Simulation and measurement of gas holdup in bubble columns

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Abstract

In this work, the effects of gas inlet height, superficial liquid velocity U_L, kinds of gas, arrangement of gas and liquid inlet, column inclination angle on gas holdup E_G were experimentally studied and simulated. In a bubble column with concurrent upward gas and liquid flow, E_G decreased with increasing gas inlet height. The effect was well correlated. The simulation results by Fluent software were also well expressed by the same equation. The effect of U_L on E_G was best expressed by the correlation of Bando et al.(1988). E_G depended scarcely upon kinds of gas. E_G by the simulation by Fluent did not depend on kinds of gas for a constant bubble diameter (d_B = 5 mm). E_G by the simulation depended significantly on the arrangement of the gas and liquid inlet. E_G by the simulation decreased with increasing column inclination angle and the effect was well expressed by the correlation of Yamashita (1985).

Keywords: gas holdup, bubble column, simulation, liquid velocity, inclination

Introduction

Bubble columns are widely used as gas liquid reactors and bio-reactors, because of simple structure and high performance. Gas holdup is a very important parameter for design and scale up of bubble columns. Therefore, there have been many studies about gas holdup in bubble columns. It has been reported that gas holdup depends on many factors such as gas and liquid velocity, physical property of gas and liquid, type and arrangement of gas spargers, gas inlet height and inclination of bubble columns.

Recently CFD has remarkably developed because of development of effective personal computers and softwares. CFD is very useful for research, design and scale up of bubble columns. In this work, the effects of inclination of a bubble column, arrangement of gas spargers, gas density and viscosity, and liquid inlet height on gas holdup were simulated by FLUENT and CFX softwares. The results were analyzed and discussed, and were compared with experimental results.

2. Experimental

Two bubble columns used were made of transparent acrylic resin. The inner diameter and height of the No.1 bubble column are 8 cm and 165 cm, respectively. The gas spargers of the No.1 bubble column were a 6 mm I.D. horizontal nozzle and were set on the wall at H_{in} = 0, 9 and 50 cm. The liquid inlet was a 20 mm I.D. single horizontal nozzle and was set 15 cm above the bottom of the bubble column on the wall. Air was used as a gas and tap-water was used as a liquid at room temperature. Liquid flowed upward concurrently with gas through the bubble column. Gas holdup was measured by pressure difference method. Pressure taps were set 5 cm and 100 cm above the bottom of the bubble column on the wall.

The cross section of the No.2 bubble column is 5 cm x 10 cm rectangular and its height is 40 cm. The gas sparger was a perforated plate of d = 5 mm and n = 18. Tap-water was used as a liquid, and air and hydrogen gas were used as gases. Liquid was fed in a batch. Gas holdup was measured visually. All runs were done at room temperature.

3. Results and discussions

3-1. Experimental results

1) Effect of gas inlet height H_{in} on E_G

Figs 1 and 2 show the effect of gas inlet height H_{in} on E_G in the 8 cm I.D. bubble column at U_L = 0 and 10.0 cm/s, respectively. E_G decreases with increasing H_{in} irrespective of U_L because the region under H_{in} becomes bubble-free. Liquid circulates in the bubble column, however, bubbles don’t fall into the region under the gas inlet.

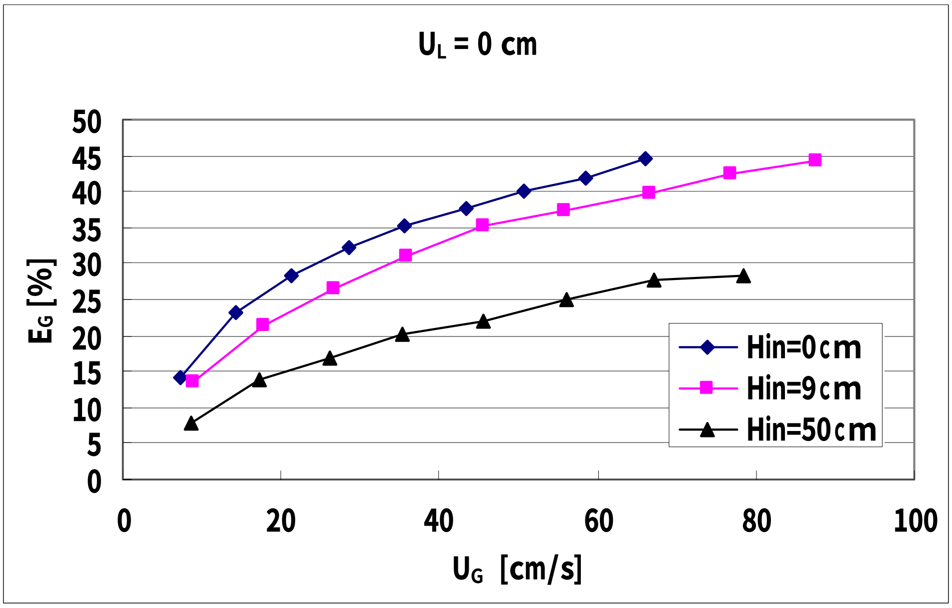

Fig.1 Effect of H_{in} on E_G at U_L = 0 cm/s.

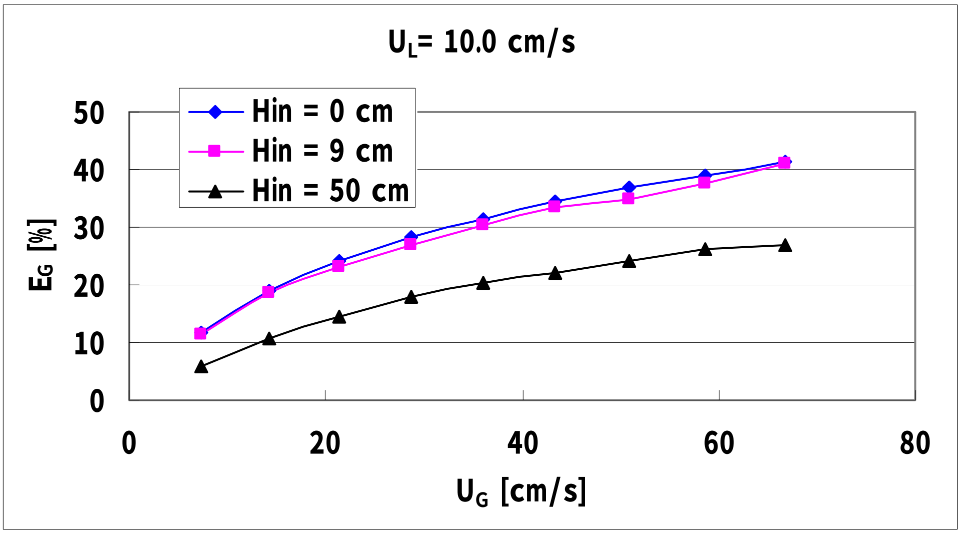

Fig.2 Effect of H_{in} on E_G at U_L = 10.0 cm/s.

In order to express the effect of H_{in} on E_G, $E_{G,cal}$ was defined by the following Equation:

$$E_{G,cal} = (1- H_{in} \ / H_T)E_{G0,\,exp} \qquad (1)$$

Where $E_{G0,\,exp}$ means gas holdup experimentally measured for H_{in} = 0 cm.

Figs. 3 and 4 show the relation between $E_{G,cal}$ and $E_{G0,exp}$ for U_L =0 and 10.0 cm/s, respectively. It is clear from Figs. 3 and 4 that $E_{G,cal}$ is nearly equal to $E_{G,exp}$.

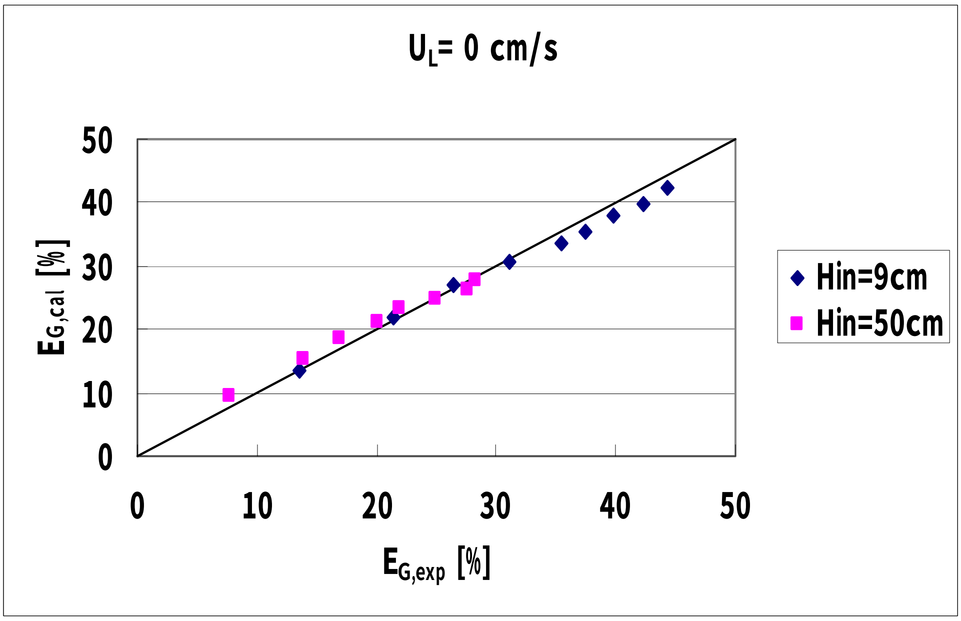

Fig.3 $E_{G,cal}$ vs. $E_{G,exp}$ at U_L = 0 cm/s.

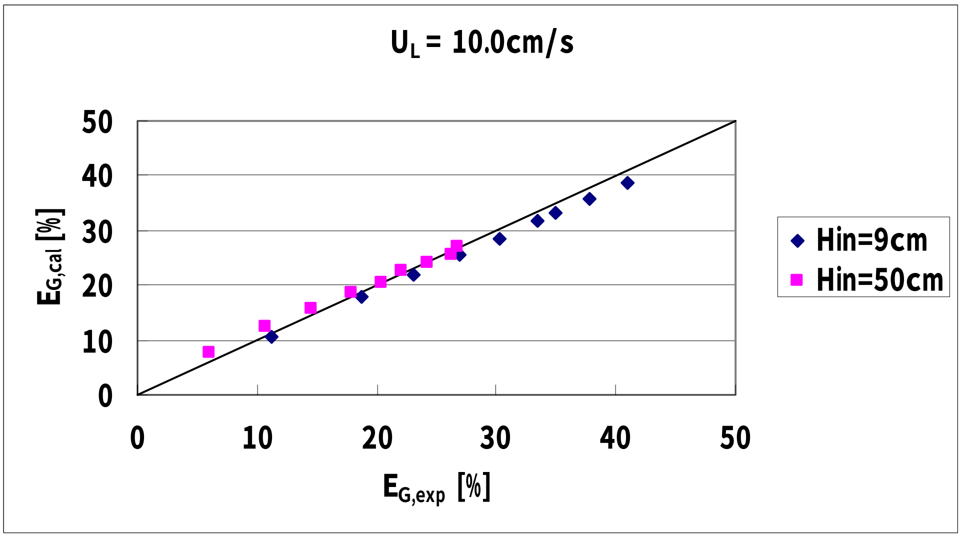

Fig. 4 $E_{G,cal}$ vs. $E_{G,exp}$ at U_L = 10.0 cm/s.

2) Effect of U_L on E_G

Fig.5 shows the effect of U_L on E_G at H_{in} = 0 cm. E_G decreases with increasing U_L because the upward liquid flow increases the rising velocity of bubbles.

There are some correlations about the effect of U_L on E_G in the bubble columns. Akita et al. (1988) presented the following equation for gas holdup in the bubble columns:

$$E_G /(1- E_G)^4 = 0.2[g(D_T)^2 \rho_L/ \gamma]^{1/8}[g(D_T)^3(\rho_L)^2/(\mu_L)^2]^{1/12}[u_s/(gD_T)^{0.5}] \quad (2)$$

$$u_s = U_G - U_L [E_G /(1- E_G)] \quad (3)$$

Bando et al. (1988) measured gas holdup in bubble columns and correlated their data by the following equations:

For bubble flow region,

$$E_G = U_G / [V_{BF} + 1.20(U_L +U_G)] \quad (4)$$

$$V_{BF} = 27 \text{ cm/s} \quad (5)$$

For churn turbulent flow,

$$E_G = U_G / [V_{CTF} + 1.36(U_L +U_G)] \quad (6)$$

$$V_{CTF} = 0.57(gD_T)^{0.5} \text{ cm/s for } D_T = 5 \text{ cm} - 14 \text{ cm} \quad (7)$$

$$V_{CTF} = 0.67 \text{ cm/s for } D_T = 14 \text{ cm} - 28 \text{ cm} \quad (8)$$

Yamashita et al. (1975) presented the following equation for gas holdup in the bubble columns:

$$E_G = U_G / [2.2(U_G + U_L) + 0.3(gD_T)^{0.5}] \quad (9)$$

Fig.6 shows the comparison between experimental data of gas holdup and Eq. (2) by Akita et al. (1988). $E_{G,\ Akita}$ means E_G calculated by Eq. (2). $E_{G,\ Akita}$ became smaller than $E_{G,exp}$ in the range of large E_G. The average error of $E_{G,Akita}$ from $E_{G,exp}$ was 11.8 %. Fig.7 shows the comparison between experimental gas holdup $E_{G,exp}$ and $E_{G,Akita}{}^{0.9}$. It is clear from Fig.7 that $E_{G,Akita}{}^{0.9}$ shows a little better agreement with $E_{G,exp}$. The average error of $E_{G,Akita}{}^{0.9}$ from $E_{G,exp}$ was 7.46 %.

Fig.8 shows the comparison between experimental data of gas holdup and the correlation of Bando et al. (1988). $E_{G,\ Bando}$ means E_G calculated from Eqs. (6) and (7). It is clear from Fig.8 that $E_{G,Bando}$ shows a good agreement with $E_{G,exp}$. The average error of $E_{G,Bando}$ from $E_{G,exp}$ was 5.51 %.

Fig.9 shows the comparison between experimental data of gas holdup and Eq. (9) by Yamashita et al.(1975). $E_{G,\ yama}$ means E_G calculated from Eq. (9). $E_{G,yama}$ is nearly equal to $E_{G,exp}$ in the range of $E_{G,exp}$ less than 30%, however becomes smaller than $E_{G,exp}$ in the range of $E_{G,exp}$ larger than 30 %. The average error of $E_{G,yama}$ was 8.87 %.

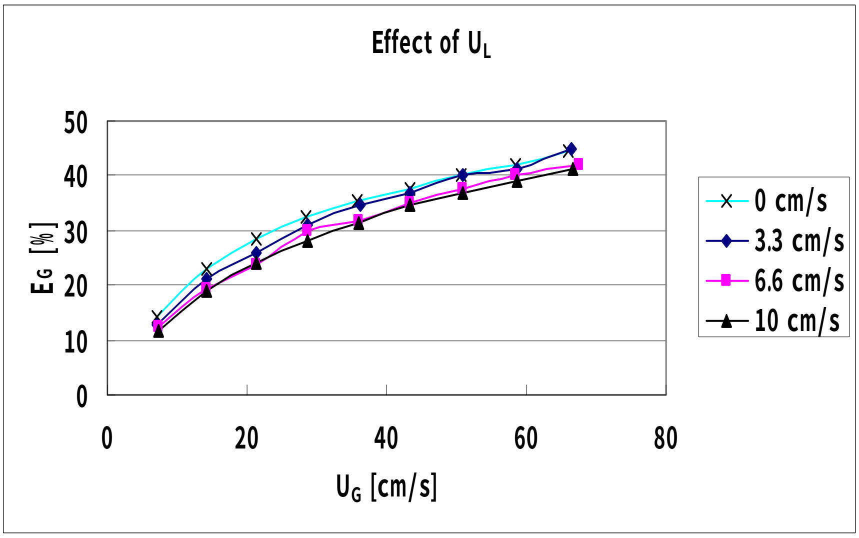

Fig.5 Effect of U_L on E_G at H_{in} = 0 cm.

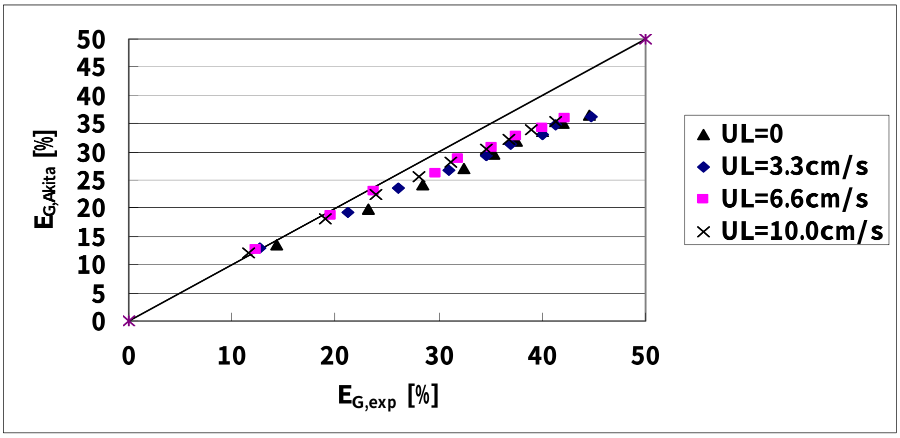

Fig.6 Comparison between $E_{G,exp}$ and $E_{G,Akita}$ by Eq.(2) for H_{in} = 0 cm.

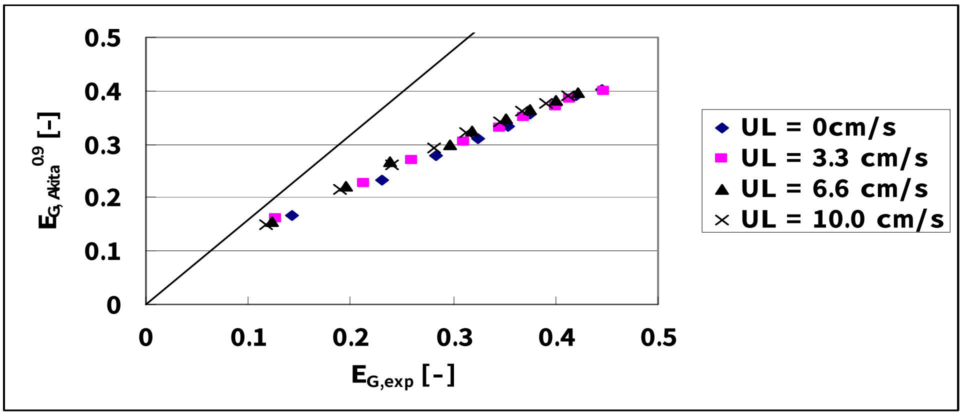

Fig.7 Comparison between $E_{G,exp}$ and $E_{G,Akita}^{0.9}$ from Eq.(2) for H_{in} = 0 cm.

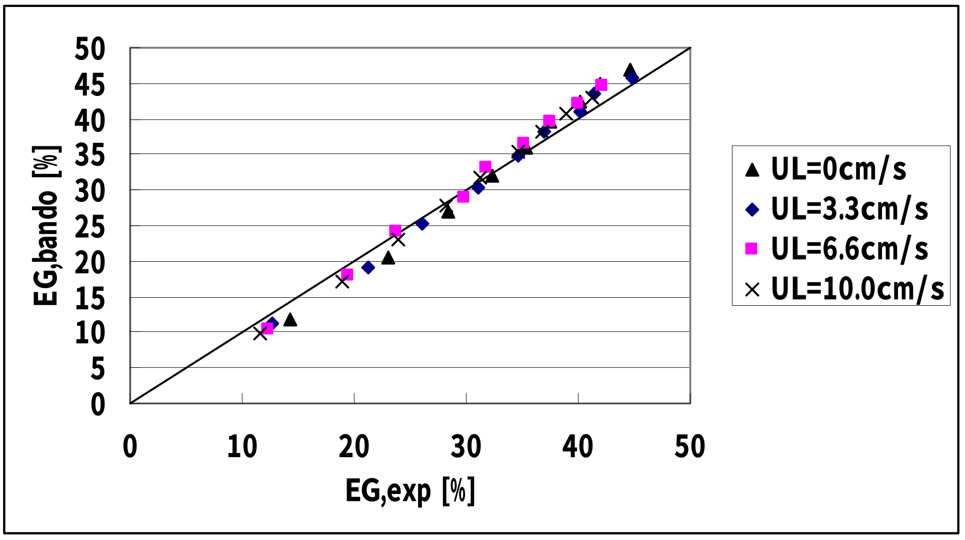

Fig.8 Comparison between $E_{G,exp}$ and $E_{G,Bando}$ calculated from Eqs.(6) and (7) for H_{in} = 0 cm.

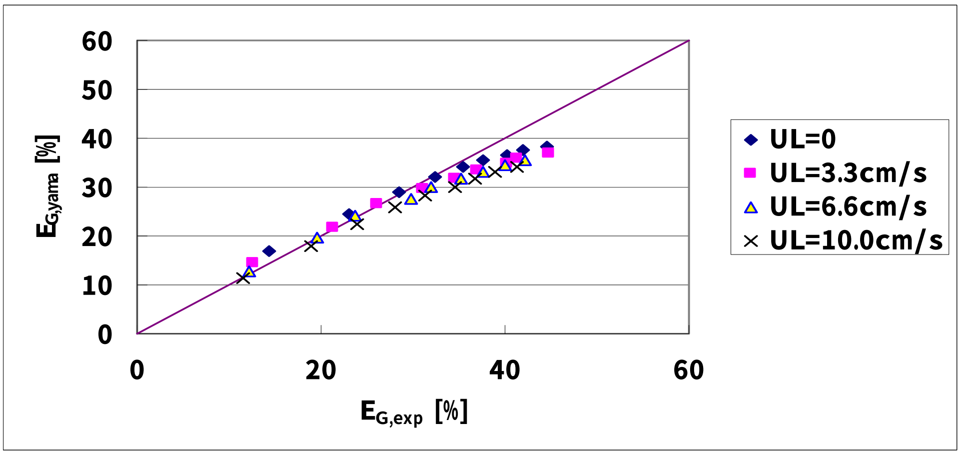

Fig.9 Comparison between $E_{G,exp}$ and $E_{G,yama}$ calculated from Eq.(9) for H_{in} = 0 cm.

3) Effect of kinds of gas on E_G

Fig. 10 shows the effect of kinds of gas on E_G in the No.2 bubble column. E_G for hydrogen is a little smaller than E_G for air in the range of U_G > 4 cm/s..

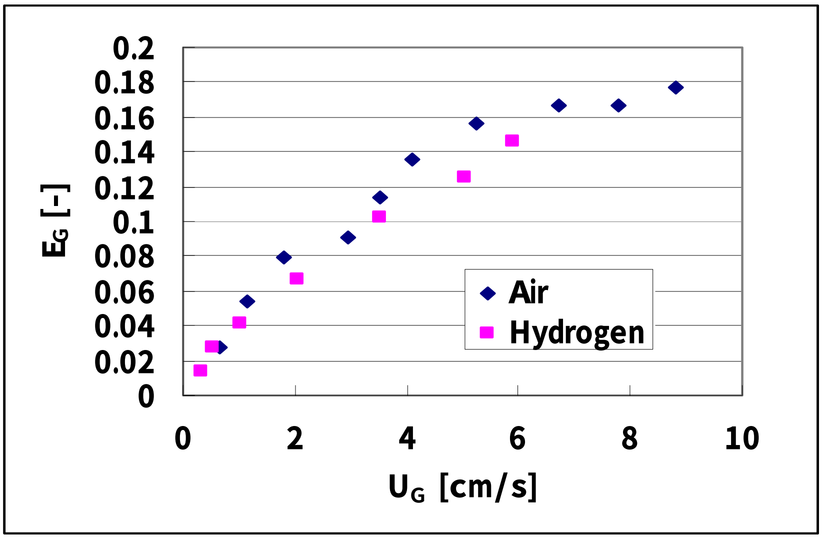

Fig.10 Effect of kinds of gas on E_G in the No.2 bubble column.

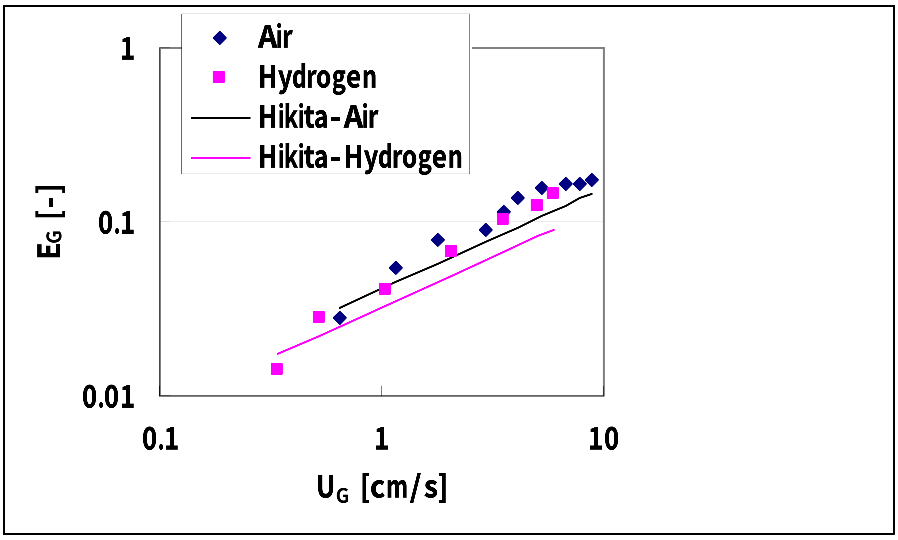

Fig.11 Comparison between the correlation by Hikita et al.(1980) and E_G in the No.2 bubble column.

Hikita et al.(1980) studied the effect of gas and liquid properties on gas holdup in the bubble column of 10 cm inner diameter and 1.5 m height. They have reported that E_G depends on $(\rho_G/\rho_L)^{0.062}(\mu_G/\mu_L)^{0.107}$ and presented the following correlation:

$$E_G = 0.672\,(U_G\,\mu_L/\gamma)^{0.578}[\mu_L^4 g/(\rho_L\gamma^3)]^{-0.131}(\rho_G/\rho_L)^{0.062}(\mu_G/\mu_L)^{0.107} \qquad (10)$$

Fig. 11 shows the comparison between Eq.(10) and experimental data in this work. E_G calculated by Eq.(10) is lower than E_G in this work, because Hikita et al (1980) used a single nozzle of 1.1 cm inner diameter as a gas sparger and the gas sparger used in this work was a perforated plate of d = 0.5 mm and n = 18. E_G for hydrogen gas by Hikita et al.(1980) is much lower than those in this work, though E_G for air by Hikita et al. (1980) is a little smaller than those in this work,

Ozturk et al (1987) have also studied the effect of kinds of gas on E_G in the 9.5 cm I.D. and 85 cm tall bubble column with organic liquids and reported that E_G depends on kinds of gas. They have also reported that the correlations of Hikita et al.(1980) and Akita and Yoshida (1973) give the best fit. Akita and Yoshida (1973) have reported that E_G does not depend on kinds of gas in the bubble column whose height is in the range of 2 m—3m. Ozturk et al (1987) have concluded that the gas-specific effects are probably related to the bubble formation at the sparger rather than the hydrodynamics in the bulk of the dispersion. Therefore, E_G depends on kinds of gas in bubble columns with small height (H_T < 1 m), however, E_G does not depend on kinds of gas in tall bubble columns (H_T > 2 m). The effect of kinds of gas on gas holdup should be studied much more.

3-2. Simulation results

1) Effect of gas inlet height H_{in} on E_G

The simulation was done by using Fluent software. The conditions of the simulation are as follows:

model = two dimensional bubble column of L = 16 cm and H = 2 m, 5 mm mesh , bubble diameter = 5 mm, width of gas and liquid inlet = 5 cm, Euler-Euler model, turbulent flow, k- ε model, steady state, air and water at 293 K.

In order to study the effect of gas inlet height H_{in} on $E_{G,}$ gas inlets were set 0, 50 and 100 cm above the bottom of the bubble column on the wall. The air and water flowed upward concurrently through the gas and liquid inlet. Fig. 12 shows the results of the simulation.

In Fig.12 U_G is equal to U_L. As seen in Fig.12, E_G decreases with increasing H_{in} because the region under the gas inlet becomes bubble-free. $E_{Gsimu,cal}$ is defined by the following equation like $E_{G,cal}$ in Eq.(1):

$$E_{Gsimu,cal} = (1 - H_{in} / H_T)\, E_{G0,simu} \tag{11}$$

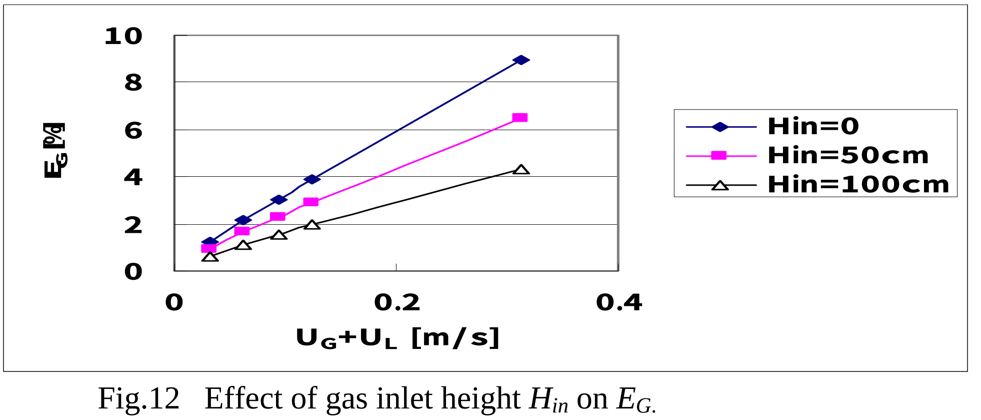

Fig.12 Effect of gas inlet height H_{in} on $E_{G.}$

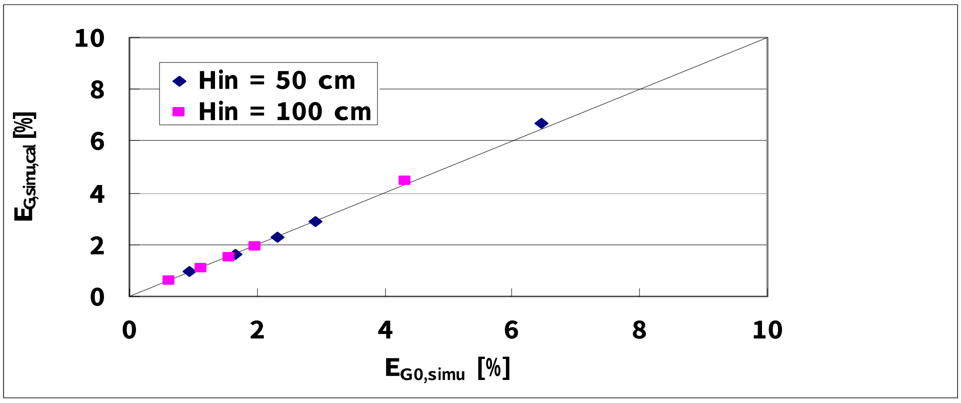

Fig.13 Comparison between $E_{Gsimu,cal}$ and $E_{G0,simu}$.

Fig.13 shows that $E_{Gsimu,cal}$ is equal to $E_{G0,simu}$. This means that the simulation results are equal to the experimental results.

2) Effect of kinds of gas on E_G

The simulation was done by using Fluent software. The conditions of the simulation are as follows:

model = two dimensional bubble column of L = 16 cm and H = 2 m, 5 mm mesh , bubble diameter = 5 mm, width of gas and liquid inlet = 5 cm, Euler-Euler model, turbulent flow, k- ε model, steady state, Hydrogen gas or Argon gas and water at 293 K.

The gas and liquid inlet was set on the center of the bottom of the bubble column. The gas and liquid flowed upward concurrently through the inlet. Fig.14 shows the simulation results.It is clear from Fig.14 that $E_{G,Hydrogen}$ is nearly equal to $E_{G.Argon}$, though density of Argon is about 20 times larger than that of Hydrogen gas. In this simulation, the diameter of bubbles for Argon gas is assumed to be equal to the diameter of bubbles for Hydrogen gas. If the diameter of bubbles for Argon gas is not equal to the diameter of bubbles for Hydrogen gas, the simulation results may be changed. It is very difficult to measure diameters of bubbles precisely. Diameters of hydrogen bubbles were nearly equal to diameters of air bubbles by visual observations.

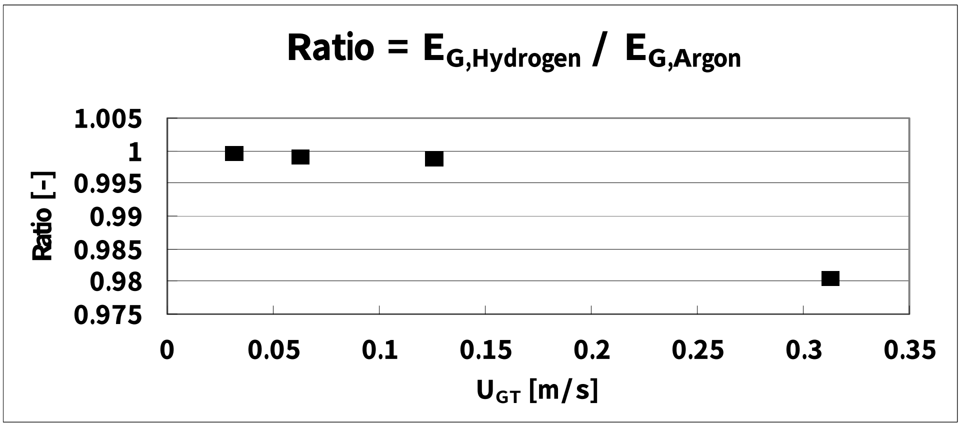

Fig.14 Effect of kinds of gas on E_G by the simulation

3) Effect of arrangement of gas and liquid inlet on E_G

The simulation was done by using Fluent software. The conditions of the simulation are as follows:

model = two dimensional bubble column of L = 16 cm and H = 2 m, 5 mm mesh , bubble diameter = 5 mm, width of gas and liquid inlet = 5 cm, Euler-Euler model, turbulent flow, k- ε model, steady state, air and water at 293 K.

In order to know the effect of arrangement of gas and liquid inlet on E_G , the gas and liquid inlet was set in the center or near the wall on the bottom of the bubble column. The gas and liquid flowed upward concurrently through the inlet. Fig.15 shows the effect of arrangement of gas and liquid inlet on E_G. E_G for the inlet in the center becomes much larger than that for the inlet near the wall, because for the inlet near the wall, bubbles rise along the wall and disperse only a little horizontally.

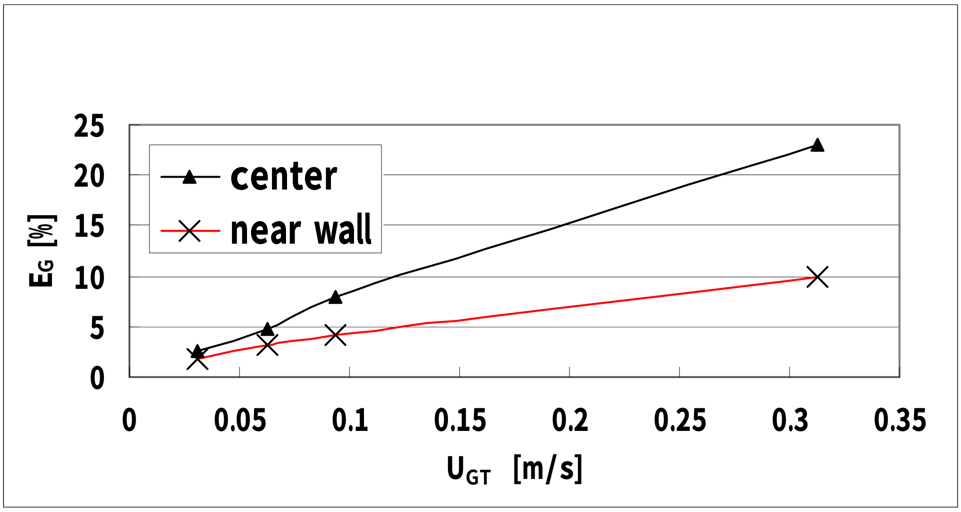

Fig.15 Effect of arrangement of gas inlet on E_G

4) Effect of column inclination on E_G

The simulation was done by using CFX software. The conditions of the simulation are as follows:

model = three dimensional bubble column of D_T = 8 cm and H_T = 90 cm, 5 mm mesh , bubble diameter = 5 mm, gas inlet = source point set at the center of the bottom, Euler-Euler model, turbulent flow, k- ε model, unsteady state, air and water at 293 K.

The dispersed phase zero equation and shear stress transport model were used in gas and liquid phase, respectively.

Fig.16 shows the simulation results. E_G decreases with increasing inclination angle θ, because bubbles rise along the upper wall. Yamashita (1985) have studied the effect of column inclination on E_G in a 8 cm I.D. and 3.5 m tall bubble column and presented the following correlation:

$$E_G = E_{G0}\,(1 - mA) \tag{12}$$

$$m = U_G^{-0.19} \tag{13}$$

$$A = \log[\{\theta + (\pi/18)\} / (\pi/18)] \tag{14}$$

Fig.16 shows E_G calculated from Eqs.(12)-(14). It is clear from Fig.16 that Eqs.(12)―（14）show a fairly good agreement with E_G by the simulation.

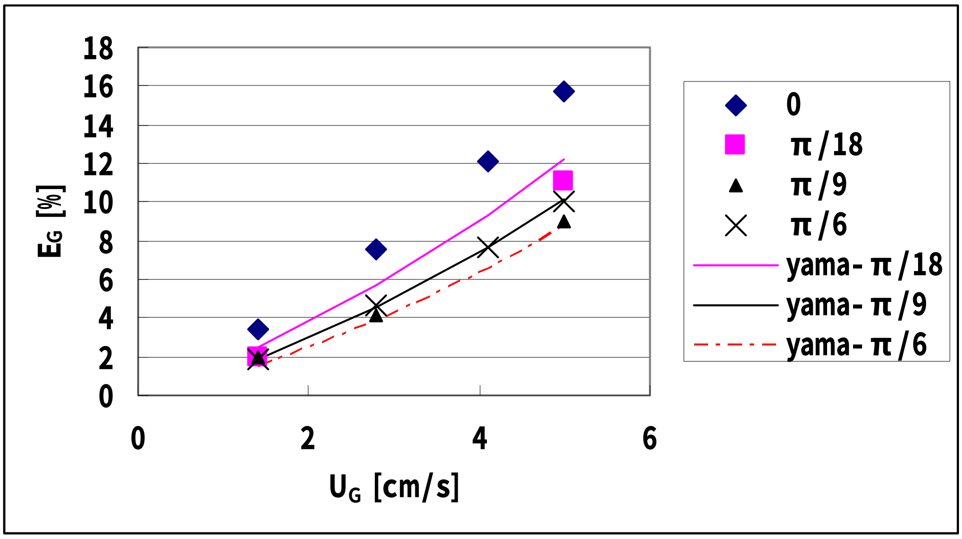

Fig.16 Effect of column inclination on E_G .
Figures in the key box mean inclination angle.

4. Conclusions

In this work, the effects of gas inlet height, superficial liquid velocity U_L, kinds of gas, arrangement of gas and liquid inlet, column inclination angle on gas holdup E_G were experimentally studied and simulated.

1) In a bubble column with concurrent upward gas and liquid flow, E_G decreased with increasing gas inlet height. The effect was well expressed by Eq.(1). The simulation results by Fluent were also well expressed by the same equation.

2) The effect of U_L on E_G was best expressed by the correlation of Bando et al.(1988). E_G depended little on kinds of gas. However, E_G by the simulation by Fluent did not depend on kinds of gas for a constant bubble diameter (d_B = 5 mm).

4) E_G by the simulation depended significantly on the arrangement of the gas and liquid inlet.

5) E_G by the simulation decreased with increasing column inclination angle and the effect was well express by the correlation of Yamashita (1985).

Notation

A	= parameter defined by Eq.(14)	[-]
d	= hole dioameter	[m]
d_B	= bubble diameter	[m]
D_T	= inner diameter of bubble column	[m]
E_G	= average gas holdup	[-]
$E_{G.Akita}$	= E_G calculated by the correlation of Akita et al.	

$E_{G.Argon}$ = E_G for Argon gas [-]
$E_{G,bando}$ = E_G calculated from Eqs. (6) and (7) [-]
$E_{G.cal}$ = E_G defined by Eq.(1) [-]
$E_{G,exp}$ = E_G experimentally measured [-]
$E_{G,Hydrogen}$ = E_G for Hydrogen gas [-]
E_{G0} = gas holdup at H_{in} =0 or θ = 0 [-]
$E_{G0, exp}$ = gas holdup experimentally measured for H_{in} = 0 cm [-]
$E_{G0, simu}$ = gas holdup obtained by simulation for H_{in} = 0 cm [-]
$E_{Gsimu,}$ cal = E_G defined by Eq.(11) [-]
$E_{G, yama}$ = E_G calculated by the correlation of Yamashita [-]
g = gravitational acceleration [m/s^2]
H = vertical height [m]
H_{in} = gas inlet height [m]
H_T = bubbling height or column height [m]
L = horizontal length [m]
m = parameter defined by Eq.(13) [$(m/s)^{-0.19}$]
n = number of holes [-]
U_G = superficial gas velocity [m/s]
U_{GT} = $U_G + U_L$ [m/s]
U_L = superficial liquid velocity [m/s]
u_s = velocity defined by Eq.(3) [m/s]
V_{BF} = rising velocity of bubbles in bubble flow defined by Eq.(5) [m/s]
V_{CTF} = rising velocity of bubbles in churn turbulent flow defined by Eq.(7) or (8) [m/s]

Greek Letters

θ = column inclination angle [rad]
μ_G = viscosity of gas [Pa・s]
μ_L = viscosity of liquid [Pa・s]
γ = surface tension of liquid [N/m]

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