EFFECTS OF GEOMETRIC PROPERTIES FOR A PERFORATED PLATE ON GAS HOLDUP IN A BUBBLE COLUMN

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Key words: Bubble Column, Gas Holdup, Perforated Plate, Distribution Parameter, Flow Parameter

The effects of geometric properties such as diameter, d, number, n and pitch, p, for holes located on a perforated plate on gas holdup, ϕ, in a bubble column were experimentally investigated while varying gas flow rate, G, and unaerated liquid height, Z_0.

In the case of constant Z_0, the volume of the spouting section above the column bottom increased with increasing d and decreasing n and p, and became negligible compared with that of the calming section at sufficiently large Z_0. As a result, the value of ϕ based on the volume of the bubble bed increased and approached that of ϕ_C based on the volume of the calming section. The value of ϕ_C was correlated to two parameters as a dimensionless expression. One was the flow parameter defined by a ratio of the reference velocities in the free and recirculated rising regions, and another was the distribution parameter for gas holdup in the recirculated rising region. Since the latter was strongly dependent on geometric properties for a perforated plate, its empirical expression was obtained as a function of the properties.

Introduction

Many correlations of gas holdup, which is one of the most fundamental and important performance factors in bubble column reactors, are listed in the literature (Shah *et al.*, 1982 etc.). In a bubble column with a perforated plate, the bubble flow usually exhibits a wide transition regime which exists between a uniform bubble flow and a heterogenous bubble flow. Also, it is a well-known fact that this regime disappears gradually with increasing hole diameter and decreasing hole number on the plate (Maruyama *et al.*, 1981, Sakata and Miyauchi, 1980, Yamashita and Inoue, 1975). In this way, it is clear that the gas holdup varies according to the flow regime since the regime of the bubble flow is influenced by various factors, such as gas flow rate, geometric properties of the column and gas distributor, and physical properties of the liquid.

In this study, we experimentally investigated the effects of geometric properties such as diameter, d, number, n, and pitch, p, of holes on gas holdup in the bubble column with a perforated plate with varying gas flow rate, G, and unaerated liquid height, Z_0.

We correlated the gas holdup, ϕ_C, in the calming section of the bubble column with a single hole orifice. Here, the calming section is the upper region in the column as shown in **Fig. 1** and the bubbles were dispersed uniformly. The following dimensionless equation for ϕ_C was proposed as a function of the flow parameter, F, at a single hole orifice (Kawasaki and Tanaka, 1995).

$$\phi_c = 1/(2.5 + 1.41F) \tag{1}$$

Here, F is defined by the ratio of the reference velocity, $u_{BO}{}^*$, in the free rising region to that, u_{GO}, in the recirculated rising region for the bubble flow. In the case of a single hole orifice, the free rising velocity, u_{BO}, of a bubble is represented by Eq. (2) (Kawasaki and Tanaka, 1995).

$$\begin{aligned} u_{BO} &= 1.41 u_{BO}{}^* \\ &= 1.41\{1.53(g\sigma/\rho)^{1/4}\} \end{aligned} \tag{2}$$

Incidentally, the following equation gives the minimal rising velocity, u_{BOmin}, (Mendelson, 1967), which was empirically obtained by Kumar *et al.* (1976).

$$u_{BO\,min} = 1.41\,(g\sigma/\rho)^{1/4} \tag{3}$$

1. Experimental

Experiments were carried out under the same conditions as our previous works (Kawasaki *et al.*,1994, Kawasaki and Tanaka, 1995). The diameter and height of the column used were 0.157 m and 2.03 m, respectively. Nine types of perforated plates made of polyvinyl chloride (0.005 m thick), with different number and pitch of holes, were used as a gas distributor. The hole diameters were d = 0.0005 and 0.002 m. The holes were located by regular triangle pitch on the cross section of each plate. The numbers of holes were 22, 88 and 356. Details of geometric properties of each plate are listed in **Table 1.** Three types of an arrangement on a plate with 22 holes are shown in **Fig. 2**, as an example.

Air was used as the gas and the liquid used was tap

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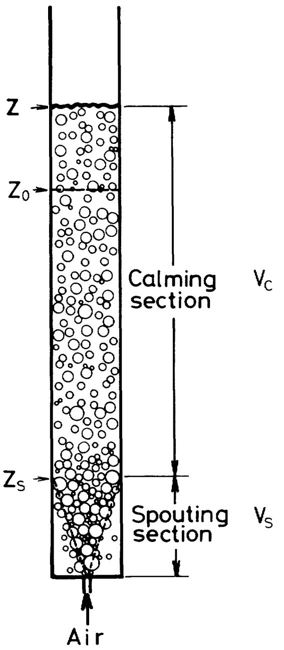

Fig. 1 Flow section in bubble column with single hole orifice

Table 1 Geometric properties for perforated plate used

d = 0.0005m			
n = 22	A = 4.32 × 10^{-6}m^2		
	P-A	P-B	P-C
p [m]	0.010	0.020	0.030
D_p [m]	0.050	0.100	0.150
n = 88	A = 1.73 × 10^{-5}m^2		
	P-D	P-E	P-F
p [m]	0.005	0.010	0.015
D_p [m]	0.050	0.100	0.150
n = 356	A = 6.99 × 10^{-5}m^2		
	P-G	P-H	P-I
p [m]	0.0025	0.0050	0.0075
D_p [m]	0.050	0.100	0.150
d = 0.002m			
n = 22	A = 6.91 × 10^{-5}m^2		
	P-J	P-K	P-L
p [m]	0.010	0.020	0.030
D_p [m]	0.050	0.100	0.150

water at 303 K. Unaerated liquid heights were 0.51, 1.0 and 1.51 m. Details of the measurement and calculation method for gas holdups were shown elsewhere (Kawasaki *et al.*, 1994, Kawasaki and Tanaka, 1995).

2. Results and Discussion

2.1 Flow patterns

In the cases of the bubble column with P-A, P-D and P-G, the spouting section, which is observed in the column with a single hole orifice (Kawasaki and Tanaka, 1995), existed similarly above the column bottom as shown in Fig. 1. When P-B, P-E and P-H were used, this section became smaller than those with P-A, P-D and P-G. In the cases with P-C, P-F and P-I, the calming section, which is a regime of the uniform bubble flow, was observed throughout the column.

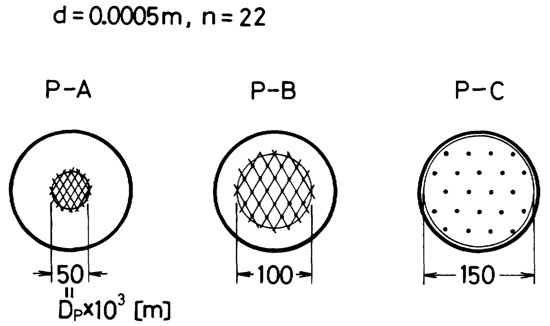

Fig. 2 Descriptive sketch of three perforated plates used

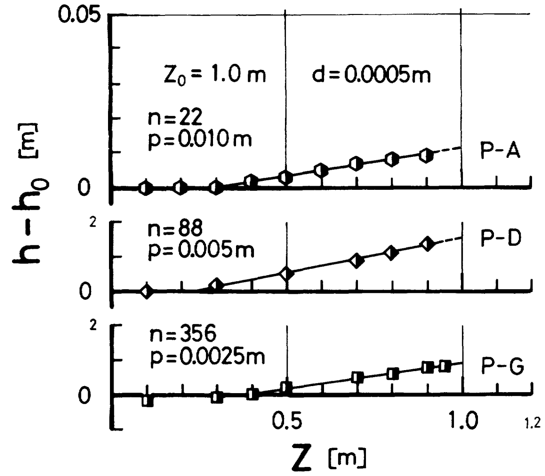

Fig. 3 Plot of h-h_0 against Z at G = 0.83 × 10^{-4}m^3·s^{-1}

At lower G, bubbles generated from each plate had nearly the same size in the calming section. In the case with P-G, however, bubbles coalesced together owing to a very small pitch as soon as they left holes. In this case, larger bubbles rose upward together with those with initial sizes. At higher G, a substantial difference in the flow pattern caused by geometric properties of the perforated plate was observed between the flow regimes. When the plates at larger n and smaller p were used, the bubble flow was obviously the recirculating turbulent flow.

Figures. 3 and **4** are plots of manometer reading, (h-h_0), against the height, Z, from the column bottom for cases with P-A, P-D and P-G at G = 0.83 and 6.67 × 10^{-4} m^3·s^{-1}, respectively. From these figures, it is found that there are spouting and calming sections in the bubble column at each G and that the value of (h-h_0) in the calming section is directly proportional to (Z-Z_S). Here Z_S is the height of the spouting section. In Fig. 3, the value of the slope, (h-h_0)/(Z-Z_S) at P-G is the minimum when compared at the same G. Bubbles seem to coalesce to large bubbles for P-G, because the value of p was small. As a result, this spouting section has the longest length among the three cases. In Fig. 4, the values of (h-h_0)/(Z-Z_S) at P-A and P-G are greatest and smallest, respectively. This tendency is similar to the result shown in Fig. 3. It is found that an optimal values of n and/or p exists which raises the gas holdup through the better dispersion and/or smaller diameter of bubbles.

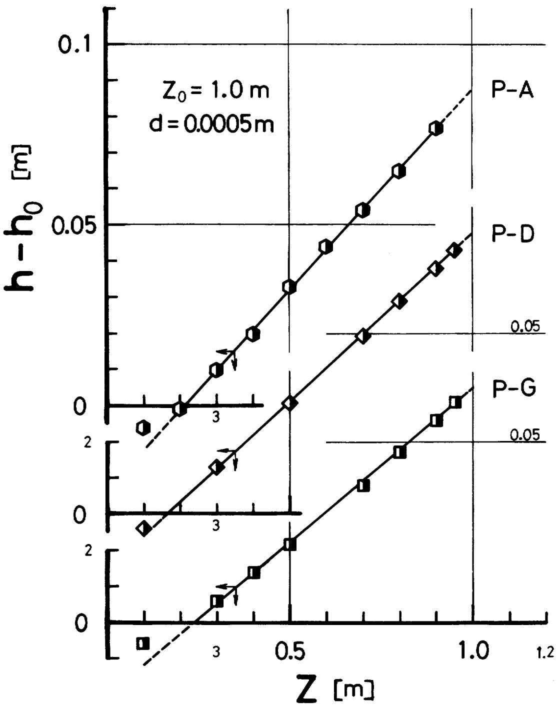

Fig. 4 Plot of h-h_0 against Z at $G = 6.67 \times 10^{-4} m^3 \cdot s^{-1}$

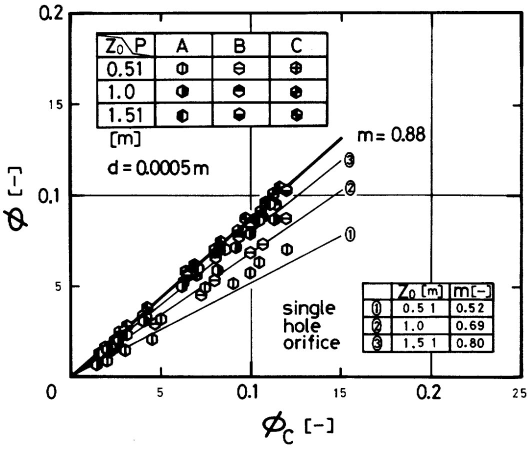

Fig. 5 Correlation between ϕ and ϕ_C at n = 22

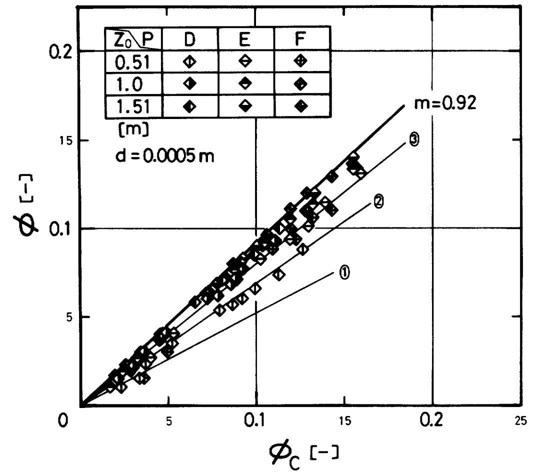

Fig. 6 Correlation between ϕ and ϕ_C at $n = 88$

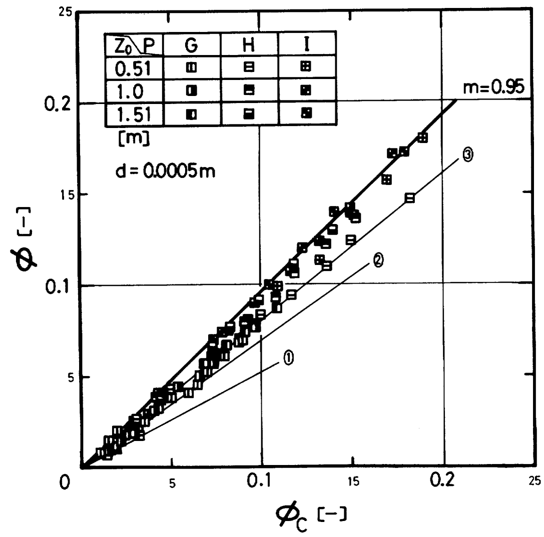

Fig. 7 Correlation between ϕ and ϕ_C at $n = 356$

2.2 Gas holdup

As the spouting and calming sections existed in the column, three gas holdups of ϕ, ϕ_C and ϕ_S are correlated by the following equation

$$\phi = (V_C / V)\phi_C + (V_S / V)\phi_S \tag{4}$$

where ϕ, ϕ_C and ϕ_S are the values based on the volumes, V, V_C and V_S, of the bubble bed, the calming section and the spouting section, respectively (Kawasaki and Tanaka, 1995). The correlations between ϕ and ϕ_C at $n = 22$, 88 and 356 are shown in **Figs. 5, 6** and **7**, respectively. Here, the values of ϕ_C are calculated by $(h\text{-}h_0)/(Z\text{-}Z_S)$ in the linear regions in Figs. 3 and 4. From these figures, it is clear that each ϕ value is directly proportional to ϕ_C. In Fig. 3, the value of ϕ_S seems to be small at low u_{G0} because of large Z_S. These values become much smaller than ϕ_C with increasing u_{G0} because of small Z_S at high u_{G0} as shown in Fig. 4. Therefore, it seems that there is no dependency of the second term of the righthand side in Eq. (4) on ϕ. With increasing n and/or p at the same D_P in these figures, it is found that the maximum value of ϕ at each Z_0 and the same range of G increases owing to good dispersion of bubbles and that the proportional constant, $m = V_C/V$, in the linear correlation becomes larger than that in the case using a single hole orifice under the same conditions of G and Z_0.

Figure 8 shows the effects of n, p and Z_0 on m at d = 0.0005 m and D_P = 0.150 m. It is found that ϕ approaches ϕ_C with the increase of Z_0, since the value of m gradually approaches 1 with the increase of Z_0 independently of n and p. It is, then, useful to use a perforated plate to enhance the gas holdup at the same G and Z_0 comparing with the case using a single hole orifice as a gas distributor.

To examine the effect of d on gas holdup, **Fig. 9** shows plots of ϕ against ϕ_C in the case of the plate with d

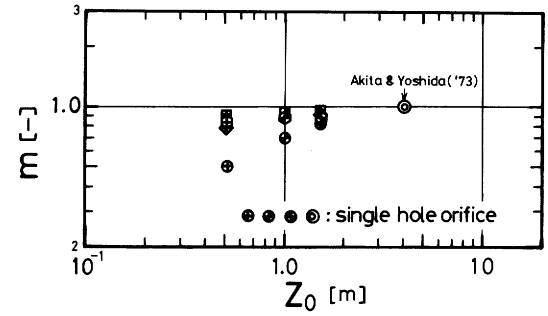

Fig. 8 Effects of n, p and Z_0 on m (Keys are shown in Figs. 5, 6 and 7)

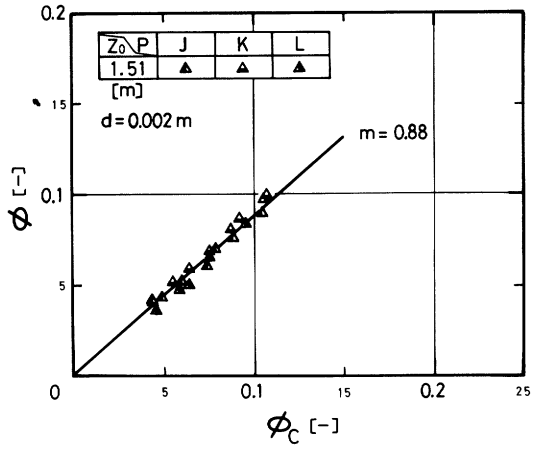

Fig. 9 Correlation between ϕ and ϕ_C at n = 22 (Z_0 = 1.51 m)

= 0.002 m. It is seen that the value of m is identical to that at d = 0.0005 m under the same conditions of Z_0 = 1.51 m, n = 22, p = 0.030 m and D_P = 0.150 m. The initial diameter of bubble generated at the hole with d = 0.002 m is usually greater than that for d = 0.0005 m owing to the large area of each hole. Bubbles generated from three plates of P-J, P-K and P-L with d = 0.002 m are broken up in the spouting section. As a result, there is no difference between the dispersed state and the diameter of bubbles in both calming sections, as the two values of m in Figs. 5 and 9 are the same. Furthermore, it is found by comparing Fig. 7 with Fig. 9 that there is a clear and remarkable difference among the effects of total area, A, of holes on gas holdup at Z_0 = 1.51 m. The geometric properties of d, n, p and D_P for the plate strongly affect performance of the bubble columns.

2.3 Gas holdup in the calming section

Figure 10 shows the effects of u_{G0}, Z_0, n and p on ϕ_C for the plates of P-C, P-F and P-I. It is found that each ϕ_C increases with increasing u_{G0} and n and decreasing p. No difference between the values of ϕ_C for each plate is observed at Z_0 = 1.0 and 1.51 m. However, the values of ϕ_C in the high range of u_{G0} at Z_0 = 0.51 m are smaller than those at Z_0 = 1.0 and 1.51 m. Furthermore, these values have a tendency to approach Eq. (1) at higher u_{G0}. The values of ϕ_C for three types of plate with d = 0.002 m agree with those calculated by Eq. (1), even if Z_0 = 1.51 m.

Here, to evaluate quantitatively ϕ_C, we consider the

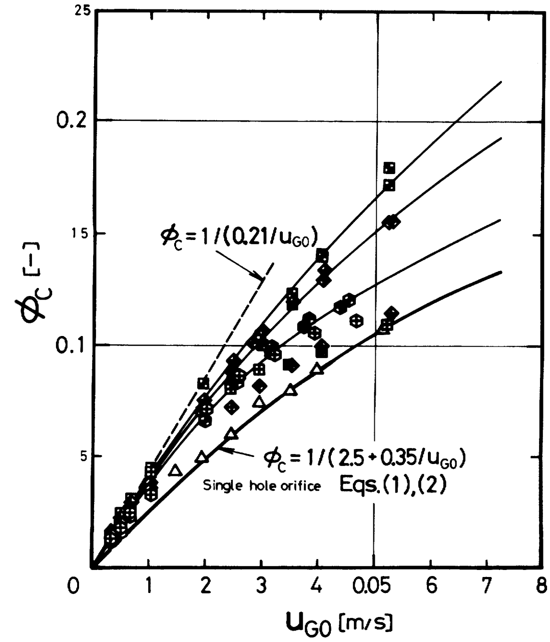

Fig. 10 Correlation between ϕ_C and u_{G0} (Keys are shown in Figs. 5, 6, 7 and 9)

tendency of ϕ_C from the viewpoint of a rising velocity, u_B(= u_{G0}/ϕ_C), for bubbles. In Fig. 10, each u_B at lower u_{G0} is seen to be constant independent of type of plate used. Since this velocity is regarded as the free rising velocity, u_{B0}, of a bubble, this flow region is the free rising region (Kawasaki and Tanaka, 1995). Also, u_{B0} at a perforated plate is generally smaller than that at a single hole orifice. In this study, the value of u_{B0} at each plate with d = 0.0005 m is 0.21 m·s^{-1} which is very close to that calculated by Eq. (3). In the cases at the plate with d = 0.002 m, however, the value of u_{B0} is 0.35 m·s^{-1}, which is equal to that estimated by Eq. (2). This value is greater than that at the perforated plate with d = 0.0005 m.

The dependence of u_{G0} on u_B at each plate is different at higher u_{G0}, even if each u_{B0} is the same. This difference of dependence is evidently caused by the geometric properties of the perforated plate. Since the value of u_B becomes greater with decreasing n and/or p, bubbles generated from such plates are easy to coalesce, as mentioned above. Especially, in the case of Z_0 = 0.51 m, u_B at higher u_{G0} is similar to that at a single hole orifice. This seems to be the very evidence of coalescence for bubbles.

2.4 Correlation of ϕ_C with flow parameter

In a bubble column with a perforated plate, geometric properties of the plate generally influence gas holdup at low u_{G0} (Maruyama *et al.*, 1981, Sakata and Miyauchi, 1980, Yamashita and Inoue, 1975). When u_{G0} becomes considerably high, the bubble flow exhibits recirculating turbulent flow and has a tendency to be independent of geometric properties. From such an opinion of the bubble flow, the flow region that showed the ϕ_C vs. u_{G0} curves in Fig. 10 is between uniform bubble flow and the transition zone.

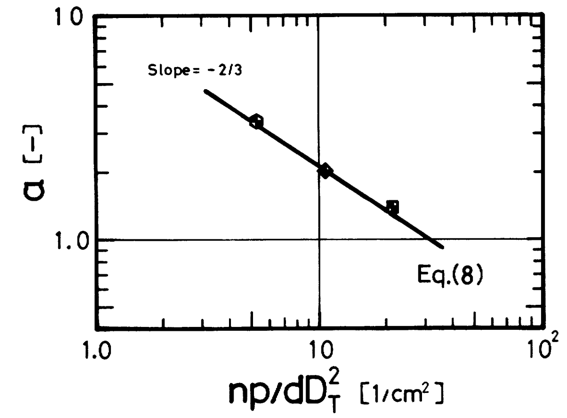

Fig. 11 Correlation between a and np/dD_T^2 (Keys are shown in Figs. 5, 6 and 7)

A dimensionless equation such as Eq. (1) is obtained by reducing the equation that was produced by Zuber and Findlay (1965). In Eq. (1), the first term and the second term in a denominator of the righthand side represent the parameter, a, which is the reciprocal of the distribution parameter, and the product of the constant and F, respectively. The distribution parameter, C_0, in two-phase flow is expressed by the following equation (Zuber and Findlay, 1965).

$$C_0 = \left(\frac{m+2}{m+n+2}\right)\left\{1 + \left(\frac{\phi_C}{\phi}\right)\left(\frac{n}{m+2}\right)\right\} \tag{5}$$

In Eq. (5), m and n are the exponents on velocity distribution of Eq. (6) and gas holdup distribution of Eq. (7), respectively.

$$v / v_0 = 1 - (r / R)^m \tag{6}$$

$$(\phi - \phi_W) / (\phi_0 - \phi_W) = 1 - (r / R)^n \tag{7}$$

where the subscripts 0 and W refer to the values evaluated at the center line and at the wall of the circular duct. Eq. (5) indicates that the value of C_0 in two-phase flow indicates the degree of influence of both distributions for velocity and gas holdup on the relation between average gas holdup and fluid flow rate. As a becomes large, the shape of the gas holdup distribution becomes parabolic. Conversely, it becomes flat at a smaller value of a.

To examine quantitatively the effects of geometric properties of a perforated plate on ϕ_C, an equation in the form of Eq. (1) is assumed to express those effects on ϕ_C. In the cases at Z_0 = 1.0 and 1.51 m in Fig. 10, the values of u_{B0} in Eq. (1) are the same, as mentioned above. The values of a are determined by comparing ϕ_C with Eq. (1) using all data observed in this study. **Figure 11** is a plot of a against the parameter, np/dD_T^2. This dimensional parameter was used as a reasonable criterion to determine the maximum gas holdup (Yamashita and Inoue, 1975) and to distinguish the flow transition (Sakata and Miyauchi, 1980). From the figure, it is found that a is proportional to the -2/3 power of np/dD_T^2. This means that an increase in n causes a decrease in a at the same d and D_T. The solid line in Fig. 11 represents the following empirical equation.

$$a = 10\left(np / dD_T^2\right)^{-2/3} \tag{8}$$

$$22 \leqq n \leqq 356,\ 0.0025 \leqq p \leqq 0.030,$$
$$0.0005 \leqq d \leqq 0.002 \qquad \text{at } D_T = 0.157\text{m}$$

Thereby, the three thin and one thick solid lines in Fig. 10 reveal the equations with a and u_{B0} at each perforated plate and a single hole orifice (Kawasaki and Tanaka, 1995). They agree with the data of ϕ_C for each gas distributor.

Conclusions

By examining empirically the effects of geometric properties for a perforated plate on gas holdup, it was obvious that the properties strongly influenced dispersion of bubbles after their generation from plates and that gas holdup varied according to such flow condition. Under the experimental conditions in this study, two flow regions that were divided into spouting and calming sections were observed in the bubble column.

Gas holdup generally increased with increasing G, Z_0 and n, and with increasing p and decreasing d at constant n. The value of ϕ_C in the calming section with each perforated plate was correlated by the dimensionless equation at Z_0 = 1.0 and 1.51 m. The equation had two parameters varying with the flow conditions. They were the distribution and the bubble rising velocity for the bubble flow. An empirical equation for the former parameter was obtained as a function of the geometric properties of the plate.

Nomenclature

a	=	reciprocal of distribution parameter	[-]
A	=	total area of holes	[m^2]
D_P	=	diameter of outermost circular shell which contains holes on gas distributor	[m]
D_T	=	column diameter	[m]
d	=	hole diameter	[m]
d_B	=	mean bubble diameter	[m]
F	=	flow parameter defined by u_B^*/u_{G0}	[-]
G	=	gas flow rate	[m^3·s^{-1}]
g	=	gravitational acceleration	[m·s^{-2}]
h	=	manometer reading	[m]
h_0	=	manometer reading at G = 0	[m]
m	=	slope (= V_C/V) in Eq. (3) and exponent on velocity distribution of Eq. (6)	[-]
n	=	hole number and exponent on gas holdup distribution of Eq. (7)	[-]
p	=	pitch of holes	[m]
R	=	duct radius	[m]
r	=	radial variable	[m]
u_B	=	bubble rising velocity	[m·s^{-1}]
u_{B0}	=	free rising velocity of a bubble	[m·s^{-1}]
u_{B0}^*	=	reference velocity in free rising region	[m·s^{-1}]
u_{G0}	=	superficial gas velocity and reference velocity in recirculated rising region	[m·s^{-1}]
V	=	volume of bubble bed (= $V_C + V_S$)	[m^3]
V_C	=	volume of calming section	[m^3]
V_S	=	volume of spouting section	[m^3]
v	=	velocity (flux)	[m·s^{-1}]
v_0	=	velocity at center line	[m·s^{-1}]
Z	=	distance from column bottom	[m]

Z_S	=	height of spouting section	[m]
Z_0	=	unaerated liquid height	[m]
ρ	=	liquid density	[kg·m^{-3}]
σ	=	surface tension	[N·m^{-1}]
ϕ	=	average gas holdup in bubble column	[-]
ϕ_C	=	gas holdup in calming section	[-]
ϕ_S	=	gas holdup in spouting section	[-]
ϕ_W	=	gas holdup at wall	[-]
ϕ_0	=	gas holdup at center line	[-]

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