HYDRODYNAMICS OF HIGH VELOCITY CIRCULATING FLUIDIZED BED RISERS OF FCC CATALYST PARTICLES

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Abstract - Fluid catalytic cracking (FCC) risers operate at solids circulation fluxes of 400 to 800 kg/s-m^2 and superficial gas velocities as high as 15 to 25 m/s. However, although extensive CFB riser studies have been conducted, most of the reported data are for risers operating at relatively low gas velocities (< 10 m/s) and modest solids circulation rates (< 200 kg/s-m^2). There is a lack of hydrodynamics data for conditions similar or close to those of commercial FCC risers. This paper discusses total pressure drop, apparent density and local solids flux measurements obtained from three 0.3-m-diameter risers 15, 22 and 24 m in height using FCC catalyst particles. The risers were operated at superficial gas velocities of 12 to 16 m/s and solids fluxes of about 70 to 700 kg/s-m^2. At low solids circulation fluxes the apparent density decreased exponentially from the bottom to the top of the riser. A dense lower region started to form as the solids flux was increased at constant gas velocity. The height of the dense region increased to nearly occupying half of one of the risers' height at the highest solids flux. A variety of radial solids mass flux profiles were found in the risers depending on the superficial gas velocity and net solids mass flux. These included parabolic profiles with highest fluxes in the core region, flatter profiles, inverted parabolic profiles with the highest values near the riser walls as well as profiles with the highest solids flux near one wall and the lowest at the opposite wall. In contrast to parabolic solids flux profiles found in small diameter CFB risers, the solids mass flux profiles in the 30-cm-diameter risers tested here were relatively more flat. And, except for very few cases attributed to entrance effects, the net solids flow direction at all radial locations was found to be upward for the conditions used in this study. This would suggest that the widely reported upflow core and downflow annulus in low gas and solids flow risers are not representative of what takes place in commercial FCC risers.

INTRODUCTION

Circulating fluidized beds (CFB) are widely used in gas-solids reaction and gas-phase catalytic reaction processes (Berruti et al., 1995; Matsen, 1997). Gas-solids reaction processes, such as coal combustion and alumina calcination, have low reaction rates and do not necessarily require high gas velocities or high solids circulation rates. Fluid catalytic cracking (FCC) of petroleum, Fischer-Tropsch synthesis and oxidation of butane are gas-phase catalytic processes. They require high riser gas velocities to promote plug flow, and thus avoid gaseous products backmixing. The high reaction rates of these processes also call for high gas velocities because of the desired short contact times between the gas and solids. FCC units operate with Geldart Group A solids and they typically operate at riser solids circulation fluxes of 400 to 800 kg/s-m^2 and superficial gas velocities as high as 25 m/s (King, 1992). Matsen (2001) reviewed apparent density data from commercial FCC risers having diameters up 88.9 cm operated at gas velocities up to 15 m/s and solid mass fluxes up to 1305 kg/s-m^2 and found that those risers were essentially operating in dense phase flow in their entire height. The objective of this study was to obtain hydrodynamic data in a large circulating fluidized bed riser at gas and solids flow conditions typical of commercial fluid catalytic cracking units. This discussion is limited to riser pressure drops, apparent densities and radial solids flux profiles.

Most studies on CFB risers have dealt with relatively low gas velocities, Ug, (< 10 m/s) and modest solids circulation mass fluxes, Gs, (< 200 kg/s-m^2). This can be attributed, in part, to limited capacities of academic research units to achieving high enough gas velocities and solids fluxes. Generally, at these low flow conditions, CFB risers consist of a dilute region towards the top and a relatively dense region near the bottom, with the height of the dense region increasing or decreasing depending on the gas superficial velocity and solids circulation rates. The top region has a dilute core in which solids flow rapidly upward surrounded by a refluxing dense annulus.

The flow behavior in high gas velocity and high solids flux CFB risers is significantly different. Van Zoonen (1962) found from a pitot tube measurement of particle velocity in a 51-mm-diameter, 10 m tall riser of FCC particles that the net particle velocity profile at the 9 m height was almost parabolic for a gas velocity of 5.5

m/s and solids fluxes of 140 to 630 kg/s-m^2. Particle velocities at the wall were always upward. Similar findings were reported by Nieuwland et al. (1996) using an optical fiber probe in a 53.6-mm-diameter x 8 m high riser operated with 129 μm sand particles at superficial gas velocities of 7.5 to 15 m/s and solids fluxes of 100 to 400 kg/s-m^2. Issangya et al. (1997a) observed that the solids suspension adjacent to the wall of a 76-mm-diameter, 6 m tall CFB riser of FCC catalyst particles at solids holdups of nearly 0.2 was relatively homogeneous. Subsequent measurements of particles flow direction with a momentum probe (Issangya et al., 1997b) showed that the solids moved upward in the wall region. Local solids flux measurements by extraction probes in the same unit (Issangya et al., 1998) at G_s > 200 kg/s-m^2, found that local solids flux profiles were all roughly parabolic and the net solids flow was upward over the whole riser cross-section. Karri and Knowlton (1998) measured radial solids flux profiles for a 175 microns sand in a 20-cm-diameter, 14 m long riser at Ug = 5.8 m/s and Gs = 15 to 195 kg/s-m^2 and found that at the lowest solids mass flux solids in the annulus moved upward very slowly. At the two intermediate solids mass fluxes annulus solids moved downward along the wall and at the highest solids mass flux the annulus solids moved up along the wall. Karri and Knowlton (1999) appear to be the first to report all three types of radial solids mass flux profiles for FCC catalyst particles, namely, parabolic profile, flatter profile and inverted parabolic profiles. Their study was conducted in a 300-mm-diameter riser. Karri and Knowlton (2002) established a regime diagram for Geldart Group A solids mapping the regions where in the annulus flow upward or downward. Using an optical fiber probe in a 76-mm-diameter, 6.4 m tall riser operated with FCC catalyst particles at Ug = 4 to 8 m/s and solids fluxes of up to 550 kg/s-m^2, Liu et al. (2002) showed that the time-mean particle velocity can be downward or upward near the wall but the upward direction was more likely at high superficial gas velocities and high net solids fluxes. Grace (2000) suggested that the flow behavior in risers at high superficial gas velocities and solids fluxes had distinct characteristics and recommended a new flow regime, the dense suspension upflow (DSU) regime. In contrast to fast fluidization, the DSU regime had solids holdups of 0.07 to 0.25 and a net upflow of solids particles at all locations. Wang (2013) using optical fiber probes measured local particle velocities in a 76 mm ID, 10 m height riser at superficial gas velocities of 3 to 9 m/s and found that solids were in upflow motion in the riser annulus region at solids circulation fluxes greater than 700 kg/s-m^2 for FCC catalyst particles. This study is a continuation of CFB riser studies at high superficial gas velocities and high solids fluxes but in in relatively larger units. The data obtained will aid in the modelling, design and operation of commercial FCC risers as well as assist in the validation of computational fluid dynamic models.

EXPERIMENTAL

Tests were conducted over a period of time in three large circulating fluidized bed (CFB) units, referred to here as CFB Unit 1, CFB Unit 2 and Two-Risers CFB Unit. All the three units had 30.3-cm-diameter PVC risers. CFB Unit 1, schematically shown in Figure 1, consisted of a 0.6-m-diameter and height z = 7.6 m fluidized bed column with baffles whose solids were transferred by a 0.25-m-diameter, 3.4 m long vertical standpipe to its 15 m tall riser. The solids circulation rate was controlled by a 0.2-m-diameter pneumatically-actuated slide valve installed just above the elbow connecting the standpipe to the riser. The standpipe was aerated at several locations along its height. The unit had 0.56 and 0.48-m-diameter first and second stage riser cyclones whose diplegs were 20 and 7.6 cm in diameter, respectively. The first stage cyclone dipleg returned solids on the fluidized bed surface via a trickle valve. The second stage cyclone dipleg returned solids to the side of the fluid bed column in the freeboard via an automatic L-valve. The fluidized bed had a 25-cm-diameter primary cyclone whose 7.6-cm-diameter dipleg also returned solids to the side of the column via an automatic L-valve. The bed primary cyclone air was fed into the inlet of the riser's secondary cyclone. The air from the cyclones was vented into the building's baghouse header. The bed fluidizing air and the riser lift air were supplied by a blower and their flow rates were measured by orifice plates.

Figure 2 shows a schematic drawing of the CFB Unit 2. The unit had a 0.9-m-diameter, 6.1 m tall fluidized bed column with a 9.8-m-long, 30-cm-diameter steel standpipe that fed solids to a 27.8 m tall riser. A Y-shaped pipe section connected the standpipe to the riser. Solids flow rate was controlled by a slide valve installed horizontally just above the Y-section. A 0.5-m-diameter primary cyclone captured and returned entrained solids to the fluidized bed through a 20-cm-diameter dipleg fitted with trickle valve. A 0.5-m-diameter secondary cyclone with a 15.2-cm-diameter, 4.36 m long dipleg returned solids to the side of the bed via an automatic L-valve at a height of 3.13 m above the air distributor. The riser lift air was supplied by a blower through a 15-cm-diameter line that had an orifice plate to measure the flow rate. The fluidized bed air was also supplied by the same blower via a 76-mm-diameter PVC line that had a butterfly valve and an orifice plate to control its flowrate. The air leaving the CFB unit was emptied into the baghouse header by a 20-cm-diameter PVC line. The fluidized bed had no baffles and it was operated with short bed heights.

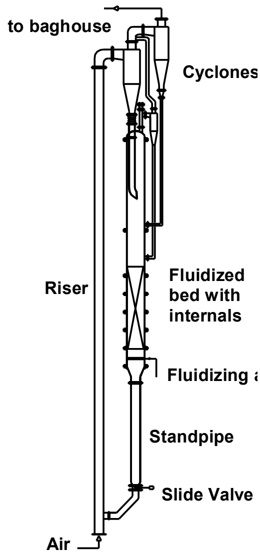

Fig. 1. Schematic drawing of CFB Unit 1. Riser ID = 30.3 cm and H = 15.24 m.

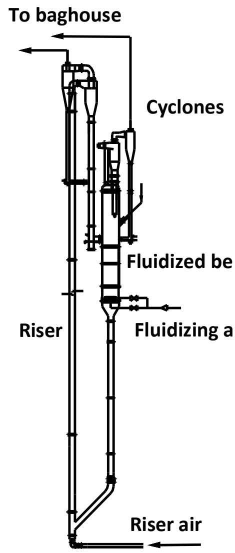

Fig. 2. Schematic drawing of CFB Unit 2. Riser ID = 30.3 cm and H = 24.2 m.

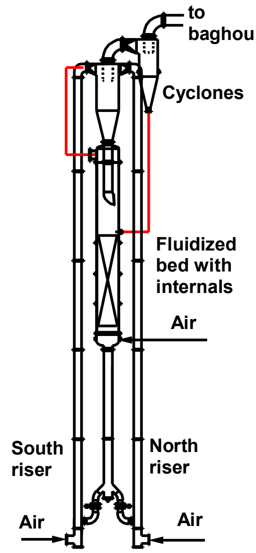

Fig. 3. Schematic drawing of the Two-Riser CFB Unit. Riser ID = 30.3 cm and H = 20.4 m.

The Two-Risers CFB unit, schematically shown in Figure 3, had a 0.9-m-diameter, 7.6 m tall fluidized bed column equipped with baffles. The bed solids entered a 0.36-m-diameter, 5.5 m long vertical standpipe. Two 20.3-cm-diameter pipes inclined at 45° split the standpipe flow into two with each entering an 18.6 m tall, 30.3-cm-diameter riser that conveyed the solids back to the fluidized bed. The fluidized bed and the two risers, referred to hereafter as south and north risers, shared a common 0.9-m-diameter primary cyclone. This cyclone had a 35.6-cm-diameter dipleg with a trickle valve that discharged solids near the bed surface. The secondary cyclone was 0.76 m in diameter and had a 15-cm-diameter dipleg that returned solids to the side of the column in the freeboard via an automatic L-valve. The exhaust air from cyclones was vented into the baghouse header. The solids circulation rate to each riser was controlled by a 0.2-m-diameter horizontal slide valve. The standpipe was aerated at several axial locations. Two blowers supplied the bed fluidizing air via a 15 cm PVC pipe and the riser lift air via two separate 25 cm PVC lines. Butterfly valves were used to regulate air flows.

The risers in the three units had smooth round elbows at their exits. Pressure drops were measured with differential pressure transmitters (Dwyer Instruments) connected by ¼-in (6.3-mm)-diameter plastic tubing to high-porosity metal snubbers attached to measurement ports on the risers.

Local solids flux was measured by solids extraction probes (Rhodes et al., 1988; Issangya et al., 1998). The extraction probe was a 12.7-mm-OD (0.5-inch), 1.25 mm (0.049 inch) thick wall stainless steel tube bent smoothly at 90 degrees. In some tests a 12.7-mm-OD (0.5-inch), 1.75 mm (0.069 inch) thick wall stainless tube was used. The net solids flux at a given radial location was obtained by subtracting the weight of solids collected with the tube facing up from that collected with the tube facing down, and then dividing the results by the sampling time and the cross-sectional area of the solids sampling tube. Solids samples were collected for periods of at least 30 s. The net solids flux in the riser was calculated by integrating the net radial solids flux profile. The suction air velocity for both sampling directions was set to be approximately equal to the superficial air velocity at that axial location in the riser. This non-isokinetic sampling method has been used successfully in many studies over many years. Karri and Knowlton (2002) found that overall solids mass fluxes obtained by integrating the extraction tube data were very close to the overall solids mass fluxes obtained by momentarily diverting the primary cyclone dipleg solids into a weighing tank. FCC catalyst particles with 3, 7, 8 and 11% < 44 μm fines content and a particle density of 1490 kg/m^3 were used in the tests. The particle size distributions of the solids are shown in Figure 4. Table 1 shows the solids flux measurement locations, and the tests operating superficial gas velocities and solids mass fluxes.

Table 1. Riser dimensions and operating conditions in the three test units.

Test Unit	Riser ID (cm)	Riser Height (m)	Solid flux measurement height, z (m)	Fines content (% < 44 μm)	Ug (m/s)	Net Gs (kg/s-m^2)
CFB Unit 1	30.3	15.24	6.7	3	12.8, 16.8	70 - 505
CFB Unit 2	30.3	24.2	13.2	7, 11	9.1, 14.3, 15.2	160 - 630
2-Risers CFB Unit	30.3	20.4	4.7, 10.1, 17.5	8	12.2	285 - 690

RESULTS AND DISCUSSION

Figure 5 shows apparent riser density (ΔP/gL) as a function of height for solids circulation mass fluxes of 364, 510, 589 and 636 kg/s-m^2 in the North riser and 355, 515, 588 and 617 kg/s-m^2 in the South riser of the Two-Risers CFB unit at an entrance superficial gas velocity of 12.2 m/s. The data were taken simultaneously in the two risers. The solids mass fluxes in the two risers were close. The intention was to operate both risers at the same Ug and Gs. The corresponding riser total pressure drops, excluding ΔP across the riser exit elbow, are included in Figure 5. It was also estimated that particle acceleration contributed significantly to the pressure drop over the bottom 2 m height above the solids entrance. Disregarding the data at the lowest measurement point, apparent density decreased roughly exponentially with increasing height for the lowest solids fluxes in both risers. The apparent solids holdup decreased from about 0.07 at the bottom to about 0.02 at the top. ΔP/gL, while still decreasing with increasing height, increased with increased Gs from around 500 to over 600 kg/s-m^2. The increase was much higher in the bottom 6 m above the acceleration zone where the apparent solids holdup increased in both risers from about 0.07 to about 0.17. The solids holdup in the upper section of the risers remained less than about 0.03. The high solids holdup values in the bottom to mid regions of the riser suggest that a dense zone was gradually building up in the risers as the solids circulation flux was increased.

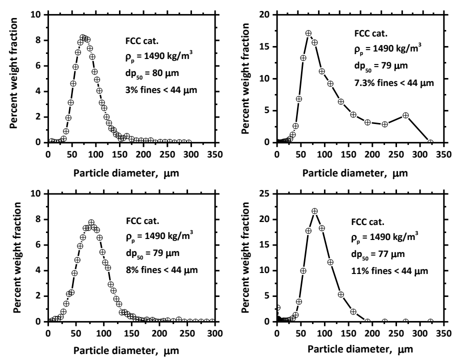

Fig. 4. Particle size distribution of FCC catalyst particles

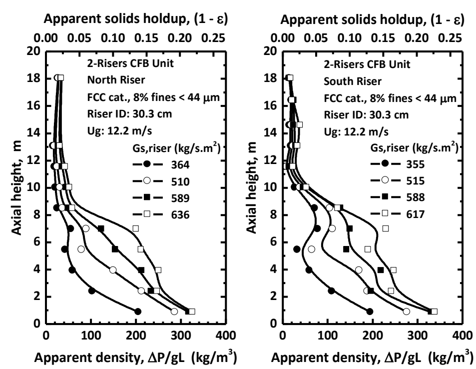

Fig. 5. Apparent density profiles in the North and South risers of the Two-Riser CFB unit at Ug = 12.2 m/s for various solids fluxes.

Figure 6 shows net radial solids flux profiles at z = 6.7 m in the CFB unit 1 riser for overall solids mass fluxes of 69, 190, 229, 334 and 368 kg/s-m^2 at a constant gas velocity of 12.8 m/s. The profiles are not parabolic, as found at low gas velocity/low solids flux risers but rather nearly flat with weak peaks on opposite radial locations

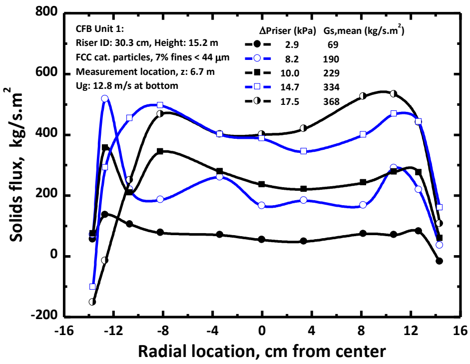

Fig. 6. Radial solids flux profiles at z = 6.7 m in the CFB unit 1 riser for Ug = 12.8 m/s and various solids fluxes.

before they drop off close the wall. The wall solids layer moved upward except for the left hand side of the riser at the highest two Gs values where solids moved downwards. It was not clear whether this was due to the solids entrance or solids exit effect propagating to mid-section of the riser. Operating at a higher superficial gas velocity of 16.8 m/s in the riser of CFB Unit 1 gave the local solids distributions shown in Figure 7 for overall solids mass fluxes of 258, 315, 415 and 505 kg/s-m^2. The solids mass flux profiles at Gs of 415 and 505 kg/s-m^2 are inverted parabola, with the solids near the wall moving upward at fluxes greater than in the riser core. The case is the same for the right hand side of the riser for Gs of 258 and 315 kg/s-m^2 but it appears that the gas velocity was not high enough to cause the inversion on the left hand side, where the solids move also upward, but the slowest. The rather flat solids mass flux profiles in Figure 6 and the inverted parabolic solids flux profiles in Figure 7 resemble the FCC catalyst particles results of Karri and Knowlton (2002) obtained in a 200-mm-diameter, 14.2 m high riser.

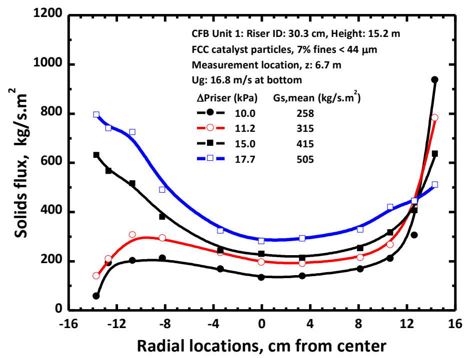

Fig. 7. Radial solids flux profiles at z = 6.7 m in the CFB unit 1 riser for Ug = 16.8 m/s and various solids fluxes.

Figure 8 gives the solids mass flux profiles in the CFB Unit 2 riser at Ug = 14.3 m/s and overall solids mass fluxes of 158, 363, 593 and 627 kg/s-m^2. The profiles for Gs = 158, 363 kg/s-m^2 are nearly flat suggesting that solids are moving upward at nearly the same flux near the wall as in the core region of the riser. At Gs = 593 and 627 kg/s-m^2, the profiles are also relatively flat or very weakly parabolic except for the data at the left side wall where the solids move upward relatively slower than in the interior for Gs = 593 kg/s-m^2 and significantly faster downward at Gs = 627 kg/s-m^2. The lower values at the left side are probably due to the entrance effect. This was the side the solids entered the riser. Figure 9 shows solids flux profile at Gs = 196 and 361 kg/s-m^2 in the CFB Unit 2 riser for a higher fines (11% < 44 μm) batch of FCC catalyst particles at Ug = 15.2 m/s. The superficial gas velocity was high enough to cause the upward inverted parabolic profile at the lower Gs value but not so at the higher Gs condition where the solids mass flux profile has the solids in the annular layer moving slower than in the core of the riser. The solids flow is upward near the wall for both conditions.

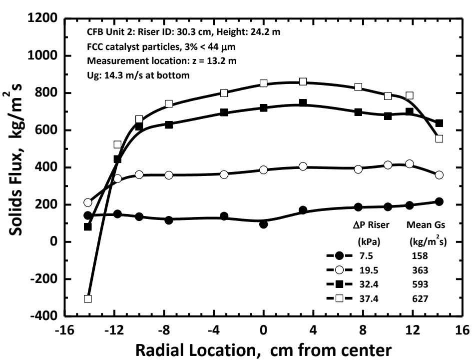

Fig. 8. Radial solids flux profiles at z = 13.2 m in CFB unit 2 riser for Ug = 14.3 m/s and various Gs values.

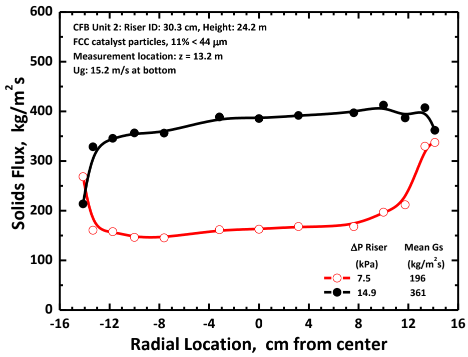

Fig. 9. Radial solids flux profiles at z = 13.2 m in CFB unit 2 riser for two solids circulation fluxes at Ug = 15.2 m/s.

Figures 10 and 11 show solids mass flux profiles obtained in the south and north risers of the Two-Risers CFB unit, respectively. The superficial gas velocity was 12.2 m/s in both cases and Gs = 216, 254, 293, 396, 467 and 593 kg/s-m^2 in the south riser and 285, 439, 510, 537, 621 and 689 kg/s-m^2 in the north riser. There is a clear asymmetry in the two plots with lowest values of solids flux being at one side of the riser. These two orientations were the side of the risers where solids entered horizontally. It appears the solids momentum at the entrances caused the incoming air to flow more on the opposite of the riser and as a result carry up more solids. The solids lift maldistribution at the entrance appears, therefore, to have propagated all the way up to the mid-height location where the solids flux profiles were measured. Otherwise, these profiles are nearly similar to downward inverted profiles in the other two CFB risers discussed above. Solids net flow was upward at all conditions in the south riser. The case was similar in the north riser except at the highest solids flux where the net annulus solids movement on the left hand side was downward.

The solids mass flux discussed thus far were collected at locations roughly mid-elevation of the three risers. Two more sets of tests were conducted with 8% fines FCC particles in the south riser of the Two-Risers CFB unit to determine if solids flux profiles are functions of axial locations. Figure 12 shows radial solids mass flux profiles at axial locations of 4.66, 10.10 and 17.47 above the solids entrance at Ug of 12.2 m/s and overall solids circulation mass flux of 350 kg/s-m^2 (average of bottom and top locations data). The solids flow direction is upward at all the three axial locations. The integrated net solids mass fluxes at the lower and upper locations are close. The solids flux at the middle location is lower than at the other two heights. The test for the middle location was conducted on a different day; therefore, it is likely the operating conditions may not exactly be matched with those of the other two locations. The shapes of the solids flux profiles are somewhat different near the wall. The data for similar tests done at a higher solids flux of 560 kg/s-m^2 are plotted in Figure 13. The shapes of the solids mass flux profiles are parabolic, i.e. solids fluxes are lowest close to the wall. The mean solids flux at the lowest elevation is significantly different from those of the upper two

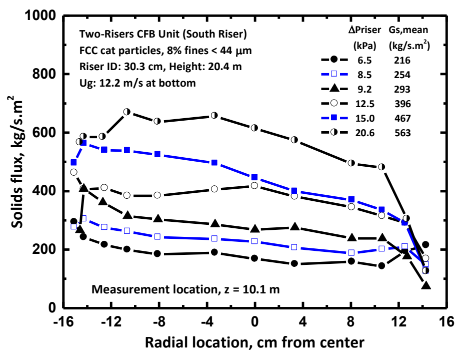

Fig. 10. Solids flux profiles at z = 10.1 m in the South riser of the Two-Risers CFB unit for Ug = 12.2 m/s and various solids fluxes.

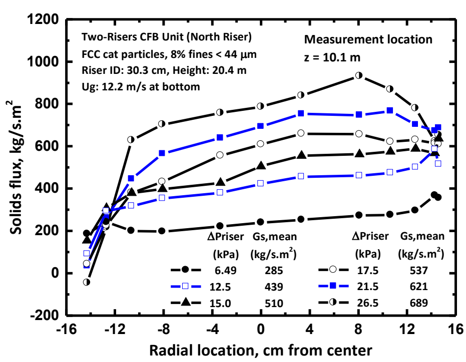

Fig. 11. Solids flux profiles at z = 10.1 m in the North riser of the Two-Risers CFB unit for Ug = 12.2 m/s and various solids fluxes.

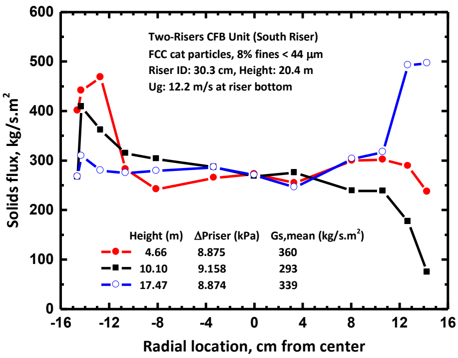

Fig.12. Radial solids flux profiles at three axial locations in the south riser of the Two-Risers CFB unit at Ug = 12.2 m/s and Gs of ~ 300 kg/s-m^2.

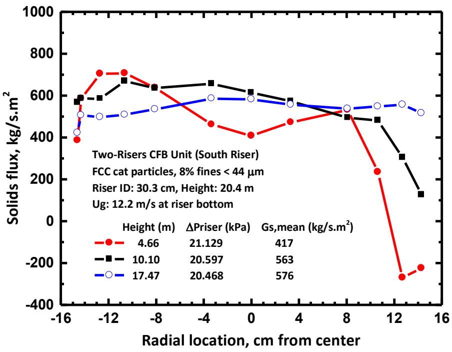

Fig. 13. Radial solids flux profiles at three axial locations in the south riser of the Two-Risers CFB unit at Ug = 12.2 m/s and Gs of ~ 570 kg/s-m^2.

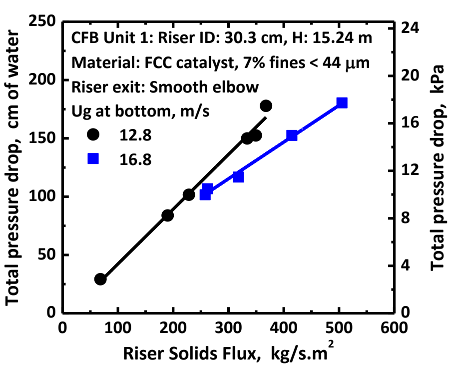

Fig. 14. Total riser ΔP versus Gs in CFB Unit 1 for Ug = 12.8 and 16.8 m/s.

elevations. The solids flux of 417 kg/s-m^2 at z = 4.66 m is significantly lower than the solids mass flux of about 570 kg/s-m^2 obtained at z = 10.10 and 17.47 m. In addition, solids moved upward at all radial locations at the mid and upper locations while there was a significant solids downward flow at the bottom location's right-hand side wall. The difference could be due to one of the things. First, the solids entered the riser on the right-hand side. It is likely that, for the high solids mass flux, the flow had not developed enough at the bottom measurement location to dissipate the asymmetry caused by the solids feed orientation. Therefore, taking measurements at only one plane was not sufficient to capture the flow pattern at that elevation. Alternatively, the solids extraction method has always been applied to the middle and upper part away from the solids acceleration region, where the flow is sufficiently developed. At high solids fluxes the bottom part of the riser is also significantly denser and the extraction technique may probably not be appropriate.

Figures 14 to 16 show the total riser pressure drop as a function of solids circulation mass flux. The solids fluxes are the cross-sectional area averaged values calculated from local solids fluxes measured about halfway the heights of the three CFB risers for a fixed superficial gas velocity. The total pressure drop across the risers varied linearly with solids circulation flux. There was, however, a change in slope in the linear increase in the north riser of the Two-Risers CFB unit when Gs exceeded about 700 kg/s-m^2. The change in slope at high solids mass fluxes could likely result from the denser lower zone of the riser growing to heights that make the pressure drop in that part of the riser more dominant.

CONCLUSION

The axial apparent density profile of a dense bottom region that transitions to a dilute top region reported in the literature for small CFB risers can also occur in large high gas flow and high solids mass flux CFB risers. A variety of radial solids mass flux profiles were found in the risers depending on the superficial gas velocity and net solids mass flux. These included parabolic profiles with high values in the core, nearly flat profiles, inverted parabolic profiles with highest values near the riser walls as well as profiles with highest solids flux near one wall and lowest at the opposite wall. Radial solids mass flux profiles did not vary significantly with axial location. Except for very few cases, the net solids flow direction at all radial locations was upward for the conditions used in this study. The local solids flux in commercial fluid catalytic cracking risers, which operate at even higher gas velocities than tested here, are very likely also upward at all radial locations and not the widely reported parabolic profiles of upward core and downward annulus flow structure.

NOTATION

Gs: Solids mass flux (kg/s-m^2)

g: Gravitational acceleration (m/s^2)

L: Length (m)

Ug: Superficial gas velocity (m/s)

z: Height (m)

ΔP: Pressure drop (kPa, cm of water)

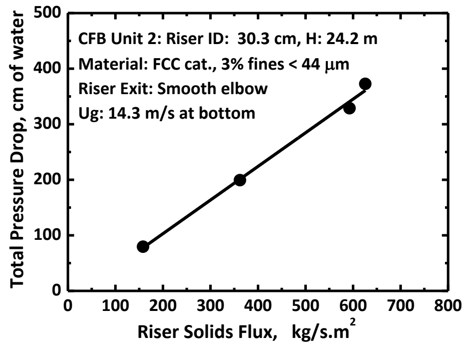

Fig. 15. Total riser ΔP versus solids flux in CFB Unit 2 for Ug = 14.3 m/s.

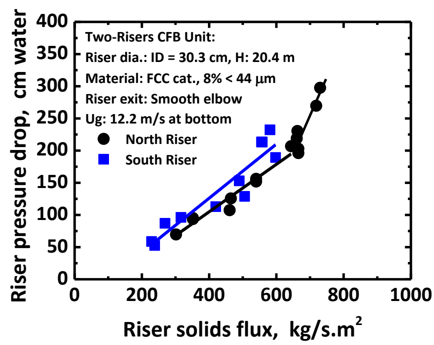

Fig. 16. Total riser ΔP versus solids flux in the 2-Risers unit for Ug = 12.2 m/s.

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