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LATERAL SOLID MIXING IN A PACKED FLUIDIZED BED

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The lateral mixing of fluidized particles in a packed fluidized bed with cylindrical screen packings was investigated from the unsteady state behavior of tracer particles. The tracer particles were activated alumina particles on which zinc acetate was adsorbed. The lateral mixing characteristics were analyzed by a diffusion model. The lateral dispersion coefficient of the particles was strongly affected by packing size, fluidized gas velocity, and the minimum fluidized gas velocity of the particles. An empirical equation for the lateral dispersion coefficient of the particles in a packed fluidized bed with cylindrical screen packings was obtained.

Introduction

Fluidized beds are used for drying of particles and in solid-gas reactors such as coal combustors, regenerators of spent activated carbon and zinc blende roasters. To analyze these processes it is very important to estimate the residence time distribution of fluidized particles in the bed.

The behaviour of fluidized particles has usually

been analyzed by the following models: turnover rate model,[6] diffusion model[2,4,5] and two-phase model.[1] However, the relationship between the model parameters of these models and the operating conditions of the fluidized bed is not established yet.

Generally, mixing of fluidized particles in an ordinary fluidized bed is very fast and to control the mixing rate, suitable internals in the bed are quite effective.

Gabor[3] investigated lateral solid mixing in a packed fluidized bed with sphere packings and analyzed it
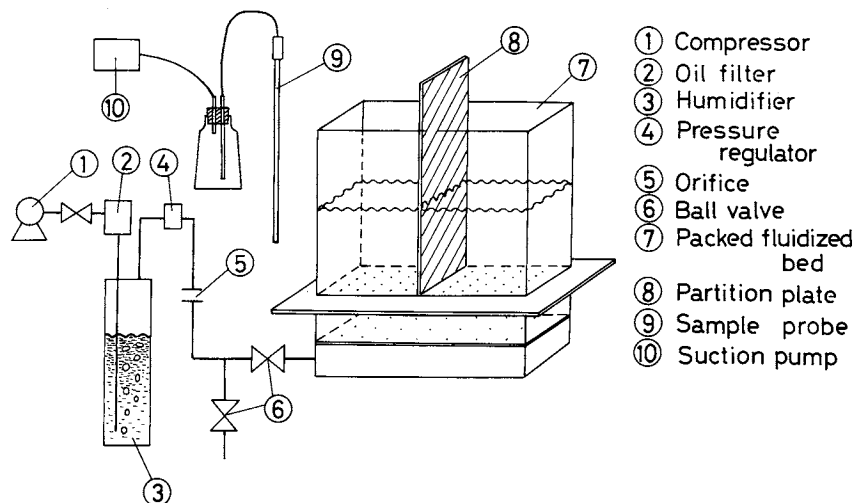
Fig. 1. Experimental apparatus of mixing.

(1) Compressor
(2) Oil filter
(3) Humidifier
(4) Pressure regulator
(5) Orifice
(6) Ball valve
(7) Packed fluidized bed
(8) Partition plate
(9) Sample probe
(10) Suction pump

Table 1. Properties of fluidized particles and size of screen packings

Properties of fluidized particles

D_p [cm]	U_{mf} [cm/s]	ϕ_s [—]	ε_{mf} [—]
0.0394	3.5	1.0	0.45
0.0477	5.0	1.0	0.45
0.0511	7.3	1.0	0.45
0.0961	21.0	1.0	0.45
0.1091	29.0	1.0	0.45

Screen packing

$$D_p^* = \sqrt{\frac{3d^2hc}{2}}$$

Sphere packing

$$D_p^* = d$$

Size of screen packings

Sign	Tailor mesh	d [cm]	hc [cm]	D_p^* [cm]	ε_b [—]
PN-3	10	1.43	1.30	1.59	0.967
PN-7	—	2.73	4.22	3.61	0.990
PN-9	6	2.00	2.54	2.48	0.990
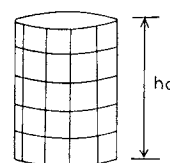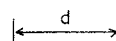
by a diffusion model. An empirical equation for the lateral dispersion coefficient was obtained.

In the present work, lateral solid mixing in a packed fluidized bed with cylindrical screen packings was investigated by using tracer particles. The lateral mixing characteristics were analyzed by a diffusion model. The effect of superficial gas velocity, packing size and minimum fluidized gas velocity upon the lateral dispersion coefficient of the particles was investigated.

1. Experimental Apparatus and Procedure

The experimental apparatus is shown in **Fig. 1**. The fluidized bed consisted of a rectangular column made of acrylic resin, 30 cm wide, 10 cm long and 50 cm high. A perforated plate made of acrylic resin of 5 mm thickness, 2 mm pore size, and 2.0 percent open area was used as the gas distributor. To make sure of the gas distribution in the bed, another perforated plate

with 0.8 percent open area was installed in the wind box 3 cm below the distributor.

To prevent the adhesion of particles to the bed wall by static electricity, air was passed through a water bath and was humidified before being supplied to the bed. The inside wall of the bed was coated with Teflon. The particles, the packings and the definition of the packing size D_p^* are shown in **Table 1**.

The tracer particles were made as follows. Six liters activated alumina was put into 8 liters water containing 268 g zinc acetate and was mixed for an hour. Zinc acetate was adsorbed on the particles, which were filtered and dried at 353 K.

The experimental procedure was as follows. The partition plate was placed in the center of the bed. The activated alumina particles were put in one side and the tracer particles were put in the other side. After fluidizing the particles for a few minutes at constant gas velocity, the partition plate was suddenly pulled

up and the particles were then fluidized for a suitable time at constant gas velocity. The fluidization was suddenly stopped by shutting quickly the ball valve. The sample particles were taken from the bed by using an 8 mm-I.D. suction probe at several points. To obtain the concentration distribution of the tracer particles in the bed, the concentration of zinc acetate in the sample particles was measured.

This concentration was measured as follows. Sample particles totaling 10 g were put into 100 ml water for an hour. The concentration of zinc acetate in the aqueous solution was determined by chelatometric titration using disodium ethylenediaminetetraacetate (EDTA). For the analysis of the concentration of tracer particles in the sample particles, the calibration curve between the concentration of the tracer particles and the titration value of EDTA was established. Before this experiment lateral mixing of the particles was visually observed by the colored tracer particles.

2. Experimental Results

It seems that the diffusion model is suitable for analysis of the lateral mixing of particles in the packed fluidized bed. From the material balance of the tracer particles, the following equation is obtained:

$$\frac{\partial c}{\partial \theta} = Dsr \left(\frac{\partial^2 c}{\partial x^2} \right) \tag{1}$$

The initial and boundary conditions

$$\theta = 0, \qquad 0 \leqq x \leqq L_1 ; \qquad c = 1$$

$$\theta = 0, \qquad L_1 < x \leqq L_H ; \qquad c = 0$$

$$x = 0, \qquad x = L_H ; \qquad \partial c / \partial x = 0$$

An analytical solution of Eq. (1) with the above conditions becomes

$$C = \frac{L_1}{L_H}$$

$$+ \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{1}{n} \sin \frac{n\pi L_1}{L_H} \cos \frac{n\pi x}{L_H} \exp \left(-\frac{n^2 \pi^2}{L_H^2} Dsr\theta \right) \tag{2}$$

The lateral dispersion coefficient of the particles Dsr is obtained from Eq. (2).

Figure 2 shows the lateral concentration distribution of the tracer particles with superficial gas velocity as a parameter. The solid line in Fig. 2 represents the calculated value from Eq. (2) in the case where the most suitable dispersion coefficient is used. From Fig. 2 the experimental results can be well expressed by the diffusion model.

To investigate the effect of elapsed time in unsteady-state mixing upon Dsr, sampling was carried out simultaneously at two points, 7.5 cm and 22.5 cm from the left wall, at constant time intervals. Dsr was calculated from the concentration of tracer
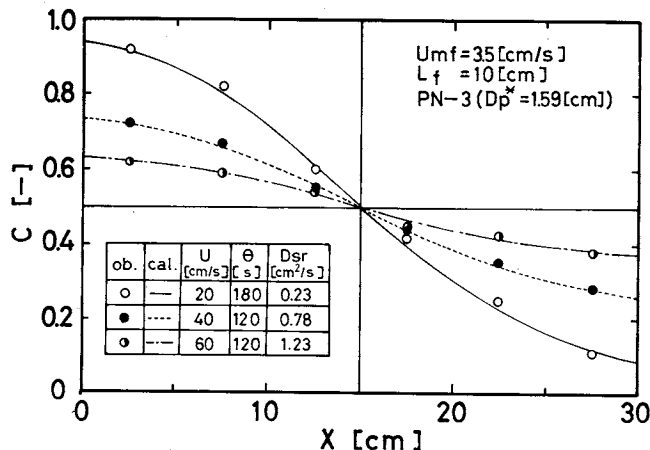

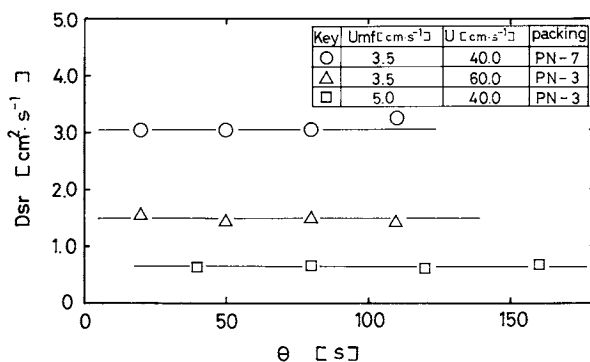**Fig. 2.** Relation between C and X.

Fig. 3. Effect of elapsed time upon lateral dispersion coefficient.

particles in the samples by Eq. (2). **Figure 3** shows the effect of elapsed time upon Dsr. From Fig. 3, Dsr is not affected by elapsed time. **Figure 4** shows the effect of bed height L_f upon Dsr. From Fig. 4, Dsr is not affected by L_f. These results are quite different from those obtained by Hirama et al.[4] in an ordinary fluidized bed. Since the movement of particles in the bed is restricted by the packings, the mixing of particles is not affected by L_f.

Figure 5 shows the relationship between the lateral dispersion coefficient of particles Dsr and $(U - U_{mf})/U_{mf}$ with packing size as a parameter. Dsr measured in the ordinary fluidized bed (no packing) also agrees with the value calculated from the empirical equation of Hirama et al.[4] **Figure 6** shows the relationship between Dsr and $(U - U_{mf})/U_{mf}$ with U_{mf} as a parameter. From Figs. 5 and 6, Dsr is proportional to $\{(U - U_{mf})/U_{mf}\}^{1.4}$. Dsr is also affected by U_{mf} and the packing size. **Figure 7** shows the effect of U_{mf} upon Dsr. From Fig. 7, Dsr is proportional to $U_{mf}^{0.96}$. **Figure 8** shows the relationship between Dsr and D_p^* with U_{mf} as a parameter. From Fig. 8, Dsr is proportional to $D_p^{*2.0}$.

Figure 9 shows the relationship between Dsr and $D_p^{*2.0} U_{mf}^{0.96} \{(U - U_{mf})/U_{mf}\}^{1.4}$. Dsr in a packed fluidized bed with sphere packings obtained by
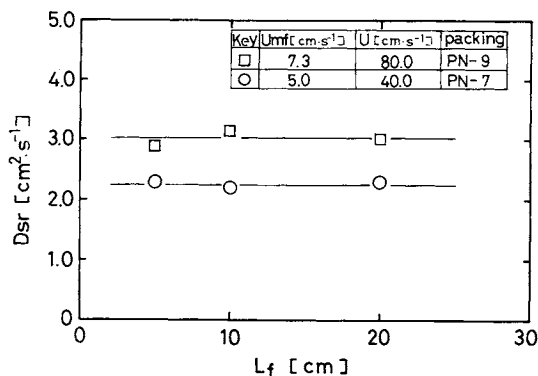
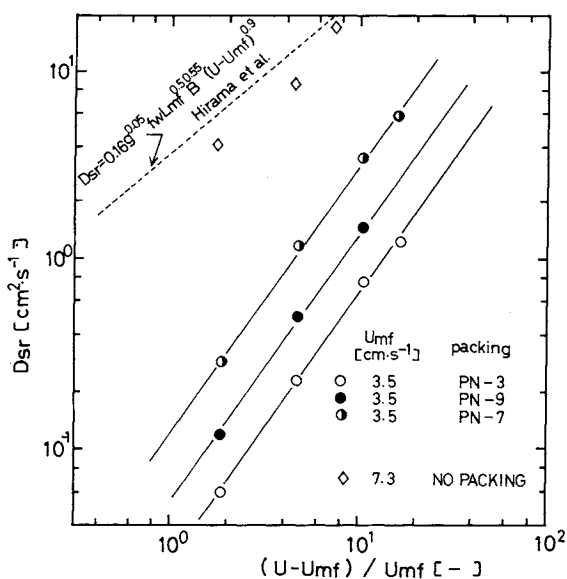Fig. 4. Effect of bed height upon lateral dispersion coefficient.

Fig. 5. Relation between Dsr and $(U-U_{mf})/U_{mf}$.

Fig. 6. Relation between Dsr and $(U-U_{mf})/U_{mf}$.

Fig. 7. Relation between Dsr and U_{mf}.

Fig. 8. Relation between Dsr and D_p^*.

Gabor[3] are well correlated in Fig. 9. From Fig. 9, the following empirical equation for the lateral dispersion coefficient of the particles in the packed fluidized bed with cylindrical screen packings and sphere packings is obtained.

$$Dsr = 0.0026 \cdot D_p^{*2.0} \cdot U_{mf}^{0.96}\{(U-U_{mf})/U_{mf}\}^{1.4} \quad (3)$$

In Eq. (3), the units of Dsr, D_p^*, U_{mf}, U are [cm²/s], [cm], [cm/s], [cm/s] respectively.

Where the applicable ranges are as follows:

D_p^*: 1.5–4.0 [cm], U_{mf}: 3.0–35 [cm/s],

U: 10–100 [cm/s].

3. Discussion

The mixing of particles in the bed is due to vigorous movement of gas bubbles. At constant superficial gas velocity, the larger the size of gas bubbles, the greater the mixing of particles in the bed. When the particles are fluidized among small-size packings, the average bubble size in the bed becomes small. From Fig. 8, the effect of packing size upon particle mixing is very
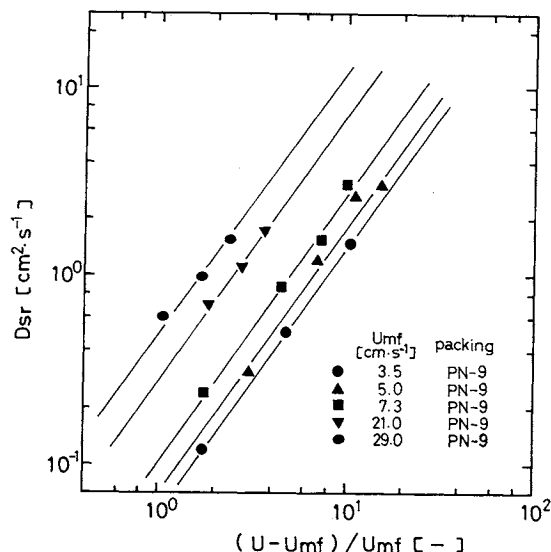
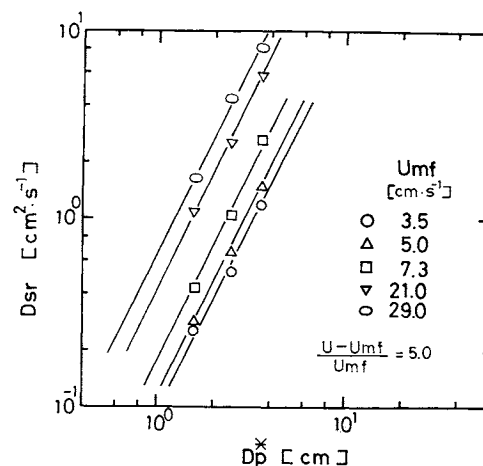large. In Eq. (3) Dsr is proportional to $D_p^{*2.0}$. At constant gas velocity, the smaller the particles and the lower the density of the particles, the more easily the particles become fluidized. Therefore, Dsr is pro-
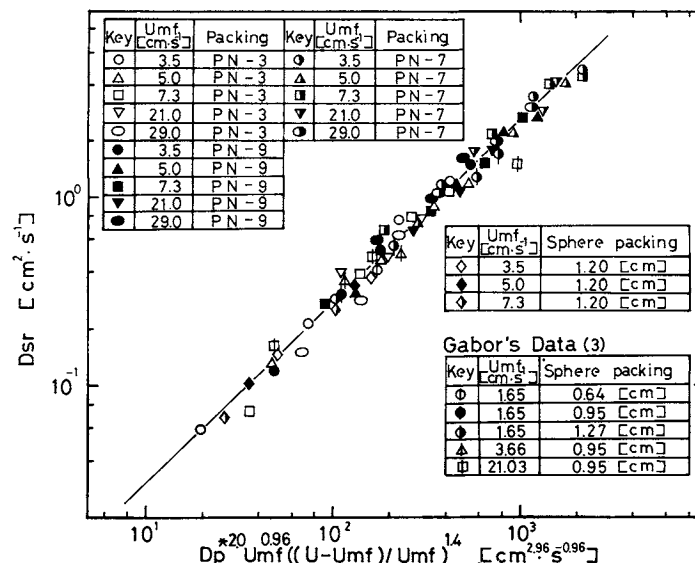
Fig. 9. Relation between Dsr and $D_p{}^{*2.0}U_{mf}^{0.96}\,((U-U_{mf})/U_{mf})^{1.4}$.
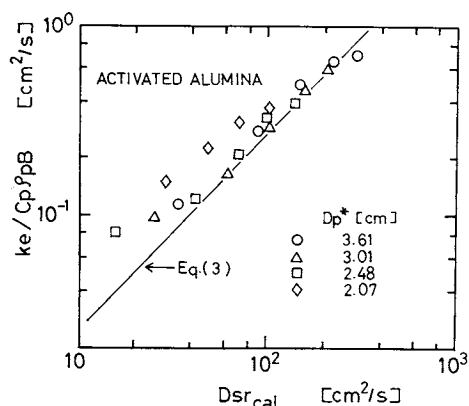

Fig. 10. Comparison of calculated Dsr with lateral thermal diffusivity.

portional to $U_{mf}^{-0.44}$. The movement of fluidized particles becomes vigorous with the increase of average gas velocity, and Dsr is proportional to $(U-U_{mf})^{1.4}$.

The mixing of fluidized particles may be the main factor in the lateral effective thermal conductivity in a packed fluidized bed. **Figure 10** compares the calculated Dsr from Eq. (3) with the lateral thermal diffusivity $ke/C_p\rho_{pB}$ obtained by Kato et al.[7] with the same fluidized particles. From Fig. 10, the lateral dispersion coefficients of particles approximately agree with the lateral thermal diffusivity.

4. Conclusion

The lateral dispersion coefficient of particles in a packed fluidized bed with cylindrical screen packings is affected by packing size, superficial gas velocity and minimum fluidized gas velocity. The following empirical equation is obtained.

$$Dsr = 0.0026 \cdot D_p{}^{*2.0}U_{mf}^{0.96}\{(U-U_{mf})/U_{mf}\}^{1.4} \quad [\text{cm}^2/\text{s}]$$

Where the applicable ranges are as follows:

D_p: 1.5–4.0 [cm], $\quad U_{mf}$: 3.0–8.0 [cm/s],

U: 10–80 [cm/s].

Nomenclature

C	= dimensionless concentration of tracer particles	[—]
C_p	= heat capacity of particles	[J/(kg K)]
$D_p{}^*$	= equivalent diameter of packing, defined as $(3d^2hc/2)^{1/3}$	[cm]
Dsr	= lateral dispersion coefficient of particles	[cm²/s]
Dsr_{cal}	= calculated lateral dispersion coefficient from Eq. (3)	[cm²/s]
d	= diameter of screen packing or sphere	[cm]
hc	= length of screen packing	[cm]
L_f	= expanded bed height	[cm]
L_l	= lateral bed length occupied by tracer particles before mixing	[cm]
L_H	= bed width	[cm]
ke	= lateral effective thermal conductivity	[J/(kg m K)]
X	= lateral distance from left wall	[cm]
U	= fluidized gas velocity corrected by fixed packing voidage	[cm/s]
U_{mf}	= minimum fluidization gas velocity	[cm/s]
θ	= elapsed time of mixing	[s]
ρ_{pB}	= bulk density of fluidized particles	[kg/m³]

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