EFFECT OF LIQUID PROPERTY ON GAS ENTRAINMENT BEHAVIOR IN A PLUNGING LIQUID JET AERATION SYSTEM USING INCLINED NOZZLES

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Key Words: Chemical Reactor, Inclined Liquid Jet, Gas Entrainment, Liquid Property, Bubble Penetration Depth, Jet Shape Change

Introduction

Gas entrainment by a liquid jet is a more attractive means of aeration than the conventional gas-sparging methods because of its simplicity in construction and operation. Most information on gas entrainment by a liquid jet, however, is that for an air-water system.

In this work, effects of liquid properties on gas

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Table 1. Physical properties of liquids

Liquid	conc.	ρ [kg/m³]	σ [mN/m]	μ [mPa. s]	Key
Water[3]		997	72.0	0.890	○
Methanol[3]	2.0 vol%	994	68.0	0.949	⊖
Ethanol[3]	2.0 vol%	994	65.8	0.961	◇
Tween 60[3]	7.5 g/m³	997	66.4	0.884	▽
KCl[3]	2.0 mol/m³	998	73.4	0.889	□
Corn-syrup	153.5 kg/m³	1047	73.5	1.20	△
	200 kg/m³	1062	73.8	1.42	▲
	300 kg/m³	1095	74.9	1.95	△
	400 kg/m³	1127	75.4	2.85	▲
	500 kg/m³	1160	75.8	4.50	▲

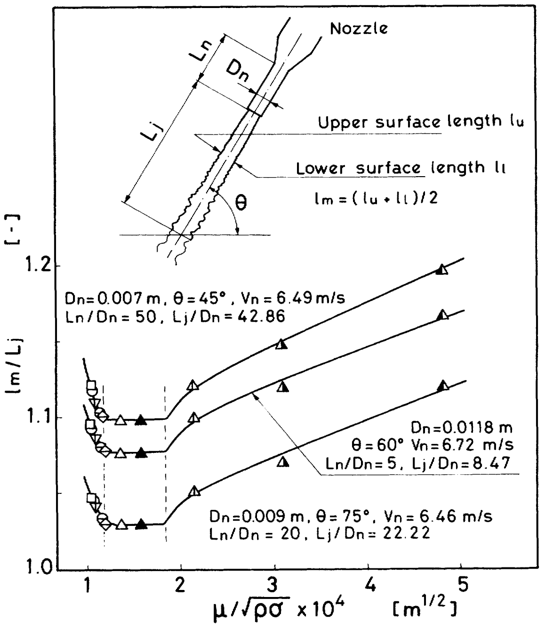

Fig. 1 Effects of liquid properties on surface disturbance of jet. (Symbols are listed in Table 1)

entrainment rate Q_g and maximum bubble penetration depth Z in an inclined liquid jet aeration system were investigated. Correlations for predicting Q_g and Z were presented.

1. Experimental

The experimental setup was the same as that used previously[3], Nozzle diameter D_n, jet angle θ, jet velocity V_n and jet length L_j were varied in the ranges of 7-11.8 mm, 45-75°, 2-13.5 m/s and 0.1-0.3m, respectively. The viscosity of liquid was varied from 1.2 to 4.5 mPa.s by adding corn-syrup (Kogo Denpun Kojyo Co. Ltd.) to water. The physical properties of the liquids are summarized in **Table 1**. Gas entrainment rate Q_g, center-line jet velocity V_m, maximum bubble penetration depth Z, etc. were measured according to respective methods described in the previous paper[3].

Surface disturbance of liquid jet was evaluated by

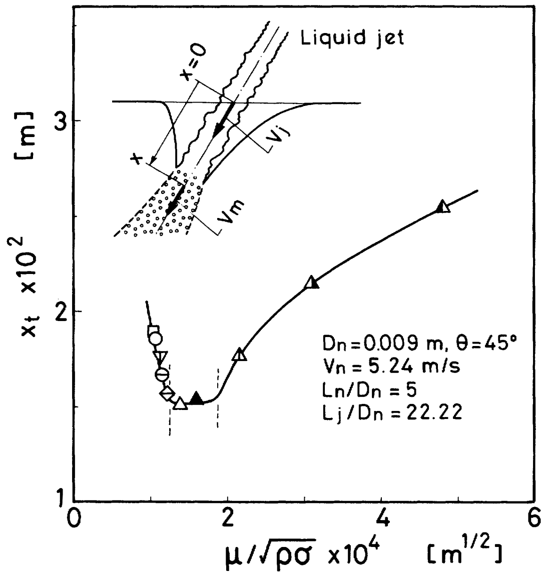

Fig. 2 Effects of liquid properties on x_t. (Symbols are listed in Table 1)

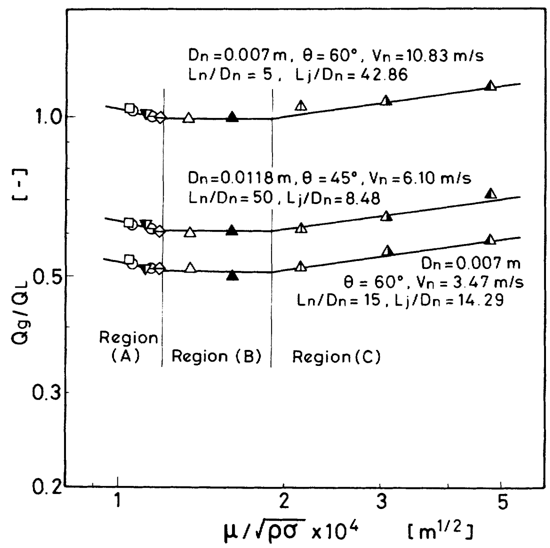

Fig. 3 Dependency of Q_g/Q_L on $\mu/\sqrt{\rho\sigma}$. (Symbols are listed in Table 1)

mean surface length of the jet l_m, which was obtained by averaging the upper and lower surface lengths of the jet. Both surface lengths of jet were measured with an opisometer on an enlarged image of a photograph of the jet.

2. Results and Discussion

2.1 Factors related to gas entrainment rate

Air entrainment by a liquid jet is known to be related to surface disturbance of the jet at the plunging point and liquid velocity near the plunging point[1,2,4]. Effects of liquid properties on these factors were first investigated.

(1) Surface disturbance of liquid jet **Figure 1** shows the relationship between $\mu/\sqrt{\rho\sigma}$ and l_m/L_j, where L_j is linear distance along the jet axis from the nozzle exit to the plunging point. The relative surface

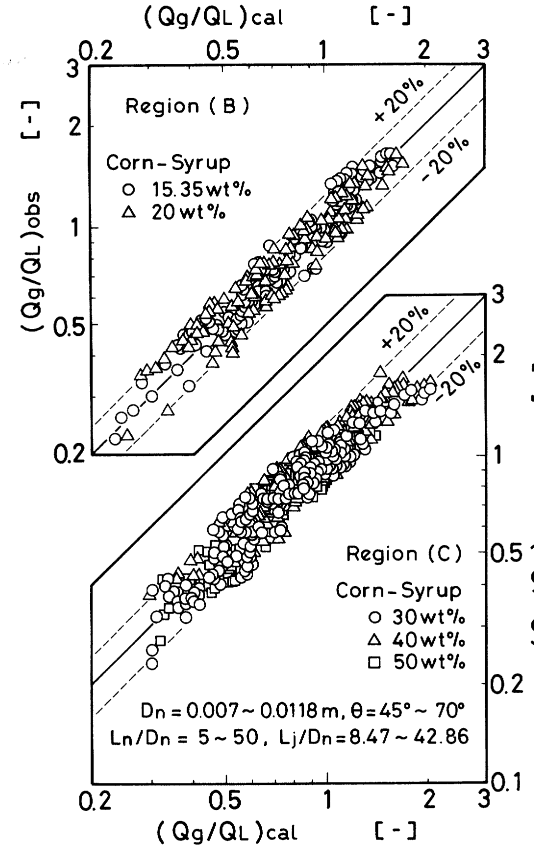

Fig. 4 Comparison of Q_g/Q_L values calculated from Eqs. (1) and (2) with those of observed.

length l_m/L_j of jet decreased first with increasing $\mu/\sqrt{\rho\sigma}$ up to about 1.2×10^{-4} m$^{1/2}$. The l_m/L_j was almost independent of $\mu/\sqrt{\rho\sigma}$ for the range between about 1.2×10^{-4} and about 1.9×10^{-4} m$^{1/2}$. With further increasing $\mu/\sqrt{\rho\sigma}$, l_m/L_j increased. These dependencies of l_m/L_j on $\mu/\sqrt{\rho\sigma}$ were the same for any set of the experimental conditions such as D_n, L_n, L_j, V_n and θ. The effects of $\mu/\sqrt{\rho\sigma}$ on l_m/L_j could be divided into three regions according to the value of $\mu/\sqrt{\rho\sigma}$.

(2) Liquid velocity near the plunging point. The center-line liquid velocity V_m at distance x from the plunging point was equal to jet velocity V_j at the plunging point up to a certain distance x_t, beyond which V_m became smaller than V_j with increasing x[3]. **Figure 2** shows the relationship between the transition distance x_t and $\mu/\sqrt{\rho\sigma}$. The effects of liquid properties on x_t were almost the same as those on l_m/L_j.

2.2 Gas entrainment rate

Figure 3 shows the effects of liquid properties, represented by $\mu/\sqrt{\rho\sigma}$, on Q_g/Q_L. The dependency of Q_g/Q_L on $\mu/\sqrt{\rho\sigma}$ seemed rather small, but it was considered to be reasonable from the results above that the effect of $\mu/\sqrt{\rho\sigma}$ on Q_g/Q_L could be divided into three regions as follows.

Region (A); $\mu/\sqrt{\rho\sigma}$ = 1.04×10^{-4}-1.2×10^{-4} m$^{1/2}$
Region (B); $\mu/\sqrt{\rho\sigma}$ = 1.2×10^{-4}-1.9×10^{-4} m$^{1/2}$
Region (C); $\mu/\sqrt{\rho\sigma}$ = 1.9×10^{-4}-4.8×10^{-4} m$^{1/2}$

Transition values of $\mu/\sqrt{\rho\sigma}$ between the regions (A) and (B), and (B) and (C) were 1.2×10^{-4} and 1.9×10^{-4} m$^{1/2}$ respectively, for any set of the experimental conditions tested.

The Q_g/Q_L values for the liquids of regions (A), (B) and (C) were correlated by the following form[3] within 20% error as shown in **Fig. 4**.

$$Q_g/Q_L = A\ Fr^{f(\sin\theta)}(L_j/D_n)^B(L_n/D_n)^C \times Oh^D(\sin\theta)^E \quad (1)$$

$$f(\sin\theta) = F(\sin\theta)^G \quad (2)$$

The values of the empirical constants, which change according to the range of L_n/D_n and V_n, are summarized in **Table 2**. The transition values of L_n/D_n and V_n were correlated for the all liquids tested as follows.

$$(L_n/D_n)_{tr} = 16.5(\sin\theta)^{-1.23} \quad (3)$$

For $5 \leqq L_n/D_n \leqq (L_n/D_n)_{tr}$

$$V_{nB} = 0.172 D_n^{-0.49} L_j^{0.40} L_n^{0.11} \times (\sin\theta)^{-0.65}(\mu/\sqrt{\rho\sigma})^{-0.15} \quad (4)$$

$$V_{n1} = 1.80 D_n^{-0.33} L_j^{0.13} L_n^{-0.09} \times (\sin\theta)^{-0.22}(\mu/\sqrt{\rho\sigma})^{0.09} \quad (5)$$

$$V_{n2} = 3.82 D_n^{-0.36} L_j^{0.21} L_n^{-0.07} \times (\sin\theta)^{-0.21}(\mu/\sqrt{\rho\sigma})^{0.09} \quad (6)$$

For $(L_n/D_n)_{tr} < L_n/D_n$

$$V_{nB} = 0.239 D_n^{-0.38} L_j^{0.40}(\sin\theta)^{-0.75} \times (\mu/\sqrt{\rho\sigma})^{-0.15} \quad (7)$$

$$V_{n1} = 10.2 D_n^{-0.21} L_j^{0.19}(\sin\theta)^{-0.27} \times (\mu/\sqrt{\rho\sigma})^{0.20} \quad (8)$$

$$V_{n2} = 11.3 D_n^{-0.34} L_j^{0.20}(\sin\theta)^{-0.25} \times (\mu/\sqrt{\rho\sigma})^{0.20} \quad (9)$$

2.3 Maximum bubble penetration depth

Dimensionless maximum bubble penetration depth Z/D_n was hardly affected by liquid properties. The following correlations[3] for liquids of the region (A) were found to be applicable to the liquids of the regions (B) and (C).

$$Z/D_n = (L_j/D_n)^a(L_n/D_n)^b 10^{f(Fr)}(\sin\theta)^c \quad (10)$$

$$f(Fr) = d + e(\log Fr) + f(\log Fr)^2 \quad (11)$$

The empirical constants, which were presented in the previous study[3], are summarized in **Table 3**.

Nomenclature

D_n	= nozzle diameter	[m]
Fr	= Froude number (= $v_n/\sqrt{gD_n}$)	[-]
g	= gravitational acceleration	[m/s^2]
l_m	= mean surface length of jet from nozzle exit to L_j	[m]
L_j	= linear distance along jet axis from nozzle exit to plunging point	[m]
L_n	= nozzle length	[m]
Oh	= Ohnesorge number (= $\mu\sqrt{\rho\sigma D_n}$)	[-]

Table 2. Values of *A, B, C, D, E, F* and *G* in Eqs. (1) and (2).

$(\mu/\sqrt{\rho\sigma})\times10^4$ [m$^{1/2}$]	L_n/D_n [-]	V_n [m/s]	A [-]	B [-]	C [-]	D [-]	E [-]	F [-]	G [-]
Liquids of region (A)	$5 \le L_n/D_n < (L_n/D_n)_{tr}$	I ; $V_{nB} \le V_n < V_{n1}$	1.6×10^{-3}	0.58	0.31	-0.19	-3.8	0.80	2.0
		II ; $V_{n1} \le V_n < V_{n2}$	6.8×10^{-3}	0.58	0.31	-0.19	-1.3	0.23	1.0
		III; $V_{n2} \le V_n$	1.5×10^{-3}	0.58	0.31	-0.19	-4.3	0.72	2.3
1.04 - 1.20	$(L_n/D_n)_{tr} \le L_n/D_n$	I ; $V_{nB} \le V_n < V_{n1}$	5.9×10^{-3}	0.51	0	-0.19	-3.8	0.80	2.0
		II ; $V_{n1} \le V_n < V_{n2}$	2.3×10^{-2}	0.51	0	-0.19	-1.3	0.23	1.0
		III; $V_{n2} \le V_n$	5.2×10^{-3}	0.51	0	-0.19	-4.3	0.72	2.3
Liquids of region (B)	$5 \le L_n/D_n < (L_n/D_n)_{tr}$	I ; $V_{nB} \le V_n < V_{n1}$	5.7×10^{-3}	0.58	0.31	0	-3.8	0.80	2.0
		II ; $V_{n1} \le V_n < V_{n2}$	2.4×10^{-2}	0.58	0.31	0	-1.3	0.23	1.0
		III; $V_{n2} \le V_n$	5.3×10^{-3}	0.58	0.31	0	-4.3	0.72	2.3
1.20 - 1.90	$(L_n/D_n)_{tr} \le L_n/D_n$	I ;$V_{nB} \le V_n < V_{n1}$	2.1×10^{-2}	0.51	0	0	-3.8	0.80	2.0
		II ; $V_{n1} \le V_n < V_{n2}$	8.2×10^{-2}	0.51	0	0	-1.3	0.23	1.0
		III; $V_{n2} \le V_n$	1.9×10^{-2}	0.51	0	0	-4.3	0.72	2.3
Liquids of region (C)	$5 \le L_n/D_n < (L_n/D_n)_{tr}$	I ; $V_{nB} \le V_n < V_{n1}$	1.4×10^{-2}	0.58	0.31	0.14	-3.8	0.80	2.0
		II ; $V_{n1} \le V_n < V_{n2}$	5.8×10^{-2}	0.58	0.31	0.14	-1.3	0.23	1.0
		III; $V_{n2} \le V_n$	1.3×10^{-2}	0.58	0.31	0.14	-4.3	0.72	2.3
1.90 - 4.80	$(L_n/D_n)_{tr} \le L_n/D_n$	I ; $V_{nB} \le V_n < V_{n1}$	5.0×10^{-2}	0.51	0	0.14	-3.8	0.80	2.0
		II ; $V_{n1} \le V_n < V_{n2}$	2.0×10^{-1}	0.51	0	0.14	-1.3	0.23	1.0
		III; $V_{n2} \le V_n$	4.4×10^{-2}	0.51	0	0.14	-4.3	0.72	2.3

Table 3. Values of *a, b, c, d, e* and *f* in Eqs. (10) and (11)

L_n / D_n [-]	L_j / D_n [-]	a [-]	b [-]	c [-]	d [-]	e [-]	f [-]
$5 \le L_n/D_n < (L_n/D_n)_{tr}$	$8.4 \le L_j < D_n < 20$	-0.27	-0.11	1.64	1.56	0.028	0.30
	$20 \le L_j < D_n < 43$	0	-0.11	1.00	1.29	0.220	0.39
$(L_n/D_n)_{tr} \le L_n/D_n$	$8.4 \le L_j < D_n < 20$	-0.27	0	1.64	1.37	0.040	0.32
	$20 \le L_j < D_n < 43$	0	0	1.00	1.54	0.720	0.55

Q_g = volumetric air entrainment rate [m^3/s]
Q_L = volumetric liquid flow rate [m^3/s]
V_j = average jet velocity at L_j [m/s]
V_m = center-line velocity of jet [m/s]
V_n = jet velocity at nozzle exit [m/s]
x = distance along jet axis from L_j [m]
x_t = transition x for deceleration of V_m [m]
Z = maximum bubble penetration depth [m]
μ = viscosity [Pa.s]
ρ = density [kg/m^3]
σ = surface tension [N/m]
θ = nozzle angle [degree]

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