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Generalized Model for Bubble Size and Frequency in Gas-Fluidized Beds

Jeong-Hoo Choi,*,† Jae-Ek Son,‡ and Sang-Done Kim§

Department of Chemical Engineering, Kon-Kuk University, Seoul 143-701, Korea, Korea Institute of Energy Research, Taejon 305-343, Korea, and Department of Chemical Engineering, KAIST, Taejon 305-701, Korea

A generalized bubble-growth model on mean bubble size and frequency has been proposed in bubbling gas-fluidized beds. Correlations on volumetric bubble flow rate, splitting frequency of a bubble, and equilibrium bubble diameter have been considered in this model. The equilibrium bubble diameter was shown to increase linearly with the ratio of volumetric bubble flux to the splitting frequency of a bubble. The proposed model was in good agreement with the extensive data reported on mean bubble size and frequency.

Introduction

The bubble size is one of many important factors in determining the hydrodynamics and performance of bubbling fluidized-bed reactors. Therefore, a lot of studies have been reported on it (Yasui and Johanson, 1958; Geldart, 1970/71; Cranfield and Geldart, 1974; Yacono, 1975; Mori and Wen, 1975; Rowe, 1976; Darton et al., 1977; Werther, 1978; Glicksman et al., 1987; Horio and Nonaka, 1987; Choi et al., 1988; Cai et al., 1993). However, the generalized bubble-growth model is rare, considering the actual volumetric bubble flow rate simultaneously and applicability to beds of Geldart's group A, B, and D particles. To derive a consistent interpretation on mean bubble size and frequency from the bubbling behaviors of fluidized beds of Geldart's group A, B, and D particles, this study proposes a generalized bubble-growth model that takes into account the volumetric bubble flow rate and bubble coalescence−splitting frequencies.

Description of the Model

The previous study (Choi et al., 1988) proposed a model on the mean bubble size and frequency in freely bubbling gas-fluidized beds in which coalescence of bubbles mainly occurs but breakup of a bubble can be neglected. For the model, it made use of the simplified collision theory to account for the coalescing frequency of the bubble with assumptions that the bubble moves upward, the time-averaged instantaneous bubble movement at a point of bed cross section is regular in angular frequency, and the bubble speed, V_b, was constant. Therefore, average bubble-rising velocity, U_b, is related as half of V_b. Bubble coalescence was considered to occur on a pair of bubbles at a time. Hence, the coalescing frequency per unit volume F_{cv} was written as

$$F_{cv} = 0.5658\pi {d_b}^2 V_b n^2 \tag{1}$$

where d_b and n are the spherical bubble diameter and the number of bubbles per unit volume, respectively.

When the number of bubbles is assumed to increase by 1 at a breakup of a bubble, the total splitting frequency per unit volume F_s can be written as

$$F_s = f_s^* n \tag{2}$$

in which f_s^* is the average splitting frequency of an original bubble.

Since $n = 6\epsilon_b/\pi {d_b}^3$, the variation of the number flow rate N_f of bubbles across the bed cross section with respect to height h above the distributor is

$$-\frac{dN}{dh} = A\left(\frac{20.37}{\pi}\frac{V_b {\epsilon_b}^2}{{d_b}^4} - \frac{6 f_s^* \epsilon_b}{\pi {d_b}^3}\right) \tag{3}$$

with an initial condition that $N_f = N_{fo}$ at $h = 0$. When minimum bubbling velocity is assumed to be minimum fluidizing velocity U_{mf} and volumetric bubble flux q_b is $(U - \beta U_{mf})$, the number flow rate N_f of bubbles across the bed cross section and bubble voidage ϵ_b are estimated from the following relations, respectively:

$$N_f = 6(U - \beta U_{mf})A/(\pi {d_b}^3) \tag{4}$$

$$\epsilon_b = (U - \beta U_{mf})/U_b \tag{5}$$

where U is the fluidizing gas velocity and β is a coefficient. For coarse particles, the minimum bubbling velocity equals U_{mf}, but for fine particles it is larger than U_{mf}. However, in the case of fine particles, the practical gas velocity is much greater than U_{mf} and not much error is included in the above approximation. About the volumetric bubble flux, basically, this study employed the n-type two-phase theory (Grace and Harrison, 1969) simplified with constant β at a given fluidizing condition.

The average bubble-rising velocity, U_b, from an equation of Davidson and Harrison (1963), which gives a more conservative estimate for design purposes with continuity in Geldart's A, B, and D beds (Kunii and Levenspiel, 1991), is

* To whom correspondence should be addressed. Phone: 82-2-450-3073. Fax: 82-2-454-0428. E-mail: choijhoo@kkucc.konkuk.ac.kr.

† Kon-Kuk University.

‡ Korea Institute of Energy Research.

§ KAIST.

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$$U_b = U - U_{mf} + 0.711(gd_b)^{1/2} \tag{6}$$

Since $U_b = V_b/2$ (Choi et al., 1988), the variation of bubble diameter d_b with respect to height h is

$$\frac{dd_b}{dh} = \frac{2.264(U - \beta U_{mf}) - f_s^* d_b/3}{U - U_{mf} + 0.711(gd_b)^{1/2}} \tag{7}$$

with an initial condition that $d_b = d_{bo}$ at $h = 0$. In eq 7, the differential dd_b/dh is proportional to the bubble void fraction, ϵ_b, as a result of the coalescing frequency approach. This result is considerably different from that $dd_b/dh \propto \epsilon_b^{1/3}$ (Werther, 1976; Hilligardt and Werther, 1986). That might result from a difference in the spatial bubble distribution considered. On the basis of the bubble interaction model (Clift and Grace, 1970), Werther (1976) has developed a statistical model of bubble growth. Werther (1976) reduced the problem of bubble coalescence in a freely bubbling bed to that in a bubble chain, assuming a regular array of equal-sized bubbles of mean diameter. However, the result of the present study is similar with the finding that $dd_b/dh \propto \epsilon_b^{5/4}$ (Glicksman et al., 1987). Glicksman et al. (1987) considered the mean coalescence rate while assuming the bubbles were in a random spatial distribution like that of the present study.

When the same coalescence and breakup frequencies occur, the bubble diameter becomes the equilibrium bubble diameter that is

$$d_{b,eq} = 6.792(U - \beta U_{mf})/f_s^* \tag{8}$$

Equation 8 shows that the equilibrium bubble diameter increases linearly with the ratio of volumetric bubble flux to the splitting frequency of a bubble. That is similar to the dimensional consideration of Glicksman et al. (1994) on the spitting frequency.

Substituting eq 8 into eq 7 and integrating with the initial condition, one can obtain

$$\left[\frac{d_{bo} - d_{b,eq}}{d_b - d_{b,eq}}\right]^b \left[\frac{(d_{bo}^{1/2} - d_{b,eq}^{1/2})(d_b^{1/2} + d_{b,eq}^{1/2})}{(d_b^{1/2} - d_{b,eq}^{1/2})(d_{bo}^{1/2} + d_{b,eq}^{1/2})}\right]^{d_{b,eq}^{1/2}} = \exp(2(h/a + d_b^{1/2} - d_{bo}^{1/2})) \tag{9}$$

where a and b are

$$a = 4.266g^{1/2}/f_s^* \qquad b = \frac{(U - U_{mf})}{0.711g^{1/2}} \tag{10}$$

The initial bubble diameter at the distributor d_{bo} can be estimated from the following correlations of Miwa et al. (1972):

$$d_{bo} = 1.38\left[\frac{A(U - U_{mf})}{N_o g^{1/2}}\right]^{0.4} \quad \text{for the perforated plate distributor} \tag{11a}$$

$$= 3.685(U - U_{mf})^2/g \quad \text{for the porous plate distributor} \tag{11b}$$

In this study the ratio of frontal to equivalent spherical bubble diameters and the ratio of eruption to frontal bubble diameters were set as 1.10 and 1.5, respectively (Choi et al., 1988). Therefore, the point frequency N_p is

$$N_p = \frac{\pi N_f d_{bf}^2}{4A} \tag{12}$$

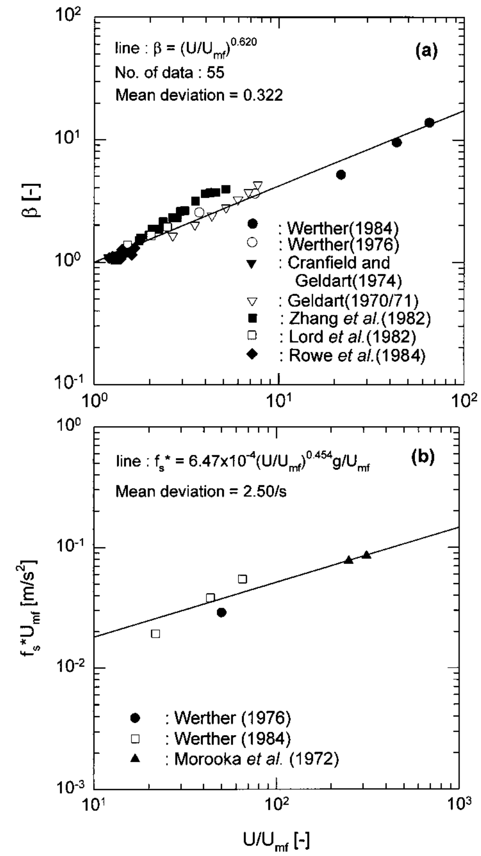

Figure 1. Relationships (a) between β and U/U_{mf} and (b) between $f_s^*U_{mf}$ and U/U_{mf}.

Volumetric Bubble Flux and Splitting Frequency of a Bubble

However, the coefficient β of volumetric bubble flux q_b and the splitting frequency of a bubble f_s^* are still unknown in the present model. To determine both unknowns, the following empirical correlations were derived from the measured data.

On the basis of the volumetric bubble flux q_b measured in beds of Geldart's group A (Werther, 1984), B (Geldart, 1970/71; Werther, 1976; Rowe et al., 1984), and D particles (Cranfield and Geldart, 1974; Lord et al., 1982; Zhang et al., 1982), q_b and β could be written as the following relations with a mean deviation of 0.322 in β (Figure 1a).

$$q_b = U - \beta U_{mf} \qquad \text{where } \beta = (U/U_{mf})^{0.620} \tag{13}$$

In the present model, one can obtain the splitting frequency of a bubble f_s^* by substituting a measured equilibrium bubble diameter and eq 13 into eq 8. It is well-known that bubble splitting is significant in the bed of Geldart's group A particles but negligible in beds of Geldart's group B and D particles. Because of this, the equilibrium bubble diameter could be observed in the bed of Geldart's group A particles but not in beds of Geldart's group B and D particles. Therefore, equilibrium bubble diameters measured in beds of Geldart's group A particles can be used to determine the correlation on the splitting frequency of a bubble. Werther (1976, 1984) and Morooka et al. (1972) observed equilibrium bubble diameters in their fluidized beds of Geldart's group A particles using a porous plate distributor ($U_{mf} = 0.0016-0.0023$ m/s, $U = 0.05-0.5$ m/s, and bed diameter = 0.079−1.0 m). According to their equilibrium bubble diameters, the splitting frequency of a bubble that increased with the gas velocity could be written as the following relation with a mean deviation of 2.50/s (Figure 1b):

$$f_s{*} = 6.47 \times 10^{-4}(U/U_{mf})^{0.454}\frac{g}{U_{mf}} \qquad (14)$$

In fact, the effect of bubble splitting on bubble growth in beds of Geldart's B and D particles, far enough from Geldart's A particles, was predicted not to be appreciable from the present model with the resulting correlations, eqs 13 and 14.

In making eqs 13 and 14 as the simplest approximations, we considered that the dense-phase gas flux and the splitting frequency of a bubble increased with the given ratio of the gas velocity to the minimum fluidizing gas velocity. In addition, the data from the bed employing the single-nozzle distributor (Morooka et al., 1972) were not used for eq 14 because the bubbling condition was guessed significantly nonuniform. The equilibrium bubble size in the bed of the single-nozzle distributor was appreciably affected by the nozzle size and larger than that in the bed of the porous plate distributor under the same fluidizing condition.

Comparison with the Experimental Data

In this model, one can estimate the axial bubble size distribution by substituting eqs 8, 10, 13, and 14 into eq 9. The bubble diameter is between the initial bubble diameter and the equilibrium bubble diameter and can be found by using the bisection method. Figure 2 and Table 1 summarize the comparison of bubble sizes determined from the present model and correlations of previous studies (Rowe, 1976; Darton et al., 1977; Horio and Nonaka, 1987; Choi et al., 1988; Cai et al., 1993) with the data (Geldart, 1970/71; Cranfield and Geldart, 1974; Glicksman et al., 1987; Werther, 1973, 1976, 1984; Zhang et al., 1982; Rowe et al., 1984; Morooka et al., 1972; Whitehead and Young, 1967; Rowe and Everett, 1972; Fryer and Potter, 1976; Stubington et al., 1984; Hatate et al., 1985). Prediction of bubble size from the present correlation was as good as that of Horio and Nonaka (1987) in beds of Geldart's group A and B particles and that of Choi et al. (1988) in beds of Geldart's group D particles. The present correlation was in reasonable agreement with the data of Stubington et al. (1984) changing the temperature from 26 to 1006 °C and the data of Rowe et al. (1984) changing the pressure from 100 to 7100 kPa. The column diameter of the compared data ranged from 0.079 to 1.22 m. However, correlations of Rowe (1976), Darton et al. (1977), Choi et al. (1988), and Cai et al. (1993) were poor in beds of Geldart's group A particles due to the absence of the splitting mechanism.

The point bubble frequency N_p on the bed cross section (Morooka et al., 1972; Choi et al., 1988) or the number flow rate N_f of bubbles across the bed cross section (Cranfield and Geldart, 1974) measured in beds of Geldart's group A, B, and D particles are compared with those calculated from the present model in Figure

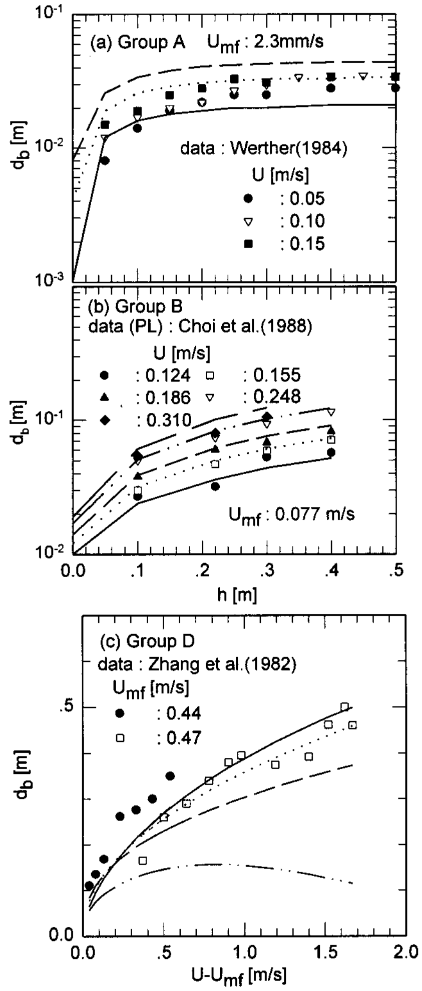

Figure 2. Comparison between the measured bubble size (symbols) and values calculated from correlations (lines) in beds of Geldart's group A, B, and D particles. (a) Lines, present theory, U (m/s): (—) 0.05, (···) 0.10, and (— — —) 0.15. (b) Lines: present theory U (m/s): (—) 0.124, (···) 0.155, (- - -) 0.186, (— ·· —) 0.248, and (— — —) 0.310 (c) (—) Present theory, (···) Rowe (1976), (— — —) Horio-Nonaka (1987), and (— ·· —) Cai et al. (1993).

3. The measured data were reevaluated as cross-sectional average values. Because bubble coalescence was dominant in most considered cases, the bubble frequency decreased as the height above the distributor increased. However, because bubble splitting was dominant for some beds of Geldart's group A particles, employing a porous plate as a distributor plate, the bubble frequency was predicted to increase initially and level off with the height. The present model agreed with the measured data reasonably well, as can be seen in the figure.

As a result, the present model on both the mean bubble size and frequency was successful over bed diameters of 0.079−1.22 m, minimum fluidizing velocities of 0.0016−0.58 m/s, excess gas velocities of 0.007−1.67 m/s, bed temperatures of 26−1006 °C, and bed pressures of 100−7100 kPa. In addition, the present model achieved continuity to interpret the mean bubble size and frequency with respect to the particle characteristics for beds of Geldart's group A, B, and D particles. Only one parameter, minimum fluidization velocity, has to be measured to calculate the mean bubble size and frequency from the present model. The present result would definitely ease the work in engi-

Table 1. Mean Deviation between Measured Bubble Diameters and Those Calculated from Various Correlations

summary of compared data							correlations and their mean deviations (in mm) from data					
authors	no. of data	U_{mf} (m/s)	Geldart's group	$U - U_{mf}$ (m/s)	temp. (°C) press. (kPa)	bed size (m)	Rowe (1976)	Darton et al. (1977)	Horio−Nonaka (1987)	Choi et al. (1988)	Cai et al. (1993)	present model
Morooka et al. (1972)	33	0.0016	A	0.298−0.498	A.T. A.P.[a]	0.079 i.d., 0.195 i.d.	270.0	211.3	15.8	308.9	157.0	16.4
Werther (1976, 1984)	36	0.0020, 0.0023	A	0.0477−0.148	A.T. A.P.	0.45 i.d., 1.0 i.d.	30.2	18.5	8.5	34.1	20.5	6.2
Whitehead−Young (1967)	111	0.025	B	0.02−0.143	A.T. A.P.	0.61 × 0.61, 1.22 × 1.22	19.8	27.1	45.2	23.8	70.2	40.5
Geldart (1970/71)	42	0.012	B	0.02−0.08	A.T. A.P.	0.308 i.d.	4.2	8.7	13.2	3.4	8.8	6.4
Rowe−Everett (1972)	66	0.0254−0.08	B	0.0127−0.155	A.T. A.P.	0.3 × 0.2, 0.3 × 0.3	12.2	5.6	7.3	12.4	6.4	10.8
Werther (1973)	22	0.018	B	0.072	A.T. A.P.	0.2 i.d., 1.0 i.d.	3.9	6.7	7.1	3.5	5.9	3.6
Fryer−Potter (1976)	26	0.017	B	0.007−0.104	A.T. A.P.	0.229 i.d.	9.2	9.2	6.8	7.2	8.0	7.9
Rowe et al. (1984)	19	0.0486−0.11	B	0.0204−0.039	A.T. 100−7100	0.175 × 0.125	5.7	8.7	5.8	7.7	9.5	11.2
Stubington et al. (1984)	32	0.028−0.073	B	0.016−0.106	26−1006 A.P.	0.102 i.d.	4.6	2.8	2.4	4.8	6.0	3.6
Hatate et al. (1985)	35	0.0089−0.332	B	0.08−0.35	A.T. A.P.	0.147 i.d.	8.1	19.7	25.0	9.9	22.9	14.9
Cranfield−Geldart (1974)	26	0.52	D	0.05−0.25	A.T. A.P.	0.61 × 0.61	13.0	14.4	13.8	14.2	15.0	11.2
Zhang et al. (1982)	20	0.28−0.47	D	0.04−1.67	47−827 A.P.	0.6 × 0.6	45.1	86.3	74.4	42.1	184.0	44.5
Glicksman et al. (1987)	9	0.58	D	0.31−0.87	A.T. A.P.	1.17 × 1.17	63.0	112.2	107.6	56.4	144.0	58.7

[a] A.T., atmospheric temperature; A.P., atmospheric pressure.

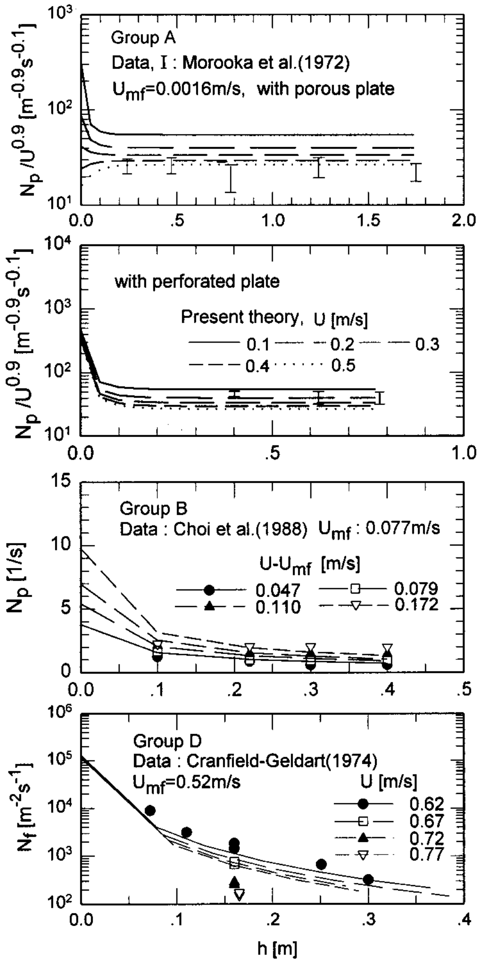

Figure 3. Comparison between measured bubble frequencies (symbols) and values calculated from the present model (lines) in beds of Geldart's group A, B, and D particles.

neering calculations and analysis of the bubbling fluidized-bed reactor.

Conclusions

A generalized bubble-growth model on the mean bubble size and frequency has been proposed, taking into account the volumetric bubble flow rate, coalescence, and breakup frequencies of bubbles. Correlations on volumetric bubble flow rate and the splitting frequency of a bubble have been considered in this model. The equilibrium bubble diameter was shown to increase linearly with the ratio of volumetric bubble flux to the splitting frequency of a bubble. The present model was successfully applicable to beds of Geldart's group A, B, and D particles.

Notation

a: variable defined by eq 10 ($m^{1/2}$)

A: bed area (m^2)

b: variable defined by eq 10 ($m^{1/2}$)

d_b: equivalent spherical bubble diameter having the same volume as that of a bubble (m)

$d_{b,eq}$: d_b in equilibrium (m)

d_{bf}: frontal bubble diameter (m)

d_{bo}: d_b at distributor (m)

F_{cv}: coalescence frequency per unit volume (1/s m^3)

F_s: splitting frequency per unit volume (1/s m^3)

$f_s{}^*$: splitting frequency of a single bubble (1/s)

g: gravitational acceleration, 9.8 (m/s^2)

h: height above distributor (m)

PL: mean-pierced bubble length (m)

n: number-based bubble concentration ($1/m^3$)

N_f: number-based bubble flow rate (1/s)

N_{fo}: N_f at distributor (1/s)

N_o: number of orifices on distributor plate

N_p: point bubble frequency (1/s)

q_b: volumetric bubble flux (m/s)

U: fluidizing gas velocity (m/s)

U_b: bubble-rising velocity (m/s)

U_{mf}: minimum fluidizing velocity (m/s)

V_b: bubble speed in the model of Choi et al. (1988) (m/s)

β: coefficient

ϵ_b: bubble voidage

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