International Journal of Multiphase Flow 58 (2014) 154–167

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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

Effects of hydrophilic particles on bubbly flow in slurry bubble column

Shimpei Ojima, Kosuke Hayashi, Akio Tomiyama *

Graduate School of Engineering, Kobe University, 1-1 Rokkodai, Nada, Kobe 657-8501, Japan

ARTICLE INFO

Article history:
Received 2 April 2013
Received in revised form 10 September 2013
Accepted 11 September 2013
Available online 20 September 2013

Keywords:
Bubble column
Slurry
Bubble coalescence
Simulation
Multi-fluid model

ABSTRACT

To investigate the effects of hydrophilic particles on slurry bubble flows in a bubble column, distributions of the local gas holdup and the bubble frequency are measured using an electric conductivity probe. Particles are made of silica and their diameter is 100 μm. The particle volumetric concentration C_S is varied from 0 to 0.40. The measured data imply that the presence of particles promotes bubble coalescence. The film drainage time for two coalescing bubbles in a quasi two-dimensional bubble flow in a small vessel is also measured to quantitatively evaluate the particle effect on coalescence. A particle-effect multiplier is introduced into a coalescence efficiency model by taking into account the data of film drainage time and is implemented into a multi-fluid model. The main conclusions obtained are as follows: (1) the local gas holdup and bubble frequency in slurry bubble flows decrease with increasing the particle concentration, (2) the hydrophilic particles enhance bubble coalescence and the enhancement saturates at $C_S \simeq 0.45$, (3) the particle effect on coalescence is well accounted for by introducing the particle-effect multiplier to the film drainage time, and (4) the multi-fluid model can give good predictions for the distribution of the local gas holdup in the slurry bubble column.

1. Introduction

Slurry bubble column reactors using the Fischer–Tropsch synthesis reaction have been utilized in various chemical plants. Since the interaction between bubbles and particles would play an important role in flow structures of the slurry bubble flow, many studies on effects of hydrophilic particles on the total gas holdup in the slurry bubble column have been carried out, e.g. Koide et al. (1984), Yasunishi et al. (1986), Khare and Joshi (1990), Li and Prakash (1997, 2000), Krishna et al. (1997), Gandhi et al. (1999), Vandu and Krishna (2004) and Mena et al. (2005). Most of them reported that the gas holdup decreases with increasing the particle concentration (Koide et al., 1984; Yasunishi et al., 1986; Krishna et al., 1997; Li and Prakash, 1997; Gandhi et al., 1999; Vandu and Krishna, 2004). Yasunishi et al. (1986) measured bubble frequencies in a slurry bubble column. They confirmed that as the particle concentration increases, the local gas holdup and bubble frequency decrease and the bubble size increases. They speculated that the interaction between bubbles and particles enhances the bubble growth at gas inlets, resulting in the reduction of gas holdup and bubble frequency. On the other hand, de Swart et al. (1996) observed slurry bubble flows in a pseudo two-dimensional column to investigate the effects of particles and found that the presence of particles promotes bubble coalescence. Most of the studies support the latter explanation on the effect of particles, that is, the hydrophilic particles enhance bubble coalescence, which makes bubble sizes larger and the bubble rising velocities larger, and therefore, the gas holdup decreases as the particle concentration increases (Hillmer et al., 1994; Krishna et al., 1997; Li and Prakash, 1997, 2000; Jianping and Shonglin, 1998; Gandhi et al., 1999; Vandu and Krishna, 2004). However the effects of particle concentration on the bubble frequency have not been made clear. Furthermore the particle effect on bubble coalescence has not been quantitatively investigated, so that it has not been taken into account in numerical simulations based on multi-fluid models (Chen et al., 2004; Troshko and Zdravistch, 2009).

In this study, distributions of local gas holdup and bubble frequency in a slurry bubble column were measured by using an electric conductivity probe to make clear the effects of hydrophilic particles on bubbly flows in the slurry bubble column. The slurry consisted of water and hydrophilic particles of 100 μm in diameter. A wide range of particle volumetric concentration, i.e. from 0 to 0.40 (0% to 40 %), was tested. A numerical method for predicting the slurry bubble flow was also proposed. A hybrid model consisting of a multi-fluid model and an interface tracking method is the basis of the numerical method (Tomiyama and Shimada, 2001; Tomiyama et al., 2006). The effect of particles on bubble coalescence was taken into account in a bubble coalescence model.

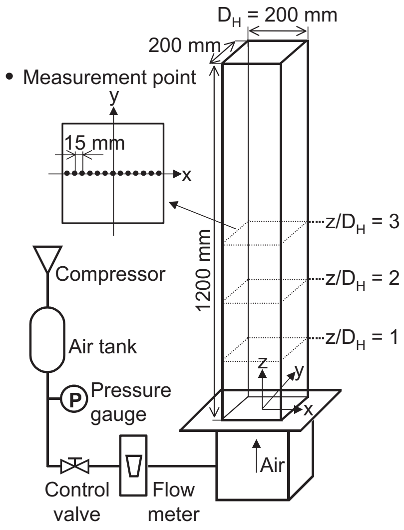
2. Bubbly flows in slurry bubble column

Fig. 1(a) shows the experimental setup. The column was made of acrylic resin and its width, depth and height were 200, 200

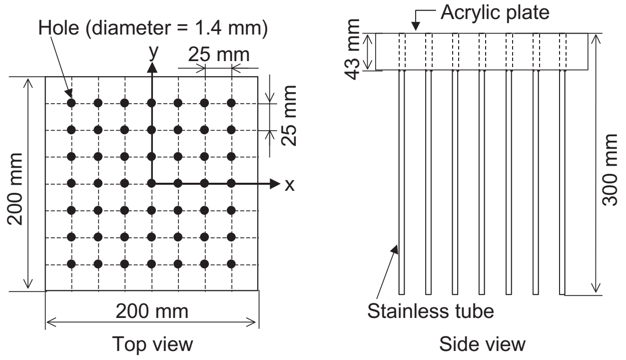
---

* Corresponding author.
E-mail address: tomiyama@mech.kobe-u.ac.jp (A. Tomiyama).

0301-9322/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijmultiphaseflow.2013.09.005



(a) Experimental setup



(b) Diffuser plate with 49 holes

Fig. 1. Experimental setup.

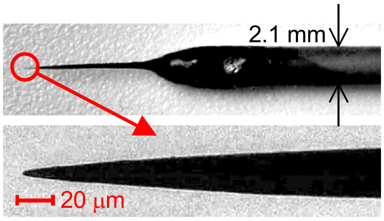


Fig. 2. Probe tip.

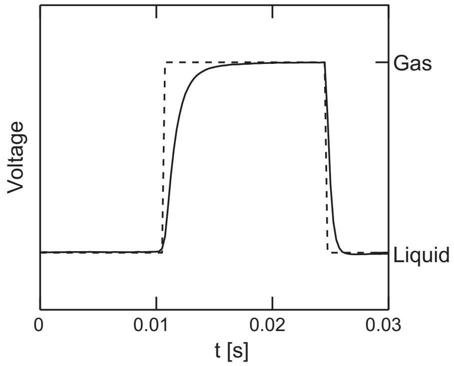


Fig. 3. Measured voltage (solid line) and processed binary signals (dashed line).

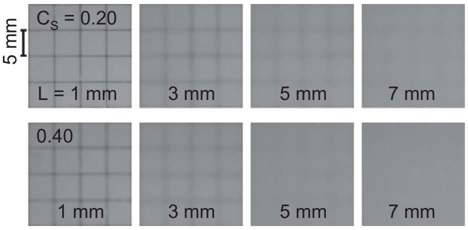


Fig. 4. Visibility of slurry (*L* is the distance from the column wall to the sheet).

and 1200 mm, respectively. The hydraulic diameter D_H of the column was 200 mm. It has been pointed out that the effect of D_H on the total gas holdup of air–water bubbly flows is not significant if $D_H > 150$ mm (Vandu and Krishna, 2004; Su et al., 2006), and therefore, the present results might be applicable not only to this column but also to larger columns. Air was supplied from the oil-free compressor (Hitachi, Ltd., SRL-2) to the column through the air chamber. As shown in Fig. 1(b), an air diffuser plate was placed at the column bottom on which 49 stainless tubes of 1.4 mm diameter and 300 mm long were flush mounted to make the flow rate from each hole the same by a large pressure drop in the tubes (Garnier et al., 2002). The air flow rate was measured using a flowmeter (Nippon flow cell, STO-4, full-scale accuracy ±3%). Water purified by using a Millipore system (Merck, Elix 3) at room temperature (20 ± 2 °C) and atmospheric pressure was used for the liquid phase. The temperature was measured by using the thermometer (Netsuken Ltd., SN3000, accuracy ± 0.5 °C). Spherical silica particles (Fuji Silysia Chemical Ltd., CARiACT®, grade code Q, product name Q-10) were used for the solid phase. The average diameter, apparent and true densities were 100 μm, 1.29×10^3 kg/m^3 and 2.25×10^3 kg/m^3, respectively, where the apparent density was evaluated by taking the volume-weighted average for the true density and density of water filling its pore volume. The particles were made of silica gel. It is known that pure silica particles are hydrophilic, e.g. the contact angle of pure silica particles measured by Galetl et al. (2010) is 15 ± 3 deg, so that the contact angle of the present particles would be within this range. The column was initially filled with slurry consisting of water and particles up to 800 mm above the diffuser plate. Superficial gas velocities, J_G, tested were 0.020 and 0.034 m/s. Maekawa et al. (2008) measured sphere-volume equivalent bubble diameter, d_B^{in}, at gas inlets using the same bubble column and at the same superficial gas velocities and confirmed that the Davidson–Schuler correlation (1960) agreed well with the measured d_B^{in} for gas–liquid two-phase bubbly flows. This correlation gives $d_B^{in} = 11$ and 13 mm at $J_G = 0.020$ and 0.034 m/s, respectively. The particle volumetric concentration, C_S, ranged from 0 to 0.40.

Local gas holdups were measured by using an electric conductivity probe at the two elevations $z/D_H = 2$ and 3, where z is the elevation from the diffuser plate. At each elevation, local gas holdups at 13 points in the x direction were measured as shown in Fig. 1(a). A platinum wire of 100 μm in diameter was used for the probe and a stainless tube of 2.1 mm in diameter supported the wire. The probe tip shown in Fig. 2 was sharpened to reduce its effects on bubble motion by electro polishing. The resultant tip diameter was less than 4 μm. The sampling rate was 4 kHz and the sampling time was 900 s for each measurement point. Fig. 3 shows an example of the measured voltage signals. The voltage steeply changes at time $t = 0.011$ s, at which the tip pierced a bubble. After the bubble passage, the voltage returned to the value of the liquid phase. These voltage signals were analyzed using a two-point multiple threshold discrimination (Žun et al., 1995) to obtain the time-averaged gas holdup, ε_B. The processed signal is also shown in the figure by a dashed-line. The