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Gas-Liquid Two-Phase Axial Backmixing Through Structured Packing at Elevated Pressure*

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Abstract An experimental study of the extent of axial backmixing in both gas and liquid phases was conducted in a 150 mm ID column packed with Mellapak 250Y corrugated structured packing. The column was operated at pressures ranging from 0.3 MPa to 2.0 MPa with nitrogen and water flowing countercurrently through the packing. The amount of axial backmixing was experimentally evaluated by the pulse response techniques using hydrogen in gas phase and an aqueous solution of NaCl in liquid phase as inert tracers. The response of the tracer was monitored by means of thermal conductivity in the gas phase and electrical conductance in the liquid phase. The experimentally determined residence time distribution (RTD) curves were interpreted in terms of the diffusion-type model. The results indicated that the axial backmixing in the gas increased notably with gas flowrate and slightly with operating pressure and liquid flowrate. The liquid-phase axial backmixing was an increasing function of both gas and liquid flowrates and insensitive to pressure. Various correlations were developed for reproducing the experimental mixing data. The agreement between experimental and correlated data appeared to be acceptable and within ±20% of difference.

Keywords structured packing, backmixing, elevated pressure, gas-liquid two-phase flow

1 INTRODUCTION

A number of experimental studies have been published on the backmixing characteristics of two-phase flow through packed column filled with random packing. To the best of our knowledge, however, only several publications have dealt with axial backmixing in two-phase flow through beds of structured packing.

Mak *et al.*[1] used a pulsed packed column and extended their earlier mixing data[2] by studying the mixing properties of the liquid during countercurrent contacting of a solid-liquid flow through Sulzer SMV-12 structured packing. They observed that as the interstitial velocities of the solids and liquid were increased, the backmixing coefficient increased. They also found that the use of high pulsation velocities could reduce the slurry mixing to a minimum.

YU *et al.*[3] investigated the axial and radial mixing characteristics of 250Y corrugated stainless steel sheet structured packing by the method of introducing tracer into two experimental columns of 300 and 1000 mm in diameter. Dye solution was used as a tracing material injected into the 300 mm column and hot water was used as the tracer in the 1000 mm column. They found that both the axial and radial backmixing coefficient increased with the increase of the interstitial velocities of gas and liquid. And the radial coefficient was bigger than the axial one. YU and Wang[4] obtained the similar results by using $KMnO_4$ solution as tracer in a column packed with Mellapak 250Y. The foregoing studies were on the axial backmixing of liquid phase. Macias-Salinas and Fair[5] measured the axial mixing of air and water under two-phase flow conditions in a large-scale packed column (0.43 m diameter) using tracer experiments. Four packings were studied: 25.4 mm ceramic Raschig rings, 25.4 mm metal Pall rings, Sulzer BX structured packing, and Flexipac 2 structured packing. The results were that the axial mixing in the gas increased with both gas and liquid rates, whereas liquid-phase axial mixing was a decreasing function of liquid rate and was insensitive to gas rate up to the flooding point. For elevated pressure operations, Kurtz *et al.*[6] gave qualitatively the effect of liquid rate on the axial backmixing of the gas phase for air-water flow in Flexipac 2Y structured packing. Wang and YU[7] measured the liquid mixing behavior in a column with Mellapak 250Y by the pulse response technique under pressures of 0.3, 0.5 and 0.6MPa in steam-water system. They found that the axial backmixing increased slightly with the increase of pressure. Recently Zhang *et al.*[8] and Tang *et al.*[9] publicized their experimental results of the gas-phase and liquid-phase axial backmixing at the pressures varying from 0.1 MPa to 2.0 MPa.

This paper was to determine the effects of gas and liquid flowrates and pressure on the axial backmixing in gas and liquid phase at two-phase flow condition through structured packing.

2 EXPERIMENTAL

Axial backmixing studies were conducted in a circular column having an inside diameter of 150 mm and containing a packed section of 1000 mm in height. The schematic diagram of the test column was shown in Fig. 1. The packing, Mellapak 250Y, was manufac-

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tured by Tianjin Univtech Corporation. Nitrogen was used as the gas phase, and water as the liquid phase. The column was operated at pressures varying from 0.3 MPa to 2.0MPa. Nitrogen was introduced at the bottom of the column through a multi-beam gas injection support plate that was used to produce uniform flow. After entering the column, the nitrogen flowed through the packing and was discharged to the atmosphere through a valve used to control the gas flowrate and the operating pressures. Water was fed at the top of the column. Upon entering the column, the water was evenly distributed over the top of the packing by means of a distributor. After flowing by gravity, the water came into contact countercurrently with nitrogen in the packing. When the gas and liquid flowrates and the operating pressure kept steady, pulses of the gas and liquid tracers were injected. The pulse of hydrogen was injected into the inlet air upstream of the distributor, thus minimizing radial concentration gradients. The pulse of the liquid tracer, NaCl solution, was injected into the liquid distributor. The orientation of the injection line inside the liquid distributor was the same with the flow direction of the inlet water, and this arrangement minimized the influence of water flow on tracer entry. The response of the tracer was monitored by means of thermal conductivity for the gas phase and electrical conductance for the liquid phase. The distance of the tracer injection point and the tracer measurement point was 1000 mm. All tracer measurements were made at the center of the cross section. The signal outputs produced by the measuring devices, the thermal-conductivity detector and the conductance meter, were connected to a computer including a KH-9251 A/D card. Then the concentration of hydrogen in nitrogen and the sodium chloride in the water could be collected continuously.

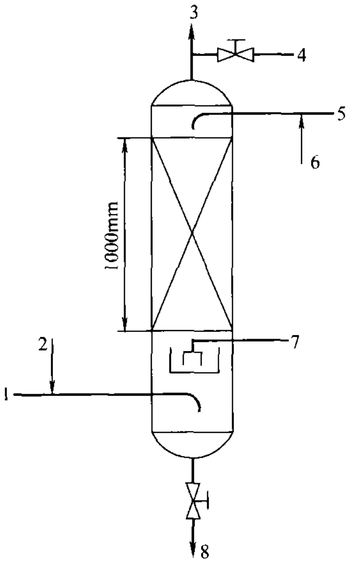

Figure 1 Schematic diagram of test column
1—air in; 2—gas phase injection port;
3—air to vent; 4—gas phase tracer measurement point;
5—water in; 6—liquid phase injection port;
7—liquid phase tracer measurement point;
8—water to drain

3 THEORETICAL MODEL

Both gas and liquid dynamic response data were reproduced with the aid of the diffusion-type model. The model was derived from a material balance for the tracer over an volume element of the packed bed. The resulting partial differential equation was

$$\frac{\partial c}{\partial t}+u\frac{\partial c}{\partial z}-D_{\mathrm{e}}\frac{\partial^2 c}{\partial z^2}=0 \tag{1}$$

where the axial backmixing coefficient D_{e} and the interstitial velocity u were assumed to be independent of concentration c, position z and time t within the column. It was also assumed that no concentration gradients exist in the radial direction. For an infinite bed or open system, the following initial and boundary conditions were used

$$c(z,0)=0 \tag{2}$$

$$\begin{cases}\lim\limits_{z\to\pm\infty} c(z,t)=0\\ \lim\limits_{z\to\infty}\displaystyle\int_{-z}^{+z} c(z,t)A\mathrm{d}z=M\end{cases} \tag{3}$$

Based on the above conditions, Levenspiel and Smith[10] presented an analytical solution of Eq.(1). At the position z, where the test-section length equaled z, the solution was

$$c(t,z)=\frac{M}{2A\sqrt{\pi D_{\mathrm{e}}t}}\exp\left[-\frac{(z-ut)^2}{4D_{\mathrm{e}}t}\right] \tag{4}$$

where M stands for the amount of tracer injected into the fluid and A is the cross-sectional area of the column. As the tracer injection was assumed to be a perfect pulse and the end effects of the packed section were neglected, Eq. (4) could be used to the finite packed bed we studied. Then based on assumed parameter values, D_{e} and u, the predicted value of c could be calculated. The best fit values of the model parameters D_{e} and u were obtained by minimizing the following objective function

$$\begin{cases}\min f(D_{\mathrm{e}},u)=\sum\limits_{i=1}^{n}(c_{\mathrm{cal}}-c_{\mathrm{exp}})^2\\ D_{\mathrm{e}}>0\\ u>0\end{cases} \tag{5}$$

Using DFP algorithm, a Fortran program[11] was written to calculate the backmixing parameters.

4 RESULTS AND DISCUSSION

4.1 Gas phase

In gas-liquid two-phase flow, the degree of backmixing in gas phase is affected not only by the gas flowrate and pressure but also by the liquid flowrate. The variations of the axial backmixing coefficient in gas phase, D_{eg}, with the interstitial velocity, u_{g}, at different pressures are shown in Fig. 2. All data in this figure were obtained at the liquid flowrate equaling to $0.8\,\mathrm{m^3 \cdot h^{-1}}$. From Fig. 2 the amount of backmixing in the gas phase is found to increase obviously with gas velocity at the same pressure and increase slightly with the pressure at the same gas velocity. It may be considered that the gas-liquid interaction force increases with the increase of the gas velocity and pressure, and then leading to the increase of the turbulence. Fig. 3 shows the effect of liquid flowrate (expressed by the liquid load, $l/\mathrm{m^3 \cdot m^{-2} \cdot h^{-1}}$) on D_{eg}. It indicates that the axial backmixing coefficient in gas phase increases slightly with the liquid load. The results can be explained in the sense that the presence of the liquid phase within the bed decreases the void space, thus intensifying the turbulence of the gas through the flow channels. It should be noted that the axial backmixing results presented in Figs. 2 and 3 were found to be dependent strongly on the gas velocity.

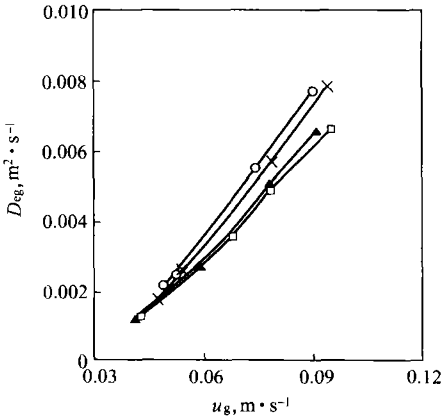

Figure 2 Variation of D_{eg} with u_{g} at different pressures in two-phase flow
($Q_l = 0.8\,\mathrm{m^3 \cdot h^{-1}}$)
p, MPa: —□— 0.7; —▲— 1.1; —×— 1.4; —○— 1.7

Because of the lack of a fundamental theory for axial backmixing in packed beds, a dimensional analysis was undertaken to express the present mixing results in terms of the major operating variables. The following correlating form was therefore used to regress the data

$$\frac{u_{\mathrm{g}} L}{D_{\mathrm{e}}} = \alpha \left(\frac{U_{\mathrm{g}} d_{\mathrm{e}} \rho_{\mathrm{g}}}{\mu_{\mathrm{g}}} \right)^{\beta} \left(\frac{p_0}{p} \right)^{\gamma} 10^{\varphi \left(\frac{U_l d_{\mathrm{e}} \rho_l}{\mu_l} \right)} \tag{6}$$

or

$$Bo_{\mathrm{g}} = \alpha Re_{\mathrm{g}}^{\beta} \left(\frac{p_0}{p} \right)^{\gamma} 10^{\varphi Re_l} \tag{7}$$

The correlation obtained from a multiple nonlinear regression analysis of the data was

$$Bo_{\mathrm{g}} = 0.0014 Re_{\mathrm{g}}^{-0.93} \left(\frac{p_0}{p} \right)^{-0.60} 10^{-0.00031 Re_l} \tag{8}$$

The difference of the correlated and experimental determined values of Bo_{g} was in ±20%.

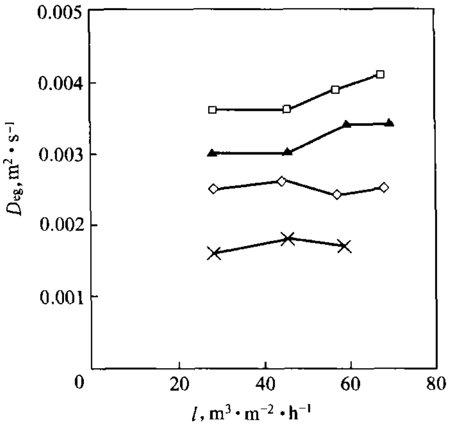

Figure 3 Variation of D_{eg} with l at different pressures in two-phase flow
p, MPa: —□— 0.7; —▲— 1.1; —◇— 1.7; —×— 1.4
Q_{g}, $\mathrm{m^3 \cdot h^{-1}}$: —□— 3.3; —▲— 3.1; —◇— 2.7; —×— 2.5

4.2 Liquid phase

Figure 4 shows the variation of the axial backmixing coefficient in liquid phase, $D_{\mathrm{e}l}$, with the interstitial liquid velocity, u_l, at different pressures in gas-liquid two-phase flow. With the increase of the interstitial velocity, the liquid backmixng increases obviously. However the pressure has a negligible effect on $D_{\mathrm{e}l}$ at the same velocity. Fig. 4 also gives the mixing results of Wang *et al.*[4] using Flexipac 2Y packing and Macias-Salinas[5] using Mellapak 250Y packing at atmosphere pressure. In their experiments, $D_{\mathrm{e}l}$ also increases as the interstitial liquid velocity increases, a similar trend observed by this paper. But there is a significant discrepancy in the values of $D_{\mathrm{e}l}$ estimated by them and this paper. This disagreement may be attributed to the combined effects of several factors such as the difference of the packings and the distributors, the different ratios of column diameter to packing size, and the use of different experimental techniques and methods of data analysis. Fig. 5 shows the variation of $D_{\mathrm{e}l}$ with gas load factor at a constant liquid load ($l = 45.2\,\mathrm{m^3 \cdot m^{-2} \cdot h^{-1}}$). It can be seen that the axial backmixng coefficient in liquid phase increases linearly with gas load factor. In this figure, the line shown is the fitted line of the experimental data. The difference between them varies over the ±15% range with moderate scattering.

According to foregoing discussion, the liquid-phase Bodenstein number was correlated as a function of the superficial Reynolds number of the liquid and the gas load factor. The correlating form was given by

$$Bo_l = \alpha \left(\frac{U_l d_{\mathrm{e}} \rho_l}{\mu_l} \right)^{\beta} 10^{\gamma F v} = \alpha Re_l^{\beta} 10^{\gamma F v} \tag{9}$$

A multiple nonlinear regression analysis was performed on the data yielding the following results

$$Bo_l = 0.0035Re_l^{-1.12}10^{-1.07Fv} \qquad (10)$$

There is a fair agreement between the correlated and experimentally determined values of Bo_l with a maximum ±20% of difference for most of the data.

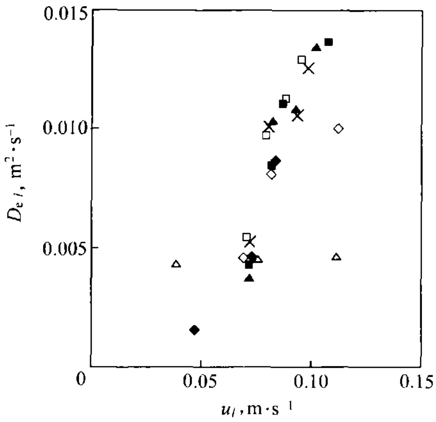

Figure 4 Variation of D_{el} with u_l in two-phase flow [$Fv = 0.15$—$0.19\,\mathrm{m\cdot s^{-1}\cdot(kg\cdot m^{-3})^{0.5}}$]
p, MPa: ◆ 0.4; ■ 0.7; ▲ 1.1; × 1.4; □ 1.7; ◇ by Macias-Salinas[5]; △ by Wang[4]

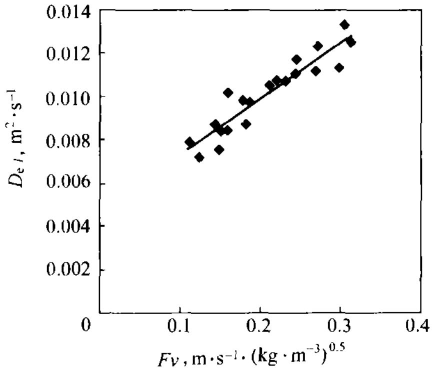

Figure 5 Variation of D_{el} with Fv in two-phase flow ($l = 45.2\,\mathrm{m^3\cdot m^{-2}\cdot h^{-1}}$)
◆ experimental data; —— fitted line

5 CONCLUSIONS

Axial backmixing properties of nitrogen and water in countercurrent flow were determined *via* dynamic response experiments for Mellapak 250Y structured packing. The axial backmixng in the gas increased with gas and liquid rates and pressure, and the axial backmixing in the liquid increases with both gas and liquid rates and is insensitive to the operating pressure. Finally various correlations were developed in terms of dimensionless quantities for the prediction of axial backmixing in both phases under countercurrent two-phase flow conditions. The agreement between experimental and correlated data appeared to be acceptable and within ±20% of difference.

NOMENCLATURE

A	cross-sectional area of the column, m^2
Bo	Bodenstein number, ($Bo = uL/D_e$)
c	concentration, kg·m^{-3}
D_e	axial backmixing coefficient, m^2·s^{-1}
d_e	equivalent diameter of the structured packing, m
Fv	gas load factor, m·s^{-1}·(kg·m^{-3})$^{0.5}$
L	test section length, m
l	liquid load, m^3·m^{-2}·h^{-1}
M	amount of the tracer, kg
p	pressure, MPa
p_0	atmosphere (= 0.1 MPa), MPa
Q	flowrate, m^3·h^{-1}
Re	Reynolds number ($Re = Ud_e\rho/\mu$)
t	time, s
U	superficial velocity, m·s^{-1}
u	interstitial velocity, m·s^{-1}
z	axial position, m
$\alpha, \beta, \gamma, \varphi$	regression constant
μ	viscosity, Pa·s
ρ	density, kg·m^{-3}

Subscripts

cal	predicted value
exp	experimental value
g	gas
l	liquid

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