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Experimental study on the spatial distribution of particle rotation in the upper dilute zone of a cold CFB riser*

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Abstract: Particle rotation plays an important role in gas-solid flows. This paper presents an experimental investigation on the spatial distribution of average rotation speed for glass beads in the upper dilute zone of a cold circulating fluidized bed (CFB) riser. It is shown that in the horizontal direction, the average rotation speed in the near-wall area is larger than that in the center area, while in the vertical direction, it decreases as the height increases. The reason resulting in this distribution is analyzed by considering several factors including particle size, particle shape, particle number density, particle collision behavior, and the surrounding flow field, etc. The effects of CFB operation conditions on the spatial distribution of average rotation speed are also studied. The results show that the increasing superficial gas velocity increases the average rotation speed of particles in the near wall area but takes nearly no effect on that in the center area. The external solids mass flux, however, takes the opposite effect. It is found that the average rotation speeds of particles in both areas are increased as the total amount of bed material increases.

Key words: Particle rotation, Gas-solid two-phase flow, Circulating fluidized bed (CFB)
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INTRODUCTION

Gas-solid flow commonly appears both in nature and in many industrial applications. Examples in the field of energy and environmental engineering are pneumatic conveying in pipes, fluidized beds, mixing devices and others. As one of the most important aspects in the flow mechanism of gas-solid flows, the motion characteristics of solid particles have been received extensive attention in many aspects, such as particle translational velocity (Shi, 2003; Dong *et al.*, 2004), particle size distribution (Kadambi *et al.*, 1998; Damaschke *et al.*, 2002), solid concentration distribution (Hyre and Glicksman, 2000; Meyer *et al.*, 2008), particle collision behavior (Alipchenkov and Zaichik, 2001; You *et al.*, 2004; Volkov *et al.*, 2005; Gui *et al.*, 2007), cluster in dense gas-solid flows (Wang *et al.*, 2005; Liu and Guo, 2006; Liu *et al.*, 2006; Helland *et al.*, 2007), segregation behavior (Goldschmidt *et al.*, 2003; Fan and Fox, 2008), and so on. However, the study of particle rotation behavior is rarely found in the literatures up to now. In general, particles in a flow not only move but also rotate due to the moments of force on them acted by the surrounding gas phase or other particles. Particle rotation may have significant influences on its motion trajectory, as well as the state of the gas phase and the whole gas-solid two-phase flow. According to the Magnus Effect, the rotation of a particle in a flow will generate a lift force, which in turn changes its moving trajectory. In some gas-solid flows, this lift force is rather significant, for example, in deposition-free transportation of pulverized coal in pipe (Cen and Fan, 1990; Hussainov *et al.*, 1996). Recent investigations have shown that the behavior of solid phase, as well as the flow field, may be affected by particle rotation in terms of energy dissipation (Yuan *et al.*, 2001;

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Goldschmidt *et al.*, 2004; Kajishima, 2004; Sun and Battaglia, 2006). It is clear that the study of particle rotation is important to the investigation of the flow mechanism of gas-solid flows.

The experimental investigation on particle rotation behavior heavily relies on the rotation speed measuring of these free particles in flows. Unfortunately this measuring is extremely difficult. Some of the previous studies focused on single particle with known rotation axis during a collision process, by means of high-speed photography (White and Schulz, 1977; White, 1982; Tsuji *et al.*, 1985; Hui and Hu, 1991) or photography using a stroboscope (Lee and Hsu, 1996; Liu, 1965). Usually, the particle used in those researches was large (several millimeters or centimeters) and was marked with some special lines or spots on its surface in advance. Meanwhile, the direction of rotation axis was also confined. A method based on laser Doppler system was presented to measure the rotation speed of irregular particles (Kale *et al.*, 1989). Although the particles could be as small as several hundred micrometers, this method was limited to pure rotation. The above methods are found rather difficult for measuring rotation speed of particles in typical gas-solid flows, where there are a large number of free moving particles with random rotation directions. Recently, the authors presented a preliminary study of the rotation motion of small glass beads in a 3D cold circulating fluidized bed (CFB) riser by using a 2D high-speed digital imaging system (Wu *et al.*, 2008a). It was found that the rotation speeds of part of those glass beads were measurable by tracing the special speckles on their surfaces or irregular shapes. Our previous efforts were focusing on the measurement methods for particle rotation speed, which include a computer-aided calculation method based on the cross-correlation of gray distribution of particle surface (Wu *et al.*, 2008b) and a manual measurement method based on the 3D reconstruction of particle rotation axis. These methods have been verified to be reliable with an error less than 10%. The average rotation speed for spherical glass beads in the upper dilute zone of a cold CFB riser, as well as other factors, such as particle size, velocity, shape, solid concentration, etc., was also investigated (Luo *et al.*, 2005; Wu, 2007).

Based on the previous investigations, this paper presents an experimental study on the spatial distribution of average rotation speed in the upper dilute zone of a CFB riser and its relationship with several operation conditions.

MATERIALS AND METHODS

The main facilities used in the experiment include a cold pilot-scale CFB system and a high-speed digital imaging system. Fig.1 shows the system diagram of the cold CFB system, which is composed of a riser with a dimension of 200 mm×200 mm×4 m ($W\times L\times H$), a down comer, a cyclone separator, a loop seal and a duster. The bed material (solid-phase) is fluidized by air that is introduced through a distributor plate, and then carried into the cyclone separator where gas-phase and solid-phase are separated. Solid-phase circulation is built up when the particles go back to the riser through the loop seal. Considering the fact of too much particle mass loading in dense and transition zones, the laser sheet light is not powerful enough to penetrate and the particles on images are overlapping, which prevent us from observing particle rotations, we have to choose a place in the upper dilute-phase zone for measuring. Spherical glass beads with an average diameter of 500 μm are used as bed material.

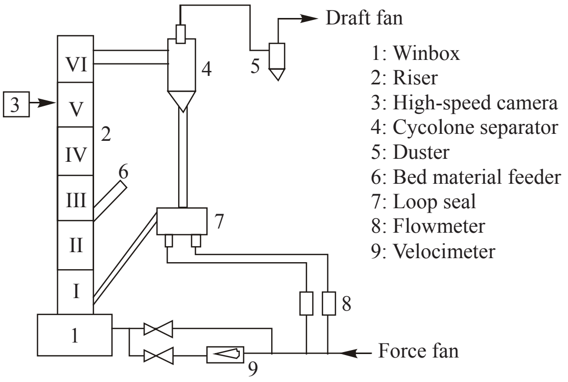


Fig.1 System diagram of the cold CFB system

The high-speed digital imaging system consists of a high-speed CMOS camera, a high-power laser sheet and a computer, as shown in Fig.2. The Redlake HG-100K camera has a CMOS color sensor with a recording rate of 1000 fps (frames per second) at full resolution of 1504×1128, and a maximal recoding rate up to 100 kfps at a reduced resolution of 32×24. In our experiment, a moderate recording rate, 5000 fps (at a resolution of 640×480) is used. An Nd:YAG laser with a wave length of 532 nm and a power of 8 W is used as illuminant. A column lens is installed to form the laser light as a fan-shaped light sheet with a depth no larger than 4 mm and an angle of flare about 30°. A vertical plane in dilute phase area of the cold CFB is illuminated by the light sheet, and at the same time, the image sequence of particles inside the plane is obtained by using the high-speed CMOS camera, in the direction perpendicular to the light plane. An example of the typical raw particle images taken in the experiment is shown in Fig.3. The particle rotation speed is measured based on these images. As the glass beads are normally not ideal spheres with smooth surfaces, some speckles on their surfaces may be recognized. When the particle rotates, the position of these speckles changes, by which the rotation angle of the particle may be determined. The particle rotation speed is the rotation angle divided by the time interval. The detailed information about the methods has been introduced elsewhere (Wu *et al.*, 2008a).

To study the spatial distribution of average rotation speed in the riser, a number of measurement points were chosen. Along the horizontal direction, 13 points were arranged in the cross-section at a height of 3.54 m above the air distributor, as shown in Fig.4. Those points are constrained in a quarter of the cross-section near both sides of the laser and the camera for the following reasons: (1) From the view point of theoretical statistics, information on a quarter of the cross-section is enough to reveal its whole picture due to the symmetrical feature along the two center lines of the cross-section; (2) In the reality, there are some difficulties for the study of the whole section area because the laser power gets weaker, and the quality of the particle image turns poor at a site far away from the laser source and the camera due to the increasing distance and disturbance from particles between the planes of laser sheet and camera. Along the vertical direction, two groups of measuring points (three for each group) are arranged in three cross-sections at the heights of 3.54 m, 2.8 m and 1.8 m above the distributor plate, respectively. One group (measurement points Nos. 13, 15 and 17) represents the vertical distribution of average rotation speed in the center area, while the other one (measurement area Nos. 5, 14, and 16) represents the situation near the boundary of the riser. For convenience, a coordinate system is defined as a base by which all the measurement points are described. The *x*- and y- directions denote the moving directions of the camera and the laser light sheet, respectively. The *z*-direction represents the height of the measurement area above the distributor plate.

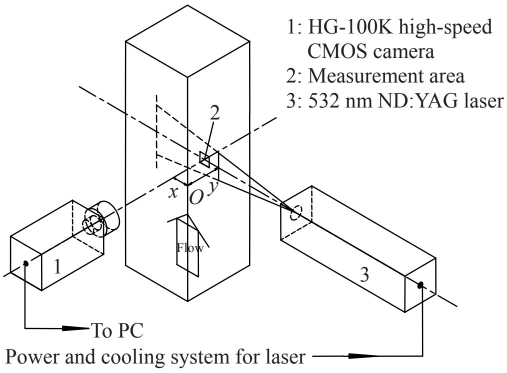


Fig.2 Arrangement of high-speed digital video camera system

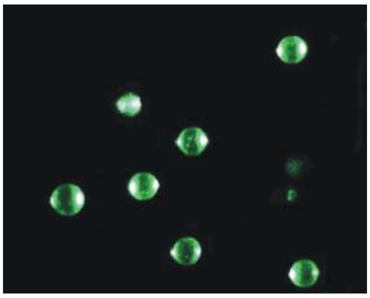
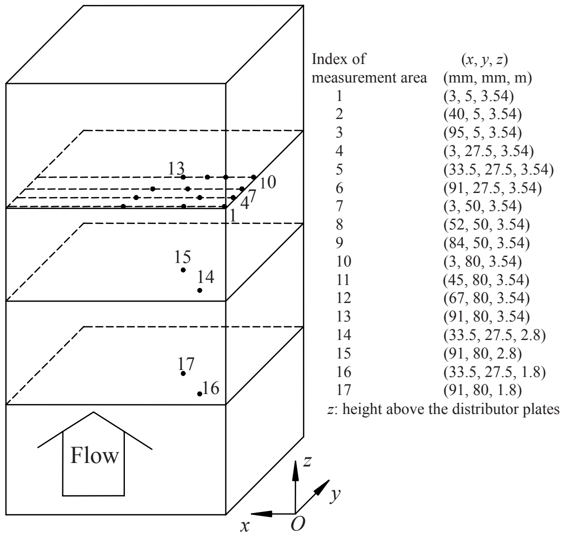


Fig.3 Raw images taken at the camera field of 6.7 mm×5 mm. Height of bed materials: 400 mm; superficial gas velocity: 5 m/s; external solids mass flux: 1.5 kg/(m^2·s); particle average diameter: 0.5 mm



Index of measurement area	(*x*, *y*, *z*) (mm, mm, m)
1	(3, 5, 3.54)
2	(40, 5, 3.54)
3	(95, 5, 3.54)
4	(3, 27.5, 3.54)
5	(33.5, 27.5, 3.54)
6	(91, 27.5, 3.54)
7	(3, 50, 3.54)
8	(52, 50, 3.54)
9	(84, 50, 3.54)
10	(3, 80, 3.54)
11	(45, 80, 3.54)
12	(67, 80, 3.54)
13	(91, 80, 3.54)
14	(33.5, 27.5, 2.8)
15	(91, 80, 2.8)
16	(33.5, 27.5, 1.8)
17	(91, 80, 1.8)

z: height above the distributor plates

Fig.4 Sketch map of measurement area arrangement

For the sake of statistical meaning, the particles used in analysis should be representative for the whole particulate system. In our method, the successful measuring of particle rotation speed depends on whether the change of position and direction of the special speckles on particle surface or shape can be clearly observed. It must be noted that not all the moving particles recorded by the camera can be measured. Statistical results show that the rotation speeds of about 20% among all the recorded particles can be determined, as shown in Fig.5. Since not all the glass beads used are essentially and physically different, the information acquired from this fraction of particles may disclose the situation of the whole particulate system. Meanwhile, a large number of particles are sampled to satisfy the requirement of statistics. For each measuring point, five groups of image sequence at a certain time interval are taken and about 35000 images are obtained. For each operation condition, the total number of particle images amounts to 600000. Both manual and computer-aided measurement methods are used. The measurement error for both methods has been found to be around 10% (Wu *et al.*, 2008b). It should be declared that both methods are time-consuming for dealing with such a large number of images. The number of particle samples for each measurement area used for statistical analysis is more than 200. The average particle rotation speed for each measurement area is given by

$$n_{\text{avg}} = \frac{1}{I}\sum_{i=1}^{I} n_i, \quad i = 1, 2, 3, \ldots, I, \tag{1}$$

where n_i denotes the instantaneous rotation speed of particle i.

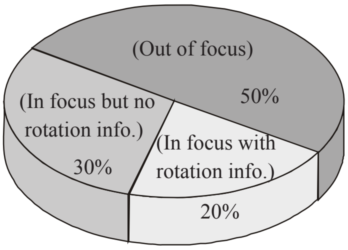


Fig.5 Statistical analysis for glass beads recorded

Once the average rotation speeds for all the measurement areas are obtained, the spatial distribution characteristics of particle rotation in the riser can be expected.

EXPERIMENTAL RESULTS AND ANALYSIS

Spatial distribution of particle rotation

The gas-solid flow in a CFB riser is a typical annulus-core flow. Normally, in its center area, the flow is characterized as a high speed and low mass loading upward flow, while in the near-wall area, a low speed and high mass loading downward particulate flow can be found. In this flow, the velocities of gas and particles as well as their mass loading are also different along the height (i.e., z-direction) of the riser. Therefore, the spatial distribution of particle rotation could be distinctive.

The spatial distribution character of average rotation speed under a stable operation condition is investigated. The CFB is working at a fixed bed height H=400 mm, a superficial gas velocity U_g=5 m/s, and an external solids mass flux G_s=1.5 kg/(m^2·s). The average particle rotation speed in the quarter of the x-y horizontal cross-section at a height of 3.54 m above the air distributor is shown in Fig.6 (a 3D surface schematic map based on real data of average rotation speeds at the corresponding measurement areas), while Fig.7 gives the corresponding result in vertical (z-direction) direction.

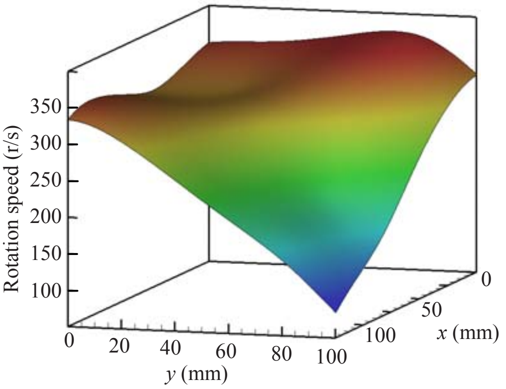


Fig.6 Average particle rotation speed distribution inside the 1/4 cross-section (3D surface schematic after interpolation and fitting)

It is found that the average particle rotation speed decreases from the inside near-wall to the center area, and so does the height of the measurement area increases. The average rotation speed in the near-wall area is found in a range of 350~450 r/s, while in the center area is much lower in the range of 100~200 r/s.

Since the rotation of a particle in a flow is affected by such factors as its size, shape, the solid

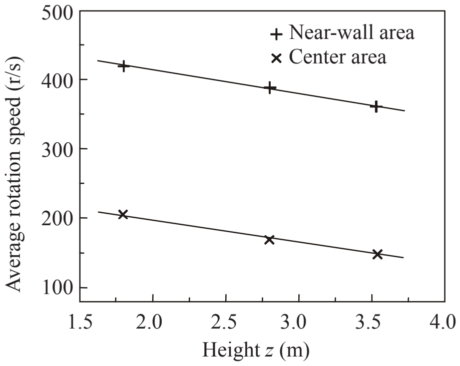


Fig.7 Average rotation speed rotation distributions in vertical (*z*-direction) direction both in the center and near-wall areas inside the riser

phase concentration, particle collision behavior, and the surrounding flow pattern, etc. (Wu *et al.*, 2008a), its rotation spatial distribution would be greatly influenced by the spatial distribution of those factors as follows:

(1) Particle size distribution. It is found that the average particle size in the near-wall area (about 620 μm) is larger than that in the center area (about 440 μm). Our previous investigation (Wu *et al.*, 2008a) showed that in the same area, the average rotation speed decreases with the increase of average particle size, which indicates that the average rotation speed in the near-wall area should be smaller than that in the center area. Therefore, particle size distribution has a negative influence on the spatial distribution of particle rotation.

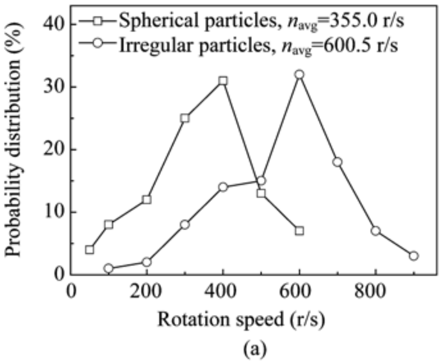
(2) Gas flow field. The gas phase in the vertical CFB riser has a typical shear flow. Since the gas velocity gradient in the near-wall area is found to be larger than that in the center area (Moran and Glicksman, 2003; Wu, 2007), it may have a positive influence on the spatial distribution of particle rotation. However, according to the calculation (Wu, 2007), the rotation speed caused by this factor is only at a level of a few ten revolutions per second, which is far below the real one measured. It is then concluded that the influence of gas flow field is minor.

(3) Particle collision and particle number density. Our previous theoretical and experimental investigations on possible rotation speed for glass beads in the CFB riser have shown that a particle may obtain a high rotation speed (thousand or hundred revolutions per second) after colliding with other particle or wall, which indicates that the spatial distribution of average rotation speed is very likely to be in connection with the distribution of particle collision rate N_c. The collision number is obtained by means of a manual method in which the particle collision number C is counted manually when the particle image sequences are observed one by one. Note that the high recording rate of 5000 fps ensures all the collision events to be observed. Together with the investigation volume ΔV and the time interval Δt, the collision rate turns out to be

$$N_c = \frac{C}{\Delta V \Delta t}. \tag{2}$$

The investigation volume is determined by the camera field range and the depth of focus. The latter may be regarded as the depth of the laser light sheet, which is about 4 mm in our experiment. Particle collision rate at different areas in the riser are manually measured and the results show that its spatial distribution basically accords with that for average particle rotation speed, i.e., from the inside near-wall area to the center area, the average particle collision rate decreases. In the near-wall area, the rate of inter-particle collision is about 30 times per second per cubic centimeter, while only 5 times per second per cubic centimeter is found in the center area. Therefore, particle collision rate is considered to be an important factor for the spatial distribution of rotation speed. As far as the particle number density is concerned, it is theoretically shown that the particle collision rate is in directly proportion to its square. Therefore, it may have an indirect influence on the spatial distribution of rotation speed since the particle collision rate increases with the increasing particle number density.

(4) Particle shape. It has been found that the average rotation speed of the irregular particles is much larger than that of the spherical ones in the near-wall area (Wu *et al.*, 2008a). However, in the center area of the riser, the effect of particle shape on particle rotation is no longer to be distinct. Comparison of the probability distribution of particle rotation speed for spherical and irregular particles in both near-wall and center areas are shown in Figs.8a and 8b, respectively. A typical rotation speed of several hundred revolutions per second is extremely high for a particle with a size of several hundred micrometers, which may decrease quickly due to a shearing moment on it exerted by the surrounding fluid. It is obvious that the effect



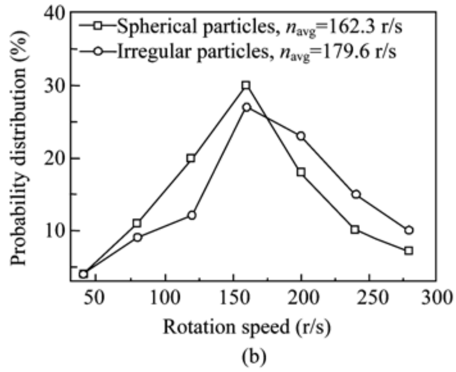


Fig.8 Comparison of the distribution of particle rotation speed for spherical and irregular particles (a) in the near-wall area and (b) in the center area (size range 450~550 μm)

of the fluid on the irregular particles is much stronger than that on the spherical particles. When the particle velocity relative to the fluid is higher, the effect of the fluid on the irregular particles can be much more distinct. A typical example is the motion of badminton in air. For the irregular particles in the CFB riser, the shape influences particle rotation in two ways: On one hand, it makes the particle rotating faster after collision; on the other hand, the rotation speed decreases much fast, especially in the case of high particle velocity relative to the surrounding fluid. In the near-wall area, the former factor may have a stronger influence on particle rotation than the latter one, which leads to a higher average rotation speed for irregular particles than for spherical ones. But in the center area, where the particle velocity relative to the fluid is higher, the two factors may have the same influence on particle rotation, so the rotation speed for both particles are hardly distinguished. From this point of view, the shape of particle may also have contributions to the spatial distribution of particle rotation in the riser.

Effect of the superficial gas velocity

In the following sections, the effects of operation parameters on the spatial distribution of the average particle rotation speed are investigated.

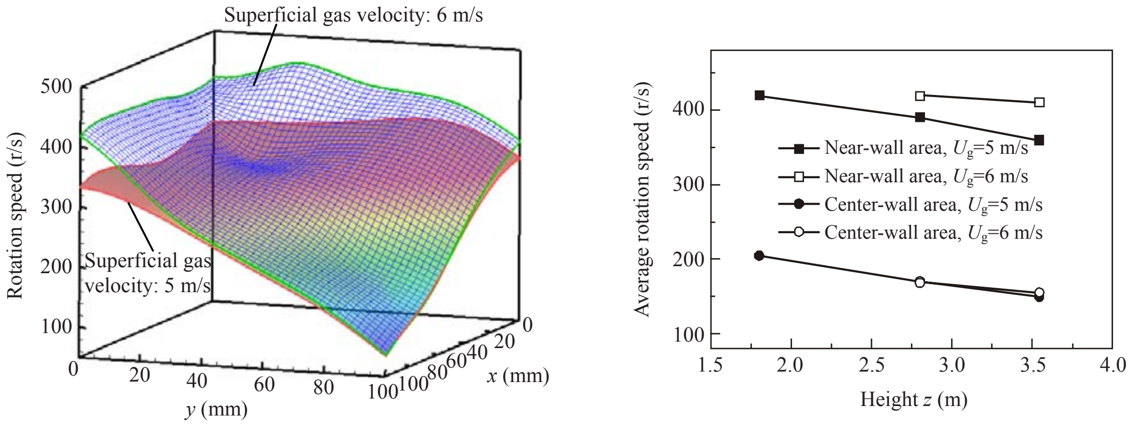
The superficial gas velocity U_g is one of the most important operation parameters for CFBs. A typical value of U_g is about 5 m/s and varies in a narrow range based on the loading in most coal combustion applications (Cen and Fan, 1990). The average rotation speeds in the 17 measuring points are measured when U_g is increased to be 6 m/s under otherwise identical conditions, i.e., the same circulating load and the same amount of bed material. Figs.9a and 9b show the comparison of the horizontal and vertical distributions of the average rotation speed for these two cases, respectively. As can be seen in Fig.9a, there is a rise of the average rotation speed, from 360 r/s to 410 r/s in the near-wall area as the superficial gas velocity increases. But the average rotation speed in the center area is almost the same. As a result, the discrepancy between the near-wall area and the center area is enlarged. In the vertical direction, as shown in Fig.9b, the trend of average rotation speed as function of the height is quite the same as the superficial gas velocity increases. But we failed to obtain particle rotation data at a height of 1.8 m above the distributor plate due to much high mass concentration in the near-wall area. It is also shown that the average rotation speed in the near-wall areas increases but not for that in the center areas as the superficial gas velocity increases.

The reason is probably as follows. When the superficial gas velocity increases, more particles in the transition and dense zone of the CFB riser are eluted into the upper-dilute zone, which increases the particle concentration. Meanwhile, the character of the annulus-core flow is more significant, i.e., the discrepancy of the particle concentration in the center area and in the near-wall area is enlarged. In the near-wall area, the increase of particle concentration leads to a rise in the particle collision rate, which is measured to be from 29 to 38 times per second per cubic centimeter. In the center area, the particle collision rate only has a slight rise (from 5 to 6.5 times per second per cubic centimeter) as the superficial gas velocity increases from 5 m/s to 6 m/s.

Effect of the circulating load

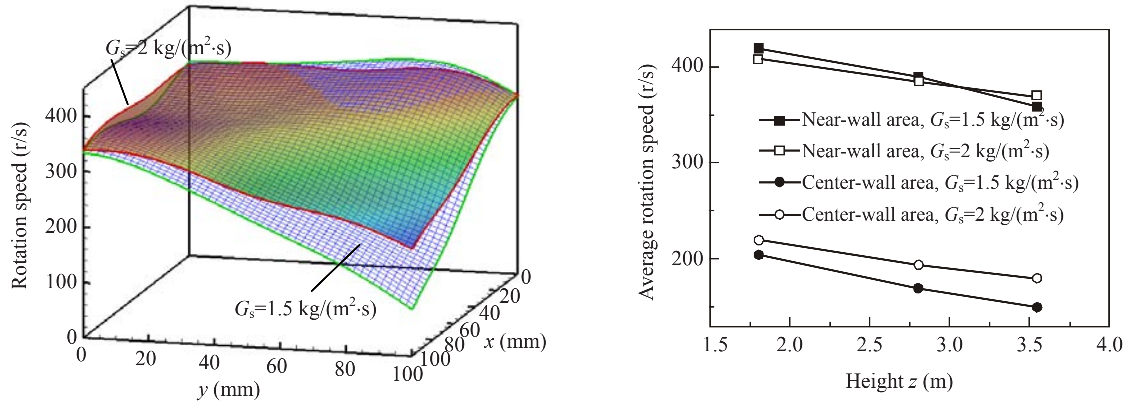
The circulating load of the CFB may also have an influence on the spatial distribution of the average rotation speed. Two cases with circulating loads of 1.5 and 2 kg/(m^2·s) were studied. The results shown in Fig.10a indicate that the average rotation speed in the center area in the latter case is much larger than that in the former one, while that for the near-wall area in two cases is nearly the same. That is to say, the discrepancy of the average rotation speed in the two areas is reduced. It is interesting that the conclusion is completely opposite comparing with that for the superficial gas velocity. In the vertical direction, as shown in Fig.10b, the trend of average rotation speed as a function of the height is quite the same as the circulating load increases.

The circulating load is the particle amount that takes part in the circulation of the riser, the down comer, the cyclone separator, and the Loop seal. The raise of the circulating load increases the amount of upward moving particles in the center area, which results in a significant increase of particle concentration as well as particle collision rate. The collision rate measured is doubled from 5 to 10 times per second per cubic centimeter as the circulating load increases from 1.5 to 2 kg/(m^2·s). Nevertheless, the increase of circulating load does not change the particle concentration and particle collision rate in the near-wall area, due to the fact that the increased amount of particles will enter the cyclone separator instead of moving downward in the near-wall area. That is probably the reason why the circulating load has little effect on the level of average rotation speed in the near-wall areas.



(a) (b)

Fig.9 Comparison of the (a) horizontal and (b) vertical distribution of particle rotation under different superficial gas velocities, G_s=1.5 kg/(m^2·s), H=400 mm

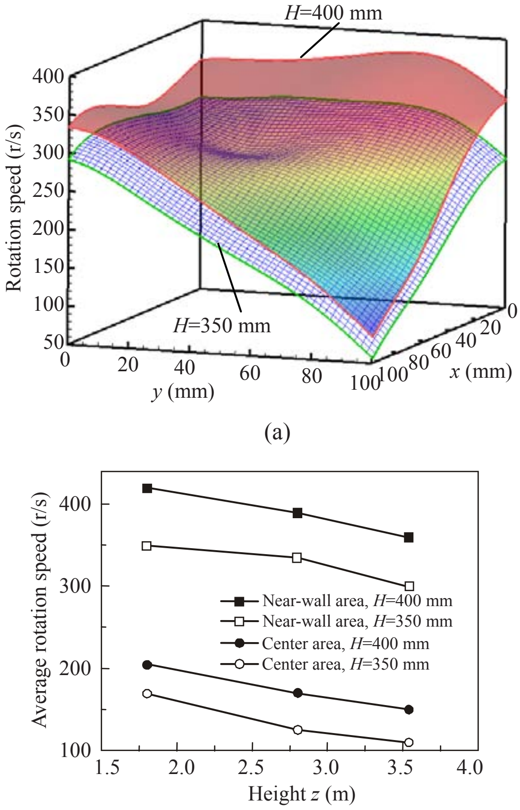


(a) (b)

Fig.10 Comparison of the (a) horizontal and (b) vertical distribution of particle rotation under different circulating loads, U_g=5 m/s, H=400 mm

Effect of the bed material inventory

The total amount of bed material, which is expressed by the static height of bed material, has a direct influence on the particle concentration and then the particle collision rate in the riser. Figs.11a and 11b show the comparisons of the horizontal and vertical distributions of the average rotation speeds for the two cases with the height of bed material H=350 mm and H=400 mm, respectively. It can be seen from Fig.11b that the average rotation speeds in both the near-wall area and center area decrease as the total amount of bed material decreases. Obviously, the effect of the total amount of bed material on particle rotation distribution is different compared to the above two parameters. The variation of the total amount of bed material makes the average rotation speed in the whole space of the upper-dilute zone of the CFB riser increase or decrease together. But the character of the spatial distribution of the particle rotation is nearly the same.



(a)

(b)

Fig.11 Comparison of the (a) horizontal and (b) vertical distribution of particle rotation under different total amount of bed materials, G_s=1.5 kg/(m^{2}s), U_g=5 m/s

As the total amount of bed material increases, more and more particles take part in the internal circulation, i.e., they move upward along the center area to the upper dilute zone and come back downward along the near-wall area. Therefore, in the upper dilute zone, not only in the center area, but also in the near-wall area, the particle concentration as well as the particle collision rate increases. It is measured that the particle collision rate varies from 23 to 29 times per second per cubic centimeter in the near-wall area, and from 3 to 5 times per second per cubic centimeter in the center area, when the height of bed material increases from 350 mm to 400 mm.

CONCLUSION

An experimental investigation on the spatial distribution of average rotation speed for glass beads in the upper dilute zone of a cold CFB riser based on a large number of particle examples has been carried out in this paper. It is shown that in the horizontal direction, the average rotation speed in the near-wall area is up to 300 r/s, which is much larger than that in the center area (around 100 r/s), while in the vertical direction, the average rotation speed decreases as the height increases. The reasons resulting in this distribution are analyzed considering several factors including particle size, particle shape, particle number density, particle collision behavior, and the surrounding flow field, etc. Several operation conditions, such as the superficial gas velocity, the external solids mass flux and the bed material inventory, are found to have influences on the spatial distribution of average rotation speed. The experimental results obtained from the cases studied show that an increment in superficial gas velocity increases the average rotation speed of particles in the near-wall area but takes nearly no effect on that in the center area. The external solids mass flux, however, takes the opposite effect. And the average rotation speeds of particles in both areas are found to increase as the total amount of bed material increases. The effects of operation parameters on the distribution of particle rotation can be explained by the variations of particle number density and particle collision rate.

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