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Hydrodynamic characteristics of a horizontal flow ejector in a rectangular chamber

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Abstract−The effects of the volumetric flow rate of primary motive water, water height, and the geometric parameters of the hydrodynamiccharacteristics of the gas suction rate and gas phase holdup were investigated in a rectangular chamber (0.22×0.26×1.2 m-high) with a horizontal flow ejector. Gas suction rate increased with increasing volumetric flow rate of the primary motive water, mixing tube length and diffuser length, but it decreased with increasing water height and nozzle diameter. The gas phase holdup was directly proportional to gas suction rate, indicating its corresponding increase with the volumetric flow rate of the primary motive water. Conversely, it decreased with increasing water height and nozzle diameter. However, the mixing tube length affected the gas phase holdup minimally compared to other operating parameters. Both the gas suction rate and gas phase holdup correlated with the dimensionless equations of operating parameters.

Key words: Gas Suction Rate, Gas Phase Holdup, Horizontal Flow, Ejector, Rectangular Chamber

INTRODUCTION

Currently, in many industries, the demand for effective contacting processes or reactions of gas-liquid or gas-liquid-solid has increased. Among multiphase contacting devices, the gas distributor as an ejector can be used effectively as it offers a large interfacial area and a high mass transfer rate.

An ejector not equipped with mechanical moving parts is a device whereby the dispersed phase (secondary fluid) of low pressure is entrained and dispersed by the motive force, which is the continuous phase (primary motive fluid) of high pressure passing through the nozzle. This type of ejector has been used in bubble columns and fluidized bed reactors with increasing utility in biochemical and waste treatment processes [1,2]. Based on the flow direction, the ejector is installed vertically or horizontally according to each system's purpose and is classified either as gas-driven or liquid-driven based on the kind of the motive fluid used as a continuous phase. The advantages of liquid-driven ejectors, used in this present study, are reduction in the cost of the gas supply and recycling of the pure gas [1].

The performance of the ejector generally depends on the velocity of the motive fluid, the pressure drop through each part, and its geometric parameters, including nozzle diameter, mixing tube length, and diffuser length [2-16]. In designing an ejector, the factors of suction rate (entrainment and aspiration); pressure drop across the entire length; phase holdup; and mass transfer characteristics are important parameters to determine quantitative relationships among its geometry, operating conditions, and performance [3] and as such have become the focus of much research. Since the ejector study of Nagel et al. in 1970 [4], research on the various aspects of vertical flow liquid-driven ejectors in the gas-liquid system has been widely conducted [2,4-7]. The dispersed efficiency and suction rate of the gas were dependent on the diffuser configuration of the ejector [3] and increased when a swirl body was inserted in the ejector nozzle [2]. At a constant, total ejector length the energetic efficiency was the same for both configurations, where the liquid was contacted with either forced or free suction gas into the ejector [6]. The gas phase holdup increased with increasing viscosity and surface tension of the liquid, whereas the mass-transfer coefficient in the ejector decreased with increasing viscosity by 60%, maximally [7]. In the vertical flow ejectors of the liquid-gas system, the correlation equations of the gas phase holdup with gas suction rate were found in previous studies [2,5,6,8-15].

In contrast to the vertical flow ejector, only few studies have been conducted for a horizontal flow ejector in the gas-liquid system [8,9]. Hence, a need exists for research and development of a horizontal flow ejector for industrial application. Bhat et al. [17] investigated ejector performance using water, glycerin, and kerosene as the motive fluid and air as the entrained fluid, while Biswas and Mitra [18] predicted aspiration rates from mass and energy balance across multi-liquid-jet horizontal ejectors and gas-liquid mixing characteristics in the system.

The aim of this study is to investigatethe effects of the liquid volumetric flow rate, chamber water height, and geometric parameters of an ejector upon the hydrodynamic characteristics of gas suction rate and gas phase holdup, using the horizontal flow ejector with water as the motive fluid and air as the entrained gas in a two phase system.

EXPERIMENTAL

Fig. 1 shows a schematic of the rectangular chamber (material; transparent polycarbonate, size; 0.22×0.26×1.2 m-high) with a horizontal flow ejector as shown in Fig. 2, made of acrylic material and installed at the bottom of the chamber. Table 1 shows the experimental parameters and conditions. All the experiments were performed at ambient temperature and atmospheric pressure. The volumetric flow rate of the motive liquid was controlled by a pump (Iwaki Co., MDG-R15C100) and measured by an electromagnetic flowmeter

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(Toshiba Co., LF-600). The accumulated gas flowmeter (Kumho Metertech, BK-G10) was used for calculating the gas suction rate (G_g), while the difference in pressure (ΔP) caused by the suction gas was measured by a differential pressure transducer (Omega, PX-154) with the gas phase holdup (ε_g) calculated from Eq. (1) and (2):

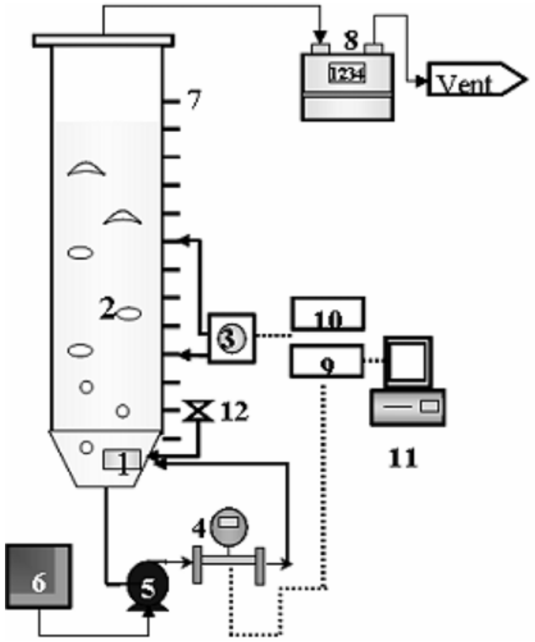


Fig. 1. Schematic of experimental setup.

1. Ejector distributor
2. Chamber
3. Differential pressure transducer
4. Electromagnetic flowmeter
5. Pump
6. On/off controller
7. Pressure tap
8. Accumulated gas flowmeter
9. Data acquisition
10. Power supply
11. Personal computer
12. Gas suction entrance

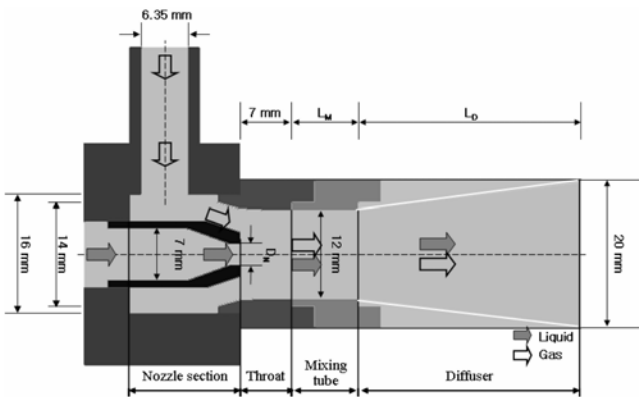
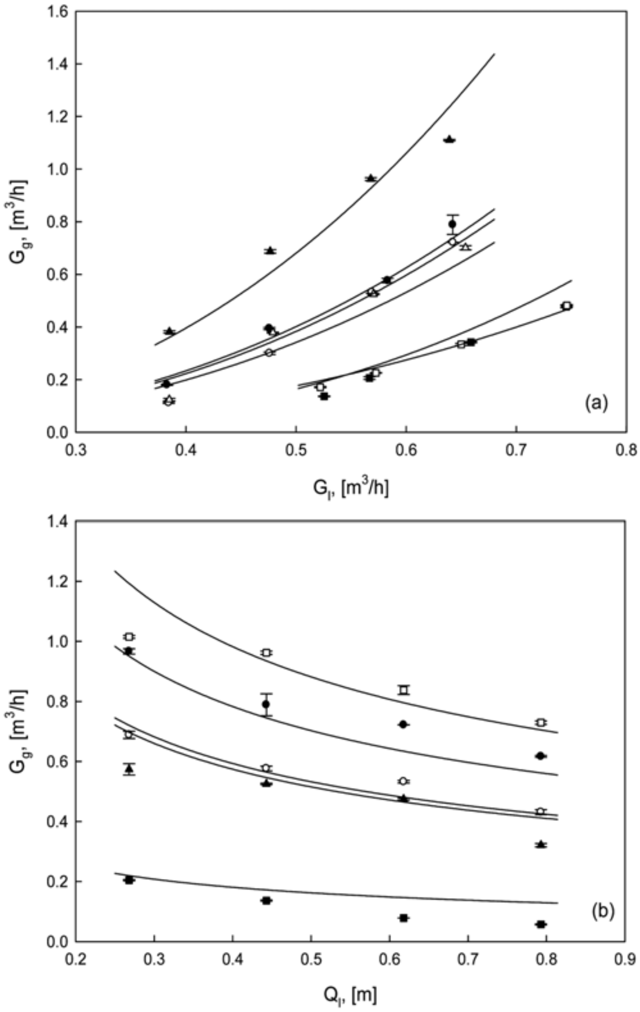


Fig. 2. Ejector gas distributor.

Table 1. Experimental parameters and operating range

Operating parameters		Ranges
Liquid volumetric flow rate, G_l (m^3/h)		0.36-0.90
Water height in the chamber, Q_l (m)		0.268, 0.443, 0.618, 0.796
Geometry	Nozzle diameter, D_N (m)	0.003, 0.004, 0.005, 0.006
	Mixing tube length, L_M (m)	0, 0.006, 0.009, 0.012
	Diffuser length, L_D (m)	0.030, 0.042, 0.060, 0.072



(a)

Symbol	Q_l, [m]	D_N, [mm]	L_M, [mm]	L_D, [mm]
●	0.44	3	9	30
○	0.62	3	9	30
■	0.44	4	9	30
□	0.44	4	12	30
▲	0.44	3	9	60
△	0.44	3	9	30
▬	Eq. (5)			

(b)

Symbol	G_l, [m^3/h]	D_N, [mm]	L_M, [mm]	L_D, [mm]
●	0.65	3	9	30
○	0.57	3	9	30
■	0.64	5	9	30
□	0.57	3	9	60
▲	0.58	3	6	30
▬	Eq. (5)			

Fig. 3. Gas suction rate with: (a) liquid volumetric flow rate; and (b) water height in the chamber.

$$\left(-\frac{\Delta P}{L}\right)=(\varepsilon_l\rho_l+\varepsilon_g\rho_g)g-\rho_l g \quad (1)$$

$$\varepsilon_l+\varepsilon_g=1.0 \quad (2)$$

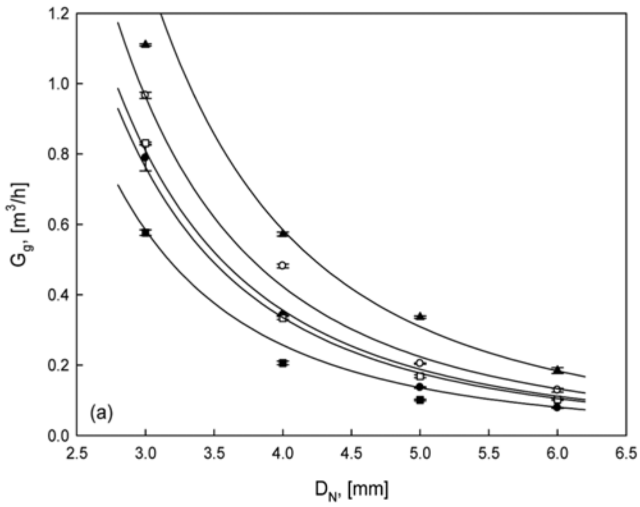
The pressure tap was set at intervals of 0.1 m from the chamber bottom.

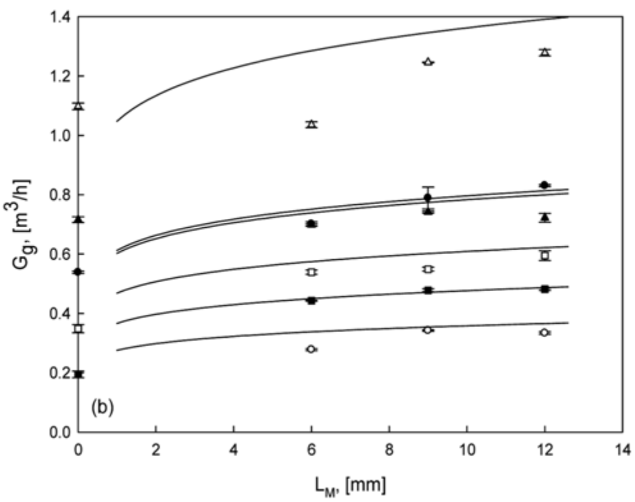
RESULTS AND DISCUSSION

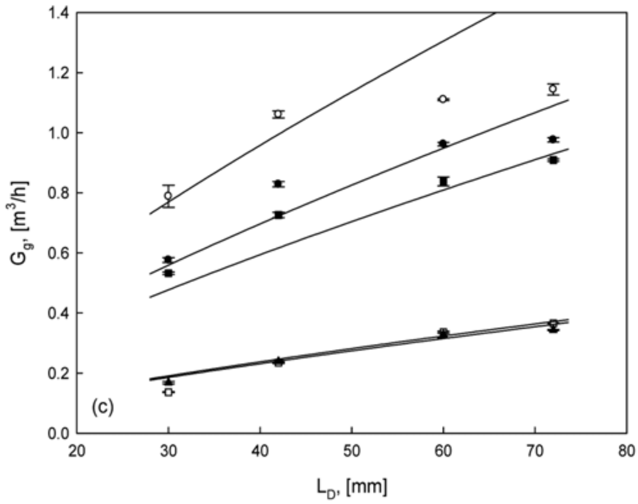
1. Gas Suction Rate

Fig. 3 shows the variation of the gas suction rate (G_g) with the volumetric flow rate of the motive liquid (G_l) and the water height in the chamber (Q_l). As shown in Fig. 3, the gas suction rate increased with increasing liquid volumetric flow rate and decreased with increasing water height. The difference in the pressure dropbetween suction entrance and throat exit in the ejector affected the gas suction rate [19], causing the pressure to drop and increasing the formation of bubbles in the ejector and increasing the liquid volumetric flow rate [15]. Hence, more momentum was transferred from the motive water to air thus the gas suction and density of bubbles increased with increasing the liquid volumetric flow rate. In contrast with the liquid volumetric flow rate, the gas suction rate decreased with increasing water height due to the increase in the outside pressure of the ejector diffuser. The predicted values of from Eq. (5) were plotted in Fig. 3 for comparison withexperimental values.

Figs. 4a-4c show the variation in the gas suction rate with the







(a)

Symbol	G_l, [m³/h]	Q_l, [mm]	L_M, [mm]	L_D, [mm]
+	0.65	0.44	9	30
◇	0.65	0.27	9	30
■	0.58	0.44	9	30
□	0.65	0.44	12	30
▲	0.65	0.44	9	60
▬	Eq. (5)			

(b)

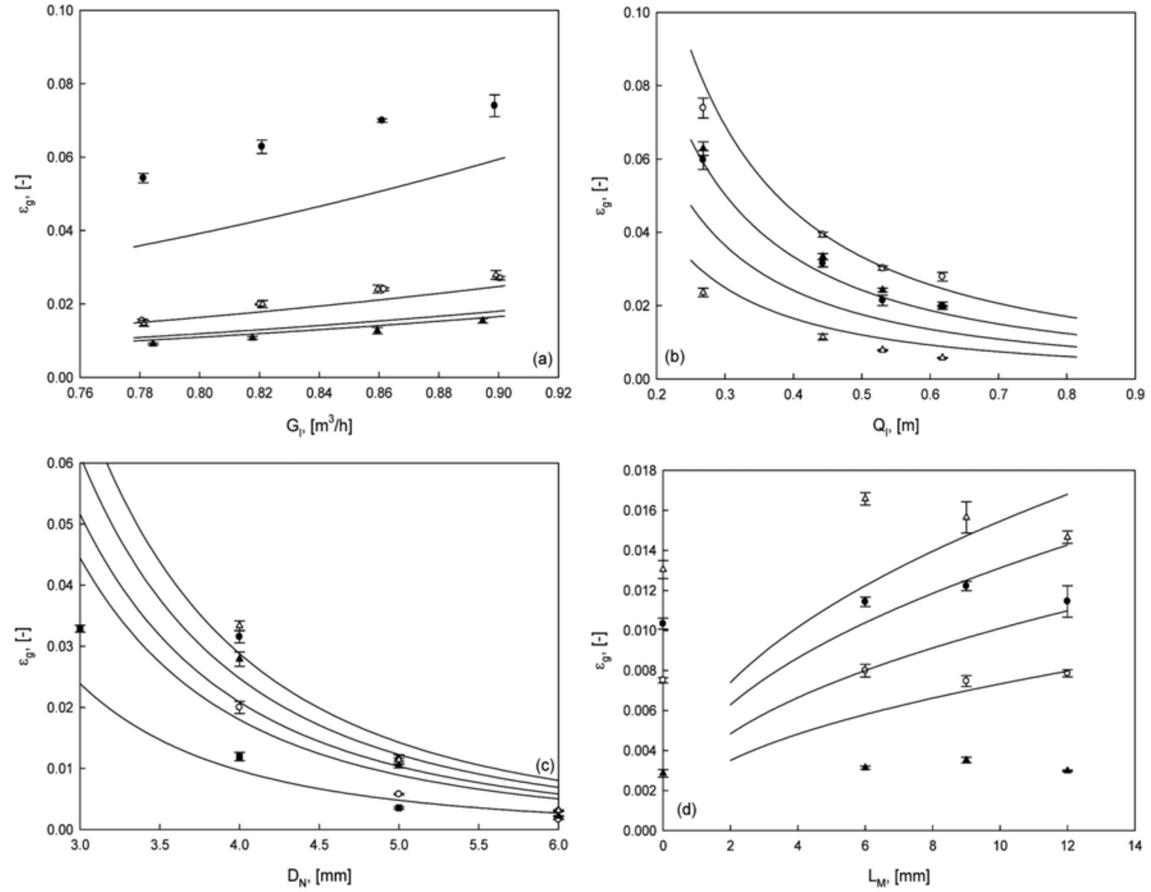
Symbol	G_l, [m³/h]	Q_l, [mm]	D_N, [mm]	L_D, [mm]
●	0.65	0.44	3	30
○	0.67	0.44	4	30
■	0.75	0.44	4	30
□	0.75	0.27	4	30
▲	0.75	0.27	4	60
△	0.66	0.44	3	60
▬	Eq. (5)			

(c)

Symbol	G_l, [m³/h]	Q_l, [mm]	D_N, [mm]	L_M, [mm]
●	0.57	0.44	3	9
○	0.65	0.44	3	9
■	0.57	0.62	3	9
□	0.66	0.44	5	9
▲	0.66	0.44	5	12
▬	Eq. (5)			

Fig. 4. Gas suction rate with: (a) nozzle diameter; (b) mixing tube length; and (c) diffuser length.

nozzle diameter (D_N), the mixing tube length (L_M), and the diffuser length (L_D) in the ejector. As can be seen in Fig. 4a, the gas suction rate decreased exponentially with increasing nozzle diameter, owing to the decrease in motive force and momentum transfer generated by the motive water. The pressure drop of the suction module and throat in the ejector also decreased with increasing nozzle diameter. As shown in Fig. 4b, the experimental values of the gas suction rate increased slightly with the mixing tube length, but soon equilibrated. Havelka et al. [2] reported that the gas suction rate only increased with the mixing tube length up to L_M/D_M=6 in a vertical upflow ejector. However, in this horizontal flow ejector study, the mixing tube length did not largely affect the change of the gas suction rate when the value of L_M/D_M was greater than 1. As shown in Fig. 4b, the experimental value of the gas suction rate was not 0, despite L_M=0, due to the presence of the throat within the ejector. Bhutada and Pangarkar [5] reported gas suction rate and gas holdup were the highest at throat length=0 in the vertical downflow ejector, whereas Havelka et al. [2] reported gas suction rate increasing with the throat



(a)

Symbol	Q_l, [m]	D_N, [mm]	L_M, [mm]	L_D, [mm]
●	0.27	4	6	60
○	0.62	4	6	60
▲	0.27	6	6	60
△	0.62	4	12	60
▬	Eq. (6)			

(b)

Symbol	G_l, [m^3/h]	D_N, [mm]	L_M, [mm]	L_D, [mm]
●	0.82	4	12	60
○	0.90	4	12	60
▲	0.82	4	6	60
△	0.82	5	12	60
▬	Eq. (6)			

(c)

Symbol	G_l, [m^3/h]	Q_l, [mm]	L_M, [mm]	L_D, [mm]
●	0.82	0.44	12	60
○	0.82	0.62	12	60
▲	0.90	0.62	12	60
△	0.82	0.44	6	60
■	0.66	0.44	6	60
▬	Eq. (6)			

(d)

Symbol	G_l, [m^3/h]	Q_l, [mm]	D_N, [mm]	L_D, [mm]
●	0.82	0.44	5	60
○	0.82	0.53	5	60
▲	0.82	0.44	6	60
△	0.86	0.44	5	60
▬	Eq. (6)			

Fig. 5. Gas phase holdup with: (a) liquid volumetric flow rate; (b) water height in the chamber; (c) the nozzle diameter; and (d) mixing tube length.

length in the vertical upflow. Therefore, the existence of the throat affects the gas suction rate. In Fig. 4c, the experimental values of thegas suction rate increased slightly with the diffuser length and then decreased and became constant after L_D=0.060 m; however, the predicted gas suction rate from Eq. (5) appeared to increase linearly.

2. Gas Phase Holdup

Fig. 5 shows the variation of the gas phase holdup with the volumetric flow rate (G_l) of the motive water entering the ejector, water height, nozzle diameter, and the mixing tube length. As can be seen in Fig. 5, the gas phase holdup increased with an increasing liquid volumetric flow rate, and decreased with both increasing water height in the chamber and nozzle diameter. An increase in the mixing tube length caused a decrease in the gas phase holdup, but the rate of the decrease was very low. In Fig. 5, the predicted values of the gas phase holdup, by correlation with Eq. (6), were plotted together to compare the experimental values. The experimental and predicted values seemed to fit reasonably well, but the effect of the diffuser length on the gas phase holdup was not investigated, as the gas phase holdup was hardly influenced by the diffuser length from the preliminary gas phase holdup experiments.

The values of the gas phase holdup were clearly proportional to the gas suction rate and related to the bubble rising velocity and bubble size. The more gas and liquid that are mixed, the smaller the size of the bubble formed. Fig. 6 shows the variation of the gas phase holdup, calculated by Eq. (1) and (2), with the gas suction rate in the rectangular chamber with a horizontal flow ejector. As can be seen, the gas phase holdup was proportional to the gas suction rate. These are similar to the results related to gas phase holdup and suction rate in previous studies on vertical flow ejectors [2,5,6, 8-15].

3. Correlation Equations

All gas suction rates and phase holdup were expressed as dimensionless,functional formulas correlated with operating parameters:

$$G_g \propto K\left(\frac{D_N\rho_l U_l}{\mu_l}\right)^{\alpha}\left(\frac{Q_l}{D_T}\right)^{\beta}\left(\frac{D_N}{D_{Throat}}\right)^{\gamma}\left(\frac{L_M}{D_N}\right)^{\delta}\left(\frac{L_D}{D_N}\right)^{\varepsilon} \tag{3}$$

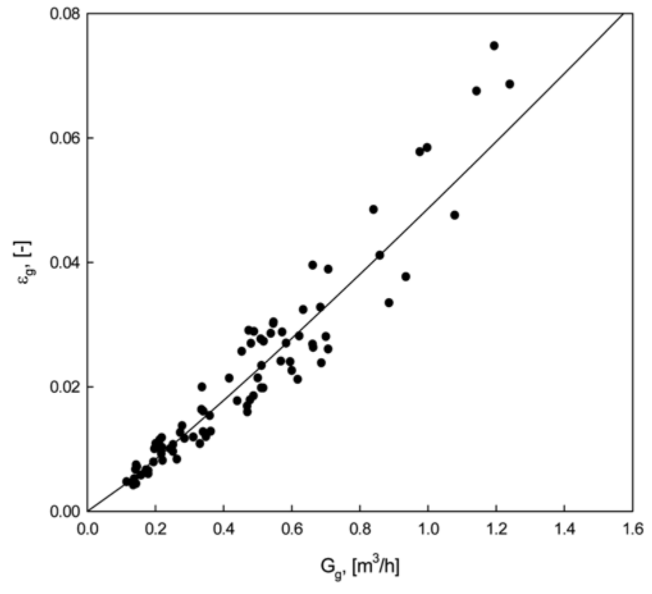


Fig. 6. Gas phase holdup with gas suction rate.

$$\varepsilon_g \propto K\left(\frac{D_N\rho_l U_l}{\mu_l}\right)^{\alpha'}\left(\frac{Q_l}{D_T}\right)^{\beta'}\left(\frac{D_N}{D_{Throat}}\right)^{\gamma'}\left(\frac{L_M}{D_N}\right)^{\delta'}\left(\frac{U_C^2}{D_T g}\right)^{\varepsilon'} \tag{4}$$

The nozzle must mainly affect gas suction rate, while the gas phase holdup functional formula clearly correlates with the gas suction rate and bubble size in the chamber. Therefore, the first term on the right side group in Eq. (3) represents the Reynolds number for the liquid velocity passing through the nozzle, and the second term represents changes in water height. Each of the other terms indicates the effects of nozzle diameter, mixing tube length, and diffuser length, (ejector geometries) on gas suction rate. The D_T is applicable to the equivalent diameter of the rectangular chamber of 0.22×0.26 m. In Eq. (4), the last term of right side group represents the Froude number, indicating the bubble size in the chamber. The diameter of the ejector throat, D_{Throat}, is 0.012 m. The density and viscosity of the water used in this study are assumed to be constants at 997 kg/m^3 and 0.0009 kg/m-s.

The following dimensionless equations of gas suction rate and phase holdup are obtained from the experimental data:

$$G_g = (3.0747\times10^{-13})\left(\frac{D_N\rho_l U_l}{\mu_l}\right)^{2.430}\left(\frac{Q_l}{D_T}\right)^{-0.485}\left(\frac{D_N}{D_{Throat}}\right)^{0.449}\left(\frac{L_M}{D_N}\right)^{0.114}\left(\frac{L_D}{D_N}\right)^{0.762} \tag{5}$$

where the correlation coefficient is 0.97 and the standard deviation is 0.064:

$0.30 \le G_l \le 0.80$ m^3/h, $0.268 \le Q_l \le 0.793$ m,
$0.003 \le D_N \le 0.006$ m, $0 < L_M = 0.012$ m, $0.030 \le L_D \le 0.072$ m

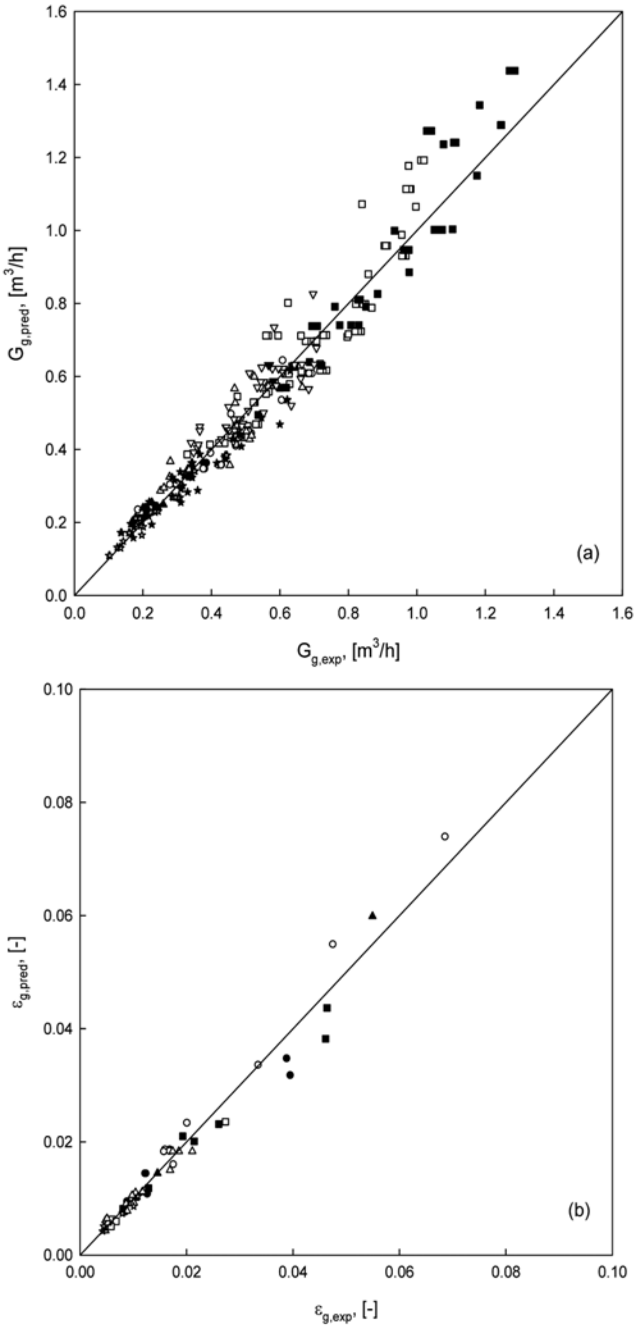
$$\varepsilon_g = (8.9708\times10^{5})\left(\frac{D_N\rho_l U_l}{\mu_l}\right)^{0.713}\left(\frac{Q_l}{D_T}\right)^{-1.4273}\left(\frac{D_N}{D_{Throat}}\right)^{-2.6195}\left(\frac{L_M}{D_N}\right)^{0.4578}\left(\frac{U_C^2}{D_T g}\right)^{1.7277} \tag{6}$$

where the correlation coefficient is 0.98 and the standard deviation is 2.55×10^{-3}.

$0.65 \le G_l \le 0.90$ m^3/h, $0.268 \le Q_l \le 0.618$ m,
$0.003 \le D_N \le 0.006$ m, $0 < L_M = 0.012$ m,

The predicted values of each equation were compared with the experimental values, as shown in Fig. 7. On the whole, the predicted values of G_g and ε_g were well-fitted with those of the experiment, but were slightly out of the range of the high liquid volumetric flow rate and low nozzle diameter because the exponent values of their terms, volumetric flow rate and nozzle diameter, are higher than those of the other terms in Eqs. (5) and (6). The Reynolds number, changed by the flow rate and nozzle diameter, is the main factor affecting gas suction rate, while the phase holdup of the gas is affected by the nozzle diameter and the Froude number as the variable of the liquid volumetric flow rate, since their exponent value is high compared to those of other operating parameters in Eqs. (5) and (6).

The following deviations of Eqs. (7) and (8) are used for comparison of our work with previous works [20]. Table 2 shows that the deviation between Eq. (6) and the experimental data in our study is much lower than that shown in previous works [2,6,8,10,12]:



(a)

Symbol	G_l, [m^3/h]	D_N, [mm]
●	0.3-0.4	3
○	0.4-0.5	3
□	0.5-0.6	3
■	0.6-0.7	3
▲	0.5-0.6	4
△	0.6-0.7	4
▽	0.7-0.8	4
▼	0.8-0.9	4
★	0.5-0.7	5
☆	0.6-1.1	6

(b)

Symbol	G_l, [m^3/h]	D_N, [mm]
●	0.4-0.6	3
○	0.6-0.7	3
□	0.5-0.7	4
■	0.7-0.8	4
▲	0.8-0.9	4
△	0.6-0.8	5
☆	0.7-0.9	6

Fig. 7. Comparison of: (a) experimental gas suction rate; and (b) experimentalgas phase holdup with predicted values.

Table 2. Mean percentdeviations between predicted gas phase hold-ups and experimental values

Authors	Mean percent deviations	
	$\bar{\delta}_1$ [%]	$\bar{\delta}_2$ [%]
This work; Eq. (6)	10.32	12.04
Zahradnik et al. [12]; $\varepsilon_g=3.47U_g$	46.42	49.40
Heijnen et al. [10]; $\varepsilon_g=\frac{U_g}{0.25}$	41.15	45.39
Cramers et al. [8]; $\varepsilon_g=7.7U_g\left(\frac{\rho_g}{\rho_l}\right)^{0.11}$	44.32	47.63
Zahradnik et al. [6]; $\varepsilon_g=2.81U_g^{0.9}$	32.23	42.68
Havelka et al. [2]; $U_s=\frac{U_g}{\varepsilon_g}-\frac{U_l}{(1-\varepsilon_g)},\ U_s=0.224$ m/s	37.68	43.74

$$\bar{\delta}_1=\frac{100}{N}\sum_{i=1}^{N}\left|\frac{\text{prediction}-\text{experimental}}{\text{experimental}}\right|_i, \tag{7}$$

$$\bar{\delta}_2=100\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\text{prediction}-\text{experimental}}{\text{experimental}}\right)_i^2} \tag{8}$$

CONCLUSION

The effects of the volumetric flow rate of primary motive water, water height, and the geometric parameters of the hydrodynamic characteristics of the gas suction rate and gas phase holdup were investigated in a rectangular chamber (0.22×0.26×1.2 m-high) with a horizontal flow ejector. An ejector offering high interfacial area and mass transfer rate was used as the gas distributor. The gas suction rate increased with the liquid volumetric flow rate and with the lengths of the mixing tube and diffuser, but the extent of the increase with the lengths was relatively low before finally equilibrating. Conversely, the gas suction rate exponentially decreased with both the water height in the chamber and the nozzle diameter of the ejector. The gas phase holdup increased with the volumetric flow rate of the motive liquid, whereas it decreased with water height in the chamber and nozzle diameter, indicating a linear proportionality to the gas suction rate. However, the gas phase holdup was hardly affected by the mixing tube length. The gas suction rate and gas phase holdup data obtained in the rectangular chamber with a horizontal flow ejector, and expressed as dimensionless equations, correlated with operating parameters. The accuracy of these equations is superior to alternative equations of previous research.

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NOMENCLATURE

D_M : diameter of mixing tube [m]

D_N : diameter of nozzle tip [m]
D_T : equivalent diameter of the rectangular chamber [m]
D_{Throat} : diameter of the ejector throat [m]
g : acceleration due to gravity [m/s^2]
G_g : gas suction rate [m^3/h]
G_l : liquid volumetric flow rate [m^3/h]
K : constant of Eq. (3)
K' : constant of Eq. (4)
L : distance between high and low pressure taps [m]
L_D : length of diffuser [m]
L_M : lengthof mixing tube [m]
N : total data number [-]
ΔP : pressure drop [N/m^2]
Q_l : water height in the chamber [m]
U_c : liquid velocity in the chamber [m/s]
U_g : gas velocity in the column [m/s]
U_l : liquid velocity passing through nozzle [m/s]
U_s : slip velocity [m/s]

Greek Letters

$\bar{\delta}_1$: average absolute deviation defined in Table 2 [-]
$\bar{\delta}_2$: root mean square deviation defined in Table 2 [-]
ε_g : gas phase holdup [-]
ε_l : liquid phase holdup [-]
μ_l : liquid viscosity [kg/m/s]
ρ_l : liquid density [kg/m^3]
ρ_g : gas density [kg/m^3]

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