Influence of Wall Roughness on the Hydrodynamics in a Circulating Fluidized Bed

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Many efforts have been made to explore the particle and gas behavior in circulating fluidized beds during the last decade. Glicksman et al. (1991) reported that protrusions as small as one particle diameter may cause a change in the voidage of a circulating fluidized bed. Since the walls of CFB combustors and other commercial CFB reactors can be quite rough, with roughness elements sometimes several times the mean particle diameter, the roughness could have a significant influence on the hydrodynamics, affecting mixing, gas-solid contacting, and heat and mass transfer in circulating fluidized-bed processes. It is therefore important to explore the influence of wall roughness on riser hydrodynamics. No other previous work has been reported on this topic.

Here, the influence of wall roughness on CFB hydrodynamics is identified by comparing the experimental results from a riser with rough walls with those from the same riser having smooth surfaces.

Experimental Setup

As shown in Figure 1, experiments were carried out in a cold model circulating fluidized-bed riser of 146 mm × 146 mm cross section with a total height of 9.14 m. The system consists of the riser, two cyclones in series, a standpipe for storing recirculating solids, and an L-valve to return solids to the base of the riser. No secondary air was added in the experiments described here. Detailed descriptions of the experimental apparatus are given elsewhere (Zhou et al., 1994; Zhou, 1995). Ottawa sand of mean diameter 213 μm, particle density 2,640 kg/m^3, and loosely packed bed voidage 0.43 was used as the bed material. The particle-size distribution is given by Zhou et al. (1994).

The protrusions which were found by Glicksman et al. (1991) to influence the hydrodynamics were of order one particle diameter. In the present work, coarse sandpaper having roughness elements approximately 0.45 mm in size, that is, about twice the mean particle diameter, was affixed to all four inner walls of the riser, right from bottom to top, and also to the underside of the top to provide a uniformly rough wall surface.

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To measure local voidage, a fiber optic particle concentration probe of outside diameter of 3 mm was used. This probe determines the time-average voidage in a region typically extending 3 to 7 mm from its tip, depending on the voidage. Measurements were obtained for 60 s periods at a frequency of 483 Hz. A second probe, a fiber optic particle velocity probe containing five 200-μm silicon optical fibers, was employed to measure both ascending and descending particle velocities.

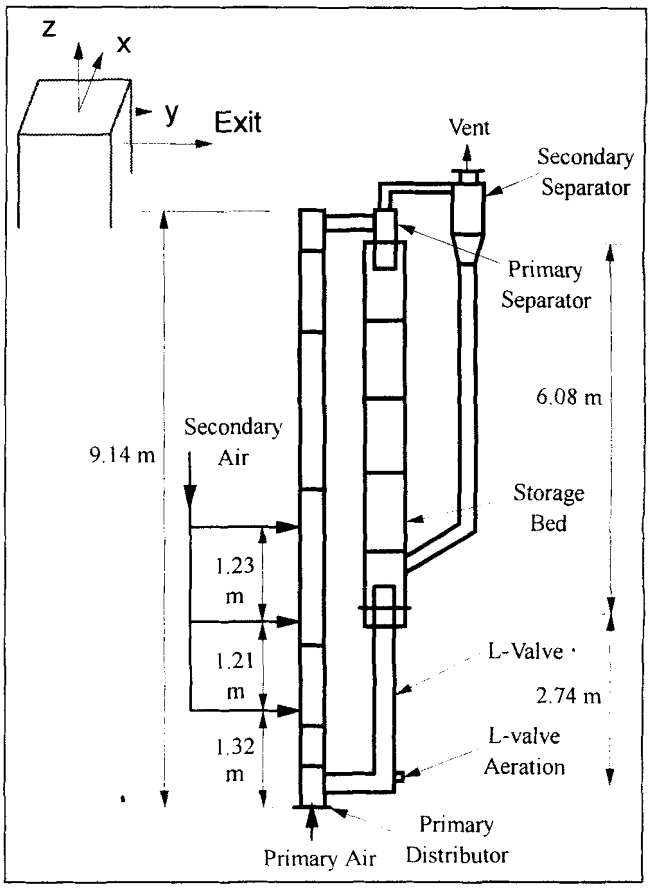

Figure 1. Experimental setup and coordinate scheme.

The sampling frequency of the velocity probe is 100 kHz. Two-thousand validated data samples were obtained for each particle velocity measurement. The head of this probe is rectangular with a width of 0.5 mm and a height of 1.8 mm. The maximum depth of field of the measuring volume of this probe is 3 mm for the voidage ϵ approaching 1. Detailed descriptions of both probes and their calibration are provided elsewhere (Zhou et al., 1994, 1995; Zhou, 1995). Both probes could be inserted and moved horizontally at a series of ports along the riser wall.

Smooth-wall and rough-wall data were compared at the 90% and 95% confidence level using the t-test. Confidence intervals were determined for both the bed voidage and particle velocity measurements based on repeat measurements. The ranges of time-mean average values for groups of repeated measurements are small, as indicated by the bars on the points indicated below. The confidence interval of each datum in this work is within the range shown by the reproducibility bars. The t-test is used below to examine the significance of differences between the smooth-wall and rough-wall column.

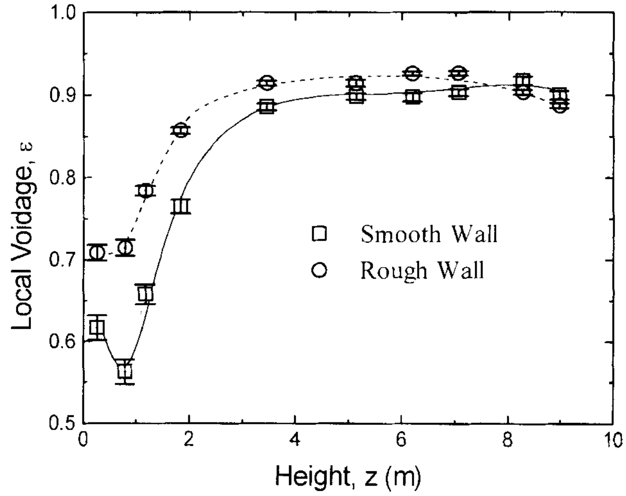

Figure 2. Axial profiles of time-mean local voidage at wall of the riser for $x/X = -1$, $y/Y = 0$, $U_g = 5.5$ m/s, $G_s = 40$ kg/m^2·s.

Experimental Results and Discussion

From our initial tests, the roughness of fresh sandpaper was found to change slightly because of erosion in the initial stages of operation of the CFB equipment. However, after the first hour, no apparent further change in the roughness of the sandpaper could be detected. This indicates that particles do touch the walls to some extent. However, the degree of contact with the wall may not be very extensive, so that the results do not necessarily contradict those of Wirth et al. (1991) and Lints and Glicksman (1993) who reported that there exists a gas layer between descending particle swarms and a smooth wall. The circulating fluidized-bed system was operated for 1.5 h before any measurements were taken to ensure that the roughness of the sandpaper did not change appreciably during the experiments reported below.

A solids circulation rate of 40 kg/m^2·s and a superficial gas velocity of 5.5 m/s were chosen for the experiments. These conditions and the sand particles were identical to those employed in earlier studies (Zhou et al., 1994, 1995) in the same riser with smooth steel walls in order to allow the influence of wall roughness to be determined.

Voidage profiles

Axial profiles of time-mean voidage near the walls of the riser with rough and smooth walls are compared in Figure 2. The reproducibility shown by the bars indicates the maximum and minimum of five repeat measurements, each lasting 60 s, for each run and each position. The differences between the rough and smooth walls are clearly greater than can be explained on the basis of experimental error. Except at the top of the riser, the voidage near the rough wall was somewhat greater than near the smooth surface. This may be because rough walls cause more turbulence and more deflection or disruption of the particle flow near the wall.

As illustrated in earlier work (Zhou et al., 1994), a bimodal probability distribution of voidage can sometimes be obtained with one peak corresponding likely to particle downflow in swarms and the other to bulk downflow of particles. Measurements adjacent to a rough wall (Zhou, 1995) showed that a single peak always appeared in the probability distribution, both at the wall and at the column axis over the entire height. This indicates that wall roughness may change the character of particle downflow near the wall.

Lateral profiles of voidage appear in Figure 3 at a height of 7.06 m above the distributor. Wall roughness is seen to increase the voidage near the wall, while it has little influence near the axis of the riser. For smooth walls, the voidage is not always highest on the axis of the riser. Instead, the voidage sometimes reaches a maximum at a location of about 0.6 to 0.8 of the half-width of the column from the axis and then decreases slightly towards the center. As described by Zhou et al. (1994), turbulence generated at the shear boundary is probably at the root of this M-shaped voidage profile. The measurements for the rough wall surface indicate a significantly flatter profile in the interior of the column.

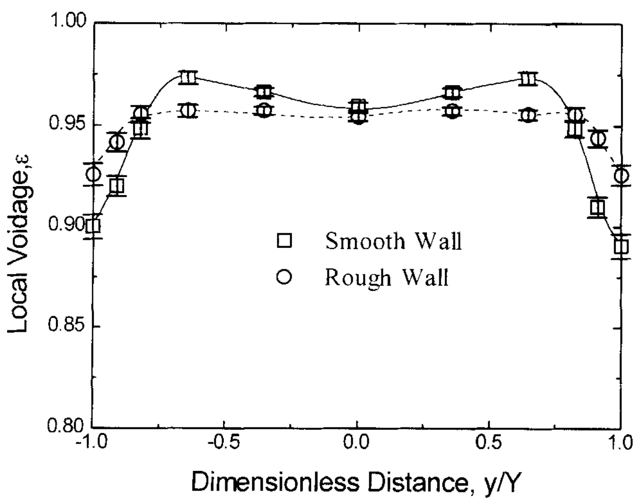

Figure 3. Lateral profiles of time-mean local voidage for $x/X = 0$, $z = 7.06$ m, $U_g = 5.5$ m/s, $G_s = 40$ kg/m^2·s.

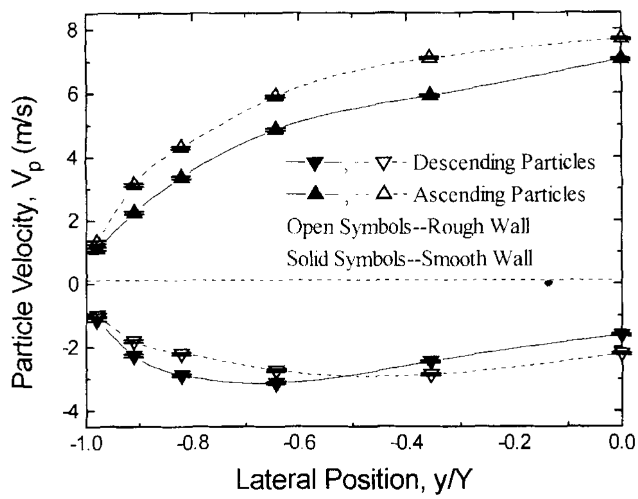

Figure 4. Lateral profiles of time-mean particle velocity for $x/X = 0$, $z = 6.2$ m, $U_g = 5.5$ m/s, $G_s = 40$ kg/m^2·s.

The voidage for the rough walls were found to be somewhat higher than for the smooth-walled column toward the corners (Zhou, 1995). This probably arises because near the corner, turbulence is caused by the roughness of both walls forming the corner.

Particle velocity profiles

Lateral profiles of particle velocity are illustrated in Figure 4. The ascending velocity was somewhat higher for the rough wall. In the core, this is probably because of a higher gas velocity caused by the thicker downflow wall layer measured for the rough wall surface at the same superficial gas velocity. The magnitudes of the velocities of particles descending near the wall were lower for the rough wall, possibly due to the increase of voidage of the particle downflow. Near the axis, descending particle velocities were slightly higher in magnitude for the rough wall than for the smooth surface.

As for the riser with smooth walls (Zhou et al., 1995), numerical integrations using the particle concentration, the ascending and descending particle velocities, and the fraction of ascending and descending particles were carried out for the rough-wall riser at heights of 5.13 and 6.20 m to see whether the calculated net particle flux matched the preset value of 40 kg/m^{2}s, determined from the descent of identifiable particles in the standpipe as proposed by Burkell et al. (1987). Integration results of 36.8 and 38.2 kg/m^{2}s were obtained, within 10% of the "true" value, helping to validate our experimental results.

Axial profiles of particle velocity at the wall and at the axis are shown in Figure 5. The reproducibility of the data was again determined by making five separate measurements for each position and condition, each measurement consisting of 2,000 validated samples. Error bars shown in Figures 4 and 5 show that the variation from one measurement to the next was small and indicate that the differences between the results for smooth and rough walls are significant. It is seen that the velocity of particle downflow at the wall, usually in the range of 0.8 to 1.5 m/s, did not vary greatly with wall roughness. This is also confirmed by t tests at significance

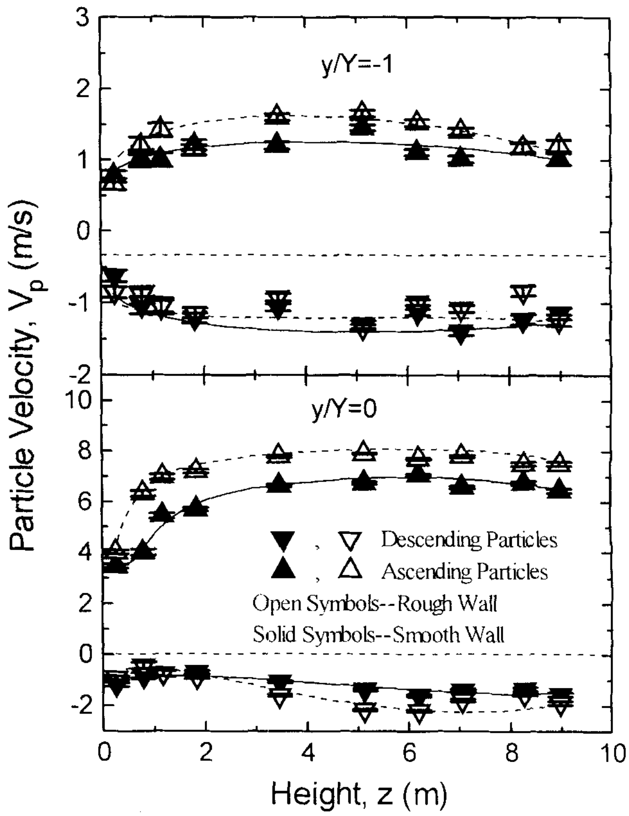

Figure 5. Axial profiles of time-mean upward and downward particle velocities for $x/X = 0$, $U_g = 5.5$ m/s, $G_s = 40$ kg/m^2·s.

levels of both 10% and 5%. It is not known whether roughness elements of size larger than 0.45 mm would have a significant influence on the velocities of particle descending near the wall. The t test was also carried out to examine the influence of wall roughness on the velocities of descending particles on the axis of the riser at $z = 3.5$ to 8.3 m. This test indicates that wall roughness influences the velocities of descending particles with confidence level of 90%, while the influence can be neglected for a confidence level of 95%. The ascending particle velocities, both along the axis and at the wall, were found to be somewhat higher for the rough walls than for the smooth walls.

Conclusions

Roughness elements were found to have an appreciable influence on the voidage and velocity of particles in a riser of square cross section, especially near the wall:

(1) The voidage was higher near the rough wall than near the smooth wall, especially near the corners, except near the top of the riser. Wall roughness had little influence on the voidage near the axis of the column. More uniform lateral profiles of voidage were obtained for the rough-walled riser than for a riser with smooth walls under otherwise identical operating conditions.

(2) T tests at significance levels of both 10% and 5% indicate that the magnitude of the velocities of particles descending near the rough wall did not vary with wall roughness. At a

confidence level of 90%, the velocities of descending particles on the axis of the riser at $z = 3.5$ to 8.3 m tended to be somewhat less than with the smooth wall, while at a confidence level of 95%, the influence of wall roughness can be neglected.

Notation

G_s = solids circulation rate, kg/m^2·s
U_g = superficial gas velocity, m/s
v_p = particle velocity in upwards direction, m/s
x, y = horizontal coordinates measured from axis of column as shown in Figure 1, m
X, Y = half-width of column cross-section, m
z = vertical coordinate measured from the air distributor, m
ϵ = local time-mean voidage

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