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Flow Characteristics of Gas-Liquid Two Phase Plunging Jet Absorber
−Gas Holdup and Bubble Penetration Depth−

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Abstract−A gas-liquid two phase plunging jet is formed through a gas sucking type multi-jet ejector nozzle. In this study, the effects of various conditions in the multi-jet ejector nozzle, the column diameter, and the liquid jet length on penetration depth of air bubbles l_B and gas holdup h_G in a gas-liquid two phase plunging jet absorber were studied experimentally. Consequently, empirical equations concerning l_B and h_G were obtained, respectively. These equations agree with the experimental data with an accuracy of ±20% for l_B and ±25% for h_G.

Key words : Gas Absorption, Plunging Jet Absorber, Biphasic Jet, Penetration Depth, Gas Holdup

INTRODUCTION

Various kinds of devices using air bubble dispersion have been widely used as high performance gas-liquid contacting devices in chemical, fermentation, and waste treatment processes. Numerous attempts have been made by many researchers [Bin et al., 1982; Bin, 1993; Burgess et al., 1972, 1973; Funatsu et al., 1988; Ide et al., 1976; Ide et al., 1986; Kusabiraki et al., 1990; Mckeoh et al., 1981; Nishikawa et al., 1976; Ohkawa et al., 1985, 1987; Smigelshi et al., 1977; Suciu et al., 1976; Tojo et al., 1982; Van de sande et al., 1975; Weisweiler et al., 1978] to improve the performance of these devices. Their performance can be markedly improved by dispersing small solute bubbles in liquid phase and simultaneously increasing the turbulence of gas and liquid.

A plunging jet absorber is used as one of such high performance devices. Over the past few decades a considerable number of studies concerning a plunging jet absorber have been made. Some of these studies have been reported on gas entrainment [Bin, 1993; Kusabiraki et al., 1990; Mckeoh et al., 1981; Ohkawa et al., 1985, 1987], gas holdup [Bin, 1993; Funatsu et al., 1988], penetration depth of air bubbles [Bin, 1993; Kusabiraki et al., 1990; Mckeoh et al., 1981; Ohkawa et al., 1987; Smigelshi et al., 1977; Tojo et al., 1982; Van de sande et al., 1975; Suciu et al., 1976; Weisweiler et al., 1978], interfacial area [Bin et al., 1982; Bin, 1993; Burgess et al., 1972, 1973] and liquid-side volumetric mass transfer coefficient [Bin et al., 1982; Bin, 1993; Funatsu et al., 1988; Tojo et al., 1982]. In all cases, most of these studies have been made on a single phase plunging liquid jet absorber, but few studies have been reported on a gas-liquid two-phase plunging jet absorber [Ide et al., 1976, 1986].

In this present work, a new type of absorber using a gas-liquid two phase plunging jet which was formed through multi-jet ejector nozzle was devised. This absorber has several advantages as follows. It doesn't need an air compressor for gas sucking and dispersion. It is simple in construction and operation, and it can provide intensive gas-liquid mixing through a gas sucking type multi-jet ejector nozzle. As it is a long column type tower, it has large gas holdup and gas-liquid contact area nevertheless with its small column volume.

The purpose of this study is to experimentally make clear the effects of various conditions in the multi-jet ejector nozzle, the column diameter, and the liquid jet length on penetration depth of air bubbles l_B and gas holdup h_G in a gas-liquid two phase plunging jet absorber.

EXPERIMENTAL

A schematic diagram of absorber and plunging jet system is shown in Fig. 1. The transparent acrylic resin column of 1.11 m height was used and the diameter of column was varied from 5×10^{-2} to 1.2×10^{-1} m. The multi-jet ejector nozzle was attached to the top of the column. Fig. 2 shows details of the nozzle. The diameter of the liquid inlet duct to the nozzle D_P was 1.8×10^{-2} m, and the nozzle diameter D was varied from 8×10^{-3} to 1.2×10^{-2} m as shown in Table 1. The diameters of the gas inlet holes were constant, 3×10^{-3} m. The vertical length of the tapered section was 2×10^{-2} m, and the length of the nozzle was constant, 2×10^{-2} m. The A perforated plate made of brass was installed in this nozzle, of which hole diameter d was varied from 2.57×10^{-3} to 4.78×10^{-3} m, and the number of holes n was varied from 3 to 6. Hole area ratio of the perforated plate m_P was varied within the range of 0.061 to 0.166. m_P is determined by the following equation.

$$m_P = nd^2/D_P^2 \qquad (1)$$

Liquid jets ejected through the perforated plate flowed into the nozzle. After liquid was mixed with gas in the nozzle, the plunging jet spouted from the nozzle, passing through a gas layer, plunged into a liquid bath through the gas liquid interface

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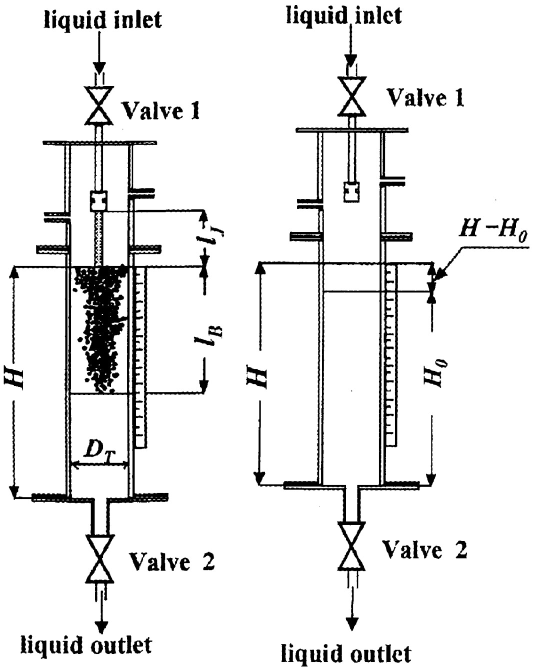


Fig. 1. Schematic diagram of absorber and plunging jet system.

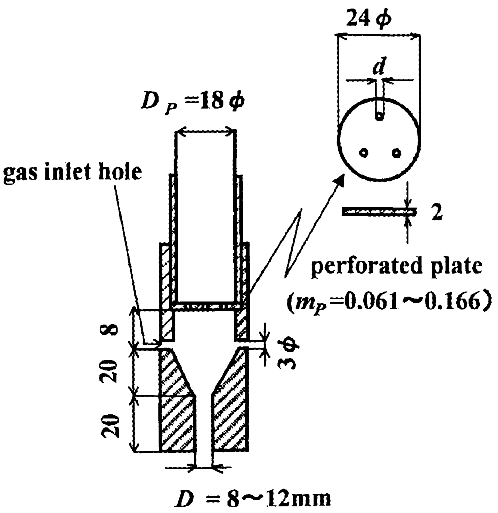


Fig. 2. Details of nozzle.

with a substantial amount of gas entrained and formed a submerged gas-liquid biphasic phase. The liquid jet length l_J, which was distance, from the nozzle exit to the liquid surface, was varied from 0.2 to 0.3 m. The penetration depth of air bubbles was measured by a scale fitted to the column wall. After the liquid flow was shut off by closing both valve 1 and valve 2 simultaneously, static dispersion height H_0 was measured. Gas holdup is given from

$$h_G=(H-H_0)/l_B \tag{2}$$

where H represents the dispersion height of air bubbles. All experiments were carried out with air-water system at atmospheric pressure and room temperature. Experimental conditions and corresponding keys used in figures are shown in Table 1.

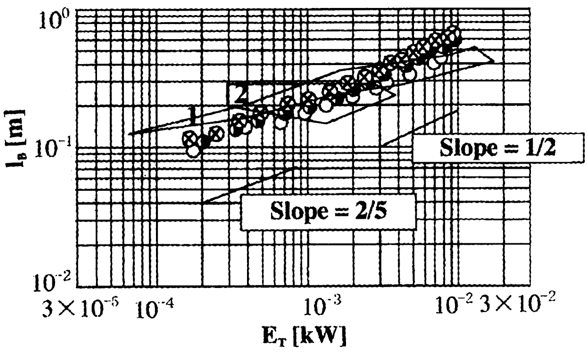
Table 1. Experimental conditions and corresponding keys

Key	D_T [m]	m_p [-]	n	d [mm]	D [m]	l_J [m]
▽		0.061	3	2.57		
▼ (half)	0.05	0.097	6	2.29		
▼		0.166	6	2.99	0.01	
◇		0.061	3	2.57		
◆ (half)	0.075	0.097	6	2.29		
◆		0.166	6	2.99		
○ (with stem)		0.061	3	2.57		
◑ (with stem)		0.097	6	2.29	0.008	
● (with stem)		0.166	6	2.99		
○		0.061	3	2.57		
◓		0.073	6	1.99		
◑		0.097	6	2.29		0.2
◒		0.10	3	3.28	0.01	
◐	0.1	0.141	2	4.78		
⊗		0.153	3	4.06		
●		0.166	6	2.99		
-○-		0.061	3	2.57		
-◑-		0.097	6	2.29	0.012	
-●-		0.166	6	2.99		
□		0.061	3	2.57		0.3
△		0.061	3	2.57		
△ (variant)	0.12	0.073	6	1.99		
△ (half)		0.097	6	2.29		
▲ (variant)		0.10	3	3.28	0.01	0.2
▲ (half)		0.141	2	4.78		
△ (crossed)		0.153	3	4.06		
▲		0.166	6	2.99		

RESULTS AND DISCUSSION

1. Penetration Depth of Air Bubbles, l_B

Fig. 3 shows the relation between l_B and E_T for various m_P under the condition D_T=0.1 m, and a comparison of l_B with those for a single phase plunging liquid jet is also shown. E_T is



	D [m]	V_N [m/s]	Author
1	0.006–0.03	1–10	Mckeoh et al., 1981
2	0.045	1–10	Tojo et al., 1982

Fig. 3. Relation between l_B and E_T for various m_P (D_T=0.1 m).

given by the sum of kinetic energy and potential energy

$$E_T = Q_L(\rho_L u_0^2/2 + \rho_L g l_Z) \tag{3}$$

where ρ_L is liquid density, u_0 is liquid velocity based on cross-sectional area of holes for the perforated plate, g is acceleration of gravity, and l_Z is liquid jet length ($=l_J+4.8\times10^{-2}$ m). As can be seen from this figure, it is found that l_B increases with increasing E_T. l_B is proportional to $E_T^{2/5}$, if E_T is less than 1×10^{-3} kW. On the other hand, l_B is proportional to $E_T^{1/2}$, if E_T is greater than this value. This is because the liquid jet under the liquid surface is dragged by downflow of surrounding liquid in the column when E_T is greater than 1×10^{-3} kW. Regions 1 and 2 surrounded by solid line designate the experimental results of Mckeoh et al.'s [1981] and Tojo et al.'s [1982], respectively. Tojo et al. [1982] reported the relationship between l_B and the jet kinetic power per unit volume of liquid content as $l_B \propto (P/V)^{1/3}$. P is equivalent to E_T in this work. The slope of their results was qualitatively similar to that of our study in the small E_T range. Fig. 4 shows relation between l_B and m_P under the condition that D_T and E_T are constant. It is found from the results of experimental data in Fig. 4 that l_B/D_P is proportional to $m_P^{-1/3}$.

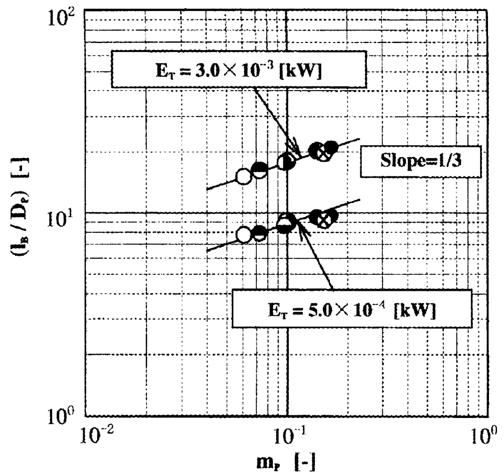


Fig. 4. Relation between l_B/D_P and m_P (D_T=0.1 m).

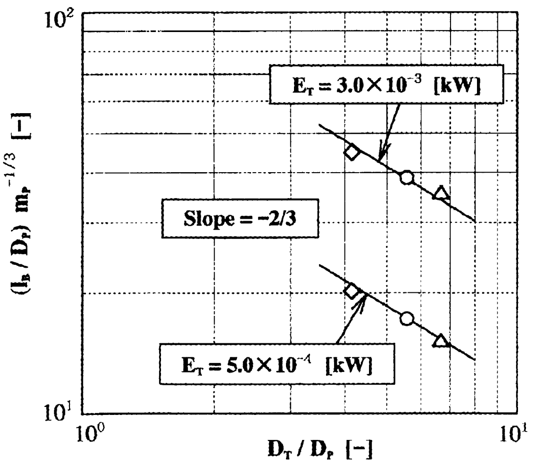


Fig. 5. Relation between $(l_B/D_P)m_P^{-1/3}$ and (D_T/D_P).

In order to clarify the effects of D_T on the penetration depth, $(l_B/D_P)m_P^{-1/3}$ was plotted versus E_T for various D_T. As a results it was found that $(l_B/D_P)m_P^{-1/3}$ decreased with D_T at constant value of E_T. Consequently, $(l_B/D_P)m_P^{-1/3}$ was plotted against D_T/D_P in Fig. 5 under the condition that E_T are constant. As can be seen from this figure, it was found that $(l_B/D_P)m_P^{-1/3}$ was proportional to $D_T^{-2/3}$. Considering the above results, $(l_B/D_P)m_P^{-1/3}(D_T/D_P)^{2/3}$ was plotted against E_T in Fig. 6.

Ultimately, the following equations concerning l_B were obtained,

for 1.0×10^{-4} kW$<E_T<1.0\times10^{-3}$ kW

$$(l_B/D_P) = 1.1\times10^3 m_P^{1/3}(D_T/D_P)^{-2/3}E_T^{2/5} \tag{4}$$

for 1.0×10^{-3} kW$<E_T<1.0\times10^{-2}$ kW

$$(l_B/D_P) = 2.2\times10^3 m_P^{1/3}(D_T/D_P)^{-2/3}E_T^{1/2} \tag{5}$$

These equations agree with all experimental data with an accuracy of ±20%.

2. Gas Holdup, h_G

h_G was also measured under the experimental condition as shown in Table 1. Fig. 7 shows relation between h_G and E_T for various m_P under the condition, D_T=0.12 m. It is found that h_G

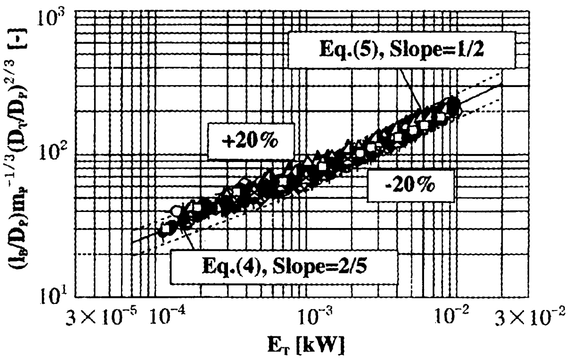


Fig. 6. Relation between $(l_B/D_P)m_P^{-1/3}(D_T/D_P)^{2/3}$ and E_T.

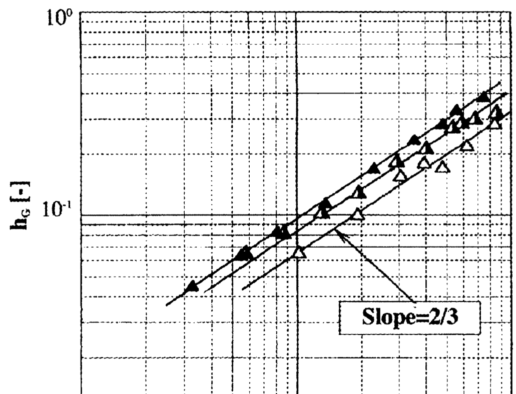


Fig. 7. Relation between h_G and E_T for various m_P (D_T=0.12 m).

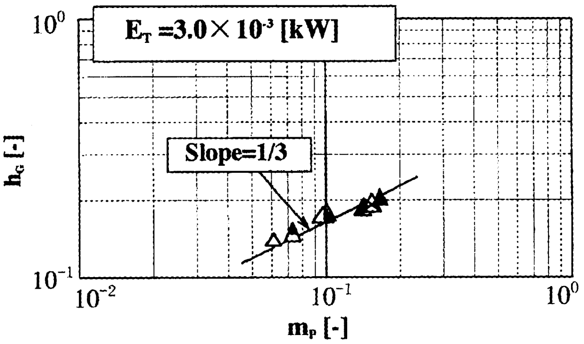


Fig. 8. Relation between h_G and m_P (D_T=0.12 m).

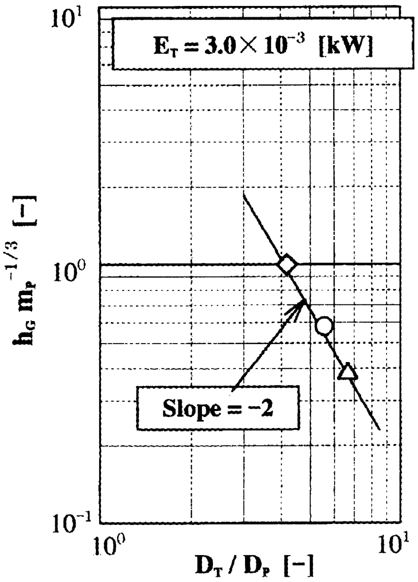


Fig. 9. Relation between $h_G m_P^{-1/3}$ and D_T/D_P.

increases in proportion to $E_T^{2/3}$. Fig. 8 shows the relation between h_G and m_P under the condition, D_T=0.12 m. From this figure, it is clear that h_G increases with increasing m_P, and that power to m_P is 1/3.

The relationship between $h_G m_P^{-1/3}$ and D_T/D_P is shown in Fig. 9 in order to clarify the effect of D_T on h_G. As a results, it was found that h_G was inversely proportional to square of D_T with constant E_T. Considering all above results concerning h_G, $h_G m_P^{-1/3} (D_T/D_P)^2$ was plotted against E_T in Fig. 10.

Consequently, the following equation concerning h_G was obtained.

$$h_G=9.0\times10^2 m_P^{1/3}(D_T/D_P)^{-2}E_T^{2/3} \quad (6)$$

This equation agrees with the all experimental data with an accuracy of ±25%.

Fig. 11 shows a comparison of the observed values of h_G in this apparatus with those in other jet-type bubble columns [Nishikawa et al., 1976; Ohkawa et al., 1985; Weisweiler et al., 1978], where other Author's h_G were obtained on the basis of dispersion height, that is, h_G=(H−H_0)/H. As can be seen from this figure, it is found that the gas-liquid two phase plunging jet absorber gives large gas holdup.

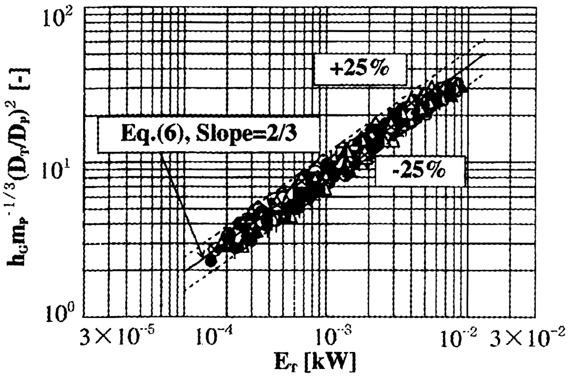
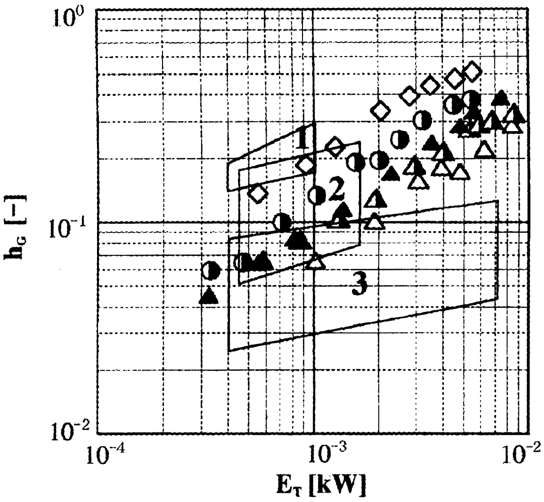


Fig. 10. Relation between $h_G m_P^{-1/3} (D_T/D_P)^2$ and E_T.



	D [m]	V_N [m/s]	D_T [m]	Author
1	0.013-0.025	0.12-0.2	0.06-0.2	Ohkawa et al., 1985
2	0.008-0.045	0-2.6	0.05-0.07	Nishikawa et al., 1976
3	0.002	0-25	0.16	Weisweiler et al., 1978

Fig. 11. Comparison of h_G observed in this apparatus with those in other jet-type of bubble columns.

CONCLUSION

The effects of various conditions in the gas sucking type multi-jet ejector nozzle, the column diameter and the length of liquid jet on penetration depth of air bubbles l_B and gas holdup h_G in a gas-liquid two phase plunging jet absorber were studied experimentally. The following conclusions were obtained in the experimental conditions of the system for $2.0<l_B/D_P<4.0\times10^1$, $2.0\times10^{-2}<h_G<6.0\times10^{-1}$, $0.061\le m_p\le0.166$, $2.78\le D_T/D_P\le6.67$, 1.0×10^{-4} kW$<E_T<1.0\times10^{-2}$ kW.

1. Penetration depth of air bubbles l_B and gas holdup h_G increased with increasing hole area ratio of the perforated plate m_P under condition that the column diameter D_T and liquid jet's total power E_T were constant.

2. l_B and h_G decreased with increasing D_T for constant E_T.

3. The empirical equations concerning l_B and h_G were obtained, respectively. These equations agree with the experimental data with an accuracy of ±20% for l_B and ±25% for h_G.

NOMENCLATURE

d : hole diameter of perforated plate [m]
D : inside diameter of nozzle [m]
D_P : diameter of the liquid inlet duct to nozzle [m]
D_T : column diameter [m]
E_T : liquid jet's total power [kW]
g : acceleration of gravity [m/s^2]
H : dispersion height of air bubbles [m]
H_0 : static dispersion height [m]
h_G : gas holdup [-]
l_B : penetration depth of air bubbles [m]
l_J : liquid jet length [m]
l_Z : distance from perforated plate to liquid surface ($=l_J+4.8\times 10^{-2}$) [m]
m_P : hole area ratio of perforated plate ($=nd^2/D_P^2$) [-]
n : number of holes of perforated plate [-]
P : jet kinetic power [kW]
Q_L : volumetric flow rate of liquid [m^3/s]
u_0 : liquid velocity based on cross-sectional area of holes for the perforated plate [m/s]
V : volume of liquid content [m^3]
V_J : jet velocity at nozzle exit [m/s]

Greek Letter

ρ_L : liquid density [kg/m^3]

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