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Flow behavior of wakes in a three-phase slurry bubble column with viscous liquid medium

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Abstract−Flow behavior of wakes has been investigated in a three-phase slurry bubble column of 0.102 m ID and 1.5 m in height. The dependence of wake characteristics such as rising velocity, frequency, holdup and equivalent size on the operating variables was examined by employing an electric resistivity probe method. The gas velocity, liquid viscosity and solid content in the slurry phase were chosen as independent parameters. The rising velocity of wake region increased with an increase in the gas velocity (4.0-12.0 cm/s), liquid viscosity (1.0-50.0 mPa·s) or solid content (0-25 wt%) in the slurry phase. The frequency and holdup of wake phase increased with increasing gas velocity, but decreased with increasing liquid viscosity or solid content in the slurry phase. The equivalent size of wake phase increased with increasing gas velocity, liquid viscosity or solid content in the slurry phase. The wake properties and holdup were well correlated with operation variables within these experimental conditions.

Key words: Wake Behavior, Three-phase, Slurry, Bubble Column, Viscous Medium

INTRODUCTION

Taking advantage of several unique features such as simplicity, low operating cost, suitability for continuous operation and effective contacting among multi-phases, the bubble columns have been utilized as reactors and contactors for continuous multi-phase processes [1,2]. One of them is the CTL (coal-to-liquid) or GTL (gas-to-liquid) process for the production of synthetic liquid fuels [3-5]. Investigations have been conducted on the bubble columns and slurry bubble columns for industrial applications and for the new emerging fields [3-7].

A bubble column is composed of rising bubbles in a continuous liquid medium. Although it looks simple, the flow behavior of rising bubbles in the column is highly irregular, since the bubbles rise randomly as a dispersed phase, propagating force and energy into the surroundings by means of coalescence and splitting. In addition, the rising bubbles are tailed by the wakes behind their rising path, due to the differences of pressures and thus streamlines between the front and the back sides of the rising bubbles. Owing to the vertical motions in the wake, the contacting intensity and efficiency among multi-phases have been extremely high in the wakes. Therefore, the energy dissipation rate, which is closely related to the transport phenomena such as momentum heat and mass transfer, in the wake can be very high [7-9]. For the analysis of the wake phenomenon which is induced by rising bubbles, the types and formation - shedding mechanism of wake phase have been studied [10,11]. Although extensive investigations have been conducted on the flow behavior of dispersed phase such as bubbles and wakes, there still remains uncertainty especially on the wake characteristics in three-phase slurry bubble columns. In addition, most of the previous investigations have focused on the wake phenomenon or phase which is tailing at the rear of a single bubble. The wake flow behavior induced by a single bubble seems to be quite important for the analysis of the mechanism; however, it has been highly sophisticated to be utilized for the actual slurry bubble column reactors.

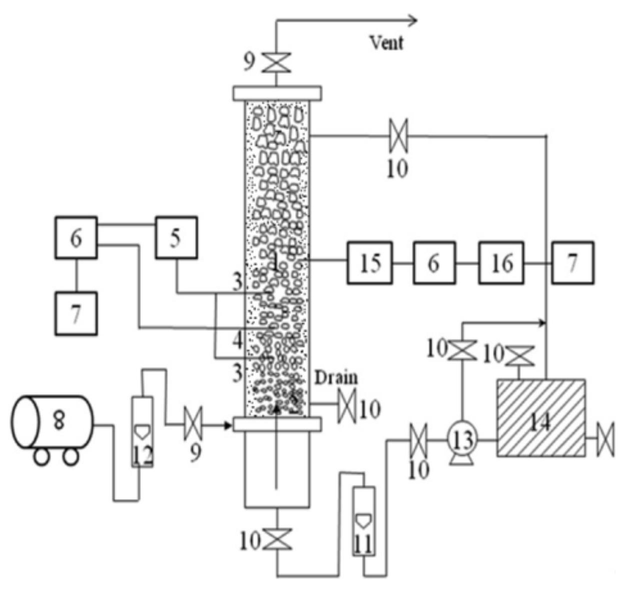

Fig. 1. Schematic diagram of experimental apparatus.

1. Main column	9. Needle valve
2. Gas distributor	10. Valve
3. Pressure probe	11. Liquid flowmeter
4. Resistivity probe	12. Gas flowmeter
5. Pressure sensor	13. Liquid pump
6. A/D converter	14. Liquid reservoir
7. Computer	15. Resistivity circuit
8. Compressor	16. Date acquisition system

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Table 1. Physical and rheological properties of liquid phase

	Dynamic viscosity (mPa·s)	Surface tension (mN/m)	Density (kg/m^3)	K (Pa·s^n)	n	Diffusivity (cm^2/s)	Kinematic viscosity (m^2/s)
Water	1	72.9	1000	0.001	1	2.22×10^{-5}	9.61×10^{-7}
CMC 0.1 wt%	11	73.2	1001	21.69×10^{-3}	0.882	0.48×10^{-5}	1.10×10^{-5}
CMC 0.2 wt%	24	73.3	1002	43.82×10^{-3}	0.847	0.26×10^{-5}	2.40×10^{-5}
CMC 0.3 wt%	38	73.6	1003	71.69×10^{-3}	0.825	0.19×10^{-5}	3.79×10^{-5}
CMC 0.4 wt%	50	73.9	1004	102×10^{-3}	0.802	0.15×10^{-5}	4.98×10^{-5}

Therefore, in the present study, characteristics of wake phase were examined in a three-phase slurry bubble column, where various bubbles with different sized are generated and their coalescence and breakage could occur simultaneously and continuously. Because, the resultant flow behavior of wake phase could be utilized for the practical applications in the various fields.

EXPERIMENTS

Fig. 1 shows the schematic diagram of experimental apparatus which was made of stainless-steel column (0.102 m×1.5 m high). A perforated plate, which was served as a gas distributor, was installed between the main column section and a 0.2 m high stainless-steel distributor box. The slurry phase was composed of aqueous solutions of carboxymethyl cellulose (CMC) and glass bead. The viscosity of liquid phase was in the range of 1.0-50 mPa·s, with a variation of CMC amount added in the tap water. The physical properties of liquid phase are listed in Table 1. The size of glass bead was in the range of 40-70 μm and solid content in the slurry phase was 0-20 wt%. Filtered, oil-free compressed air, which was used as a gas phase, was admitted at the bottom of the column through the gas distributor [12-14].

After steady state was attained in an adjusted experimental condition, the bubbles as well as wakes were measured. The wake characteristics such as rising velocity, frequency, holdup and size were measured by means of a dual electrical resistivity probe method. The probe, which was applied by 1.75 V DC, was installed at 0.4 m from the gas distributor. The probe consisted of two 7 mm diameter stainless-steel pipes coated with epoxy resin. The vertical and horizontal distances between the tips of the two probes were 2 mm and 3 mm, respectively. The probes were located at the center between the wall and the center of the column. The tips of the probes were made of 0.2 mm platinum wire to detect the difference in conductivity of gas and liquid [5,7].

The detected analogy signals, which were obtained at the preselected sampling rate, were stored on a personal computer with the DT2805 Lab card. The sampling rate and time were 1,000 HZ and 30 sec, respectively, comprising a total sample length of 30,000, which was enough to detect the fuel spectrum of the signals [4,5]. The wake characteristics were determined from the relationship be-

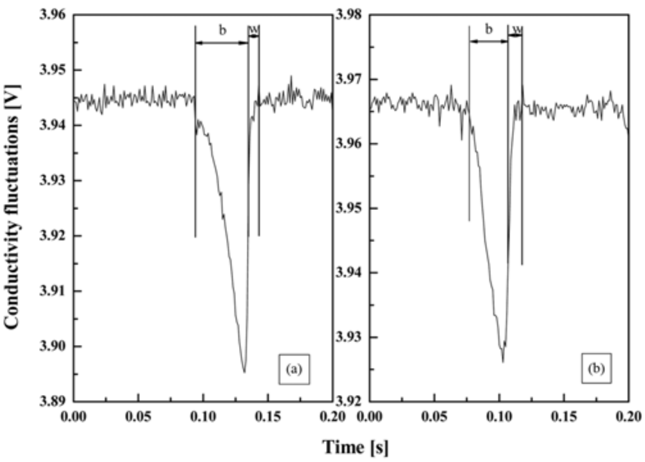

Fig. 2. Typical examples of bubble and wake in a viscous bubble column.

		$U_G\times10^2$ [m/s]	$\mu_L\times10^3$ [Pa·s]	S_C [wt%]
(a)	:	10	11	5
(b)	:	12	11	5

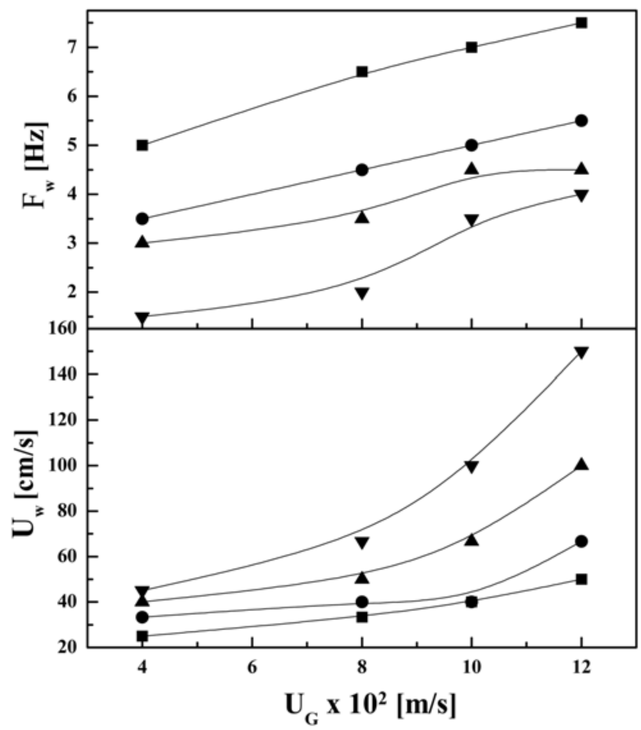

Fig. 3. Effects of gas velocity on the rising velocity and frequency of wake in a three-phase slurry bubble column.

		■	●	▲	▼
$\mu_L\times10^3$ [Pa·s]	:	1	5	11	38
S_C [wt%]	:	5	25	25	25

tween the reformed and digitized probe signals and the wake dwell and lag time.

RESULTS AND DISCUSSION

Typical examples of bubble and wake phase detected by the probes in the three-phase slurry bubble columns can be seen in Fig. 2. The wake region can be distinguished from the bubble phase at the back of the bubble. Effects of gas velocity on the frequency and rising velocity of wake phase, which were obtained from the relationship between the reformed and digitized probe signals, can be seen in Fig. 3. The frequency and rising velocity increase with increasing gas velocity. The increase of gas velocity can lead to the increase of gas input into the slurry bubble column, which results in the increase of the number of bubbles and thus of bubble coalescence in the column. Since the bubbles are tailed by wakes as a dispersed phase, the number of wakes could also increase in line with that of bubbles, with an increase in the gas velocity. In addition, the wake regions could also coalesce with each other whenever bubble coalescence could occur. It has been reported that the bubble rising velocity increases with increasing gas velocity [14-16]; thus, the rising velocity of the wake region can also increase with increasing gas velocity, since the rising bubbles are tailed by wakes.

Effects of liquid viscosity on the frequency and rising velocity of wake phase can be seen in Fig. 4. The frequency decreases but the rising velocity increases, with an increase in the liquid viscosity. It is noted that the bubble frequency decreases but the rising velocity of bubbles increases, with increasing liquid viscosity. These can be due to the fact that the bubble coalescence could increase with increasing liquid viscosity [14-16]. Since the buoyancy force acting on the bubbles, which is due to the difference of density between the bubble and slurry phase, increases with increasing bubble size, the rising velocity of wakes as well as bubbles could increase with increasing liquid viscosity. Because, the bubble coalescence increases and thus the frequency of bubbles decreases, with an increase in the liquid viscosity in three-phase slurry bubble columns [6-9]. Effects of solid content on the frequency and rising velocity of wake region can be seen in Fig. 5. The frequency of wake phase decreases gradually but the rising velocity increases, with increasing solid content in the slurry phase. The amount of solid content in the slurry phase could act on the bubble coalescence in that the solid particle could inhibit bubbles from contacting with slurry phase, which results in the increase of probability of bubbles contacting each other, that is, the increase of bubble coalescence. Since the coalescence and breaking or disintegration of wakes are quite similar to those of bubbles in the three-phase slurry bubble columns, the effects of solid content on the wake motion and flow behavior could be also explained as motioned above.

Effects of gas velocity on the wake holdup can be seen in Fig. 6. The holdup of wake was determined from the relationship between the reformed and digitized probe signals of wake dwell and lag time [7,11]. As expected, the wake holdup increases with increasing gas velocity in three-phase slurry columns. As indicated, the wake phase

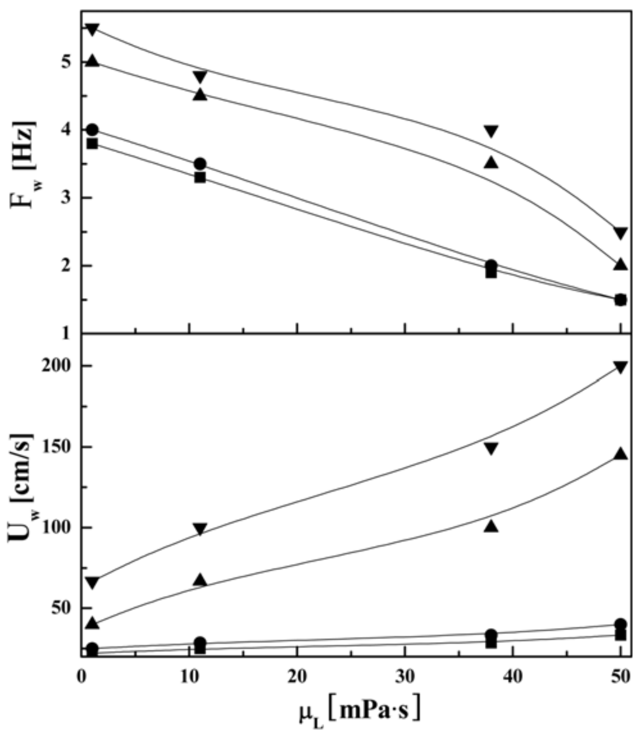

Fig. 4. Effects of liquid viscosity on the rising velocity and frequency of wake in a three-phase slurry bubble column.

		■	●	▲	▼
$U_G\times10^2$ [m/s]	:	4	4	10	12
S_C [wt%]	:	5	15	25	25

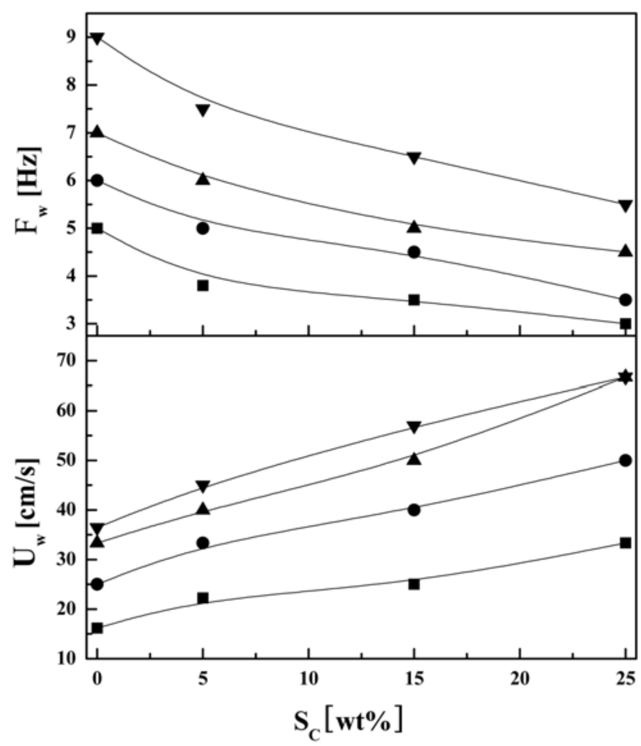

Fig. 5. Effects of solid content in the slurry phase on the rising velocity and frequency of wake in a three-phase slurry bubble column.

		■	●	▲	▼
$U_G\times10^2$ [m/s]	:	4	8	10	12
$\mu_L\times10^3$ [Pa·s]	:	1	11	11	1

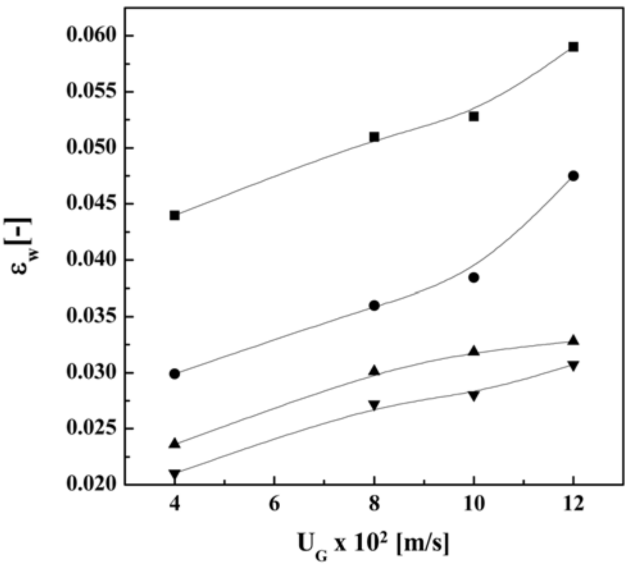

Fig. 6. Effects of gas velocity on the wake holdup in a three-phase slurry bubble column.

		■	●	▲	▼
$\mu_L\times10^3$ [Pa·s]	:	11	1	11	38
S_C [wt%]	:	5	25	25	25

is a tailing at the rear of the rising bubbles, and thus, the amount of tailing could increase with increasing bubble holdup by increasing gas input into the slurry column. Therefore, we can state that the gas-liquid contact could be more effective with increasing gas velocity, since the wake holdup increases with increasing gas velocity. It has been understood that the contacting flow of fluid element in the wake phase is quite vigorous owing to the vortex motion at the rear of the rising bubbles. Since the wake phase has been assumed to be composed mainly of liquid or slurry phase, the contact between the gas bubbles and liquid phase in the wake region could be most effective in the column. This can be the reason why the energy dissipation rate can be high in the wake region [1,2,11-13].

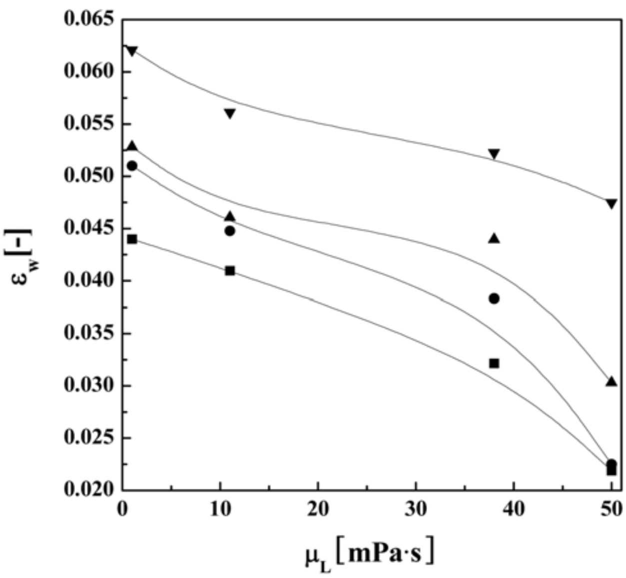

Fig. 7. Effects of liquid viscosity on the wake holdup in a three-phase slurry bubble column.

		■	●	▲	▼
$U_G\times10^2$ [m/s]	:	4	8	10	10
S_C [wt%]	:	15	15	15	5

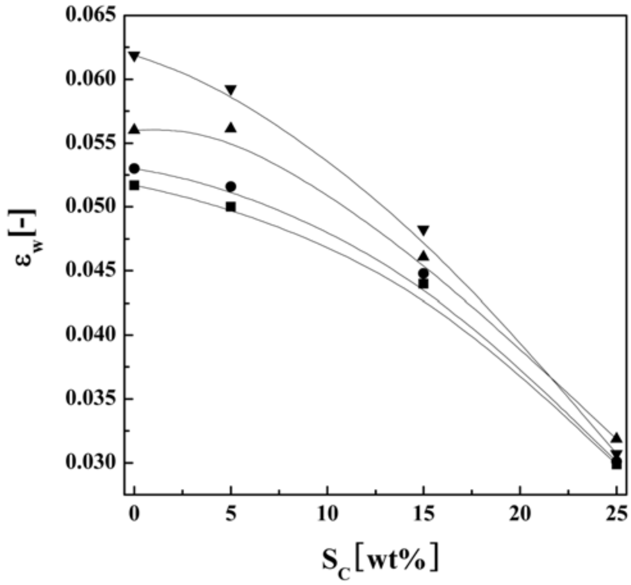

Fig. 8. Effects of solid content in the slurry phase on the wake holdup in a three-phase slurry bubble column.

		■	●	▲	▼
$U_G\times10^2$ [m/s]	:	4	8	10	12
$\mu_L\times10^3$ [Pa·s]	:	1	11	11	38

Effects of liquid viscosity and solid content in the slurry phase on the wake holdup in the column can be seen in Figs. 7 and 8. Here the wake holdups decrease gradually with increasing liquid viscosity or solid content in the slurry phase. Since the bubble coalescence and thus wake coalescence could increase with increasing liquid viscosity or solid content in the slurry phase, the holdups of wake region could decrease with increasing liquid viscosity or solid content in the slurry phase, as in the cases of bubble holdups [1,2].

The equivalent size of wakes was determined from the determined values of frequency and holdup, and this value was checked based on the concept that the shape of wake would be ellipsoidal. And then, the equivalent diameter of it was determined as a spherical shape which has the same volume as that of an ellipsoid. Thus obtained equivalent size of wake region is shown in Figs. 9-11, as a function of gas velocity liquid viscosity and solid content in the slurry, respectively. In these figures, the wake size increases with increasing gas velocity, liquid viscosity or solid content in the slurry phase. As indicated, the size of the wake region can be increased in the condition that the coalescence between wake regions could be more frequent. Since the contact and coalescence of the wake region are accompanied by those bubbles, the wake size increases in line with the increase of bubble size. In other words, the coalescence and contact of the wake region can increase with increasing gas velocity, liquid viscosity or solid content in the slurry phase.

The frequency, rising velocity, holdup and equivalent size of wake region have been well correlated in terms of operating variables as

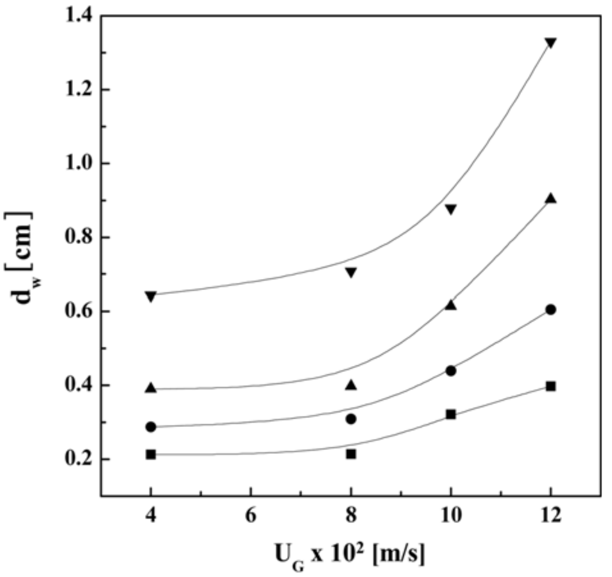

Fig. 9. Effects of gas velocity on the wake equivalent diameter in a three-phase slurry bubble column.

		■	●	▲	▼
$\mu_L \times 10^3$ [Pa·s]	:	1	1	11	38
S_C [wt%]	:	5	15	15	15

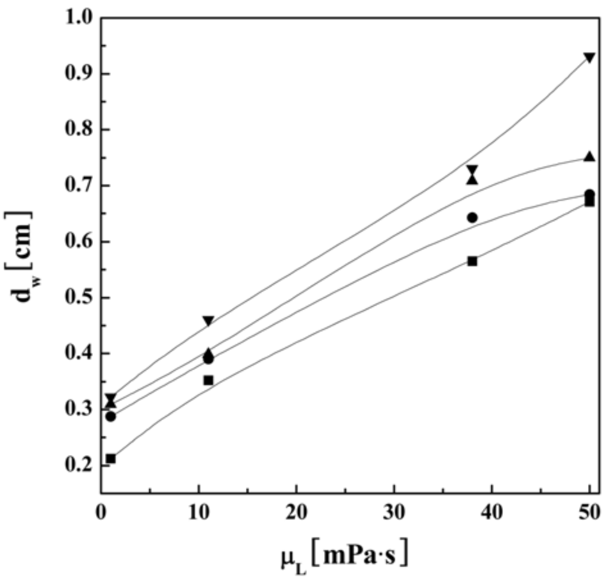

Fig. 10. Effects of liquid viscosity on the wake equivalent diameter in a three-phase slurry bubble column.

		■	●	▲	▼
$U_G \times 10^2$ [m/s]	:	4	4	8	10
S_C [wt%]	:	5	15	15	5

Eqs. (1)-(4):

$$F_W=3.150U_G^{0.62}\ S_C^{-0.24}\ \mu_L^{-0.21} \quad (1)$$

$$U_W=3.174U_G^{0.78}\ S_C^{0.37}\ \mu_L^{0.15} \quad (2)$$

$$\varepsilon_W=0.070U_G^{0.29}\ S_C^{-0.36}\ \mu_L^{-0.11} \quad (3)$$

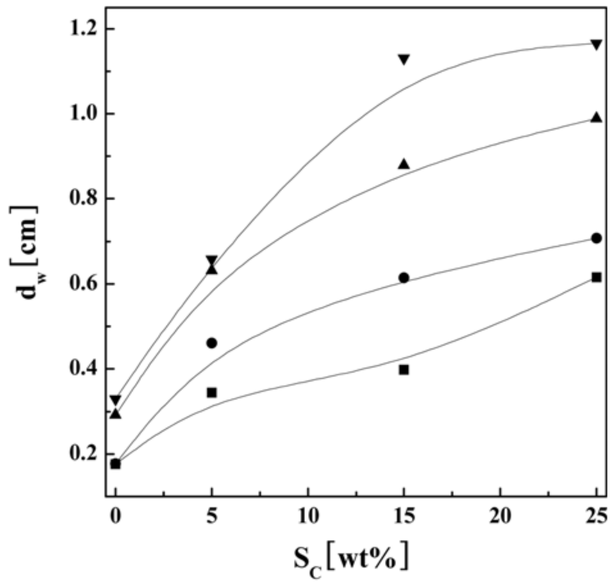

Fig. 11. Effects of solid content in the slurry phase on the wake equivalent diameter in a three-phase slurry bubble column.

		■	●	▲	▼
$U_G \times 10^2$ [m/s]	:	8	10	10	12
$\mu_L \times 10^3$ [Pa·s]	:	11	11	38	38

$$d_W=0.056U_G^{0.51}\ S_C^{0.29}\ \mu_L^{0.25} \quad (4)$$

The correlation coefficients of Eqs. (1)-(4) are 0.90, 0.92, 0.91 and 0.92, respectively.

CONCLUSION

The wake properties such as frequency, rising velocity, and equivalent size and its holdup were successfully examined in a three-phase slurry bubble column by employing the resistivity probe method. The frequency of wake region increased with increasing gas velocity but decreased with increasing liquid viscosity or solid content in the slurry phase. The rising velocity and equivalent size of wake region increased with increasing gas velocity, liquid viscosity or solid content in the slurry phase. The holdup of wake region increased with increasing gas velocity, but it decreased with increasing liquid viscosity or solid content in the slurry phase. The wake properties and its holdup were well correlated in terms of operating variables as:

$$F_W=3.150U_G^{0.62}\ S_C^{-0.24}\ \mu_L^{-0.21}$$
$$U_W=3.174U_G^{0.78}\ S_C^{0.37}\ \mu_L^{0.15}$$
$$\varepsilon_W=0.070U_G^{0.29}\ S_C^{-0.36}\ \mu_L^{-0.11}$$
$$d_W=0.056U_G^{0.51}\ S_C^{0.29}\ \mu_L^{0.25}$$

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NOMENCLATURE

d_P : particle diameter [μm]
d_W : equivalent diameter [cm]
D : column diameter [m]
F_w : wake frequency [Hz]
K : consistency index in power-law model [PaS^n]
L : column height [m]
S_C : solid content [wt%]
t : time [sec]
U_G : gas velocity [m/s]
U_W : wake rising velocity [cm/s]

Greek Letters

a : diffusivity [cm/s]
ε_w : wake phase holdup [-]
μ_L : liquid viscosity [mPa·s]
n : kinematic viscosity [m/s]
ρ_G : gas density [kg/m^3]
ρ_L : liquid density [kg/m^3]
ρ_S : solid content density [kg/m^3]
s : surface tension [mN/m]

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