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Dispersion characteristics of dissimilar materials in a fluidized bed with unevenly distributed fluidizing air



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ABSTRACT

Large-scale internally circulating flows of gas and particles might form under unevenly distributed fluidized air in a fluidized bed. Compared with bed materials, the present study investigated dissimilar particles with different sizes and density moving and mixing through the developed image technique in an internally circulating fluidized bed (ICFB). The concentrations of the tracer particles were obtained by the image analysis method. The inhomogeneity degree and lateral dispersion coefficients of the tracer particles were also calculated, with the results indicating that the degree of inhomogeneity decreases with the increasing dispersed time. The lateral dispersion coefficients of tracer particles with a lower density (for a similar diameter) are larger than those with a higher density. It is clear that the different air distribution methods play an important role in the lateral dispersion of the tracer particles.

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1. Introduction

The adequate dispersion of the fuel (e.g., coal, biomass, and waste) and small fuel feed points are beneficial to promoting the mixing of the fuel and air in fluidized-bed combustion [1,2]. On the one hand, the fluidized air velocity in fluidized bed decreases near the wall due to the wall effect. This may lead to a local internal circulating flow, induced by the velocity gradient of the gas particle flow. On the other hand, the artificially uneven distribution of fluidized air can also result in a local internal circulating flow [3,4], which might improve the lateral dispersion. The fluidized velocity changes in the fuel heating zone can affect the volatile release rate, the combustion rate, and the heat transfer rate between the high-temperature bed materials and fuel particles [5–7].

Attempts have been made to identify the formation and function of an ICFB. Merry and Davidson [8] investigated regular particle circulation patterns produced by an uneven distribution of fluidized air, namely, the "Gulf Stream" effect. A theoretical model was built to describe motion in the particulate phase by treating the solid phase and the interstitial fluid phase separately. The results obtained according to the model were in reasonable agreement with experimental observations. Bemrose et al. [9] considered the behavior of segregating fluidized beds, where particles too large and/or dense to be lifted by

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bubble wakes are moved towards collection zones by the circulating bed materials. The circulation was controlled by producing an imbalance in the air supplies to different zones of the distributor, tilting the distributor (so that the flow is up the slope), or the use of a spout as a pump. The three methods mentioned above have been employed as the main ways to induce an internal circulating flow in fluidized beds [3–7,10–16]. Thus, this fluidized bed is called an ICFB.

Recently, many tracer methods have been introduced in solids motion and mixing studies, such as the salt particle tracer method [17], magnetic particle tracer method [18], radioactive particle tracer method [19,20], and phosphor tracer method [21,22]. Lin and Moslemian et al. [19,20] developed the radioactive particle tracking technique to investigate the solid motion and recirculation in fluidized beds. Du and Ran et al. [21,22] applied the phosphor tracer method to study the lateral mixing of solids in the riser. Furthermore, Garncarek et al. [13] developed the technique of positron emission particle tracking to track the changing position of a tracer particle in a fluidized bed, where differential air injection was used to produce the particle circulation.

The lateral mixing of particles in fluidized beds has been widely investigated in detail [23–30]. Hyre and Glicksman et al. developed a method for approximating the axial and lateral distributions of solids in the upper region of a circulating fluidized bed (CFB) [25]. Bi et al. [26] studied the lateral mixing of coarse particles in fluidized beds with fine particles. To determine lateral solid diffusion coefficients in a narrow fluidized bed, Grasa and Abanades et al. [27] reported an image analysis technique that traces the dispersion of phosphorcoated particles in the bed. According to Glicksman et al., [28] a



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thermal tracing technique was applied to study the mixing characteristics in a 1/4 scale model of a pressurized bubbling fluidized bed combustor. Huang et al. [29] tested the effects of the feeding mode, air velocity, static bed height, and particle size on the particle mixing in a novel annular spouted bed.

The image technique has also recently been widely applied to achieve comprehensive two-dimensional visualization in fluidized beds in recent years [5,14,15,27,31–33]. Through visualization experiments, Bin et al. [14] confirmed that there is a transverse movement of bubbles from the high-velocity side to the low-velocity side in internally circulating fluidized beds. Wei et al. [15] developed a particle image technique to analyze the dispersion of tracer particles (with similar properties to the bed materials) in an ICFB. Also, Shen et al. [32] developed a digital image processing technique to investigate the biomass mixing in a bubbling fluidized bed gasifier.

Thus far, there have been many publications about the characteristics of the particle movement in an ICFB [14,15,24,34]. Nevertheless, there has been little research on the lateral mixing of particles in an ICFB, especially for dissimilar materials. The adequate mixing and excellent dispersion of the different materials are important for a fuel to achieve complete combustion in a fluidized bed. The object of this study is to explore the movement and dispersion characteristics of dissimilar tracer particles using the image technique in an ICFB. The lateral diffusion coefficients and inhomogeneity degrees of the tracer particles were determined by image analysis.

2. Experimental design

Fig. 1 shows the experimental system, including a fluidized bed with a chevron-shaped distributor and a video recording and processing system. The fluidized bed that is 200 mm long, 60 mm wide and 400 mm high is considered a 2-D model [35]. The bed is divided into three zones, and each is supplied air separately. The lengths (x) of the zones are 50 mm, 100 mm and 50 mm, respectively. The images of the particle movement were recorded by a camera through a PMMA (polymethyl methacrylate) window installed in the apparatus.

The characteristics of the bed material and tracer particles are shown in Table 1, and the shape of the particles approaches that of a sphere. Millet is used as a bed material because of its uniform particle size and appropriate density. Polypropylene, mung beans, soybeans, and red beans are used as different tracer particles. In Case 1 (see Fig. 2a), a high air velocity ($2.0U_{mf}$, where U_{mf} is the superficial air velocity of millet at the minimum fluidization) is employed on both sides of the bed, where the fluidized bed is formed, defined as a fluid bed or fluid zone. A low air velocity is used in the middle of the bed ($0.8U_{mf}$), where a moving zone is formed, defined as a moving bed. For Case 2 (Fig. 2b), two internal circulating flows are induced in the bed: a high air velocity Table 1

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	Particles	$d_p(10^{-3} \text{ m})$	$\rho_c(kg/m^3)$	$\rho_p(\text{kg/m}^3)$	U _{mf} (m/s)	З
Bed	Millet	1.5	854	1185	0.8	0.28
material	Mung bean	3.5	8/8	1283	1.1	0.32
narticles	Sovbean	3.88	229 727	901 1252	0.97	0.38
particles	Red bean	6.11	818	1249	1.5	0.35

is employed in the middle of the bed $(2.4U_{mf})$, and a low air velocity is used on the sides of the bed $(1.4U_{mf})$. The ratios of momentum between the fluidizing and moving bed regions were 2.50 in Case 1 and 1.71 in Case 2. Table 2 shows the conditions of the experiments, and the average values of different particles diameter were obtained via narrow screening method as well the errors of average particles diameter were all below 15%.

3. Results and discussion

3.1. Experimental results

The experiment was repeated three times to confirm good reproducibility for each test. For the tests of group No. 1, data of a typical test are selected to process and analyze. For the tests of group No. 2, the data of all three tests were processed. At the beginning of the tests, the tracer particles were quickly added to the moving bed (the zone with lower air velocity). The mixing process of the bed materials and tracer particles was recorded by the camera, where a white color indicates the bed materials and black the tracer particles (see Fig. 3).

From the pictures, it can be observed that the bed materials rise in the fluid zone, then in the top of the bed move laterally to the moving zone, and finally move down axially to the bottom of the bed, as shown by the arrowhead in the picture. Thus, the internal circulation of particles is formed in the ICFB.

As shown in Fig. 3, the tracer particles quickly descend and disperse into the fluid zone when they enter into the moving bed zone. Next, the tracer particles move laterally to the fluid zone, where they are carried by the bubbles' wake and move upwards. Then, the foregoers of the tracer particles begin to mix with the bed materials. When the trace particles return to the moving zone from the fluid zone, they have mixed with the bed materials and cannot be identified clearly. Finally, the trace particles totally disperse in the bed materials.

To analyze the distribution of the tracer particles, the image is separated into 45×35 grids, each including 8×8 points of image elements. The color of each image element is determined by the three primary colors, i.e., red, blue, and green, corresponding to color values from 0



Notations: x-length; y-height; z-width.

Fig. 1. Schematic of the fluidized bed with unevenly distributed fluidized air.



Fig. 2. The distribution of the fluidizing air.

Table 2

Condition of the experiments.

Groups	Bed material	Tracer particles	Air distribution	Camera	Data processing method
No.1 group	Millet	Polypropylene, mung bean	Case 1	SONY DSC-T3	Analysis the typical process
No.2 group	Millet	Soybean, red bean	Case 1 & Case 2	SONY DSC-T3	Average of the data

to 255 in the computer system (see Fig. 4). An average color value is calculated for each image element, and a threshold color value is used to determine if this image element represents the tracer particles.

The numbers of tracer particles and total particles are counted by an image processing code. The ratio between the two numbers is calculated as the tracer particle concentration in the grid line. Fig. 5 shows the distribution of the tracer particles with time for the typical conditions of the experiments, where *x* and *y* stand for the dimensionless length and height, respectively. The contour is used to describe the distribution of tracer particles, and the gap between two lines stands for a concentration difference of 0.4. It seems clear that the initial stage of the mixture has a large high-concentration area of tracer particles, but the highconcentration region disappears gradually with the passing time in different pictures of different tracer particles. This phenomenon may be caused by the tracer particles rolling up constantly because of the bed materials within the vortex motion. Then, the concentrated area of the tracer particles diminishes gradually so that the bed materials and tracer particles mix evenly in the end.



(a) t=0.29 s

(b) t=0.62 s

(c) t=1.04 s



(d) t=1.45 s





Fig. 3. Tracer particles dispersion in the fluidized bed with uneven air distribution.



Fig. 3 (continued).

3.2. Calculation results

3.2.1. Inhomogeneity of tracer particles

The degree of inhomogeneity might be used to describe the distribution of the tracer particles in a fluidized bed. In this work, the degree of inhomogeneity h is simply evaluated using the measure

$$h = \frac{\sigma}{n_{ave}} \tag{1}$$

where σ is the standard deviation of the tracer particle numbers within the grid squares; n_{ave} is the average value of the tracer particle number in the total fluidized bed at eight different time points (see Figs. 3 and 5).

$$\sigma = \sqrt{\sum_{i=1}^{N_{grid}} (n_{i,par} - n_{ave})^2 / (N_{grid} - 1)}$$
(2)

$$\mathbf{n}_{ave} = \sum_{m=1}^{N_t} \left(\sum_{i=1}^{N_{grid}} n_{i,par} / N_{grid} \right)_m / N_t \tag{3}$$

where $n_{i,par}$ is the number of tracer particles within a grid square, which is different from the equation in reference [15]; N_t is the number of time points, which is equal to the number of pictures considered ($N_t = 8$); and N_{grid} is the number of grid squares, which is determined by the image elements within one grid square.

The value of h means the homogeneity degree of the tracer particle distribution, which decreases with the increasing degree of homogeneity. The value h is dependent on the scale of the grids and the image elements in each grid. Thus, it is only a qualitative value to describe the degree of the homogeneous distribution of the tracer particles. Fig. 6 shows the h value for six conditions, corresponding to the pictures in Fig. 3. Because the diffusion degree of the tracer particles constantly changes with time, the h value in Case 1 changes greatly during 3–5 s



(e) t=1.04 s (f) t=1.29 s (g) t=1.54 s (h) t=1.79 s (VI) red bean as tracer particles (Case 2, Group No.2)

Fig. 3 (continued).

(Fig. 6(a-d)), and this duration is 1.5-2.5 s for Case 2 (Fig. 6(e-f)). It can be observed that the *h* value decreases with time and tends to a constant (0.5), indicating that the distribution of tracer particles becomes more homogeneous with time.

3.2.2. Dispersion coefficients

Because the test ICFB bed is approximately a 2-D model, the initially added tracer particles may be assumed to be evenly distributed along the bed width, i.e., $\partial/\partial z = 0$. The bed may be assumed as a shallow bed, and therefore only the lateral dispersion is considered. Because the bed and the fluidized air distribution are both symmetrical about



Fig. 4. The collection illustrative plates of the gray scale.

the governing equation of the tracer particle dispersion in the fluidized bed is given as follows: $\frac{\partial C_x}{\partial t} = D_{sr} \frac{\partial^2 C_x}{\partial x^2}$

the middle axis of the bed, only half of the bed is considered. Then,

$$\frac{1}{\partial t} = D_{sr} \frac{1}{\partial x^2}$$

$$t = 0, 0 \le x \le L', C = 1$$

$$t = 0, L' \le x \le L_0, C = 0$$

$$x = 0, x = L_0, \frac{\partial C}{\partial t} = 0$$
(4)

Solving Eq. (4) gives

$$C(x,t) = \frac{L'}{L_0} + \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{1}{n} \sin\left(\frac{n\pi L'}{L_0}\right) \cos\left(\frac{n\pi x}{L_0}\right) \exp\left(-\frac{n^2\pi^2}{L_0^2}D_{\rm sr}t\right)$$
(5)

where L_0 —the length of the fluidized bed, m; L'—the length of the bed along which the tracer particles are put in, m; C_x —the average concentration of tracer particles in the *x* direction; ratio of number of tracer



Fig. 5. Distribution of tracer particles' concentrations with time.

particles to total number of particles, dimensionless; D_{sr} – lateral dispersion coefficient of tracer particles, m²/s; and *x*—lateral distance along the dispersion direction, m.

The 2-D concentration of tracer particles is obtained by image analysis performed on every grid (with a total of 45×35 grids, each including 8×8 points of image elements). The average concentration distribution of the tracer particles along the lateral direction, C_x , is calculated from the 2-D concentration distribution. C_x is the 2-D concentration's average value along the *y* direction. To obtain the lateral diffusion coefficient, D_{sr} is first assumed to be a small value, and then it is put into Eq.uation (5), from which C_x is calculated and compared with the data by the image analysis. Then, D_{sr} is incremented by a small step value, and the calculation is repeated. When the difference between the calculated C_x and the experimental C_x attains the smallest value, the lateral coefficient of ICFB (D_{sr}) is finally obtained.

Table 3 shows the average lateral dispersion coefficients of tracer particles in the ICFB and Fig. 7 showed the all calculated dispersion coefficients for soybean and red bean in Case 1 and 2 with three experiments. Clearly, the dispersion coefficient of the polypropylene particles $(6.49 \times 10^{-4} \text{ m}^2/\text{s})$ is larger than that of the mung beans $(4.19 \times 10^{-4} \text{ m}^2/\text{s})$. The reason is that the diameter of a polypropylene particle is similar to that of a mung bean, and the density of the former is smaller than that of the latter. In the fluidized bed, the movement of polypropylene may thus be easier to follow in the bed materials than that of a mung bean. The more quickly the tracer particles move, the larger the lateral dispersion coefficient it has. In addition, the minimum fluidized air velocity of the polypropylene particles is also smaller than that of the mung beans.

The densities of the soybean and red bean are very similar, but the diameter of the soybean is larger. The minimum fluidized air velocity of the soybean is also larger than that of the red bean. Under the same air distribution, the soybean particle moves more slowly than the red bean. Thus, the dispersion coefficient of the soybean $(10.4 \times 10^{-4} \text{ m}^2/\text{s})$ should be smaller than that of the red bean



(a) polypropylene as tracer particles (Case 1, Group No.1)



(c) soybean as tracer particles (Case 1, Group No. 2)



(e) soybean as tracer particles (Case 2, Group No.2)



(b) mung beans as tracer particles (Case 1, Group No.1)



(d) red bean as tracer particles (Case 1, Group No. 2)



(f) red bean as tracer particles (Case 2, Group No.2)

 $(14.2 \times 10^{-4} \text{ m}^2/\text{s})$ (e.g., in Case 1 in Table 3). However, in Case 2 in Table 3, the lateral dispersion coefficients of the two are very similar $(8.7 \times 10^{-4} \text{ m}^2/\text{s and } 7.9 \times 10^{-4} \text{ m}^2/\text{s}$, respectively) because of the change in the air distribution manner.

For the soybean and red bean, the lateral dispersion coefficients in Case 1 are larger than those in Case 2, as well a relative stable estimate

Table 3 Lateral dispersion coefficients of the tracer particles in the ICFB.

Sorts of tracer particles	Case 1	Case 2 ^a
	$\overline{D_{sr}(\times 10^{-4}\mathrm{m^{2}/s})}$	
Polypropylene	6.49	-
Mung bean	4.19	-
Soybean	10.4 ± 2.3	8.7 ± 1.8
Red bean	14.2 ± 3.3	7.9 ± 1.7

^a No test data for polypropylene and mung bean in Case 2.

Fig. 6. Degree of inhomogeneity with time.

can be achieved with three experiments, as shown in Fig. 7. It seems that the air distribution in Case 1 (high velocity on the side and low velocity in the center) is better for the lateral dispersion of the tracer particles than that in Case 2 (high velocity in the center and low velocity on the side). Also, it is beneficial for circulation and lateral dispersion of tracer particles in ICFB due to the bigger momentum ratio (2.50) in Case 1 than that of in Case 2 (1.71).

4. Conclusion

A particle imaging technique was developed to analyze the movement course and the dispersion of dissimilar particles in an ICFB. The concentration distribution and the degree of inhomogeneity of dissimilar particles were calculated for various particle dispersion pictures. The degree of inhomogeneity *h* is used to evaluate the distribution of the tracer particles, which decreases with the increasing dispersion time. In the fluidized bed, the minimum fluidized air velocity of the tracer



Fig. 7. The calculated dispersion coefficients for soybean and red bean in Case 1 and 2.

particles with lower density (for a similar diameter) is smaller than that of those with a higher density. The movement of the former may be easier to follow in the bed materials than the latter. Thus, the lateral dispersion coefficients of the former are also larger than those of the latter. Compared with the lateral dispersion coefficients of the soybean and red bean in Case 1 and Case 2, it can be deduced that the air distribution in Case 1 (high velocity on side and low velocity in center) is better for the lateral dispersion of tracer particles than that in Case 2 (high velocity in center and low velocity on side) in the ICFB.

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