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Simulation of Gas Holdup in a Bubble Column with a Draft Tube for Gas Dispersion into an Annulus

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Simulation of the gas holdup E_G in a bubble column (ID: 16 cm; height: 100 cm) with a draft tube for an air–water system and for gas dispersion into an annulus was performed using CFX software. The gas holdup obtained by the simulation $E_{G,sim}$ was found to strongly depend on the bubble diameter. $E_{G,sim}$ was nearly equal to the correlations of Yamashita (1998) and Koide et al. (1983) for $E_G < 0.1$, whereas $E_{G,sim}$ was much larger than their correlations when $E_G > 0.1$.

1. Introduction

Bubble columns with a draft tube are extensively used as bioreactors and gas–liquid reactors. The gas holdup E_G is a critical parameter when designing and scaling up bubble columns. Many studies have investigated E_G. Recently, the use of Computational Fluid Dynamics has remarkably increased due to the availability of inexpensive and powerful PCs and effective software. Simulations are very useful for researching and scaling up bubble columns. In this study, we simulated the effects of the bubble diameter, lower clearance C, inner diameter D_i of the draft tube, and the superficial gas velocity U_G on E_G in a bubble column with a draft tube for gas dispersion into an annulus and an air–water system. The results obtained were compared with the correlations of Yamashita (1998) and Koide et al. (1983).

2. Previous Experimental Studies

2.1 Gas holdup E_G in bubble columns without a draft tube

Hughmark (1967) obtained the following correlation for E_G:

$$E_G = [2 + (0.35/U_G)\,(\rho_L\gamma/72)^{1/3}]^{-1} \qquad (1)$$

Otake et al. (1981) studied gas holdup in a bubble column (ID: 5 cm; height: 150 cm) with upward and downward liquid flow and obtained the following correlation for E_G for bubbly flow:

$$(U_G/E_G) - u_L/(1-E_G) = 18.74(\gamma d^2 g^{-1}\rho_L^{-1})^{1/6}(1-E_G) \qquad (2)$$

Bando et al. (1988) studied gas holdup in bubble columns and developed the following correlation for E_G for bubbly flow in the range D = 5–28 cm:

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$$U_G/E_G = V_{BF} + 1.20(U_L+U_G) \quad (3)$$

$V_{BF} = 27$ cm/s for water

$$U_G/E_G = V_{CTF} + 1.36(U_L+U_G) \quad (4)$$

$V_{CTF} = 67$ cm/s for churn-turbulent flow and $D > 14$ cm

Akita et al. (1988) obtained the following correlation:

$$E_G/(1-E_G)^4 = 0.2\,(gD^2\rho_L\gamma^{-1})^{1/8}\,(gD^3\gamma^{-2})^{1/12}\,U_S(gD)^{-0.5} \quad (5)$$

$$U_S = U_G - U_L E_G/(1-E_G) \quad (6)$$

Yamashita and Inoue (1975) developed the following correlation for an air–water system:

$$E_G = U_G/\{2.2U_G + 0.3(gD)^{0.5}\} \quad (7)$$

Hills (1976) obtained the following correlation:

$$U_G/E_G = 24 + 1.86(U_G+U_L)^{0.93} \quad (8)$$

Seno et al. (1990) developed the following correlation for bubbly flow in a bubble column (ID: 4.6 cm; height: 136 cm):

$$U_G/E_G - U_L/(1-E_G) = 1.24(U_G\mu_L\gamma^{-1})^{0.23}(g\mu_L{}^4\rho_L{}^{-1}\gamma^{-3})^{-0.095}(gd_b)^{0.5}(1-E_G) \quad (9)$$

2.2 Gas holdup E_G in bubble columns with a draft tube for gas dispersion into an annulus

Koide et al. (1983) presented the following correlation of E_G in the bubble column for gas dispersion into an annulus:

$$E_G/(1-E_G)^4 = 0.160(U_G\mu_L\gamma^{-1})^{0.964}(\rho_L\,\gamma^3 g^{-1}\mu_L{}^{-4})^{0.294}(D_i/D)^{-0.222}(d/D)^{-0.0237} \quad (10)$$

Yamashita (1998) studied the effect of a draft tube on gas holdup in a 16 cm-ID bubble column for gas dispersion into an annulus and obtained the following correlation for $C = 3$–12.5 cm, $\alpha = 0.375$–0.875, $L_d = 50$–140 cm, and $H_L = 60$–155 cm:

$$E_G = E_S(1-\alpha^N) \quad (11)$$

$$N = 15.6(L_d/H_L)^{-0.30} \quad (12)$$

2.3 Average bubble diameter

Gas holdup in bubble columns is thought to be strongly dependent on the bubble diameter. Akita and Yoshida (1974) measured the bubble size by a photographic method and obtained the following correlation for the Sauter mean diameter d_s in a bubble column:

$$d_s/D = 26(D^2 g\rho_L/\sigma)^{-0.5}(gD^3/\nu^2)^{-0.12}(U_G\,g^{-0.5}D^{-0.5})^{-0.12} \quad (13)$$

The following equation is derived from Eq. (13) for d_s of an air–water system at 293 K:

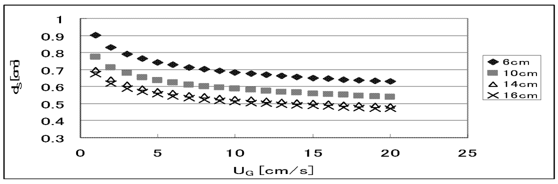

Fig. 1 Effect of U_G and D on Sauter mean diameter d_s in a bubble column for an air–water system at 293 K.

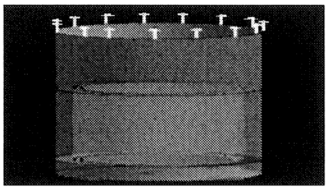

Fig. 2 Model of bubble column with a draft tube

$$d_s = 1.543 U_G^{-0.12} D^{-0.3} \tag{14}$$

Fig. 1 shows the dependence given by Eq. (14) for the Sauter mean diameter d_s on U_G and D in a bubble column. The dependence on U_G occurs because fluidization in the bubble column becomes more vigorous and more small bubbles are generated due to bubble breakup at high gas velocities.

3. Simulation by CFX Software

Simulations were performed using CFX software. Fig. 2 depicts the simulation model of a bubble column with a draft tube. The bubble column had a diameter D of 16 cm and a height of 100 cm. The mesh size was 10 mm. The red regions on the base indicate gas inlets, which were treated as source points in the CFX software. The four gas inlets were set at R = 7.25 cm at the base of the bubble column. There was no source point at the center of the base. The gas inlets were 1 cm in diameter. The inner diameter D_i of the draft tubes was varied in the range 2–12 cm. The draft tubes were 5 mm thick and had a length L_d of 50 cm and a lower clearance C in the range 0–10 cm.

The following simulation conditions were used. The gas was air and the liquid was water; both were at 298 K. A three-dimensional simulation was performed using the Euler–Euler method. The gas turbulence was modeled using the dispersed phase zero equation. The shear stress transfer model was used as the turbulence model for the liquid. The Grace equation with a volume fraction correction factor n = 2 was used for the drag force, while the Lopez de Bertodano equation with a dispersion coefficient of 0.3 was used for the turbulent dispersion force. The Sato enhanced eddy viscosity was used for the turbulence transfer between the gas and the water. The simulation was performed for non-steady-state conditions. Although the lift force, the virtual mass force, and the wall effect are known to be non-drag forces acting on bubbles, they were neglected in this simulation.

4. Results and Discussion

4.1 Effect of bubble diameter d_b on gas holdup E_G with a draft tube

Figs. 3 and 4 show the effects of d_b and U_G on $E_{G,sim}$ in bubble columns with D_i = 2 and 12 cm, respectively. These figures show that $E_{G,sim}$ at U_G = 5 cm/s is much larger than that at U_G = 1 cm/s and that the effect of d_b on $E_{G,sim}$ at U_G = 5 cm/s is also much larger than that at U_G = 1 cm/s. The reason for this is not clear. Figs. 3 and 4 clearly show that $E_{G,sim}$ has a slight dependence on d_b in the range d_b = 3–10 mm. The rising velocity of

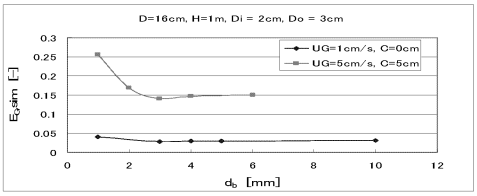

Fig. 3 Effect of d_b and U_G on $E_{G,sim}$ for D_i = 2 cm.

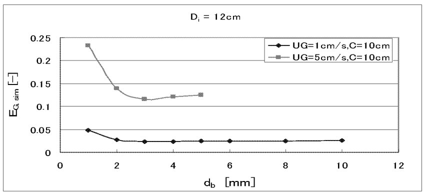

Fig. 4 Effect of d_b and U_G on $E_{G,sim}$ for D_i = 12 cm and C = 10 cm.

the bubbles increases with increasing d_b. Therefore, E_G decreases with increasing d_b. The minimum in $E_{G,sim}$ in Figs. 3 and 4 may be a result of using the Grace model.

4.2 Effect of U_G on E_G in a bubble column with no draft tube

Fig. 5 shows the effect of U_G on $E_{G,sim}$ at d_b = 3 mm in a 16-cm-ID bubble column with no draft tube. $E_{G,sim}$ increased increasing with U_G. Fig. 5 also compares $E_{G,sim}$ with $E_{G,exp}$ gas holdups obtained from the correlations reported by many different researchers. $E_{G,sim}$ is nearly equal to $E_{G,exp}$ when U_G < 5 cm/s. However, $E_{G,sim}$ is much larger than $E_{G,exp}$ when U_G > 5 cm/s and it approaches the $E_{G,exp}$ values of Hills (1976) and Bando et al. (1988), which are much larger than those obtained by other investigators. The reason why their values are much greater than those of other researchers is currently unclear, but their values are considered to be overestimates. $E_{G,sim}$ is larger than $E_{G,exp}$ (except for those of Hills (1976) and Bando et al. (1988)) for the following reason. For U_G > 5 cm/s, churn-turbulent flow occurs in the bubble column and large bubbles rise. Therefore, the gas holdup is smaller than $E_{G,sim}$, because $E_{G,sim}$ was obtained for d_b = 3 mm. For U_G > 5 cm/s, the simulation needs to consider the effect of bubble coalescence and breakup.

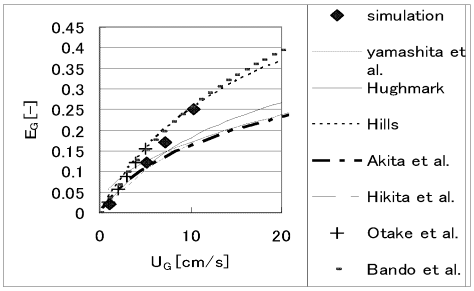

Fig. 5 Effect of U_G on gas holdup in bubble column with no draft tube.

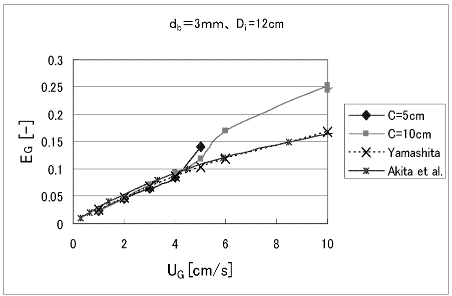

Fig. 6 Effect of U_G on E_G at D_i = 12 cm and d_b = 3 mm

4.3 Effect of U_G on gas holdup in a bubble column with a draft tube for gas dispersion into an annulus

Fig. 6 shows the effect of U_G on $E_{G,sim}$ at D_i = 12 cm, C = 5 and 10 cm, and d_b = 3 mm in a bubble column with gas in an annulus. $E_{G,sim}$ increased with increasing U_G. For $U_G \leq 5$ cm/s, $E_{G,sim}$ is nearly equal to the gas holdups obtained by Yamashita and Inoue (1975) and Akita et al. (1988). However, $E_{G,sim}$ is much larger than their gas holdup when $U_G \geq 5$ cm/s because churn-turbulent flow occurs in the bubble column and large bubbles rise. In this study, $E_{G,sim}$ was obtained for $d_b = 3$ mm. $E_{G,sim}$ at $C = 5$ cm was nearly equal to that at $C = 10$ cm. Yamashita (1998) also found that gas holdup does not depend on C for $C \geq 3$ cm.

Fig. 7 shows the effect of U_G on $E_{G,sim}$ at $D_i = 2$ cm, $C = 0$ and 5 cm, and $d_b = 3$ mm in a bubble column for gas in an annulus. $E_{G,sim}$ also increased with increasing U_G. For $U_G \leq 4$ cm/s, $E_{G,sim}$ is nearly equal to the gas holdup obtained by Yamashita and Inoue (1975) and Akita et al. (1988), whereas for $U_G \geq 4$ cm/s, $E_{G,sim}$ is much larger than their gas holdups. $E_{G,sim}$ at $C = 0$ cm was nearly equal to that at $C = 5$ cm. This may be because D_i had a limited effect on E_G due to the small D_i.

4.4 Comparison of $E_{G,sim}$ with gas holdups of previous correlations

Fig. 8 compares $E_{G,sim}$ with the correlation given by Eq. (11) obtained by Yamashita (1998) $E_{G,Yama}$. E_S in Eq. (11) represents the gas holdup in a bubble column without a draft tube. Therefore, E_G given by Eq. (7) was used for E_S. For $E_G < 0.1$, $E_{G,sim}$ is nearly equal to $E_{G,Yama}$, which was calculated using Eq. (11). However, for $E_{G,Yama} > 0.10$, $E_{G,sim}$ is much larger than $E_{G,Yama}$. This may be because larger bubbles rise when $E_{G,Yama} > 0.10$.

Fig. 9 compares $E_{G,sim}$ and the gas holdup given by Eq. (10) obtained by Koide et al. (1984) $E_{G,Koide}$. For $E_{G,Koide} < 0.13$, $E_{G,sim}$ is nearly equal to $E_{G,Koide}$, whereas $E_{G,sim}$ is much larger than $E_{G,Koide}$ when $E_{G,Koide} > 0.13$. The explanation for this may be the same as that given for Fig. 8.

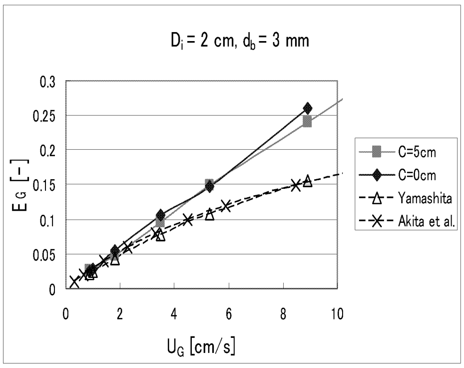

Fig. 7 Effect of U_G on E_G at $D_i = 2$ cm and $d_b = 3$ mm.

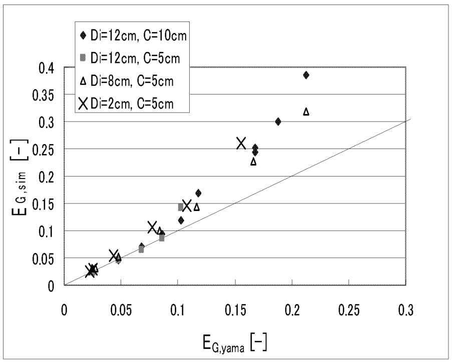

Fig. 8 Comparison of $E_{G,sim}$ and Eq. (11) by Yamashita (1998)

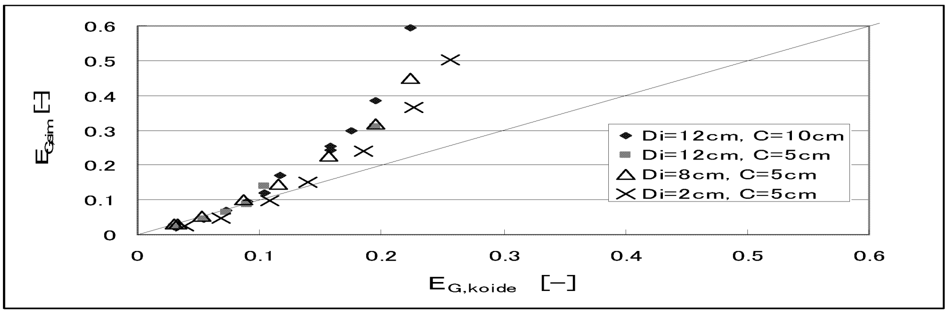

Fig. 9 Comparison of $E_{G,sim}$ and Eq. (10) by Koide et al. (1983)

5. Conclusion

1) For $U_G > 5$ cm/s, the simulation must consider bubble coalescence and breakup.
2) $E_{G,sim}$ was nearly equal to the correlations for the gas holdup obtained by Yamashita (1998) and Koide et al. (1984) for gas holdups smaller than 0.1. However, for gas holdups larger than 0.1, $E_{G,sim}$ became much larger than the correlations for the gas holdup obtained by Yamashita (1998) and Koide et al. (1983).

Nomenclature

C = clearance between lower end of draft tube and bottom of bubble column, d = hole diameter of gas inlet, d_b = bubble diameter, d_s = Sauter mean diameter of bubble, D = inner diameter of bubble column, D_i = inner diameter of draft tube, D_o = outer diameter of draft tube, E_G = average gas holdup in bubble column, $E_{G,exp}$ = E_G obtained in correlations obtained in earlier studies, $E_{G,sim}$ = E_G obtained from simulation, E_s = gas holdup in bubble column with no draft tube, g = gravitational acceleration, H_L = height of clear liquid, L_d = length of draft tube, n = volume fraction correction factor of the Grace model, N = parameter defined by Eq. (12), R = radial distance from the center, U_G = superficial gas velocity, U_s = velocity defined by Eq. (6), V_{BF} = bubble rising velocity for bubbly flow by Bando, V_{CTF} = bubble rising velocity for churn-turbulent flow by Bando, $\alpha = D_o/D$, ρ_L = liquid density, γ = surface tension of liquid, $\nu = \rho_L/\mu_L$, μ_L = liquid viscosity.

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