiography [23], particle image velocimetry (PIV) [24], phase Doppler anemometry (PDA) [25], etc. Among these non-intrusive techniques, high-speed photography is widely employed as a direct visualization technique for the measurement of bubble shape, size and velocity due to its capability of catching instantaneous behavior and continuously recording [26–28]. Obviously, this method requires liquids transparent and having relatively low gas holdup in near wall region.

In this paper, a laser image system was constructed for visualization and determination of the process of the simultaneous bubbles formation from two neighboring orifices submerged in shear-thinning fluids. The processes of twin bubbles formation were directly visualized and real-time recorded by CCD camera and computer by means of He–Ne laser as light source with the beam expanding and light amplification. As a sequel of the previous work with single orifice system [29], the shape evolution of twin bubbles formed in shear-thinning fluids was compared with that in Newtonian fluids, and also the influences of solution mass concentration, orifice diameter and orifice interval on bubble detachment volume as well as the bubble shape were investigated experimentally.

2. Experiment

2.1. Experimental setup

The experimental facility consists of two parts: bubble generation system and the laser image measurement system as shown in Fig. 1. Bubble generation system mainly includes a Plexiglas square tank with dimension 15 cm × 15 cm × 50 cm, which was considered to be large enough and allow neglecting the effect of the wall on the shape and size of bubbles. A Plexiglas plate (15 cm × 5 cm cross-section and 1 cm thick) with two identical polished orifices (inside diameter 1 mm) was placed inside the tank 10 cm above the bottom for generating bubbles. Two stainless tubings with inside diameter 2 mm linked the nitrogen cylinder, rotameters and orifices. Relative to the fixed right orifice, the left orifice was movable horizontally to adjust facilely the orifice spacing. Considering the range of pressure inside bubble, nitrogen pressure was maintained at little more than 0.1 MPa through adjusting a regulation valve, thus gas flow rate could be showed accurately by the rotameters calibrated. Nitrogen bubbles were always generated synchronously at stable frequency from the twin submerged orifices by adjusting the gas flow rate properly. In laser image measurement system, the laser beam emitted by He–Ne laser source passed through spatial filter and collimating lens then became a parallel beam, and subsequently passed through experimental tank filled with CMC aqueous solutions. The tank should be carefully adjusted to keep the bubble at the center of beam spot, the process of bubble growth and detachment were magnified suitably and imaged on frosted glass receiving screen by an amplifying lens. Simultaneously, these images were saved in hard disk by CCD camera and computer picture collection card. Finally, bubble volumes were calculated by analyzing the collected images using self-developed treatment software. To be clearer, it is necessary to keep the forth and back planes of the tank strictly parallel, both planes vertical.

2.2. Experimental conditions

CMC (AR; MW: 5×10^6; Tianjin Kermel Chemical Reagent Co. (Tianjin, China)), and distilled water were used in the experiments. The experiments were conducted under various conditions as follows: temperature: 293.15 ± 1.00 K; mass concentrations (same as below) of CMC aqueous solution: 0.75%, 1.0% and 1.5%; orifice diameters (D_o): 1 mm, 1.6 mm and 2.4 mm; orifice interval: $1D_o$, $2D_o$ and $3D_o$; gas flow rate: 0.1 ~ 1.0 ml/s. The rheological characteristics of CMC aqueous solutions were measured by Rheometer of StressTech (REOLOGICA Instruments AB, Sweden), Moreover, in order to compare the shape evolution of twin bubbles in Newtonian fluid, 97% glycerol aqueous solutions was used and its physical properties was measured. The behavior of shear-thinning of those fluids can be adequately described by

Table 1
Viscosity of glycerin solutions and rheological parameters of CMC solutions.

Fluid	η_0 (Pa s)	η_∞ (Pa s)	λ/s	η
0.75%CMC	0.959	0.001	0.185	0.521
1.0%CMC	4.620	0.001	0.557	0.469
1.5%CMC	12.06	0.001	1.762	0.421
97.0%GL	0.765	0.001	/	1

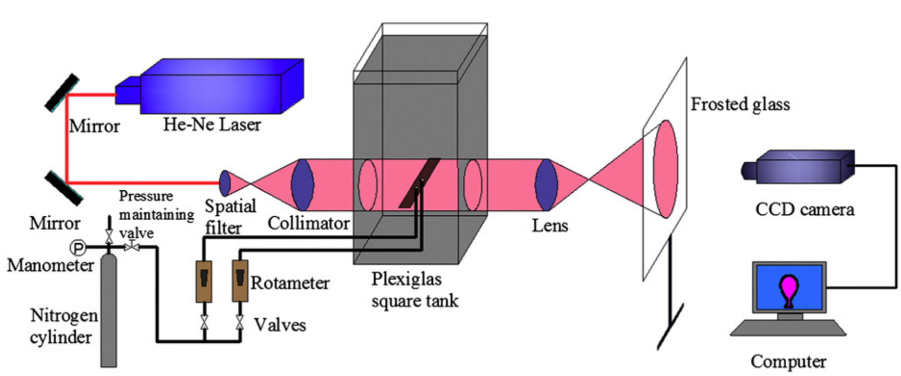

Fig. 1. Schematic representation of the experimental apparatus.

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