Influence of Membrane Walls on Particle Dynamics in a Circulating Fluidized Bed

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Membrane walls composed of vertical tubes connected by fins, as shown in Figure 1, are commonly employed as heat-transfer surfaces to remove heat from circulating-fluidized bed (CFB) combustors. The riser reactors are rectangular or square in cross section. The membrane tubes influence the dynamics of gas and particle flow in CFB risers. Wu et al. (1990) reported that particles were stripped from a flat smooth wall by upflowing gas more readily than from a membrane surface where downflowing particles appear to be protected in the fin region. Local heat-transfer coefficients near a membrane wall have been shown to be nonuniform by Andersson and Leckner (1992) and Lockhart et al. (1995). Andersson and Leckner (1994) observed highly concentrated particle downflow with a long residence time in the fin area.

Despite the importance of the membrane wall geometry to CFB combustors, little research has been carried out with respect to the influence of the membrane wall geometry on the flow and voidage in CFB risers. To understand the heat-transfer mechanism and erosion near the membrane wall, a better picture of local flow structure is needed. In this study, simulated membrane walls were installed in an experimental cold model CFB riser to investigate their influence on local hydrodynamics. Both voidage and particle velocity near the tubes were measured using separate fiber optic probes. Experimental results are compared with corresponding results for the same riser with smooth flat walls.

Experimental Setup

The experiments were carried out in a steel circulating fluidized-bed riser of inside cross section 146 mm × 146 mm square and with a total height of 9.14 m. Details are given elsewhere (Zhou et al., 1994, 1995). Half-round plexiglass rods of 25.4-mm dia. were affixed vertically by double-sided tape to all four inner walls of the CFB riser, right from bottom to top, to simulate membrane wall surfaces in a CFB combustor. The ratio of rod diameter d to the pitch p was set at 0.75, i.e., $p = 33.9$ mm, where p is the distance between the centerlines of two adjacent fins. Measurements around a centrally located (i.e., remote from corners) membrane tube were conducted at points A, B and C in Figure 1, where $\alpha = 48°$ for point B. (x and y are horizontal coordinates in this figure.) Lateral profiles of voidage and particle velocity were also measured along the three parallel lines through A, B, and C shown in Figure 1, from $y = 0$ to the wall, through ports on a specially designed window. The measuring window can be located at four different levels, allowing axial profiles to be obtained. There are four additional ports at other heights for $\alpha = 90°$.

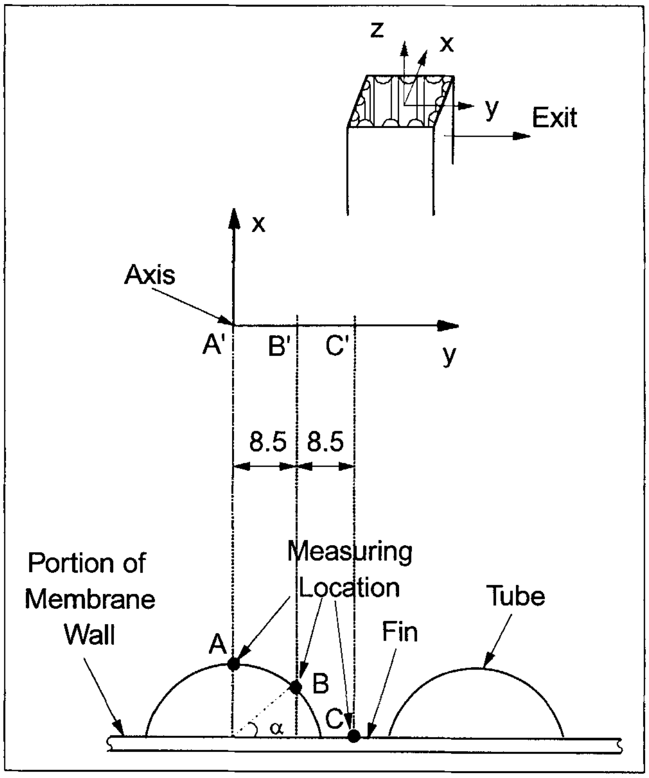

Figure 1. Membrane wall showing locations where voidage and particle velocity measurements were taken.
Dimensions are in mm.

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The fiber-optic particle concentration probe of 3-mm o.d. 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 sensor containing five 200-μm silicon optical fibers, was employed to measure both ascending and descending particle velocities. Two of the fibers transmit light to the measuring volume, while the other three carry reflected light to photocells. The sampling frequency for this probe was 100 kHz. The probe only determines velocities of particles traveling vertically, by only accepting measurements which are within 1% of each other from adjacent pairs of fibers, one pair above the other. 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 local voidage ϵ approaching 1. Detailed descriptions of both probes and their calibration are provided elsewhere (Zhou et al., 1994, 1995; Zhou, 1995).

Ottawa sand of mean dia. 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). Air at atmospheric temperature was the gas. The superficial gas velocity was measured with an orifice meter. The time-of-descent technique (Burkell et al., 1988) was employed to measure the solids circulation rate.

Experimental Results and Discussion

For comparison purpose, operating conditions were identical to those used previously in the same riser without inserts, i.e., with flat smooth walls and superficial air velocities of 5.5 and 7.0 m/s, and solids circulation rates of 40 and 60 kg/m^2·s. The solid particles were also the same as in earlier experiments with the flat riser walls.

As in previous work (Zhou et al., 1994, 1995), each data point for both voidage and particle velocity has been obtained by averaging five separate measurement periods. The reproducibility of the data obtained for the membrane wall riser is indicated by bars showing the range between the maximum and minimum of the five determinations. The 95% confidence interval of each datum is within the range shown by the reproducibility bars. The t-test has been employed to compare the magnitude of the data, with a confidence level of 95% to examine the influence of the membrane wall.

Voidage Profiles

With the voidage probe flush with the membrane surface, axial profiles of voidage near the membrane wall on the fin ($\alpha = 0°$), on the side ($\alpha = 48°$), and on the crest ($\alpha = 90°$) are shown in Figure 2. (z is the vertical coordinate measured from the primary air distributor.) The voidage in the fin area is lower than near the crest. It is also lower than near the wall of the riser with a flat smooth wall surface (Zhou et al., 1994). The voidage near the crest is higher than for the flat wall (Zhou et al., 1994) for the same operating conditions, $U_g = 7.0$ m/s and $G_s = 40$ kg/m^{2}s, where U_g is the superficial gas velocity and G_s is the solids circulation rate. As in the corners of the riser (Zhou et al., 1994), particles in the "valleys" formed by the fin and two adjacent tube surfaces are protected and therefore relatively difficult to strip off the wall. This protection is not available for particles near the crests of the membrane tubes. As a consequence, streamers of high particle concentration are more easily formed in the fin regions of the membrane wall, while on the crests, streamers are easily disturbed by upflowing gas, leading to higher voidage near the crests. For the same reason, the particle renewal rate from the core of the riser is higher along the crests and lower along fins of the membrane wall, compared to a flat wall in the same riser.

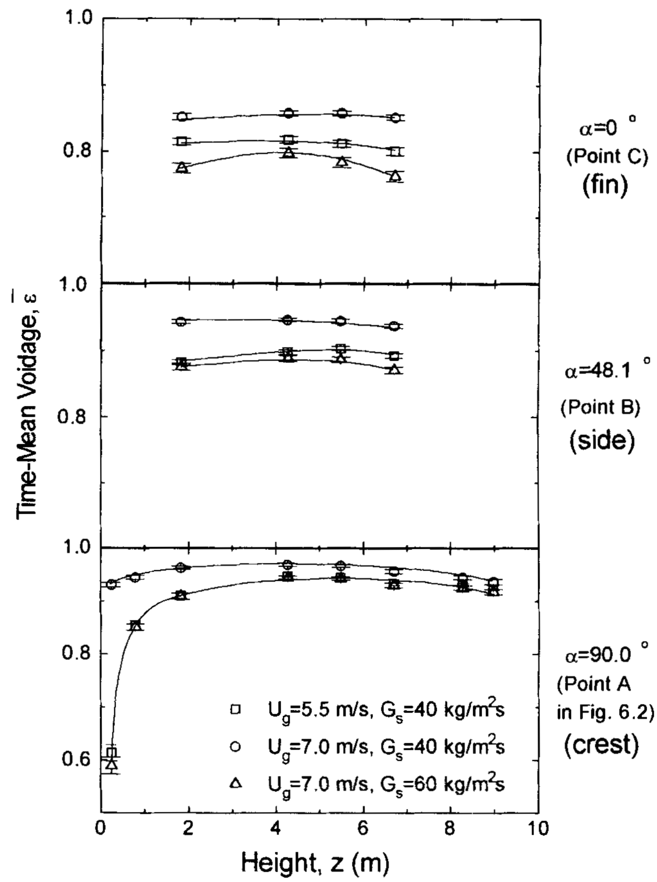

Figure 2. Axial profiles of voidage near membrane wall showing influences of operating conditions and location on surface.

The influence of superficial gas velocity and solids circulation rate is also indicated in Figure 2. Similar to the riser with flat walls (Zhou et al., 1994), the voidage in both the fin and the crest regions increased with increasing superficial gas velocity and with decreasing solids circulation rate.

Lateral profiles of voidage for $z = 6.7$ m, $U_g = 5.5$ m/s and $G_s = 40$ kg/m^2·s are plotted in Figure 3. The voidage is always lower near the wall and increases towards the $y = 0$ axis. The membrane surface only influences voidage significantly in the vicinity of the wall. For the same lateral position y near the wall, voidage increases from AA′ through BB′ to CC′ (Figure 1). This is probably because of the greater distance from CC′ to the wall. However, for the same distance from the wall, voidage decreases from AA′ to CC′. The voidage at $y = 0$ with membrane walls is around 0.96, very

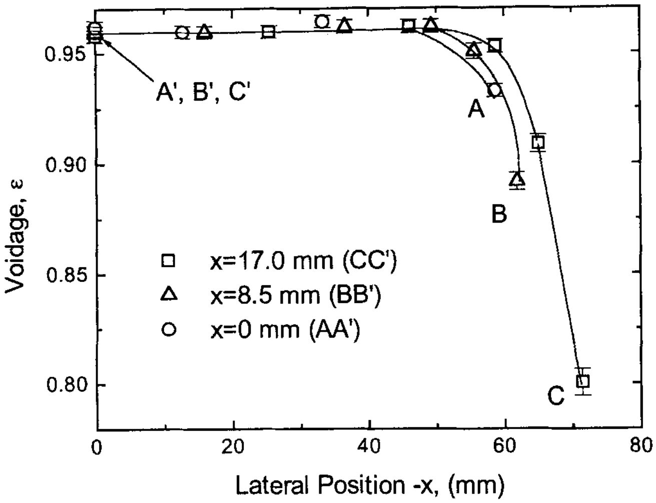

Figure 3. Lateral voidage profiles for $z = 6.7$ m, $U_g = 5.5$ m/s, and $G_s = 40$ kg/m^2·s along the three parallel dotted lines shown in Figure 1.

close to the value obtained with flat walls for the same operating conditions (Zhou et al., 1994). Thus, the membrane wall has very little influence on the voidage near the axis of the column. The M-shaped lateral profiles described by Zhou et al. (1994) for the flat-wall riser are less easily seen in the riser with membrane wall surfaces.

Particle Velocity Profiles

Profiles of vertical ascending and descending particle velocities and the fraction of particles descending near the membrane wall are plotted in Figure 4. These were obtained with the velocity probe flush with the membrane surface. Similar to particle velocities for the riser with flat walls, the magnitudes of both ascending and descending particle velocities first increase from the bottom with height and then decrease near the top because of the end effect discussed by Zhou et al. (1995). The fraction of particles found to be descending decreased somewhat with z near the bottom and then increased near the top. Near the membrane wall, the ascending particle velocity is highest in the crest region and lowest in the fin region. The fraction of particles descending is considerably higher in the valley or fin of the membrane wall than at the crest.

The mean velocity of descending particles near the flat wall was in the range of 0.8 to 1.5 m/s (Zhou et al., 1995). This range is also valid for particles near the crest of the membrane tube; however, the magnitude of the descending particle velocity in the fin area, as indicated in Figure 4, was greater than 2 m/s, associated with the elevated particle concentration in the fin region. The measurements of both particle velocity and voidage indicate that particle behavior in the fin region is similar to that near the riser corners where voidage and ascending particle velocity are low, while the magnitude of velocity and the fraction of descending particles are relatively high (Zhou et al., 1994, 1995).

The voidage and particle velocity results confirm early explanations of heat-transfer phenomena near membrane walls. In particular, for short surfaces (Lockhart et al., 1995) local heat-transfer coefficients are higher on the fin than on the crest, while the opposite is true for long heat-transfer surfaces (Andersson and Leckner, 1992). The former arises because of the greater concentration of particles at the fin, while the latter can be explained by the low particle renewal rate in the fin area, causing the particles there to rapidly approach the temperature of the heat-transfer surface.

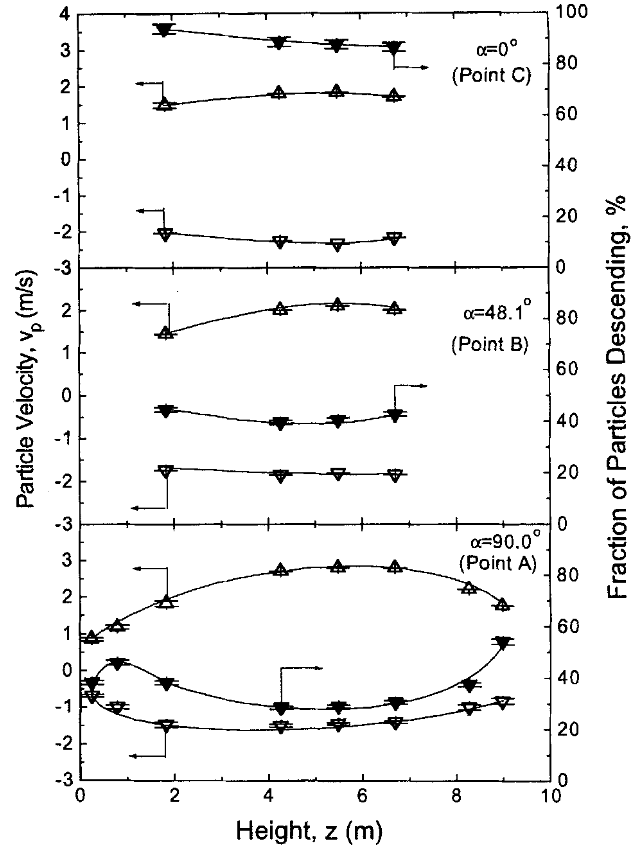

Figure 4. Axial profiles of vertical particle velocity and fraction of particles which are descending for $U_g = 5.5$ m/s and $G_s = 40$ kg/m^2·s.

Figure 5 illustrates the lateral profiles of particle velocity and fraction of particles descending along AA′, BB′ and CC′ (see Figure 1) at $z = 6.7$ m for $U_g = 5.5$ m/s and $G_s = 40$ kg/m^2·s. As for the lateral voidage profiles, the influence of the membrane wall is only significant near the wall. The fraction of descending particles increases monotonically in traversing from $y = 0$ to the wall. As for the riser with flat walls (Zhou et al., 1995), the magnitude of the descending particle velocity first increases with increasing y because the gas velocity decreases laterally (Yang et al., 1993); after a maximum is reached, the magnitude of the descending particle velocity then decreases towards the wall, probably because of wall friction. On the other hand, the particle ascending velocity decreases monotonically towards the wall.

Conclusion

Membrane walls influence local voidages and particle velocities in the outer region of a CFB riser of square cross section. Similar to the corners of a square riser, the valleys

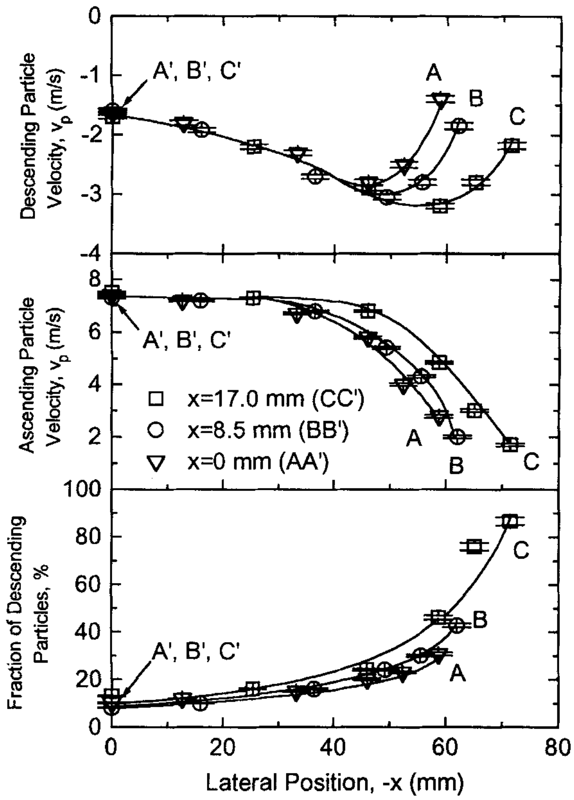

Figure 5. Lateral profiles of particle velocities and fraction of particles descending for $z = 6.7$ m, $U_g = 5.5$ m/s and $G_s = 40$ kg/m^2·s.

formed by the fin and two adjacent membrane tubes protect particles from upflowing gas. There is very little influence of the tubes in the core of the riser. Along the outer membrane surface, the voidage is lowest in the fin area and highest on the crest of the tubes. The magnitude of the downflowing particle velocity is highest in the fin area and lowest in the crest area along the membrane tube. The results are consistent with local heat-transfer measurements on membrane water-wall surfaces.

Acknowledgment

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