International Journal of Multiphase Flow 92 (2017) 161–170

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

The minimum in-line coalescence height of bubbles in non-Newtonian fluid

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ARTICLE INFO

Article history:
Received 10 November 2016
Accepted 17 March 2017
Available online 18 March 2017

Keywords:
Bubble
Coalescence height
Non-Newtonian fluid
Multiphase flow

ABSTRACT

The minimum in-line coalescence height of bubbles generated from a submerged nozzle was investigated experimentally in shear thinning non-Newtonian fluid at lower Reynolds number (2∼60). Carboxymethyl cellulose sodium (CMC) aqueous solution and carbon dioxide were used as the liquid phase and the gas phase, respectively. The process of the formation, movement and in-line coalescence of bubbles was visualized and recorded by a high-speed digital camera. The influences of bubble size, bubble generation frequency and liquid property on the minimum in-line coalescence height of bubbles were investigated by changing nozzle diameter, gas flow rate and the mass concentration of CMC aqueous solutions. For a given liquid, the generating frequency and size of bubbles increased but the minimum coalescence height of in-line bubbles decreased when the nozzle diameter and gas flow rate were increased. When the nozzle diameter and gas flow rate were fixed, the shear-thinning effect of CMC aqueous solution became stronger with increasing CMC mass concentration, which led to the increase in both the terminal rise velocity and average acceleration of the trailing bubble, consequently, the minimum in-line coalescence height of bubbles decreased. An empirical correlation for estimating the minimum in-line bubble coalescence height was proposed, the calculating values accords well with experimental data with a mean relative deviation only 7.6%.

1. Introduction

The gas-liquid two-phase flow widely exists in many industrial fields, such as food, pharmaceuticals and petrochemical industries (Karamanev, 1996; Koynov et al., 2005; Terasaka and Shibata, 2003). Gas phase is usually dispersed into liquid as bubbles to form bubbly flow in gas-liquid contact equipment (Khamadieva and Böhm, 2006). The gas-liquid contact time and interfacial area have significant effect on the mass transfer, heat transfer, momentum transfer and chemical reaction rate in gas-liquid system (Aboulhasanzadeh and Tryggvason, 2014; Kishore et al., 2008; Martín et al., 2007; Radl and Khinast, 2007), and they could be remarkably changed by the behavior of bubble generation, motion, coalescence and breakup. The liquid phase in bubbly flow includes Newtonian fluids (such as water, and glycerin) or non-Newtonian fluids frequently encountered in industry and daily life including blood, protein, crude oil, polymer solution, etc., in which the liquid property plays a critical role for heat and mass transfer performance in the gas-liquid two-phase system (Martín et al., 2008). Compared with the Newtonian fluid, the non-Newtonian fluid exhibits many distinctive characteristics such as shear thinning, jet expansion, tubeless siphon, rod-climbing, etc. Consequently, the behavior of bubble generation, collision, coalescence and breakup in non-Newtonian fluids are extremely complicated (Celata et al., 2004; Chen et al., 2005; Lin and Lin, 2009), up to now, it remains still far from fully understanding.

The studies in past decades have demonstrated that movement of bubbles in gas-liquid system could be primarily attributed to two factors: the liquid property and the gas phase condition including bubble number, size and spatial distribution. Compared to the simplest single bubble rising behavior (Zhang and Fan, 2003), the process of generation, motion and interaction for a bubble cluster is considerably complex (Annaland et al., 2005; Mitre et al., 2010; Olmos et al., 2001). Katz and Meneveau (1996) investigated the impacts of Reynolds number, bubble diameter and bubble distance on the rising process of several spherical air bubbles in stagnant water, they found that the bubble relative motion velocity could be predicted by a model combined with the flow field and wake structure of a single bubble. Furthermore, the rise phenomenon of several vapor bubbles and the bubble train in one-

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http://dx.doi.org/10.1016/j.ijmultiphaseflow.2017.03.011
0301-9322/

Notation

D	nozzle inner-diameter, m
d	bubble diameter, m
g	gravitational acceleration, m·s^{-2}
K	consistency coefficient, Pa·s^{n}
L_i	distance between nozzle and leading bubble, m
n	flow index
Re	Reynolds number
t_i	time for leading bubble rise to L_i, s
t_T	total time of trailing bubble rising before collision with leading bubble, s
U_{b1}	leading bubble rise velocity, m·s^{-1}
U_{b20}	initial rising velocity of the trailing bubble, m·s^{-1}
x_i	distance between leading bubble and trailing bubble, m

Greek Letters

γ	shear rate, s^{-1}
μ	liquid viscosity, Pa·s
ρ	density of liquid phase, kg·m^{-3}
σ	surface tension, N·m^{-1}

component liquid systems R-114 and FC-72, were investigated respectively by Celata et al. (2004) and a prediction model for bubble rise velocity containing wake effect was obtained by analyzing the influence of bubble size. Differently, the bubble motion in non-Newtonian fluid would be dramatically affected by the liquid rheological property, the bubble shape, rise velocity and rise trajectory are more complicated. Esmaeili et al. (2015) thought that the effect of viscosity and elasticity for non-Newtonian fluid on the gas hold-up and bubble size distribution could be analyzed and described based on the ratio of elastic and viscous moduli (G'/G"). Moreover, Orvalho et al. (2015) studied the influences of bubble size, approach velocity and liquid viscosity on the movement and coalescence of pairwise bubbles, meanwhile, they also investigated the bubble contact time T and bubble coalescence efficiency E. Imaizumi et al. (2014) numerically investigated the rheological behavior of viscoelastic fluid around the rising bubbles using mesh deformation tracking method, and found that the negative wake of the leading bubble was stemmed from the accumulation and release of the shear strain energy. In addition, Jiang et al. (2010) studied the nonlinear dynamics of in-line nitrogen bubbles rising in non-Newtonian fluids (CMC aqueous solution) using multi-scale method.

Although the wake effect of the leading bubble for bubbly flow in non-Newtonian fluid has been verified by experimentally and could be quantitatively described (Monica et al., 2016), moreover, the terminal rising velocity of bubble could be also precisely predicted (Tomiyama et al., 2002), the understanding on the bubbles in-line coalescence phenomenon in non-Newtonian fluid are insufficient. To our best knowledge, the study on the minimum bubble in-line coalescence height remains still lacking so for, obviously, precise prediction on the height is of significant importance to design and tailor an expected reactor with proper dimension.

In this paper, the carboxymethyl cellulose sodium (CMC) aqueous solutions and carbon dioxide were used as the liquid phase and the gas phase, respectively. The effects of bubble size and bubble generation frequency on the minimum bubble in-line coalescence height were investigated by changing the nozzle diameter and gas flow rate. The mass concentration of the CMC aqueous solutions was varied to explore the role of the liquid rheological property on the minimum coalescence height. A prediction model of minimum in-line coalescence height of bubbles in shear thinning non-Newtonian fluid was proposed on the basis of the analysis of the terminal bubble rise velocity and wake effect.

2. Experimental apparatus and method

The experimental setup mainly contains two parts: the bubble column and image capture system as shown in Fig. 1. The bubble column consists primarily of the transparent rectangular Plexiglas tank with dimensions $0.15 \times 0.15 \times 1.4$ m. The wall effect of gas-liquid system could be negligible for the small bubbles with diameter less than 5 mm (Cheng et al., 2010). All experiments were carried out at room temperature (298.15 K) and atmospheric pressure (101.3 kPa). Firstly, carbon dioxide was introduced into the bottom of Plexiglas tank filled with CMC aqueous solution that has been saturated by CO_2 before starting experiment. Then the stable and continuous in-line bubbles generated through the nozzle submerged in the center of column bottom were recorded by the high-speed camera. The bubble size and generation frequency were controlled through changing the diameter of the immersed nozzle (0.7 mm, 0.9 mm and 1.2 mm) and the gas flow rate (5~30 ml min^{-1}), respectively. The gas flow rate was controlled through the pressure reducing valve and digital mass flow controller. The densities of CMC aqueous solutions were measured by densimeter (AntonPaar DMA5000, Germany) and the surface tensions were measured by the optical contact angle measuring device (OCA15EC, Dataphysics). Rheological properties of the solutions were obtained by a DV-III ultra programmable rheometer (Brookfield Engineering Laboratories, USA), the relation between the viscosity and shear rate was shown in Fig. 2 and it could be correlated by the power law model (Liu et al., 2013)

$$\mu = K\gamma^{n-1} \tag{1}$$

where μ is the liquid viscosity, K is the consistency coefficient, γ is the shear rate and n is the flow index. The rheological parameters and physical properties of CMC aqueous solutions are summarized in Table 1.

The image capture section includes the high-speed camera (Motion Pro Y5, REDLAKE Global, USA), light and computer. Corresponding software (MotionStudio) was appropriate and convenient to regulate exposure time and frame rate. The process of bubble generation, motion, coalescence in the gas-liquid system could be distinctly recorded.

The moment when the trailing bubble detached from the nozzle is set as zero. Subsequently, the trailing bubble rises steadily until colliding and coalescing with the leading bubble, the distance between the nozzle and the location of coalescence was defined as the minimum in-line bubbles coalescence height H_c. A whole coalescence process of in-line bubbles could be seen in Fig. 3.

3. Numerical methods

The flow field of bubbles was obtained by Fluent 6.2.26 (2D) software in this work. The interaction and motion of bubbles were simulated by the volume of fluid (VOF) method based on the piecewise linear interface representation (PLIC), the power-law model and the continuous surface force model (CSF). The continuity equation and the momentum equation could be described as follows:

$$\nabla \cdot \vec{u} = 0 \tag{2}$$

$$\frac{\partial}{\partial t}(\rho\vec{u}) + \nabla \cdot (\rho\vec{u}\vec{u}) = -\nabla p + \nabla \cdot (2\mu\vec{D}) + \vec{F_S} + \rho\vec{g} \tag{3}$$

where $\vec{\mu}$ is the velocity vector of bubble, $\vec{D}$ is the stress tensor, p is the pressure and $\vec{F_S}$ is the surface tension. The density and viscosity