

Profiles of Liquid Velocity and Turbulence Intensity in a Bubble Column

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Abstract

The mean velocity and turbulence intensity profiles of liquid were measured in a bubble column whose cross section was 7 cm × 7 cm square by using Laser Doppler Velocimeter. The results were discussed and correlated.

The profiles of mean liquid velocity depended upon the height above the gas distributor H and the bed Height H_T .

The profiles of liquid turbulence intensity were expressed by the following equation:

$$\begin{aligned}\sigma/\sigma_0 &= (1-\phi)^n \\ \sigma_0 &= 13.0 V_G^{0.5}\end{aligned}$$

n depended upon the vertical position in the column.

Introduction

Bubble columns are widely used as gas-liquid contactors and bioreactors. To design bubble columns effectively, it is very important to know the behavior of liquid in the bubble columns. Though there have been several investigations¹⁻⁵⁾ about profiles of mean liquid velocity, effects of height above gas distributors and shape of the cross section of the bubble columns upon liquid flow behavior remain obscure. And there have very few reports about turbulence of liquid in the bubble columns^{1,3)}.

In this study, profiles of mean liquid velocity and turbulence intensity of liquid at certain cross sections of different heights above the gas distributor in a bubble column whose cross-section was square were measured by using Laser Doppler Velocimeter. Results were analysed and discussed.

1. Experimental

Figure 1 shows the schematic diagram of the experimental apparatus. The bubble column was made of Pylex glass and had 7 cm × 7 cm square cross section and height of 40 cm. The gas chamber was 7 cm × 7 cm square cross sectional and 20 cm high. The gas distributor used was a perforated plate made of polyvinyl chloride resin ($t = 5$ mm). The arrangement of holes was shown in Fig. 2. The condition of the gas distributor was as follows: $\delta = 0.3$ mm, $N = 5$, $p = 2$ cm.

Air was used as gas and tap water was used as liquid. During a run, liquid was neither

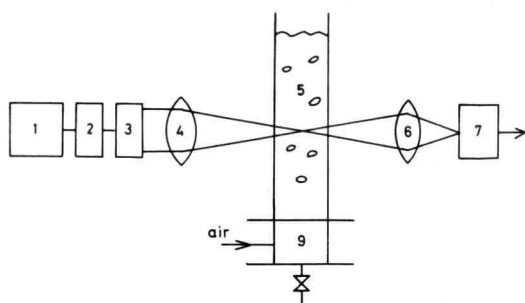


Fig. 1. Schematic diagram of experimental apparatus.

1. 5 mW He-Ne laser
2. beam splitter
3. frequency shifter
4. focusing lens
5. bubble column
6. collecting lens
7. photomultiplier
8. to signal processor

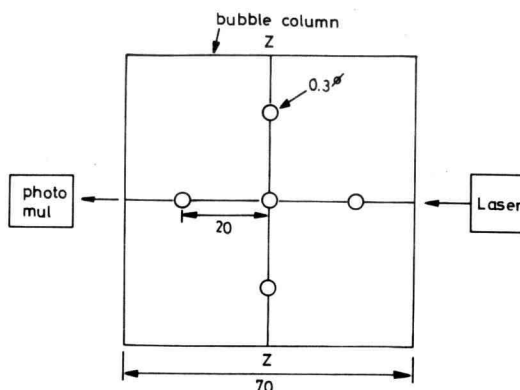


Fig. 2. Arrangement of holes on gas distributor :
 $\delta = 0.3$ mm, $N = 5$, $p = 20$ mm, $t = 5$ mm

fed nor discharged.

Average gas holdup ε_G in the bubble column was obtained from the difference in height of the bubbling layer and the clear liquid.

Bubble sizes were measured by photographic method. Bubbles were regarded as oblate ellipsoids and lengths of major axis a_i and minor axis b_i were measured. Then, volumes of bubbles were calculated by Eq. (1).

$$V_i = \frac{\pi}{6} a_i^2 b_i \quad (1)$$

Average diameter \bar{d} and maximum diameter d_{\max} of bubbles were calculated by Eq. (2) and Eq. (3), respectively.

$$\bar{d} = \left(\frac{6}{\pi} \frac{\sum_{i=1}^{N_T} V_i}{N_T} \right)^{1/3} \quad (2)$$

$$d_{\max} = \left(\frac{6}{\pi} V_{\max} \right)^{1/3} \quad (3)$$

The profiles of mean velocity and turbulence intensity of liquid at the several cross sections above the gas distributor were measured by using Laser Doppler Velocimeter (LDV). Experimental conditions are shown in Table 1. The LDV system used was made by KANOMAX. Fine particles of alumina were used as the seeds in the bubble column to

Table 1. Experimental conditions

H_T	H	V_G
[cm]	[cm]	[cm/s]
30-35	4.2, 17.5	0.025-0.33
10-11	8.8	

scatter the focused light. The optical system used in this study was fixed to the ground and the bubble column was mounted on a movable table. The table could be adjusted in three dimensional directions.

2. Results and Discussions

2.1 Average gas holdup ε_G and average rising velocity of bubble swarms U_b

Figure 3 shows gas holdup ε_G . It is found in this figure that ε_G increases with gas superficial velocity V_G . ε_G was expressed by the following equation:

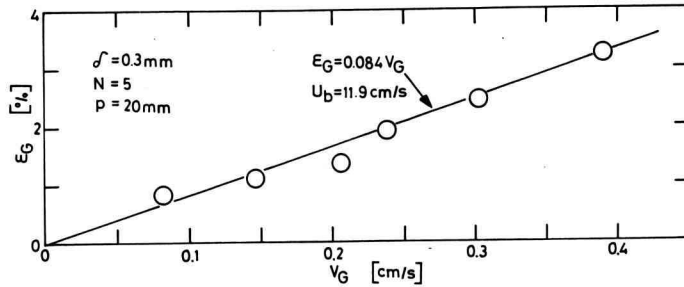


Fig. 3. Average gas holdup ε_G .

$$\varepsilon_G = 0.084 V_G \quad (4)$$

So, U_b was obtained from Eq. (4):

$$U_b = V_G / \varepsilon_G = 11.9 \text{ cm/s} \quad (5)$$

2.2 Average bubble diameter \bar{d} and maximum bubble diameter d_{\max}

\bar{d} and d_{\max} increased with V_G as shown in Fig. 4. They were expressed by the following equations:

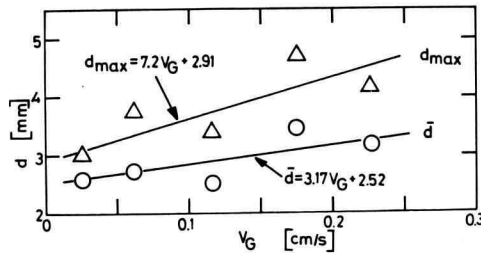


Fig. 4. Mean bubble diameter \bar{d} and maximum bubble diameter d_{\max}

○ \bar{d}
△ d_{\max}

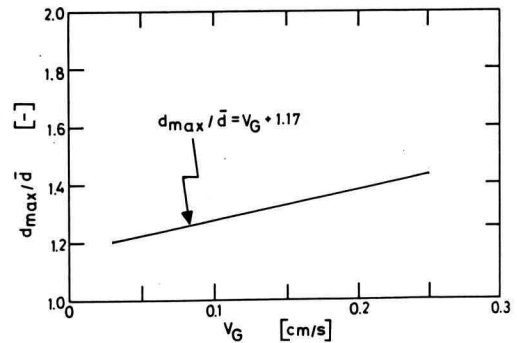


Fig. 5. d_{\max} / \bar{d} vs. V_G

$$\bar{d} = 3.17 V_G + 2.52 \quad (6)$$

$$d_{\max} = 7.2 V_G + 2.91 \quad (7)$$

where \bar{d} , d_{\max} and V_G are expressed in mm, mm, and cm/s, respectively.

Figure 5 shows the ratio (d_{\max}/\bar{d}) obtained from Eqs. (6) and (7). The ratio increases with V_G as shown in Fig. 5 and was expressed by the following equation:

$$d_{\max}/\bar{d} = V_G + 1.17 \quad (8)$$

where the range of V_G is 0.025 cm/s-0.25 cm/s.

2.3 Profiles of average liquid velocity U

Figures 6-8 show the examples of the results. From these figures it is clear that U is upwards in the central region of the column, that U is downwards in the outer region of the column and that profiles of U are dependent upon the height above the gas distributor H and the bed height H_T .

2.3.1 U in case of $H_T = 30-35$ cm

Figures 6 and 7 show the examples of the results. From these figures it is known that U decreases as the dimensionless distance ϕ from center increases. U was expressed by the

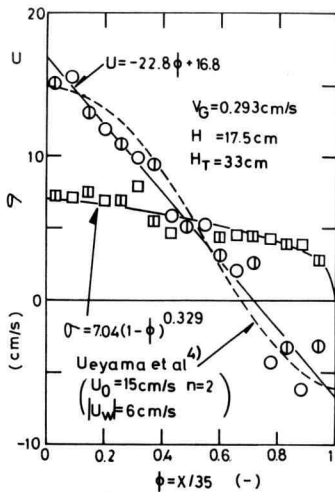


Fig. 6. Profile of U and σ at $V_G = 0.293$ cm/s, $H = 17.5$ cm and $H_T = 33$ cm: --- = calculated by Eq. (26) with $U_0 = 15$ cm/s and $U_w = -6$ cm/s

- U one side of the center
- ⊕ U the other side of the center
- σ one side of the center
- ⊠ σ the other side of the center

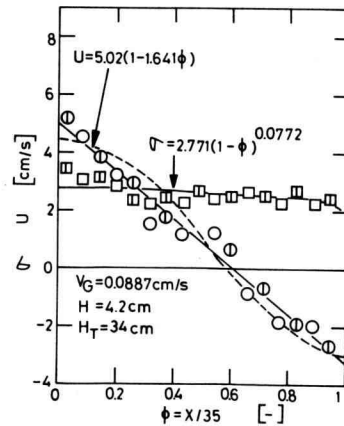


Fig. 7. Profile of U and σ at $V_G = 0.0887$ cm/s, $H = 4.2$ cm and $H_T = 34$ cm: --- = calculated by Eq. (26) with $U_0 = 4.5$ cm/s and $U_w = -3$ cm/s. Keys are same as those in Fig. 6.

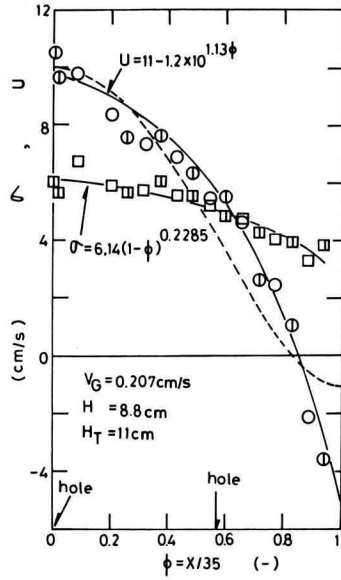


Fig. 8. Profile of U and σ at $V_G = 0.207$ cm/s, $H = 8.8$ cm and $H_T = 11$ cm: --- = calculated by Eq. (26) with $U_0 = 11$ cm/s and $U_w = -1.0$ cm/s. Keys are same as those in Fig. 6.

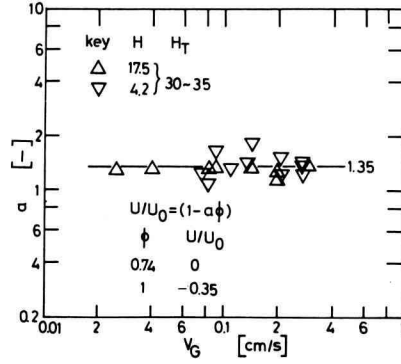


Fig. 9. a vs. V_G

following equation :

$$U/U_0 = (1 - a \cdot \phi) \quad (9)$$

where U_0 is U at the center of the column, a is constant and ϕ is dimensionless distance from center.

It is clear from Fig. 9 that a is independent of H and V_G . a was expressed by the following equation :

$$a = 1.35 \quad (10)$$

From Eqs. (9) and (10), U is expressed by the following equation :

$$U/U_0 = (1 - 1.35 \cdot \phi) \quad (11)$$

From Eq. (11), U/U_0 becomes zero at $\phi = 0.741$. So the following relation can be obtained :

$$S_+/S_- = 1.217 \quad (12)$$

where S_+ is the cross-sectional area where U is upwards and S_- is the area where U is downwards. From Eq. (12) it is known that the area where U is upwards is about 20% larger than where U is downwards.

2.3.2 U in case of $H_T = 10-11$ cm

The profiles of mean liquid velocity U were measured at $H = 8.8$ cm. Figure 8 shows an example of the results. U decreased as ϕ increased, but did not obey Eq. (11). It might be because $H = 8.8$ cm was very near to the top surface of the bubbling bed ($H_T = 10-11$ cm). U was expressed by the following equation:

$$U = b(1 - c \cdot 10^e \phi) \quad (13)$$

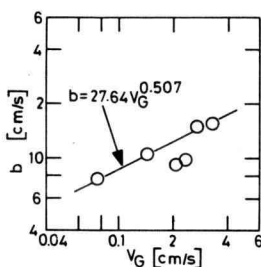


Fig. 10. b vs. V_G

where b , c and e are constant.

b increased with V_G and was expressed by the following equation as shown in Fig. 10:

$$b = 27.6 V_G^{0.507} \quad (14)$$

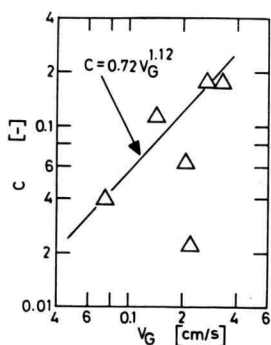


Fig. 11. c vs. V_G

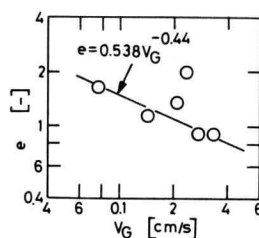


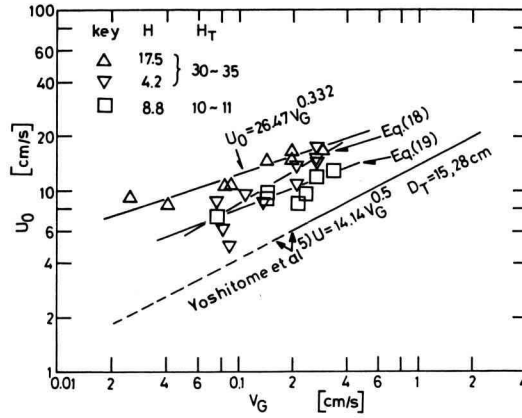
Fig. 12. e vs. V_G

Though one of the data deviated very much, c increased with V_G and was correlated with the following equation as shown in Fig. 11:

$$c = 0.72 V_G^{1.12} \quad (15)$$

e obeyed the following equation as shown in Fig. 12:

$$e = 0.538 V_G \quad (16)$$

Fig. 13. U_0 vs. V_G

2.3.3 Average upwards liquid velocity at the center of the column U_0

U_0 at $H = 17.5$ cm and $H_T = 30-35$ cm was higher than that at $H = 8.8$ cm and $H_T = 10-11$ cm as shown in Fig. 13. As $H = 8.8$ cm is very near the top surface of the bed ($H_T = 10-11$ cm), liquid flow is thought to be different from that at $H = 17.5$ cm. U_0 at $H = 4.2$ cm and $H_T = 30-35$ cm was nearly equal to that at $H = 8.8$ cm at small V_G , but it became equal to that at $H = 17.5$ cm at large V_G . This might be because $H = 4.2$ cm was near the gas distributor. U_0 was expressed by the following equations:

for $H = 17.5$ cm and $H_T = 30-35$ cm

$$U_0 = 26.47 V_G^{0.332} \quad (17)$$

for $H = 4.2$ cm and $H_T = 30-35$ cm

$$U_0 = 10.06 V_G^{0.377} \quad (18)$$

for $H = 8.8$ cm and $H_T = 10-11$ cm

$$U_0 = 31.22 V_G^{0.54} \quad (19)$$

2.4 Profile of liquid turbulence intensity σ

Figures 6-8 show σ , where σ is defined by the following equation:

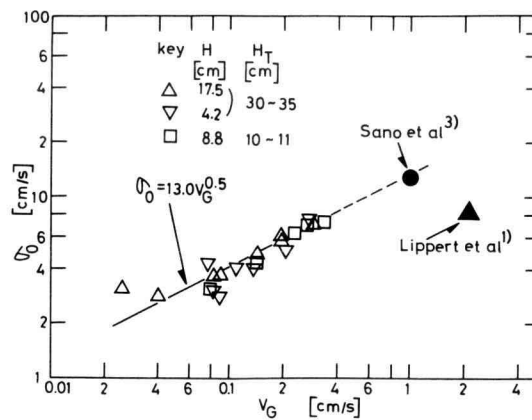
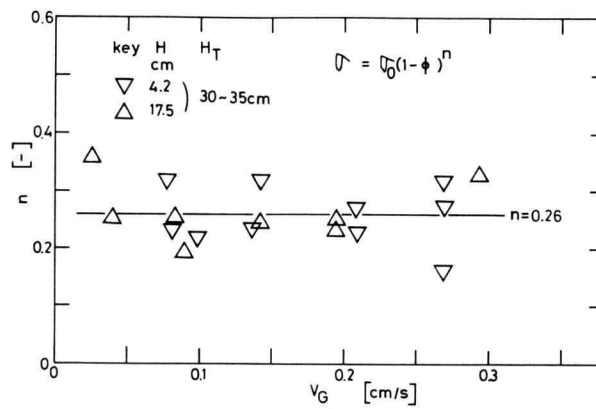
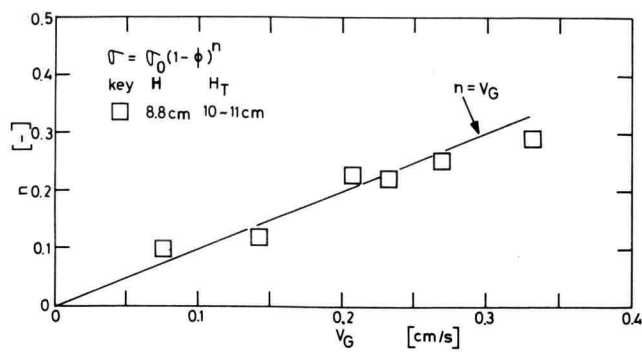
$$\sigma = \sqrt{\bar{U}^2} \quad (20)$$

It is known from these figures that σ decreases a little as ϕ increases. σ was expressed by the following equation irrespective of H :

$$\sigma = \sigma_0(1 - \phi)^n \quad (21)$$

where σ_0 and n are constant.

σ_0 increased with V_G and was independent of H and H_T as shown in Fig. 14. σ_0 was

Fig. 14. σ_0 vs. V_G Fig. 15. n vs. V_G Fig. 16. n vs. V_G

correlated by the following equation :

$$\sigma_0 = 13.0 V_G^{0.5} \quad (22)$$

n was dependent upon H and H_T and was expressed by the following equations as shown in Figs. 15 and 16 :

$$\text{for } H_T = 30\text{--}35 \text{ cm and } H = 4.2, 17.5 \text{ cm} \quad n = 0.26 \quad (23)$$

$$\text{for } H_T = 10\text{--}11 \text{ cm and } H = 8.8 \text{ cm} \quad n = V_G \quad (24)$$

2.5 Comparison of this work with the previous ones

2.5.1 Profile of U

Ueyama et al⁴⁾ derived Eq. (25), based on the liquid circulation theory and recommended $n = 2$ in Eq. (25).

$$\frac{U + |U_w|}{U_0 + |U_w|} = \frac{n+2}{n} \left[1 - \left(\frac{r}{R} \right)^2 \right] - \frac{2}{n} \left[1 - \left(\frac{r}{R} \right)^{n+2} \right] \quad (25)$$

Substituting ϕ for (r/R) and $n = 2$ in Eq. (25), one can obtain the following equation :

$$U = (U_0 + |U_w|)(1 - \phi^2)^2 \quad (26)$$

Figures 6-8 show the comparison of Eq. (26) with data of this work. It is clear from Figs. 6 and 7 that Eq. (26) shows fairly good agreement with this work. But Fig. 8 shows that Eq. (26) deviates much from data at $H = 8.8$ cm. So, it is found that Eq. (26) can apply to the profiles at $H = 4.2$ cm and 17.5 cm, but not to the profiles near the top surface.

2.5.2 U_0

Figure 13 shows the comparison of this work with that of Yoshitome et al⁵⁾. Yoshitome et al⁵⁾ measured the drag force acting a spherical float at $V_G \geq 2$ cm/s and $D_T = 15$ and 28 cm. The data of this work were much higher than the value extrapolated from their data. This reason might be because Yoshitome et al⁵⁾ used large spherical float ($D_p = 17.5\text{--}37.5$ mm)

2.5.3 Profile of σ

Data of σ in bubble columns are very few. Sano et al³⁾ measured turbulence intensity σ of liquid at $V_G = 1$ cm/s and $D_T = 10$ cm with tracing the motion of a tracer particle in liquid by a high speed cine camera. Lippert et al¹⁾ measured σ at $V_G = 2\text{--}2.2$ cm/s and $D_T = 15$ cm with a shielded anemometer probe. They used an air-lift loop reactor. Though Sano et al³⁾ and Lippert et al¹⁾ did not give any equation to express profiles of σ , their data can be expressed by the following equations as shown in Fig. 17 :

for σ of Sano et al³⁾

$$\frac{\sigma}{12.7} = \left(1 - \frac{r}{R} \right)^{0.104} \quad (27)$$

for σ of Lippert et al¹⁾

$$\frac{\sigma}{8.43} = \left[1 - \left(\frac{r}{R} \right)^2 \right]^{0.5} \quad (28)$$

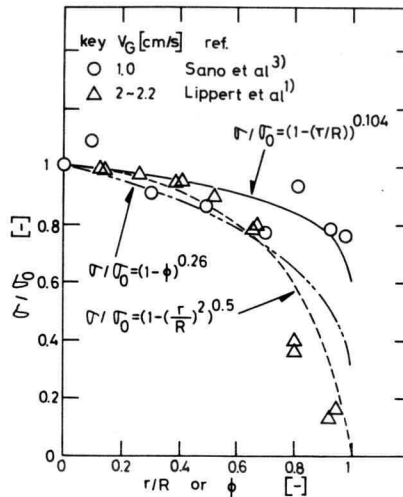
Fig. 17. Profile of σ/σ_0

Figure 17 shows the comparison of the profiles of σ . From this figure it is clear that profiles of σ depend upon the investigators. This might be because the experimental conditions were very different.

2.5.4 σ_0

Figure 14 shows the comparison of σ_0 . It is clear from Fig. 14 that σ_0 of Sano et al.³⁾ lies on the extrapolation of Eq. (21) with Eq. (22), and that σ_0 of Lippert et al.¹⁾ is much lower than the extrapolation of Eq. (21) with Eq. (22). This might be because Lippert et al.¹⁾ used an air lift loop reactor. More investigations are needed.

Conclusions

The mean velocity and turbulence intensity profiles of liquid at the several cross sections above the gas distributor were measured in a bubble column by using Laser Doppler Velocimeter and the following informations were obtained :

- 1) At very small superficial gas velocity V_G , gas holdup increased with V_G and was expressed by Eq. (4).
- 2) Mean diameter \bar{d} and maximum diameter d_{\max} of bubbles were correlated by Eqs. (6) and (7), respectively. The ratio (d_{\max}/\bar{d}) increased with V_G and was expressed by Eq. (8).
- 3) Liquid circulation existed even at very small V_G in the bubble column. Profiles of mean liquid velocity depended upon the height above the gas distributor H and the bed height H_T and were expressed by Eq. (9) and Eq. (12).
- 4) Profiles of liquid turbulence intensity σ were expressed by Eq. (21) with Eqs. (22)-(24).

Literature cited

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Nomenclature

a	= constant	[—]
a_i	= length of major axis of i -th bubble	[mm]
b	= constant in Eq. (13)	[cm/s]
b_i	= length of minor axis of i -th bubble	[mm]
c	= constant in Eq. (13)	[—]
\bar{d}	= mean diameter of bubbles (= defined by Eq. (2))	[mm]
d_{\max}	= maximum diameter of bubbles (= defined by Eq. (3))	[mm]
D_p	= diameter of float	[mm]
D_T	= diameter of column	[cm]
e	= constant in Eq. (13)	[—]
H	= height above gas distributor	[cm]
H_T	= bed height	[cm]
n	= constant	[—]
N	= number of holes	[—]
N_T	= total number of bubbles measured	[—]
p	= pitch of holes	[cm]
r	= radial distance	[cm]
R	= radius of column	[cm]
S_+	= cross-sectional area where U is upwards	[cm ²]
S_-	= cross-sectional area where U is downwards	[cm ²]
t	= thickness	[mm]
U	= vertical mean liquid velocity	[cm/s]
U_b	= average rising velocity of bubbles	[cm/s]
U_0	= U at center of column	[cm/s]
U_w	= U at wall of column	[cm/s]
V_G	= superficial gas velocity	[cm/s]
V_i	= volume of i -th bubble	[mm ³]
Z	= width of perforated plate	[mm]
δ	= hole diameter	[mm]
ε_G	= average gas holdup	[—]

σ	= turbulence intensity of liquid (= defined by Eq. (20))	[cm/s]
σ_0	= σ at center of column (= $\phi = 0$)	[cm/s]
ϕ	= dimensionless distance from central axis of column	[—]