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Effects of liquid height on gas holdup in air–water bubble column

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ABSTRACT

Effects of the initial liquid height, H_0, of air–water bubble columns on the total gas holdup, α_G, were investigated in this study. Systematic databases of α_G in a rectangular and a cylindrical column of the hydraulic diameter D_H of 200 mm were obtained. An image processing method was applied to high-speed video images of the liquid height to obtain accurate gas holdup data. Ranges of the superficial gas velocity, J_G, and the dimensionless liquid height, H_0^* (= H_0/D_H), were $0.025 \leqslant J_G \leqslant 0.40$ m/s and $1.5 \leqslant H_0^* \leqslant 5.0$, respectively. The bubbly flows observed in these ranges could be classified into either the heterogeneous bubbly flow consisting of bubbles much smaller than D_H or that with huge bubbles of the column-width scale. The main parameter governing the flow regime transition was J_G. The gradient, $d\alpha_G/dJ_G$, of α_G with respect to J_G was of use in flow regime identification. The increase in H_0^* decreased α_G because a long bubble residence time at a high H_0^* leads to the increase in the mean bubble diameter due to bubble coalescence. The Froude number using H_0 as a characteristic length well correlates α_G at various H_0. An empirical correlation of α_G in terms of the Froude number was then proposed. Comparing the correlation with the α_G data showed that the correlation can give good evaluations of α_G in the rectangular and cylindrical columns by tuning model parameters.

1. Introduction

Accurate prediction of the total gas holdup, α_G, in a bubble column is of great importance in column design. Many studies on α_G, therefore, have been carried out to elucidate effects of the superficial gas velocity, J_G, the hydraulic diameter, D_H, of the column and fluid properties [1–5]. Various α_G correlations have also been proposed [2,4,6–12]. In spite of a large number of studies on α_G, only a few of them investigated effects of the initial liquid height, H_0, on α_G [13–17]. Though it is known that α_G decreases with increasing H_0, this effect has not been taken into account in α_G correlations.

Measurements of α_G in a rectangular bubble column were carried out in this study at various dimensionless liquid heights, H_0^* (= H_0/D_H), to investigate effects of H_0 on α_G and flow structure. An empirical correlation of α_G expressed in terms of a dimensionless group including H_0 was then obtained. The applicability of the correlation to α_G in cylindrical bubble columns was also examined.

2. Experimental

2.1. Experimental setup

Fig. 1 shows the experimental setup. The rectangular column with the square cross section was made of transparent acrylic resin for flow visualization. The column height was 2000 mm. Since effects of D_H on α_G are known to be weak for $D_H \geqslant 150$ mm [1,3,16], the column width was set at 200 mm, so that D_H is also equal to 200 mm.

Air supplied from the compressor (Iwata, RDG-150C) flowed into the column through the air dryer (Iwata, SLP-1501 EB) and the air chamber. The air diffuser plate of 5 mm in thickness (Fig. 2) was placed at the bottom of the column. The hole diameter, d_h, the number of holes, N_h, the hole pitch, p_h, and the ratio, r_h, of the total opening area to the area of column cross-section were 1.4 mm, 49, 25 mm and 0.18%, respectively.

Water at room temperature (19 ± 1 °C) and atmospheric pressure was used for the liquid phase. The water was supplied from the Amagasaki purification plant in Japan and its electrical conductivity is 170 μS/cm. The initial liquid height, H_0, was varied from 300 to 1000 mm. The ratio, H_0^*, of H_0 to D_H, therefore, ranged from 1.5 to 5.0.

The gas volume flow rate was measured using the flowmeters (Nippon flow cell, NVP-I, FLT-H; Tokyo Keiso, AM-1000, full-scale accuracy ±1.5%). The measured flow rate was converted into the volume flow rate at the middle height of the liquid level by taking into account gas expansion due to the decrease in static pressure. The range of J_G defined at the latter location was from 0.025 ± 0.001 to 0.40 ± 0.01 m/s, where the uncertainties were evaluated at 95% confidence.

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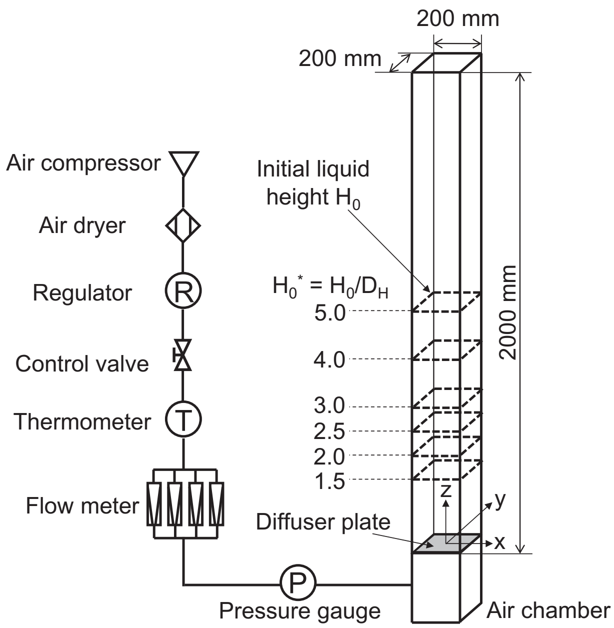

Fig. 1. Experimental setup.

2.2. Measurement method

The gas holdup in the bubble column was measured by processing images of the free surface. The images were taken using a high-speed video camera (IDT, Motion Pro X-3) with the spatial and temporal resolutions of 0.36 mm/pixel and 1/100 s, respectively. As shown in Fig. 3, they were transformed into binary images. Then the instantaneous liquid height, $H(x, t)$, at the horizontal position x and the time t was detected using a region growing method [18]. The mean liquid height at t was calculated as

$$\overline{H(t)} = \frac{1}{D_H}\int_{-D_H/2}^{D_H/2} H(x,t)dx \tag{1}$$

The total gas holdup was then calculated as

$$\alpha_G = \frac{1}{T}\int_{t_1}^{t_1+T} \frac{\overline{H(t)} - H_0}{\overline{H(t)}}dt \tag{2}$$

where t_1 is the time, at which the recording was started, and T the sampling time. Instantaneous and time-averaged $\overline{H(t)}$ at $J_G = 0.40$ m/s are shown in Fig. 4. The instantaneous $\overline{H(t)}$ fluctuates largely, whereas the time-averaged $\overline{H(t)}$ for $T > 2$ s converges to within ±0.5% deviations. The sampling time was therefore set at 30 s to assure the accuracy of mean values. The relative standard errors in α_G were evaluated by repeating the measurement 10 times under the conditions of $J_G = 0.025$ and 0.40 m/s and $H_0^* = 1.5$ and 5.0. The errors in α_G were within ±2% in all the cases.

Successive gray-scale images of flows were taken by using a high-speed video camera (Fastcam SA-X2, Photron Ltd.). The imaging region was the whole column. The shutter speed and the frame rate were 1/20,000 and 500 fps, respectively. The sampling time was 20 s (10,000 frames). The spatial resolution of the flow visualization was 0.49 mm/pixel, i.e. about 200 pixels for the column width. Four fluorescent lights were used for back illumination.

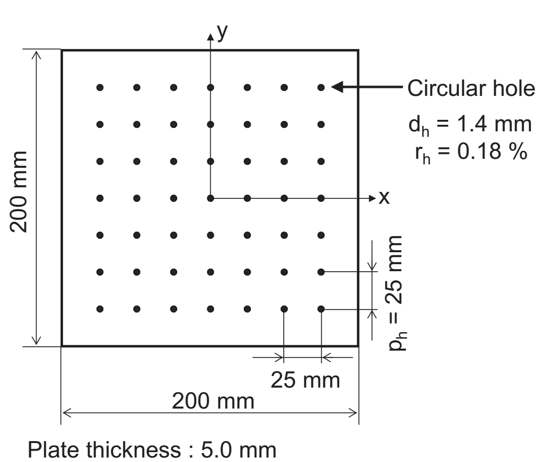

Fig. 2. Diffuser plate.

3. Results and discussion

3.1. Flow structure and gas holdup

Images of bubbly flows at $H_0^* = 1.5$ are shown in Fig. 5(a). The superficial gas velocity increases from the left to the right figures. At $J_G = 0.025$ m/s, bubbles generated from the diffuser plate were likely to immediately accumulate toward the column center region. The bubble number density was therefore relatively higher in the center region than in the near wall region, as reported in our previous study [19]. The high bubble number density region, in other words, the high gas holdup region, consisting of bubble swarms fluctuated in time. Due to the strong liquid updraft by the bubble swarms in the center region, column-scale vortical structures were formed. Increasing J_G made the bubble number density and the bubble size higher and larger, respectively. At $J_G = 0.10$–0.15 m/s, many bubbles of several-centimeter sizes were formed here and there. Such bubbles were not observed in the vicinity of the diffuser plate, and therefore, they were formed by bubble coalescence.

Further increase in J_G caused a change in the flow structure, i.e. huge bubbles of the column-width scale were formed for $J_G \geqslant 0.20$ m/s. The frequency of huge bubble formation at $J_G = 0.20$ m/s was however low compared with the higher J_G cases. The flow structure in the time duration without the presence of huge bubbles was close to that at $J_G = 0.15$ m/s. Hence, the flow at $J_G = 0.20$ m/s was in a transitional regime. Most of huge bubbles were formed at $z/D_H \sim 2$, where z is the height measured from the bottom of the column. This implies that huge bubbles required a certain time duration to grow. Passages of huge bubbles strongly agitated the flow over the whole column cross section. Though both of the above-mentioned flows are heterogeneous, the former and latter are referred to as regimes 1 and 2, respectively, in the following discussion.

Fig. 5(b) and (c) shows flows at higher H_0^*. Being similar to the flows in Fig. 5(a), the flows can also be classified as either regime 1 or regime 2: the flows for $J_G \leqslant 0.15$ m/s are in regime 1 and those for $J_G \geqslant 0.25$ m/s are in regime 2 because of the presence of huge bubbles. Hence the flow regime mainly depends on J_G and the effect of H_0 on it is not large. The formation of huge bubbles in regime 2 was also observed at $z/D_H \sim 2$. They did not break up into small bubbles and rose up to the free surface. The huge bubbles possessed strong wake entrainment effects, i.e., many bubbles entrained into their wake regions were drifted upward.

Total gas holdups are shown in Fig. 6. The α_G data are also given in Appendix. The α_G monotonously increases with J_G and this tendency is similar to that in the so-called pure heterogeneous regime [20]. The gradient $d\alpha_G/dJ_G$ evaluated by using a backward difference scheme is shown in Fig. 7. It decreases with increasing J_G for $J_G < 0.2$ m/s, whereas it is almost constant for $J_G > 0.2$ m/s. Since