A Comparison of Flow Development in High Density Gas-Solids Circulating Fluidized Bed Downer and Riser Reactors

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Comparison of flow development in high density downer and riser reactors is experimentally investigated using fluid catalytic cracking particles with very high solids circulation rate up to 700 kg/m^{2}s for the first time. Results show that both axial and radial flow structures are more uniform in downers compared to riser reactors even at very high density conditions, although the solids distribution becomes less uniform in the high density downer. Solids acceleration is much faster in the downer compared to the riser reactor indicating a shorter length of flow development and residence time, which is beneficial to the chemical reactions requiring short contact time and high product selectivity. Slip velocity in risers and downers is also first compared at high density conditions. The slip velocity in the downer is much smaller than in the riser for the same solids holdup indicating less particle aggregation and better gas-solids contacting in the downer reactors. © 2015 American Institute of Chemical Engineers *AIChE J*, 61: 1172–1183, 2015
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Introduction

Fluidization is a process which involves the flow of solids in contact with a fluid being gas, liquid or gas and liquid. In gas-solids fluidization systems, when enough gas is introduced into a bed filled with particles supported by a distributor, particles can be fluidized.[1] Several flow patterns or regimes have been identified with increasing gas velocity, that is, fixed bed, particulate fluidization, bubbling, fluidization, turbulent fluidization, fast fluidization, and pneumatic transport.[2] Studies on bubbling and turbulent fluidization (conventional fluidization) were the main focus in the 1960s and 1970s.[3] Since the early 1980s, substantial attention have been shifted to high velocity fluidization, that is, circulating fluidized beds (CFBs).[3] Compared to conventional fluidized beds, CFBs have many attractive features, such as high throughput per unit reactor volume and independent gas and solids flow rate control.[4–7] Over the years, with a growing interest in combustion, gasification, and fluid catalytic cracking (FCC), more and more attention has been paid to CFBs.[6,8]

Conventionally, there exist two types of gas-solids CFB operations, a concurrent upflow in a riser, where the gas-solids suspension flows up against gravity, and a concurrent downflow in a downer, where the suspension travels downward at the aid of gravity.[9] The industrial application of CFB riser reactors can date back to the 1940s, when the FCC process was first developed.[10] Since then, the flow characteristics in the riser have been delineated and understood in both the industrial and the academic fields. Due to the counter-gravity flow, CFB risers tend not to have uniform gas and solids flow structure; with more particles accumulate at the riser bottom and near the wall inside the reactors.[4,9,11–13] The nonuniform axial and radial flow structure has many disadvantages, for example, there is serious gas by-passing through the core dilute region and extensive backmixing of solids in the wall region. This leads to reduced gas-solids contacting efficiency, long residence time and poor distribution of chemical products.[4,7,14] The downer reactor was developed in an attempt to overcome the disadvantages of the riser reactors.[15–17]

As a result of gravity assistance, the flow in the downer is closer to plug flow, resulting in more uniform profiles of solids holdup and particle velocity.[4] Besides, the downer reactor also provides many other advantages over the riser, such as reduced solids aggregation, less backmixing, and shorter residence time.[4,18,19] The unique features of the downer enable it to be effectively used in many chemical processes, where the demand on selectivity of intermediate products is of main concern. One such potential application is heavy oilô FCC.[19]

Studies on the downer reactor started in the 1990s[16] and there is now a substantial amount of understanding of the flow behaviors in the downer.[4,9,20–27] The downer has a

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distinct axial flow structure in the downer due to the concurrent gas-solids flow in the direction of gravity. Wang et al.[15] measured axial pressure gradients distributions along the downer and found that the downer could be divided into three axial zones: the first acceleration zone, the second acceleration zone, and the constant velocity zone. The review of the early studies on downer is given by Zhu et al.[4] In some earlier studies, the cross-sectional average solids holdup was calculated from the pressure gradient, which was not an accurate approach as the friction between gas-solids suspension and the wall had been neglected, especially in the particle acceleration zone, where part of the pressure loss was due to particle acceleration.[28–30] Later on, the study by Johnston et al.[18] on the axial solids holdup and particle velocity profiles showed more details about the entrance section of the downer. Wei and Zhu[9] studied the axial solids mixing behavior and compared the similarities and differences between the downer and the riser. Ma and Zhu[22] measured heat transfer inside the same downer. Luo et al.[31] conducted some experiments on the characteristics of mass transfer with the adsorption of CO_2 tracer by activated charcoal particles. Recently, Li et al.[32] reported the hydrodynamics and reactor performance using a hot model reaction (ozone decomposition) in a downer. Those studies were, however, carried and with low solids circulation rates, less than 200 kg/m^{2}s,[23,24,27] even though many industrial CFB reactors such as FCC (where solids flux normally ranges from 400 to 1200 kg/m^{2}s)[33] are operated at much higher solids circulation rate with higher solids holdup.

Research has indicated that there are significant differences between the low and high solids circulating flux CFBs in terms of hydrodynamics, in both riser and downer reactors. Based on a theoretical analysis, Bi and Zhu[34] had classified CFB risers into high flux and/or high density ($G_s \geq 200$ kg/m^{2}s, $\varepsilon_s \geq 0.1$) CFBs (HFCFB/HDCFB) and low density CFBs (LDCFB). In a CFB riser, Contractor et al.[35] found that the dense region at the bottom can extend to the whole riser leading to a high density riser with overall solids holdup of 0.15–0.20 at high solid circulation rates. Issangya et al.[12,36,37] presented that axial homogenous flow with no downward flow near the wall could be achieved at high solids circulation rate up to 400 kg/m^{2}s. Liu et al.[38] thereafter reported that gas backmixing became lower using the same high density operating conditions. In the study by Pärssinen and Zhu,[39] a high solids flux of 550 kg/m^{2}s was reached and both axial and radial solids holdup profiles became less uniform under higher solids flux. Bi[40] compared mixing behavior between LDCFB to HDCFB and illustrated a clear transition of axial mixing from LDCFB to HDCFB. Zhu and Zhu[5] proposed a novel circulating-turbulent fluidized bed (C-TFB) operated with low gas velocity and high solids flux, resulting in a high-density flow with solids holdup of up to 0.25 through the entire C-TFB with a nearly uniform axial solids flow and negligible downflow giving rise to a good gas-solids contact. Conversely, in a special effort to achieve high solids holdup, Liu et al.[41] designed a special high-density downer, where a 0.66 m tall funnel with 250 mm top diameter was placed at the top of a 25 mm and 5 m tall downer to preaccelerate the particles, so that they can be fed into the downer at their terminal velocity so as to facilitate high solids flux condition. With this particular apparatus, an average solids holdup as high as 0.07–0.09 was achieved at solids circulation rate (G_s) over 400 kg/m^{2}s using FCC particles. Chen and Li[42] reported that solids concentration reached 0.14 with a maximum solids flux of 200 kg/m^{2}s under very low superficial gas velocities ($U_g = 0.8$–1.2 m/s). Guan et al.[26] proposed a triple-bed system including a CFB downer and the solids holdup was up to 0.03 in the fully developed region with $G_s = 439$ kg/m^{2}s. However, most of these experiments concentrated on solids holdup mainly inferred from the axial pressure profiles. Although many studies on hydrodynamics in both the riser and downer reactors had been carried out, there is little research focused on comparison of hydrodynamics between the riser and downer, especially at high density/flux conditions.

A good understanding of the flow structures in the CFB reactors is critical for proper industrial design. The solids flow structure in the CFB reactors affects the gas-solids contacting efficiency, heat and mass transfer, conversion, and the product selectivity of chemical reactions.[4] Studies of solids distribution, flow development and solids acceleration will lead to successful scale-up and process modification. The purpose of the present study is, therefore, to systematically study and compare the solids flow development using an optical fiber probe in a downer and a riser within a wide operating conditions, in particular, at high solids flux conditions.

Experimental Facilities

Figure 1 shows multifunctional CFB (MCFB) unit used for this study. It is mainly consisted of a riser with an inner diameter of 76 mm and length of 4 m, two downers with an inner diameter of 76 mm and height of 5.8 m, and an inner diameter of 50 mm and height of 5.1 m, a downcomer with an inner diameter of 213 mm, and storage tank with an inner diameter of 457 mm. A compressor capable of delivering up to 283 m^3/min air at 241 kPa (1000 SCFM at 35 psi) supplied compressed air for the test facility. FCC particles with a mean diameter and particle density of 76 μm and 1780 kg/m^3 were used.

The multifunctional CFB (MCFB) could be operated as a CFB riser or a CFB downer. For CFB riser operations, particles in the storage tank were fluidized and flowed into the bottom of the riser. They were then carried up through the riser by the riser air. The riser had a gas distributor made of perforated plates (2 mm × 176 holes, 12% opening area). At the top of the riser, particles and gas were separated by primary, secondary, and tertiary cyclones and most of the particles were returned to the downcomer and further down to the solids storage tank. Fine particles leaving from the cyclones were trapped by the bag filter and returned periodically to the downcomer. The gas was then discharged into the atmosphere. When the MCFB was under a downer operating mode, solid particles were first lifted through the riser, separated by the primary cyclone at the top of the downcomer and then fed into the downers. A diverter valve switched the solids flow from the downcomer to the downer side. A second diverter valve directed the particles to the appropriate downer for experiments. At the top of either downer, there was a gas-solids distributor, where the particles were distributed across the downer cross-section. The gas-solids suspension traveled downward to a special designed smooth downer exit. Most particles were fast separated and returned into the solids storage tank. The downer air was further stripped of the entrained fine particles by two cyclones before it finally passed through the bag house. After the

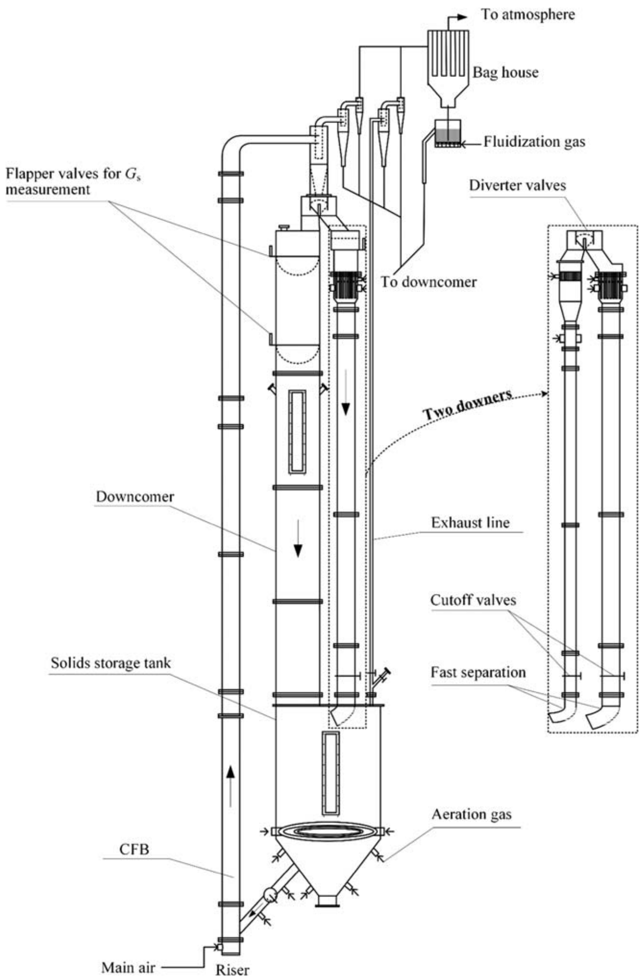

Figure 1. Multifunctional circulation fluidized bed system.

separation process, about 99% particle could be captured and retained in the storage tank.

The solids circulation rate in the downer are not controlled separately but rather by the solids flow rate in the riser. When measuring the solids circulation rate, particles from the primary cyclone flow into a self-designed solids circulation rate measuring column located on the top of the downcomer by the diverter valve switched to the downcomer side. The measurement column are sectioned into two halves with a central vertical plate and two flapper valves fixed at the top and the bottom of the two-half section. By appropriately flipping over the two valves from one side to the other, solids circulated through the system can be accumulated on one side of the measuring section for a given time period to provide the solids circulation rate.

Most of the experimental work in this study was carried out in the 76 mm downer and riser under a wide range of operating conditions. To obtain high flux and high density in the downer, some experiments were conducted in the 50 mm downer. There were ten axial measuring ports ($z = 0.59$, 1.02, 1.94, 2.85, 3.77, 4.78, 5.84, 7.78, 9.61, and 10.09 m above the riser gas distributor) on the 76 mm riser, nine axial measuring ports ($z = 0.22$, 0.61, 1.12, 1.63, 2.13, 2.64, 3.26, 4.02, and 4.99 m) on the 76 mm downer, and seven axial measuring ports ($z = 0.22$, 0.76, 1.27, 1.78, 2.35, 3.26, and 4.18 m) on the 50 mm downer. Measurement were made at six the radial direction ($r/R = 0$, 0.316, 0.548, 0.707, 0.837, and 0.950, where r is the distance from the center and R is the downer radius) at each axial level of the CFB system. These positions other than the central one were determined by dividing the column cross-section into five equal areas and determining the midpoint of each of these areas. A reflective-type optical fiber probe was used to obtain the solids holdup and particle velocity in the bed. Details of this optical fiber probe can be found elsewhere.[43] To study hydrodynamics, the data sampled at a frequency of 100 kHz and 1,638,400 data points were collected per measurement so that a detailed dynamic nature of the flow structure could be fully determined. All measurements were repeated at least five times.

Results and Discussion

Flow development of solids holdup in the downer and riser reactors

Figure 2 compares the axial flow development profiles of the cross-sectional average solids holdup in the downer and the riser. The cross-sectional average solids holdup was obtained by averaging the local solids holdups measured at five radial positions (excluding the center point). In the downer and riser, the average solids holdup decreases with increasing distance from the distributor indicating that the flow structure is developing along the CFB column. The length of the flow development zone was defined as the distance required for the solids holdup to become constant. The operating conditions affected the lengths of the flow development zone in both the riser and the downer. Increasing U_g or decreasing G_s reduced the length of the flow development zone. Taking $U_g = 5$ m/s as an example, at low solids circulation rate ($G_s = 100$ kg/m^{2}s), the distance for achieving constant solids holdup was only 1 m in the downer, while it was 2 m in the riser. Increasing G_s to 300 kg/m^{2}s, the distance extended to 2 m in the downer and the length for the flow development zone in the riser increased to 4 m. Conversely, decreasing U_g at fixed G_s will shorten the length to achieve fully developed status in the downer and the riser. For example, when solids circulation rate is 100 kg/m^{2}s in the downer, the fully developed region is much longer at $U_g = 1$ m/s than that at $U_g = 5$ m/s as clearly shown in Figure 2c.

Comparing with the flow development in the downer and riser, it was found that the flow development in the downer was much faster than in the riser. This was reasonable because of the different acceleration forces in the downer and riser. In downer reactors, the gas-solids suspension flows in the same direction as gravity, so solids will first be accelerated by both drag force from the gas and the gravitational force. In the riser, particles travel against gravity and the only driving force is supplied by gas flow (drag force). Therefore, the particles will move faster in the downer than in the riser.

The axial profiles of the solids holdup have a similar trend in both reactors: near the distributor, the average solids holdup decreases very quickly followed by a gradual decrease further along the column toward the outlet of the reactor. As expected, average solids holdup increase with the increase of solids circulation rate (G_s) and/or the decrease of superficial gas velocity (U_g) in both reactors. Furthermore, changes in the average solids holdup along the column are

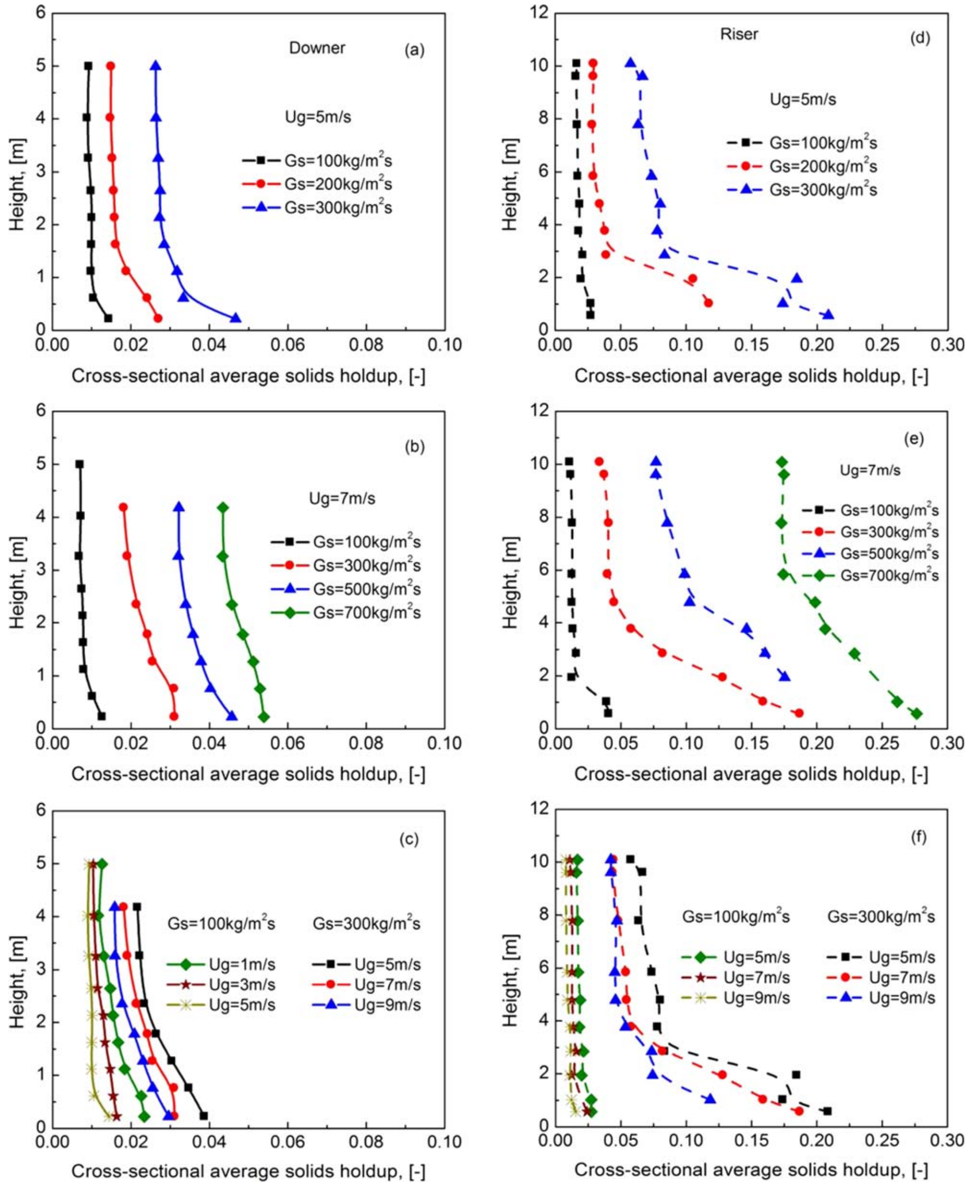

Figure 2. Average axial solids holdup under different operating conditions in the downer and riser.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

more significant with changing of solids circulation rate than that of superficial gas velocity in both reactors. For example, in the downer, the average solids holdup increases from 0.009 to 0.015 (i.e., increases by 62%) when G_s increases from 100 to 200 kg/m^{2}s at fixed superficial gas velocity, $U_g = 5$ m/s. At a constant solids circulation rate ($G_s = 100$ kg/m^{2}s), the average solids holdup decreases only by 26% when U_g increases from 1 to 5 m/s.

To gain a better understanding of the local flow development, Figure 3 shows the profiles of local solids holdup at different axial locations in both riser and downer reactors under different operating conditions. In the downer and the riser reactors, the local solids holdup at all radial positions increases with increasing solids flux.

It is clear that the shapes of the solids holdup in the radial direction in the downer are different from those of the riser. In general, the radial distributions of solids holdup in the downer are more uniform. At the entrance of the downer, solids holdup fluctuates to some extent because of the distributor effects as the flow is not fully established. At a distance of 1.2 m below the downer distributor, a more clear-cut radial profile is formed with solids holdup increasing slightly from the downer centre toward the wall. At low solids circulation rates, the radial distribution of solids holdup is almost uniform in the whole cross-sectional area. With increasing solids circulation rate, the radial nonuniformity becomes higher with higher solids holdup in regions close to the wall compared to the centre. Large differences in the solid holdups between the wall and center were observed at the highest solids circulation rate of 500 kg/m^{2}s. With the flow development further down the column, such nonuniformity in radial distribution is reduced.

Comparing with the downer reactor, the nonuniformity in the riser is far more significant. Even at the lowest solids circulation rate ($G_s = 100$ kg/m^{2}s), there is a definite "core-annular" structure in the radial direction. With increasing solids circulation rate, such "core-annular" profiles of solids holdup change into parabolic in shape with very high density

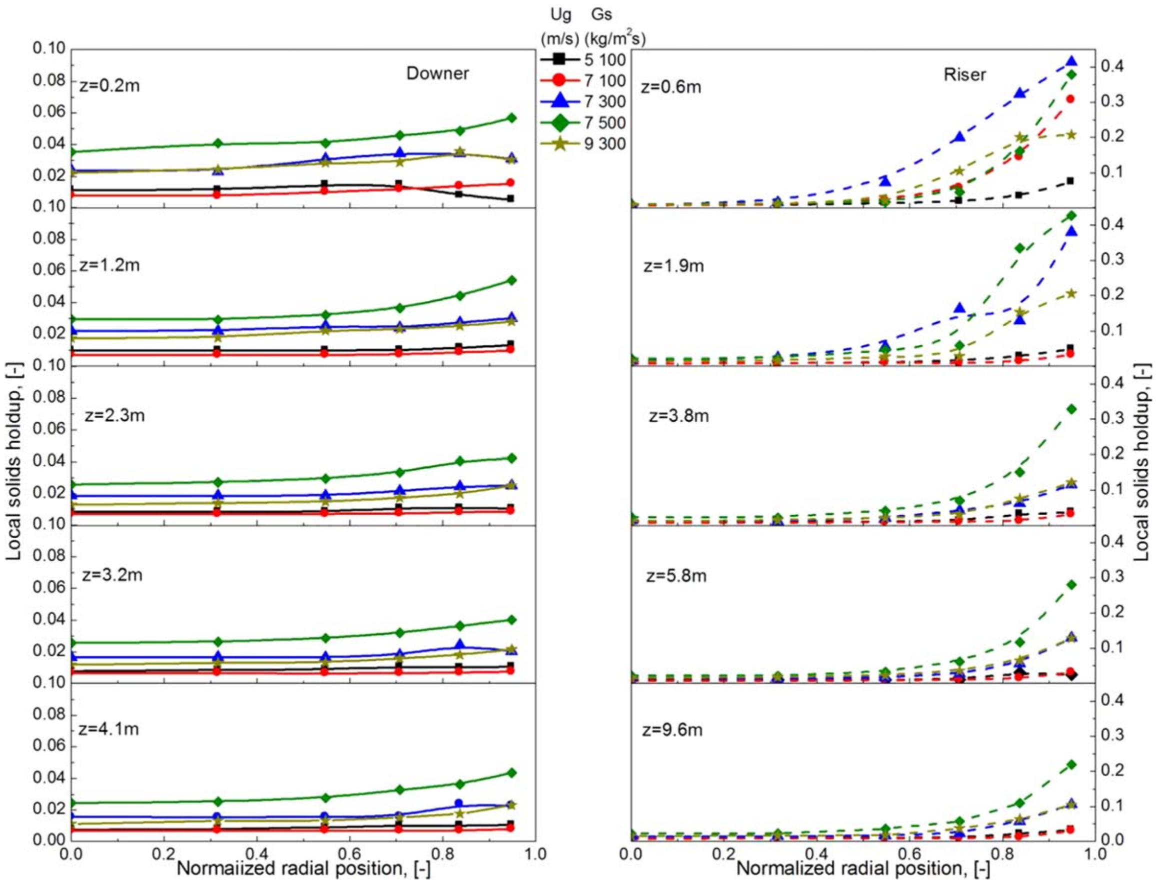

Figure 3. Local solids holdup in different axial positions.

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region near the wall indicating a significant particle aggregation in this region as reported by many investigators. Similar to the downer, the radial solids holdup profile are more uniform in the upper section than in the lower section indicating the flow development from the riser inlet to the outlet.

From the above discussion, the nonuniformity of the local solids holdup exists in both riser and downer reactors. To further investigate the local flow development of solids holdup, it is better to divide the whole cross-sectional area into three parts: the central region taking up 40% of the entire area ($r/R = 0.0$–0.548), the middle region ($r/R = 0.548$–0.837) and the wall region ($r/R = 0.837$–1.0). Figure 4 shows the difference in the flow development of the three radial regions under different operating conditions.

In the downer, taking $U_g = 7$ m/s and $G_s = 200$ kg/m^{2}s as an example, in the central region, the solids holdup is low and becomes nearly constant at the entrance region for about 0.5 m below the distributor. There is no significant difference between the central and the middle region. Obvious variation of the solids holdup happens in the wall region, where the solids holdup decreases gradually with increasing distance until approximately 1.5 m below the downer distributor. Compared to the first two regions, more changes occur in the lower part of the downer column indicating that the flow development of solids holdup in the wall region is slower than that of the first two regions. Conversely, in the riser, solids holdup in the first two regions develops quickly to become constant within 2 m from the riser distributor. The tendency of the flow development in the first two regions is almost the same. However, in the wall region ($r/R = 0.837$–1.0), the solids flow develops more slowly and becomes fully developed at the level of almost 4 m. It can be concluded from Figure 4 that increasing U_g accelerates the flow development, whereas an opposite trend is observed with increasing G_s.

The flow development can also be shown by the radial nonuniformity index (RNI), a parameter used to quantify the radial uniformity of the solids holdup distribution. The RNI of solids holdup, RNI(ε_s), can be defined as[44]

$$\mathrm{RNI}(\varepsilon_s) = \frac{\sigma(\varepsilon_s)}{\sigma(\varepsilon_s)_{\max}} = \frac{\sigma(\varepsilon_s)}{\sqrt{\bar{\varepsilon}_s(\varepsilon_{s,mf} - \bar{\varepsilon}_s)}} \tag{1}$$

where $\sigma(\varepsilon_s)$ is the standard deviation of the radial solids holdup, $\sigma(\varepsilon_s)_{\max}$ is the maximum possible standard deviation, $\bar{\varepsilon}_s$ is the average solids holdup, and $\varepsilon_{s,mf}$ is the highest possible solids holdup. The values of the RNI(ε_s) vary between 0 and 1. If the particles were completely dispersed surrounded by solids-free gas in the column, the RNI(ε_s) value would be 0. Conversely, if there were an "ideal segregated flow" with only gas flow in the core and all solids flow in the annular at $\varepsilon = \varepsilon_{mf}$, the value of RNI($\varepsilon_s$) would be 1.

Figure 5 shows the RNI(ε_s) in the downer and the riser under the same operating conditions. In the downer, the RNI(ε_s) value varies between about 0.01–0.07 indicating that the solids flow in the downer is nearly uniform under such operating conditions. For each operating conditions, there is a clear development along the column, with RNI(ε_s) tending to decrease with increasing the distance below the downer distributor. Meanwhile, the RNI(ε_s) is

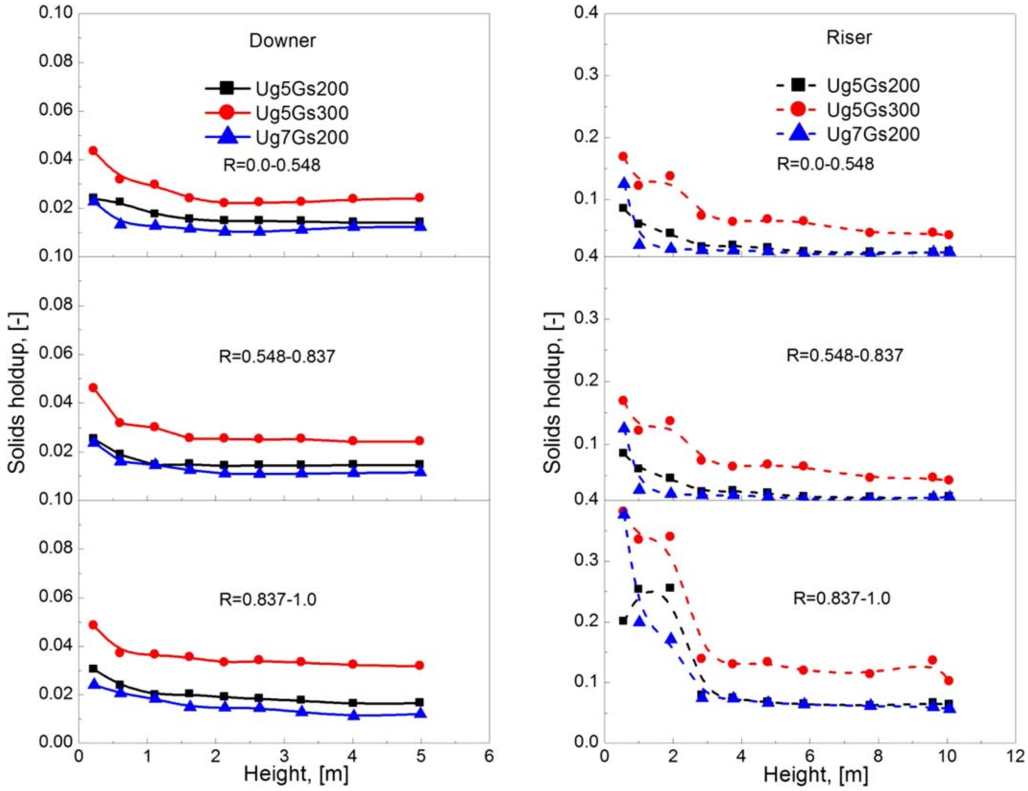

Figure 4. Flow development of the local solids holdup in the downer and riser reactors.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

much higher at higher solids circulation rate and/or lower superficial gas velocity, indicating that the flow nonuniformity becomes more significant at high G_s and/or lowô U_g. For the comparable operating conditions, in the riser, the RNI(ε_s) value differs between about 0.1–0.7 which is ten times higher than in the downer.

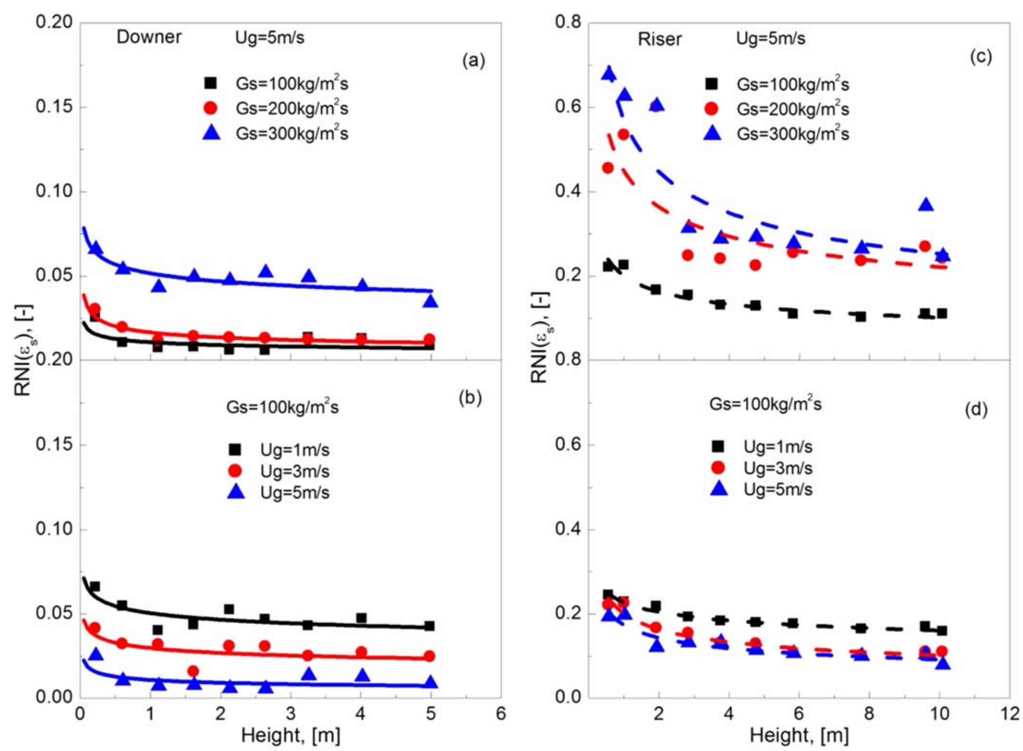

Figure 5. Radial nonuniformity index (RNI) of solids holdup under different operating conditions in the downer and riser.

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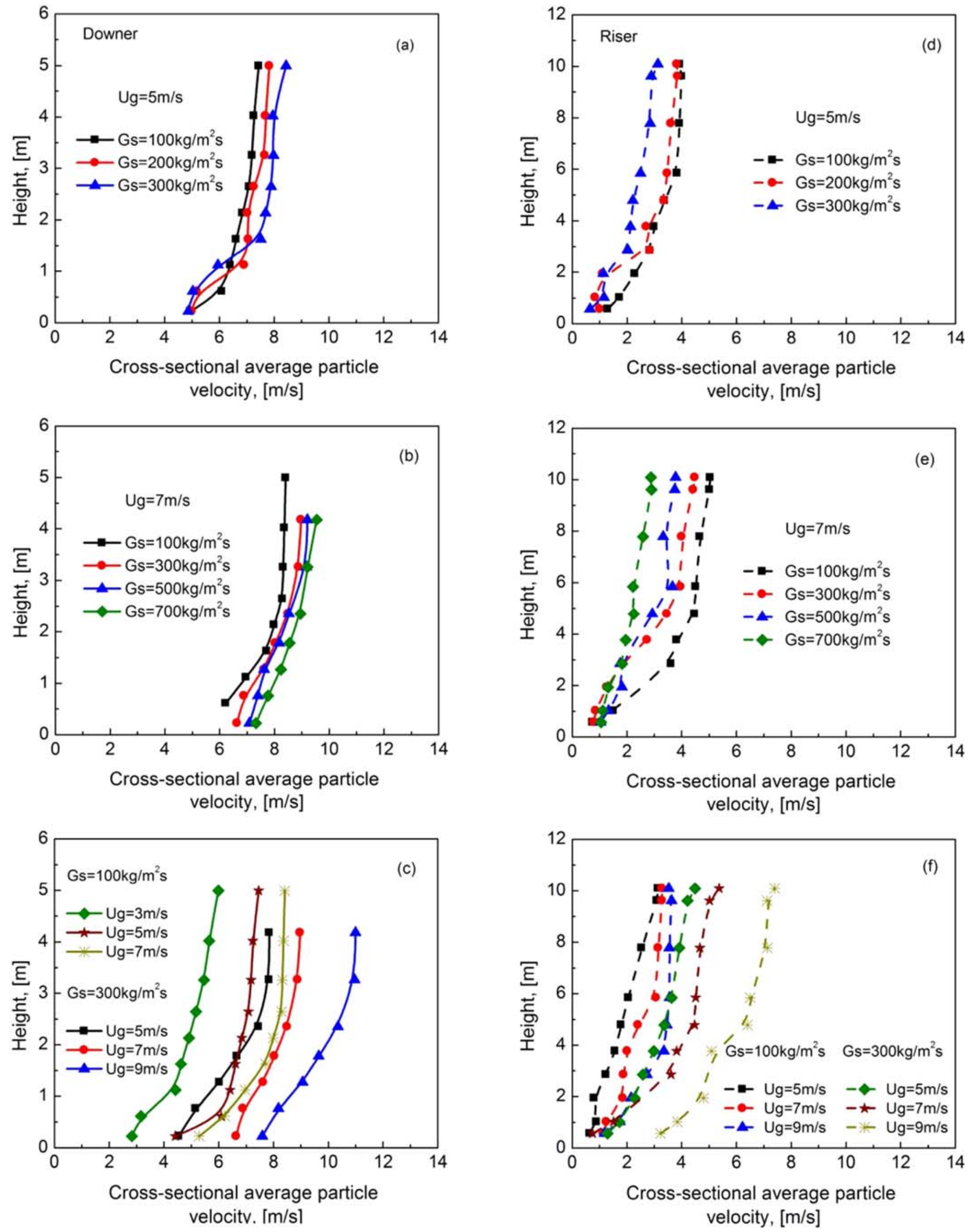

Figure 6. Average particle velocity under different operating conditions in the downer and riser.

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Flow development of particle velocity

Particle velocity is considered as one of the key parameters which can be used to characterize a gas-solids system. In a gas-solids system, superficial gas velocity (U_g) and solids circulation rate (G_s) are the main variables influencing the particle velocity. Figure 6 shows the axial profiles of particle velocity with U_g ranging from 3 to 9 m/s and G_sô varying from 100 up to 700 kg/m^{2}s.

As shown in Figure 6a, in the downer, the cross-sectional average particle velocity increases rapidly near the column entrance (1–2 m below the downer distributor), and then increase at a slower acceleration rate as it reach as a constant value near the outlet of the downer. As reported by many other researchers,[4,9,14–17] solids are accelerated at a very high rate due to the large initial difference in velocity between the gas and the particle. When the particle velocity is higher than the gas velocity, particles will be accelerated by gravity and decelerated by the gas drag so that the acceleration rate slows down and finally the particle velocity approaches a constant further down in the downer column. In addition, operating conditions greatly affect the particle velocity in the downer. At a fixed superficial gas velocity, an increase in solids circulation rate will slow down the flow development of the particle velocity. For example, when G_s is 700 kg/m^{2}s the particle velocity profile increases monotonically over the entire length of the downer as shown in Figure 6b. For a constant G_s, the acceleration of particle velocity is extended beyond the whole downer column at the lowest superficial gas velocity ($U_g = 3$ m/s). With an

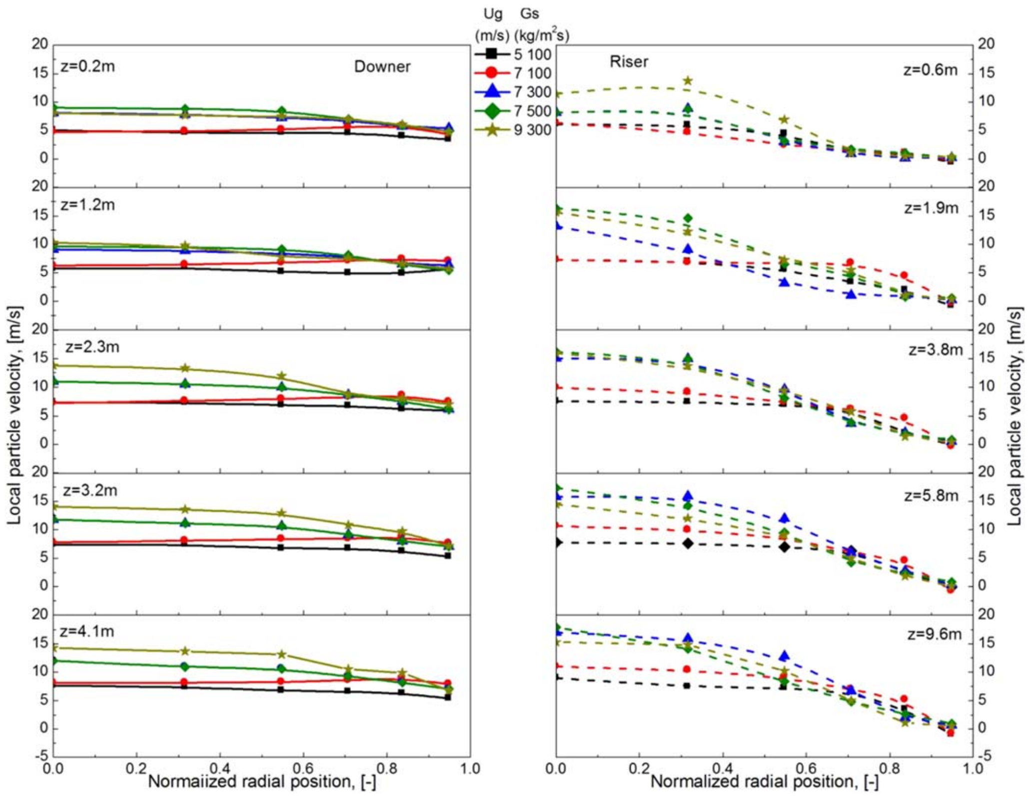

Figure 7. Local particle velocity in different axial positions.

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increase in superficial gas velocity, the particle velocity increases at each axial position and the flow development becomes faster as shown in Figure 6c. Compared to the downer reactor, particle velocity in the riser has a similar trend with an acceleration section in the riser bottom followed by a relatively flat velocity profile toward the riser outlet as plotted in Figures 6d–f. Particle velocity increases with increasing superficial gas velocity in the entire reactor as shown in Figure 6f. However, significant difference in particle velocity between the riser and the downer is that the particle velocity in the riser is always smaller than that in the downer under the comparable operating conditions as shown in Figures 6a–e. In other words, particles in the riser, where gas-solids flow against gravity, are accelerated only by the gas drag and the velocity is always smaller than the gas velocity. In the downer, the velocity of the particles, which move in the direction of gravity, is smaller than gas velocity at the entrance and then exceeds the superficial gas velocity. In addition, particle velocity in both riser and downer reactors is more sensitive to the changes of superficial gas velocity than solids circulation rate.

To investigate the details of the particle velocity development in both reactors, Figure 7 shows the local particle velocity along the bed axial heights with superficial gas velocity ranging from 5 to 9 m/s and solids circulation rate varies between 100 and 500 kg/m^{2}s.

In the downer, particle velocity is relatively higher in a wide central region and decreases gradually toward the bed wall. In the riser, a highly non-uniform radial distribution of particle velocity is observed. Particle velocity is very high in the central region and begins to decrease significantly not far from the riser center. The operating conditions clearly affect the profiles of particle velocity as shown in Figure 7. With increasing superficial gas velocity under the same solids circulating rate, particle velocity increases at each radial position in the downer and riser reactors. However, the effects of G_s on the particle velocity in the downer are different from that in the riser. In the downer, particle velocity always increases with increasing of the G_s at all radial positions, while in the riser, particle velocity increases in the center and decreases in the near wall region with the increase of the G_s.

Figure 8 shows the development of local particle velocity in the three radial regions defined above for different operating conditions. Generally, the particle velocity distribution in the three radial regions in the downer shows no significant difference indicating a uniform local particle velocity distribution across the downer. Particle velocity increases faster in the entrance region due to the more rapid particle acceleration. Further down along the column, particle velocity is almost unchanged showing a fully developed flow. In the riser, however, the flow structure in these three radial positions is very different. Particle velocity in the central region is higher than that in the middle region and the wall region. The reason could be that more solids occupy the wall region and restrict the gas flow in this region resulting a "core-annular" structure in the riser. To retain a certain superficial gas velocity across the column, the gas velocity has to be significantly higher in central region,[38] leading to higher particle velocity, as have also been observed by Pärssinen and Zhu.[45]

Based on the above discussion, flow structure in both downer and riser reactors is significantly different and is affected by the operating conditions. From Figures 3a–e and 6a–e, it is seen that the two main operating parameters, that is, superficial gas velocity and solids circulation rate have different influences on the solids holdup and particle

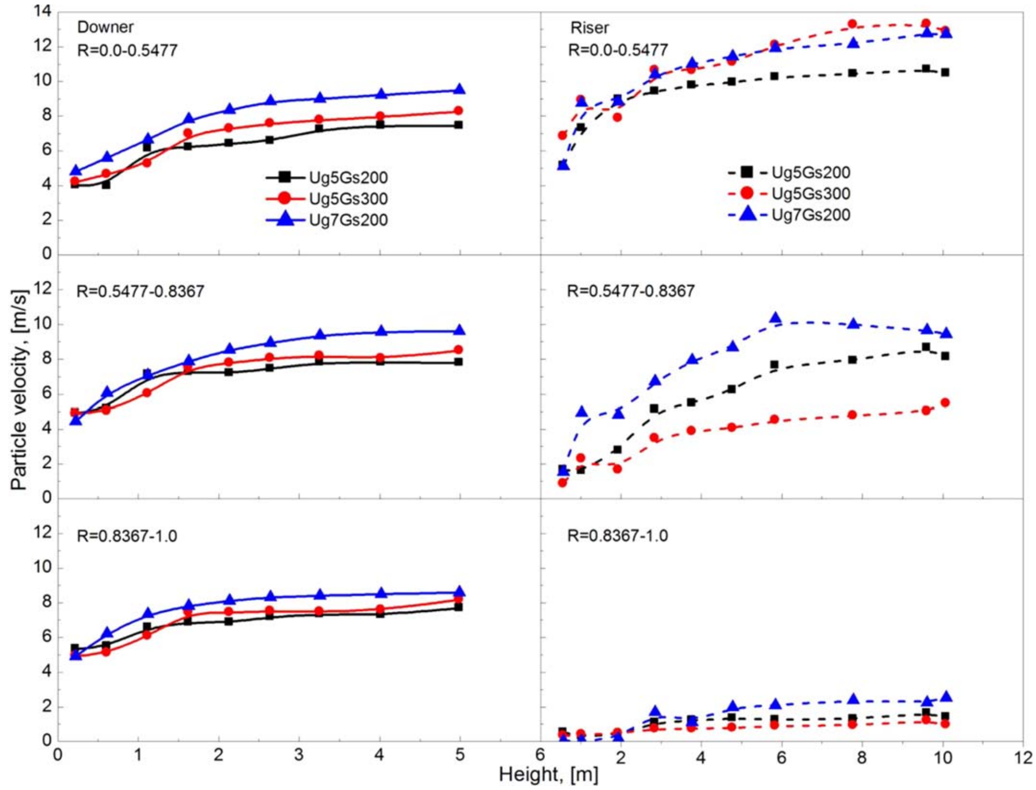

Figure 8. Flow development of local particle velocity in the downer and riser.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

velocity. Figures 9a–d show the effects of superficial gas velocity and the solids circulation rate on the overall average solids holdup in both downer and riser reactors.

As shown in Figures 9a–d, the overall solids holdup in both downer and riser reactors decreases with increasing superficial gas velocity or decreasing solids circulation rate. In the downer, a linear relationship is observed between solids holdup and superficial gas velocity and the slope is almost unchanged at high solids fluxes as shown in Figure 9a. The mean solids holdup in the entire reactor (the overall average solids holdup) is greater than 0.05 when G_s is 700 kg/m^{2}s, which is higher than found in previous studies[9,13–17] (usually smaller than 0.01 in most downers) in the downer. In the riser, as shown in Figure 9c, the solids holdup decreases gradually with increasing superficial gas velocity when solids circulation rate is lower than 300 kg/m^{2}s. For high solids circulation rate (>300 kg/m^{2}s), solids holdup decreases significantly with the increase in U_g. For the highest G_s of 700 kg/m^{2}s, the solids holdup was higher than 0.15 indicating an entirely high density riser. In addition, comparing Figures 9a, b in the downer or Figures 9c, d in the riser, solids holdup has different sensitivities to the operating conditions. In other words, the slope of the linear relationship between solids holdup and the superficial gas velocity is much smaller than that related to the solids circulation rate. This clearly verifies that the effect of superficial gas velocity on solids holdup is less significant than that of solids circulation rate as the analysis based on Figures 3a–e also showed.

One dimensional slip velocity of the downer and riser reactors

As mentioned in the introduction, solids aggregation in a traditional CFB riser can be avoided by operating the concurrent downflow CFB mode. In that case, the contact efficiency of the gas-solids flow can be enhanced. The one dimensional slip velocity can provide some understanding of cluster formation in fluidized bed reactors.[46,47] The slip velocity is calculated from macroscopic continuity equations, which relate gas flux G_g, solids flux, G_s, gas density ρ_g, particle density ρ_p, and solids holdup ε_s, in the suspension flow:for downer reactor

$$U_{slip} = V_p - V_g = \frac{G_s}{\rho_p \varepsilon_s} - \frac{U_g}{1-\varepsilon_s} \tag{2}$$

for riser reactor

$$U_{slip} = V_g - V_p = \frac{U_g}{1-\varepsilon_s} - \frac{G_s}{\rho_p \varepsilon_s} \tag{3}$$

Figure 10 represents the variation of slip velocity against the average solids holdup in both downer and riser. Apparently, slip velocity increases with increasing solids holdup. High solids holdup enhances the clustering phenomenon and decreases the gas drag force between the gas and clusters leading to the increase of the slip velocity. Besides, it is also seen that the relationship between the slip velocity and the superficial gas velocity is nearly linear and the slopes of the corresponding lines are almost the same at different solids circulation rates in the riser.

An increase of superficial gas velocity at fixed solids holdup leads to a decrease of slip velocity in the downer. It is also seen that there was a negative slip velocity for the downer at high superficial gas velocities. At a certain solids holdup in the downer, gas flows faster at high superficial gas velocity resulting in higher actual gas velocity. Therefore, the difference between the gas velocity and the particle velocity will become small leading to the decrease in slip

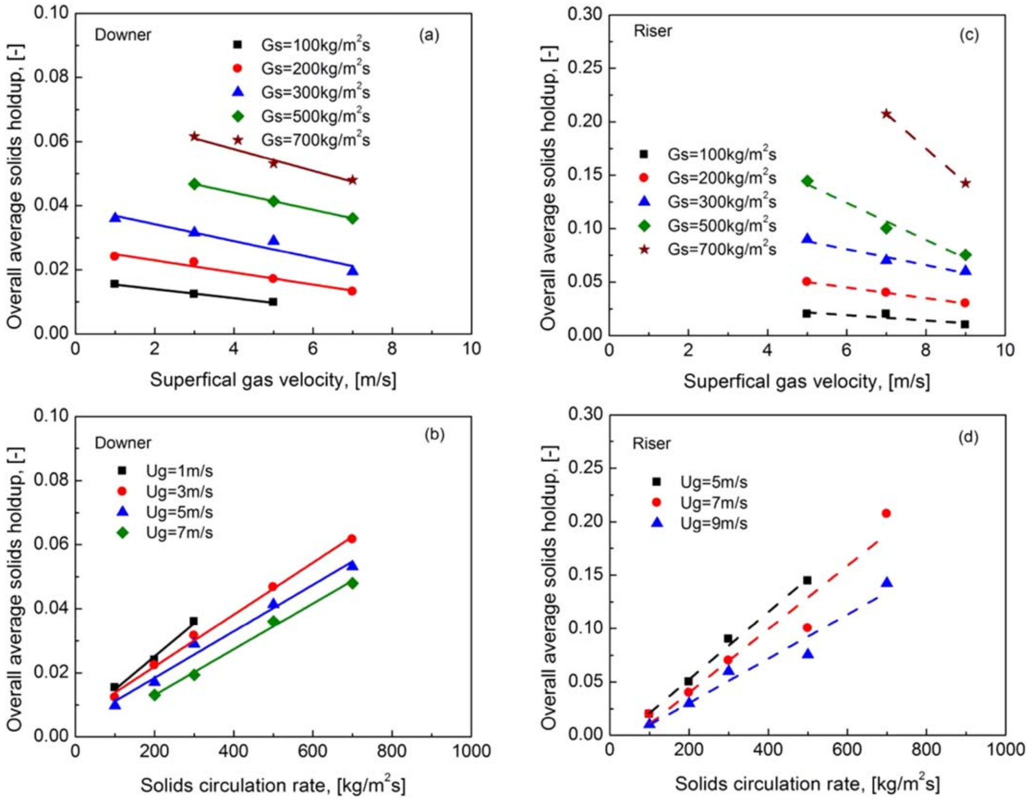

Figure 9. Effect of operating conditions on the solids holdup in the downer and riser.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

velocity or even giving a negative slip velocity. Other studies[20,48–50] have also found that the slip velocity decreased with increasing superficial gas velocity in the downer. In the riser, conversely, the slip velocity is 2–8 m/s which is comparable to the data ranging from 2 to 10 m/s reported by Issangya et al.[51] and Yan et al.[52] The slip velocity in the riser is much higher than that in the downer indicating that solids aggregation in the riser is more significant compared to the downer. Due to the concurrent down-flow in direction of gravity in the downer, particles with high velocity may cause the gas velocity to increase around them resulting in intensive turbulence between the gas and the solids. The high gas-solids turbulence would lead to high intensity interactions between the phases. The cluster could not exist stably in the downer because of the strong interaction between gas and solid phases. While in the riser particle aggregate into the cluster so that the gas drag is diminished by the shielding effect of the external particles,[53] and the particle velocity decreases or becomes negative. Therefore, a cluster can be stable in the riser. Similar results were reported by Wei et al.[9] But such high slip velocity may also simply be due to the more significant lateral segregation in the riser discussed in Sections Flow development of solids holdup in the downer and riser reactors and Flow development of particle velocity. Finally, it is noted that the slip velocity in the riser increases with the increase of superficial gas velocity different when compared to the downer.

Potentials of the high density downer reactor in chemical reaction engineering

The above results and discussions indicate that there is a significant difference in flow behavior in the high density downer and riser reactors. First, solids acceleration is much faster due to the aid of gravitational force in the downer so that the length to achieve fully developed status is much shorter under similar operating conditions than that in the riser. Second, the axial distribution of solids holdup and particle velocity is much more uniform in the downer compared to the riser, especially under high density conditions, indicating a reduced axial backmixing in downer reactors.[4,9] Third, the radial distribution of solids holdup in the suspension in the downer is much more uniform than that in the riser. Although the radial profiles of solids holdup and particle velocity in the downer become less uniform at high density conditions than that at low ones, it is still more favorable than that in the high density riser. For a gas phase catalytic reaction in the CFB reactors, short length of the flow development is beneficial to the reaction as axial solids dispersion and radial nonuniformity are much greater in the developing section, which would lead to undesirable gas and solids flow patterns and nonuniform gas solids suspension residence time. This undesirable flow behavior in the developing section can reduce the main product yields such as gasoline and diesel due to over-cracking and coking in the FCC process. Therefore, a downer reactor would be beneficial in such a process due to its faster acceleration and reduced flow development length, where very short residence time is essential.

For high density conditions, higher local solids concentration results in the reduction in the drag coefficient.[44] In the riser, the reduction of drag decreases the upward particle velocity, which in turn, increases the tendency for particle aggregation. Increased particle aggregation would further reduce the drag and the local particle velocity, leading to less uniform radial profile of solids holdup and particle

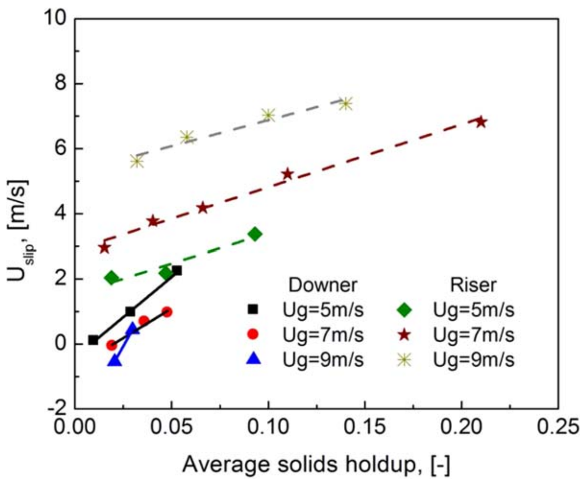

Figure 10. Variations of one dimensional slip velocity with the average solids holdup.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

velocity.[54] However, in the downer, a reduced gas drag will result in increased downward particle velocity leading to the increase in gas velocity. The increased local gas and solids velocity tend to reduce the extent of particle aggregation, thus increasing the gas drag. Therefore, the system stabilizes by itself and a more uniform radial flow structure is obtained in the high density downer. In this case, the more uniform redial distribution in high density downer reactors would ensure better gas and solids lateral mixing, which is essential for good gas-solids contacting and therefore for high productivity and selectivity.

It can be concluded that the uniform flow both axially and radially in the high density downer will benefit the conversion and selectivity of chemical reactions like the FCC of oil. A high density downer can provide excellent heat and mass transfer, which is very useful for the applications requiring high gas/solids feeding ratios and relatively short reaction time such as heavy oil catalytic cracking and light olefins catalytic cracking processes.

Conclusions

The flow behavior in the upflow and downflow CFBs is investigated at various superficial gas velocities with very high solids circulation rate of 700 kg/m^{2}s.

Solids holdup and particle velocity profiles are much more uniform in the downer compared to the riser. Solids acceleration is much faster in the downer reactor leading to a shorter length of flow development, which is beneficial to the chemical reactions requiring short contact time and high product selectivity.

Local solids holdup and particle velocity are also more uniform in the downer than in the riser under similar operating conditions. Although the local flow behavior becomes less uniform under high density conditions in both riser and downer reactors, the uniformity in the downer is still greater than in the riser due to the self-stabilizing mechanics in the downer.

One dimensional slip velocity in both the riser and the downer increases with increasing solids holdup. The slip velocity in the downer is much smaller than that in the riser for the same solids holdup indicating less particle aggregation and better gas-solids contacting in the downer reactors.

Due to better axial and radial flow behavior in the downer reactor, especially at high solid flux conditions, downer reactors are likely to find applications in the near future.

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