Optik 125 (2014) 1871–1874

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Influence of orifice spacing on twin bubbles formation in shear-thinning fluids: Laser image measurement

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ARTICLE INFO

Article history:
Received 9 May 2013
Accepted 10 October 2013

Keywords:
Laser image
Bubble formation
Shear-thinning
Orifice spacing

ABSTRACT

A laser image system for investigating the influence of orifice spacing on twin bubbles formation in shear-thinning fluid was established. The bubbles formation process at two orifices 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 the orifices spacing $1D_o$, $2D_o$ and $3D_o$ (D_o orifice diameter). The results reveal that the minute bubbles can be imaged clearly and amplified without distortion in the higher concentration solutions, and therefore the shape and size of bubbles are obtained accurately. With the increase of orifice spacing, bubble instantaneous volume in shear-thinning fluid decreases at the radial expansion stage but then increases at vertical elongation period, and the deformation and deviation of bubbles forming goes down due to the reduced interaction of adjacent bubble.

1. Introduction

Bubbly flow in non-Newtonian fluids have received much concerns due to its significance in industrial application, such as chemical, biochemical, environmental, petrochemical processes [1,2]. In such typical equipments as bubbles column and air-lift bioreactor, the bubble formation processes are frequently encountered and orifice spacing is vital to bubble dynamics and the transport processes in gas–liquid two phases, since bubble shape, bubble growth rate, bubble detached volume, and even the velocity of departing bubble influence significantly bubble behavior of interaction and coalescence. As a fundamental phenomenon, the dynamics behavior of twin bubble formed at two submerged orifices plays an important role in taking overall insight into the complex behavior of bubbles swarm in non-Newtonian fluid under industrial condition.

However, due to the complex behavior resulted from hydrodynamic interactions among individual bubbles, few studies have addressed the case of multiple orifices as an extension of single orifice bubble formation [3]. The corresponding investigations have been focused on bubble detachment volume obtained by both experimental measurement [4] and theoretical correlation [5,6], the effect of gas chamber volume [7] and pressure fluctuations [8], and bubble frequency [9,10]. Recently, a few researchers extended to the complicated behavior of multi-bubble formation coupled with its coalescence at two neighboring orifices [11,12]. However, the mechanism of two bubbles formation remains still far from fully understood up to now. For example, even for two-orifice simultaneous bubbling, there exists obviously such two different behaviors as repulsion and attraction even coalescence at whiles. Furthermore, due to the inherent complex nature of non-Newtonian fluids, much less is known about multi-bubble formed in these fluids compared with that in Newtonian fluids.

Nevertheless, in these investigations on bubbling flow, plenty of experimental investigations were performed by various methods [13], 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 [14], optical fiber probes [15], ultrasound probes [16] and hot film anemometry [17]. But, 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 [18], γ-ray radiography [19], particle image velocimetry (PIV) [20], phase Doppler anemometry (PDA) [21]. 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 [22–24]. Obviously, this method requires liquids transparent and having relatively low gas holdup in near wall region.

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0030-4026/$ – see front matter © 2013 Elsevier GmbH. All rights reserved.
http://dx.doi.org/10.1016/j.ijleo.2013.10.034

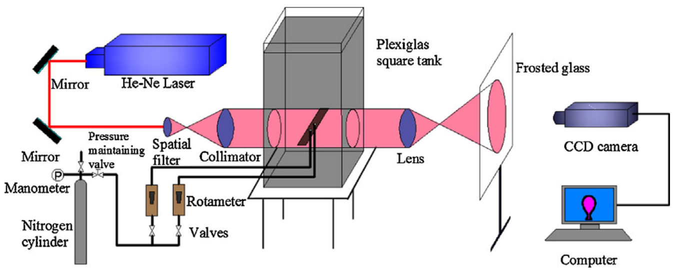

Fig. 1. Schematic representation of the experimental apparatus.

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 with various spacing. The processes of twin bubbles formation in shear-thinning fluids 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. The shape and volume of twin bubbles formed from two identical orifices with various spacing were studied by comparing with that of single one under the same condition.

2. Experiment methods

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 2.4 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 is movable horizontally to adjust facilely the orifice spacing, as shown in Fig. 2. 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 were vertical.

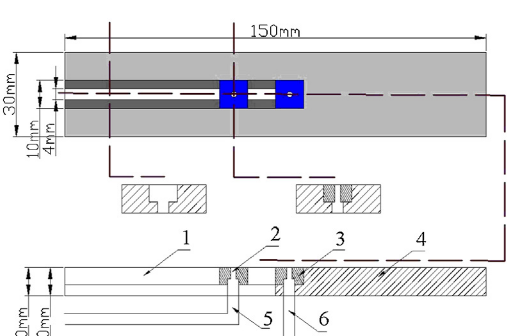

Fig. 2. Structure diagram of test section with orifices. (1) Horizontal chute, (2) orifice, (3) replaceable Plexiglas cap, (4) test section, (5) sliding stainless pipe, and (6) fixing stainless pipe.

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

Fluid	η_0 (Pa s)	η_∞ (Pa s)	λ (s)	n
1.5%CMC	12.06	0.001	1.762	0.421
97.0%GL	0.765	0.001	/	1

2.2. Experimental conditions

The setup described above was employed to study twin bubbles formation in CMC and glycerin aqueous solutions under various conditions: mass concentrations (same as below) of CMC and glycerin solution: 1.5% and 97%; orifice diameters (D_o): 2.4 mm; orifice spacing: $1D_o$, $2D_o$ and $3D_o$; gas flow rate: 0.2 ml/s. The rheological characteristics of CMC aqueous solutions were measured by Rheometer of StressTech (REOLOGICA Instruments AB, Sweden). The behavior of shear-thinning of those fluid can be adequately described by Carreau model (Eq. (1)) under experimental shear range and the result was shown in Table 1.

$$\frac{\eta-\eta_\infty}{\eta_0-\eta_\infty}=\left[1+(\lambda\dot{\gamma})^2\right]^{(n-1)/2} \quad (1)$$

where η_0, η_∞, λ and n are zero-shear viscosity, infinite shear viscosity, time constant and flow index respectively.

3. Results and discussion

3.1. Bubble shape evolution

A visualization sequence for synchronous formation of twin bubbles in 1.5% CMC aqueous solution is presented in Fig. 3. It is indicated that as case of single bubble, twin-bubble formation also undergoes expansion (0–80 ms), elongation (80–240 ms) three stages. However, compared with perfect tear drop shape of single bubble, the asymmetrical deformation of twin-bubble may take place as a result of the interaction of neighboring bubble, which is closely related to orifice spacing. For case of $1D_o$, both bubbles initially grow spherically owing to dominant effect of surface tension during first stage. While during the second stage, the influence of buoyancy on bubbles become important gradually with the growth

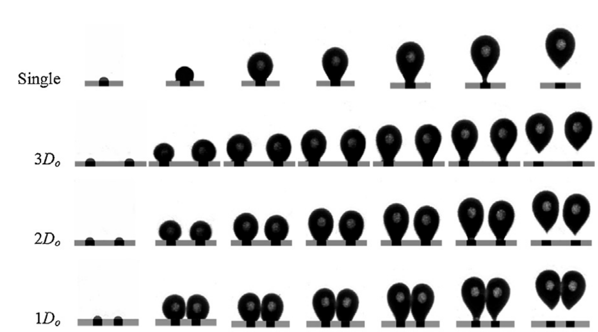

Fig. 3. Bubble shapes in CMC solution at different times.