

# AXIAL MIXING IN BUBBLE COLUMN WITH SUSPENDED SOLID PARTICLES

HIROMITSU KOJIMA, HIROYUKI ANJYO AND YASUHIRO MOCHIZUKI

Department of Chemical Engineering, Ikutoku Technical University, Atsugi 243-02

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## Introduction

Three-phase bubble columns are widely used in chemical process industries as absorbers or reactors. In analyzing data on product yields or overall reaction rate obtained from laboratory or pilot plant studies where relatively small-scale bubble-column slurry reactors are used, the axial mixing properties of solid and liquid should be taken into account.

Several works<sup>2,4,5)</sup> have been published on the axial mixing of liquid phase in three-phase bubble columns. Both Kara *et al.*<sup>2)</sup> and Kelkar *et al.*<sup>5)</sup> pointed out that the effect of gas distributor design on the dispersion coefficient was pronounced at low gas velocity.

In the present work, the effect of gas distributor design on both solid and liquid phase axial dispersion coefficients was experimentally investigated, using a three-phase bubble column of relatively small diameter.

## 1. Experimental Apparatus and Procedure

A pyrex glass tube of inner diameter 55 mm was used as a bubble column. A porous plate, perforated plates and a single nozzle (inner diameter 3 mm, outer diameter 10 mm) fitted on a conically shaped bottom with a cone angle of  $\pi/3$  rad were used as gas dispersers. Glass beads-water slurry was prepared in a stirred vessel and supplied by a roller pump into the column cocurrently with gas flow. The slurry was allowed to overflow at the top of the column. The height of the gas-liquid-solid contacting section was in the range of 0.9 to 1.2 m.

Potassium chloride (KCl) aqueous solution used as a tracer was dispersed into the column through the perforated plate at the top of the column. Feed rate of tracer solution was one-tenth that of slurry. After tracer distribution was brought to steady state, a small amount of slurry was sampled at five points along the column. KCl concentration was determined

by conductivity measurement. Solid concentration in the sampled slurry was measured gravimetrically.

Gas holdup was determined by static pressure difference measured at four points along the column.

The range of experimental variables is shown in Table 1.

## 2. Determination of Axial Dispersion Coefficient

### 2.1 Axial dispersion coefficient in liquid phase

On the basis of the one-dimensional dispersion model, axial distribution of potassium chloride used as a tracer at steady state is given by

$$C_T = \beta \exp(u_L y / \varepsilon_L E_L) \quad (1)$$

where  $\beta$  is an integral constant to be determined. Liquid-phase dispersion coefficient  $E_L$  and constant  $\beta$  were determined by fitting the values of  $C_T$  observed at five points along the column to Eq. (1) using the least-squares method.

### 2.2 Apparent dispersion coefficient of solid particles

On the basis of the one-dimensional dispersion model, solid distribution in the bubble-column slurry reactor under continuous operation is given by the following equation.

$$\ln\{(C + \phi)/(1 + \psi)\} = (1 - Y)/\{(1 - \varepsilon_G)\psi\} \quad (2)$$

where

$$Y = y/Z_T \quad (3)$$

$$C = c_p/c_F \quad (4)$$

$$\psi = E_p/[Z_T\{(1 - \varepsilon_G)v_p - u_L\}] \quad (5)$$

$$\phi = u_L/\{(1 - \varepsilon_G)v_p - u_L\} \quad (6)$$

In Eqs. (5) and (6), settling velocity of solid particles,  $v_p$ , is assumed to be independent of solid concentration. Free settling terminal velocity was employed as the settling velocity to simplify the analysis procedure, as in our previous works<sup>6,7)</sup> where apparent dispersion coefficients of solid particles were found to be independent of solid concentration.

Received October 1, 1985. Correspondence concerning this article should be addressed to H. Kojima. H. Anjyo is now with Babcock-Hitachi, K.K., Tokyo 100. Y. Mochizuki is now with Sizuoka Mori Shigyou Co., Ltd., Yaizu, 425.

**Table 1.** Range of experimental variables

$D_T$ [m]	0.055
Gas distributor	Porous plate ( $\delta = 185 \mu\text{m}$ ) Perforated plate ( $d = 1.05 \text{ mm}$ , $n = 31$ ) Perforated plate ( $d = 1.05 \text{ mm}$ , $n = 7$ ) Single nozzle fitted on conically shaped bottom (3 mm i.d. $\times$ 10 mm o.d.)
$u_G \times 10^2$ [m/s]	2.01–11.3
$u_L \times 10^2$ [m/s]	0.096–0.27
Solid particles	glass beads $D_p = 0.105\text{--}0.125 \text{ mm}$
Solid concentration in feed $c_F$	3.1–62 kg/m <sup>3</sup>

Dimensionless parameter  $\psi$  was evaluated by the least-squares method using observed values of solid concentration at five points along the column, and apparent dispersion coefficients were determined.

### 3. Experimental Results and Discussion

#### 3.1 Gas holdup

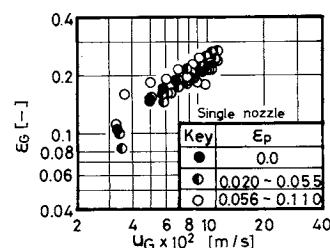
An increase in solid holdup decreased gas holdup when the porous plate was used as a gas distributor. A trend of bubble coalescing behaviour was visually observed by increasing the solid holdup when the porous plate was used as a gas distributor. When the perforated plate was used as a gas distributor, an increase in solid concentration did not result in lower gas holdup.

Gas holdup data observed when a single nozzle was used as a gas distributor are shown in Fig. 1. In this case, gas holdup was not influenced by solid holdup and was consistent with that in the case where perforated plates were used as gas distributor.

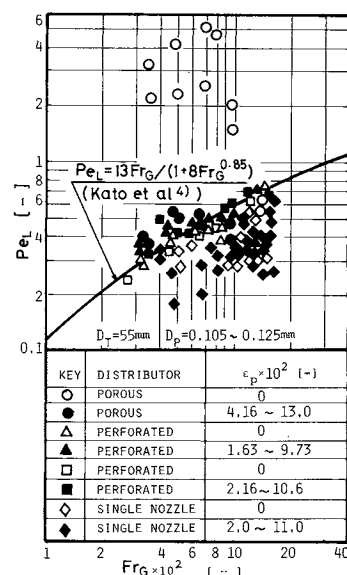
The effect of solid concentration on gas holdup agreed well with the observation of Kato *et al.*<sup>3)</sup>

#### 3.2 Axial dispersion in liquid phase

As an attempt to compare the present experimental results with the empirical equation proposed by Kato *et al.*,<sup>4)</sup> a plot of Péclet number against Froude number is shown in Fig. 2. As indicated, when a porous plate was used in the gas-liquid system and the bubbly flow regime was prevailing, values of Péclet number became larger than those of Kato *et al.*<sup>4)</sup> In the bubble flow regime, circulating flow rates in the bubble column were low, hence liquid-phase dispersion coefficients seemed to decrease. The value of Péclet number in this work became smaller than those of Kato *et al.*<sup>4)</sup> when a single nozzle was used as a gas distributor. Although the reason for this behaviour is unknown at the present time, it might be considered that the conically shaped bottom enhanced more liquid circulation than the flat bottom and that liquid-phase mixing was pronounced.



**Fig. 1.** Gas holdup in bubble column with a single nozzle fitted on conically shaped bottom.



**Fig. 2.** Correlation of  $Pe_L$  with  $Fr_G$ .

When the perforated plate was used for the air-water system, or for the air-water-glass beads system and when a porous plate was used and the coalesced bubble flow regime was prevailing, our results agreed well with the correlation of Kato *et al.*<sup>4)</sup>

Although the measurement of axial dispersion coefficient was attempted in a column of 95 mm diameter, the data obtained by the present method were so dispersed that no information was obtained on the effect of gas distributor design.

#### 3.3 Apparent dispersion coefficient of solid particles

The Péclet number for observed values of dispersion coefficient is plotted against Froude number in Fig. 3, which shows that the effect of gas distributor design on apparent dispersion coefficient of solid particles was not significant. This agrees with the results obtained by Imafuku *et al.*<sup>1)</sup>

The relationship between Péclet number and Froude number under the present experimental conditions is expressed approximately by the following equation:

$$Pe_p = 10 Fr_G^{0.76} \quad (7)$$

The above equation is shown in Fig. 3 as a solid line. Predicted values of  $Pe_p$  by the correlation of

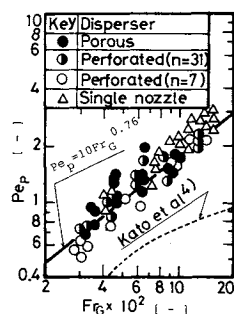


Fig. 3. Correlation of  $Pe_p$  with  $Fr_G$ .

Kato *et al.*<sup>4)</sup> are shown in Fig. 3 as a broken line. The  $Pe_p$  values predicted by the Kato *et al.*<sup>4)</sup> correlation are much smaller than those obtained experimentally in the work. This discrepancy was caused by the fact that in the present work, free-settling terminal velocity was used as the settling velocity of solid particles, while Kato *et al.*<sup>4)</sup> used a hindered settling velocity that was expressed as a function of gas velocity, liquid volume fraction and free-settling terminal velocity.

## Conclusions

The dispersion coefficient of liquid phase observed when coalesced bubble flow regime seemed to be prevailing agreed well with the correlation proposed by Kato *et al.*<sup>4)</sup>

When a single nozzle fitted on a conically shaped bottom was used as gas distributor, the dispersion coefficient became larger than that predicted by Kato *et al.*<sup>4)</sup>

The apparent dispersion coefficient of solid particles was not influenced by distributor design.

## Nomenclature

$C$	= dimensionless concentration of solid particles defined by Eq. (4)	[—]
$c_p$	= solid concentration	[kg/m <sup>3</sup> ]

$c_F$	= solid concentration in feed slurry	[kg/m <sup>3</sup> ]
$c_T$	= KCl concentration	[kmol/m <sup>3</sup> ]
$D_p$	= diameter of solid particles	[mm]
$D_T$	= diameter of bubble column	[m]
$d$	= hole diameter in perforated plate	[mm]
$E_L$	= dispersion coefficient of liquid phase	[m <sup>2</sup> /s]
$E_p$	= apparent dispersion coefficient of solid particles	[m <sup>2</sup> /s]
$Fr_G$	= Froude number defined as $u_G/\sqrt{gD_T}$	[—]
$g$	= gravitational acceleration	[m/s <sup>2</sup> ]
$n$	= number of holes in perforated plate	[—]
$Pe$	= Péclet number defined as $u_G D_T/E_L$ or $u_G D_T/E_p$	[—]
$u$	= superficial velocity	[m/s]
$v_p$	= free-settling terminal velocity	[m/s]
$y$	= coordinate along axis of column	[m]
$Y$	= dimensionless coordinate along axis of column	[—]
$Z_T$	= height of gas-liquid-solid contacting section in bubble column	[m]
$\beta$	= integral constant in Eq. (1)	[kmol/m <sup>3</sup> ]
$\delta$	= effective diameter of sintered particles in porous plate	[μm]
$\varepsilon$	= fractional holdup	[—]
$\phi$	= dimensionless parameter defined by Eq. (6)	[—]
$\psi$	= dimensionless parameter defined by Eq. (5)	[—]

## <Subscripts>

$G$	= gas phase
$L$	= liquid phase

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