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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 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 phosphor-coated 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 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%.

Table 1
The characteristics of the materials.

	Particles	$d_p(10^{-3}$ m)	ρ_c(kg/m^3)	ρ_p(kg/m^3)	U_{mf}(m/s)	ε
Bed material	Millet	1.5	854	1185	0.8	0.28
	Mung bean	3.5	878	1283	1.1	0.32
Tracer particles	Polypropylene	3.88	559	901	0.97	0.38
	Soybean	7.0	727	1252	1.8	0.42
	Red bean	6.11	818	1249	1.5	0.35

3. Results and discussion

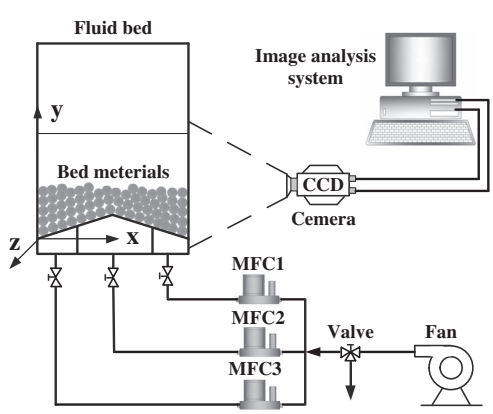
3.1. Experimental results

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.

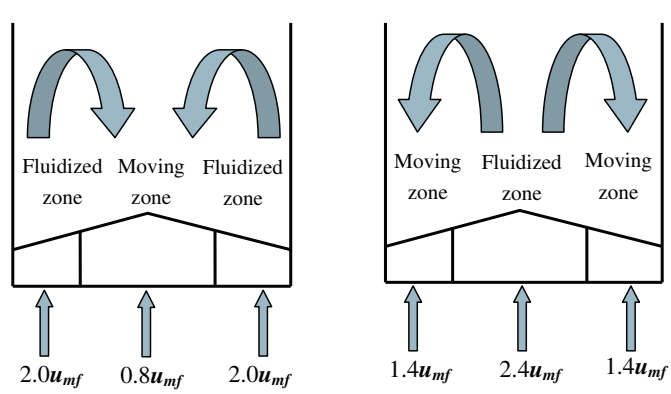
As shown in Fig. 3, the tracer particles quickly descend and disperse into the fluid zone when they enter into the moving bed zone. Next, the tracer particles move laterally to the fluid zone, where they are carried by the bubbles' wake and move upwards. Then, the foregoers of the tracer particles begin 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.



(a) Case 1 (b) Case 2

Fig. 2. The distribution of the fluidizing air.

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