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Effects of column diameter and liquid height on gas holdup in air-water bubble columns

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ABSTRACT

Experiments on the total gas holdup, α_G, in air–water cylindrical bubble columns were carried out to investigate effects of the column diameter, D_H, and the initial liquid height, H_0, on α_G. Ranges of D_H and H_0 were $160 \leqslant D_H \leqslant 2000$ mm and $400 \leqslant H_0 \leqslant 4000$ mm, respectively. The superficial gas velocity, J_G, was varied from 0.025 to 0.35 m/s. The characteristics of gas holdup showed that all the flows in the present experiments were pure heterogeneous. The following conclusions were obtained for α_G in air–water bubble columns: (1) the effects of D_H and H_0 on α_G are negligible when scaling up from small to large bubble columns, provided that α_G in the small columns are obtained for $D_H \geqslant 200$ mm and $H_0 \gtrsim 2200$ mm. The height-to-diameter ratio is useless in evaluation of the critical height, above which α_G does not depend on H_0, (2) for the above ranges of D_H and H_0, Akita-Yoshida's and Koide's correlations can give good evaluations of α_G for a wide range of J_G by tuning the model constants, (3) for $D_H < 200$ mm, the decrease in D_H increases the population of large bubbles, which results in the decrease in α_G, and (4) for $H_0 \lesssim 2200$ mm and $D_H \geqslant 200$ mm, α_G at a constant J_G decreases with increasing H_0 and approaches an asymptotic value, and the Froude number using J_G and H_0 as the characteristic scales well correlates α_G in this regime.

1. Introduction

Bubble column reactors have been widely used in chemical, biochemical and metallurgical industries and so on [1,2]. The total gas holdup, α_G, of a bubble column is basic information required in column design, scale-up and the optimization of operating conditions. There are various parameters affecting α_G such as the superficial gas velocity J_G, column geometries, fluid properties, the types of gas spargers and so on. Many studies on the effects of these parameters have therefore been carried out [3–15]. Among the geometric parameters, the column diameter, D_H, and the liquid height in a column are of great importance in scale-up [7]. When dealing with the effects of the liquid height on α_G, the liquid height, H_C, in operation (aeration height) or the initial liquid height, H_0, before starting aeration has often been used. It is known that D_H and H_0 affect α_G when they are less than certain critical values, whereas α_G is independent of D_H and H_0 at larger values [3–7,11]. Hence the knowledge on α_G in lab-scale bubble columns obtained for D_H and H_0 larger than the critical values would be useful in designing pilot- and industrial-scale columns [7].

Wilkinson et al. [7] investigated the effects of D_H on α_G at several D_H and system pressures. Comparisons between α_G at $D_H = 150$ and 230 mm showed that D_H has little influence on α_G for the pressure ranging from 0.1 to 0.62 MPa. They also compared their data at $D_H = 150$ mm with those at $D_H = 50$ mm [16] and pointed out that the latter are much larger than the former due to the presence of wall affecting the flow structure. Many studies after Wilkinson et al. [7] assumed that α_G is independent of D_H, provided that $D_H \geqslant 150$ mm. However, in these comparisons between α_G at different D_H, H_0 were not the same. Lemoine et al. [11] investigated effects of D_H on α_G in alumina–loaded slurry bubble columns by using a neural-network-based α_G correlation developed by Behkish et al. [17,18]. The correlation indicated that D_H affects α_G even for $D_H > 150$ mm and D_H is required to be >700 mm to make α_G independent of D_H. Leonard et al. [2] supported this criterion in their recent review paper for bubble column reactor technology. The effects of H_0 were however not accounted for in the neural-network-based correlation as a parameter in the input layer of the neural network. The uncertainty in the predicted α_G due to the neglect of the H_0 effect is therefore not clear. Although Lemoine et al. [11] pointed out that the α_G data obtained by Vandu and Krishna [19] showed that α_G decreased with increasing D_H up to $D_H = 630$ mm, H_0 also increased with increasing D_H in their experimental condition.

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Thus the D_H effect on α_G must be investigated while keeping H_0 constant. Koide et al. [20] measured α_G in a large-scale air–water bubble column of $D_H = 5500$ mm and compared α_G with those in columns of D_H from 100 to 600 mm. In spite of some scatter in the α_G data, α_G in the large D_H column were similar to those in the smaller columns. Koide et al. [5] also investigated the effects of D_H on α_G in air–water bubble columns for $100\ \text{mm} \leqslant D_H \leqslant 300$ mm and at $H_0 = 1500$ mm. They concluded that α_G in the air–water heterogeneous bubbly flows is independent of D_H. The data however clearly show some D_H effect for D_H less than 218 mm.

In contrast to the studies on D_H, there are only a few studies on the H_0 effect on α_G [7,10,12,14,15]. As is well known, the increase in H_0 decreases α_G at H_0 smaller than a certain critical value. Several criteria for the critical H_0 have been proposed in the dimensionless form as H_0/D_H, e.g. $H_0/D_H = 4$ [21], 5 [7] and 7 [5]. Most of studies on bubble columns therefore carried out experiments for $D_H > 150$ mm and $H_0/D_H > 5$. The critical H_0 is 10,000 mm for the Wilkinson criterion when $D_H = 2000$ mm. It has not been investigated using large bubble columns whether or not H_0 affects α_G up to that large value of H_0. The H_0/D_H might be an inappropriate indicator for representing the effects of H_0 at least for $D_H \geqslant 150$ mm since D_H should be excluded in consideration of the dynamic similarity if D_H plays no role in α_G.

Experiments on α_G of air–water heterogeneous bubbly flows in a column of $D_H = 200$ mm at various H_0 up to 1000 mm were carried out in our previous study [14]. The parameters in the experiments were J_G and H_0 only, and the α_G data were well correlated in terms of the Froude number defined by using J_G and H_0 as the characteristic scales and an α_G correlation in terms of the Froude number was proposed. However the applicability of the Froude number in correlating α_G in columns of different sizes has not been examined.

Total gas holdups in air–water bubble columns were measured in this study to obtain systematic databases of α_G at various H_0 and D_H, which allowed us to investigate the D_H and H_0 effects independently. The ranges of D_H, H_0 and J_G were $160 \leqslant D_H \leqslant 2000$ mm, $400 \leqslant H_0 \leqslant 4000$ mm and $0.025 \leqslant J_G \leqslant 0.35$ m/s, respectively.

2. Experimental

2.1. Experimental setup

Fig. 1 shows the experimental setup. The cylindrical bubble columns of $D_H = 160$, 200 and 300 mm were used. They were made of transparent acrylic resin for visualization. The stainless steel diffuser plate of 5 mm thickness was placed at the bottom of the columns. Bubbly flows in bubble columns are often classified into either homogeneous or heterogeneous flow regimes. The former tends to be formed at low J_G, and the increase in J_G makes flows heterogeneous. Flows in bubble columns having diffuser plates with gas inlet holes of large diameters, d_h, can however be heterogeneous even at low J_G as reported in literature, e.g. Wilkinson et al. [7], Zahradník et al. [9] and Ojima et al. [22]. The bubbly flow is referred to as the pure-heterogeneous flow when the homogeneous regime does not appear, and the pure-heterogeneous regime is realized for $d_h > 1$ mm [9]. The present study focused only on α_G in the pure-heterogeneous regime. Therefore $d_h = 1.4$ mm in the present experiments. The ratio, r_h, of the total hole area to the cross-sectional area of the column was set at 0.18%. Consequently the numbers, N_h, of holes were 23, 37 and 83 for $D_H = 160$, 200 and 300 mm, respectively. The holes were located so as to be equidistant from each other as shown in Fig. 2, where the hole pitch, p_h, was 25 mm.

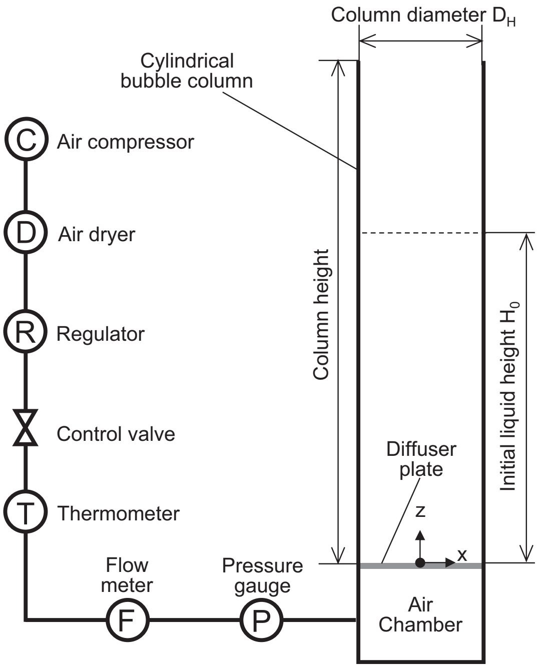

Fig. 1. Experimental setup.

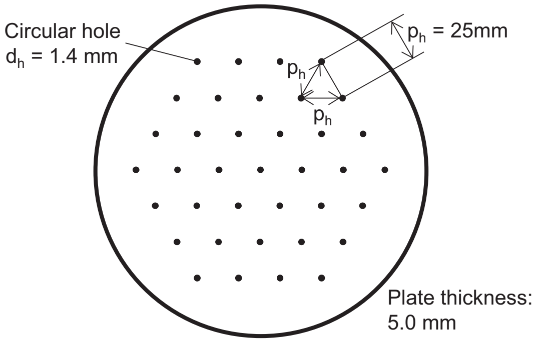

Fig. 2. Diffuser plate ($N_h = 37$).

The bubble column was initially filled with tap water at room temperature (19 ± 1 °C) and atmospheric pressure. The H_0 was varied from 400 to 1800 mm. Air supplied from the compressor (Iwata, RDG-150C) flowed into the column through the air dryer (Iwata, SLP-1501 EB), the air chamber and the diffuser plate. 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 was from 0.025 ± 0.001 to 0.35 ± 0.01 m/s, where the uncertainties were evaluated at 95% confidence.

The physical properties of the gas and liquid phases are as follows: the liquid density $\rho_L = 998$ kg/m^3, the gas density $\rho_G = 1.2$ kg/m^3, the liquid viscosity $\mu_L = 1.0 \times 10^{-3}$ Pa·s, the gas viscosity $\mu_G = 1.8 \times 10^{-5}$ Pa·s, and the surface tension $\sigma = 0.072$ N/m.

Two larger bubble columns of 7000 mm high were also used to measure α_G for larger H_0, i.e. up to $H_0 = 4000$ mm. Their D_H were 450 and 2000 mm. The spargers for the former and latter were a plate-type and an arm-type sparger, and (d_h, N_h, r_h, p_h) = (5.0 mm, 152, 1.88%, 22 mm) and (5.0 mm, 372, 0.23%, 10 mm) respectively. The J_G was ranged from 0.057 ± 0.002 to 0.28 ± 0.01 m/s. The water