Lateral Flux and Velocity of FCC Particles in a CFB Riser

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The radial profiles of the lateral solids mass flux and the lateral solids velocity were determined for FCC particles in a 7 m tall circulating fluidized bed riser 0.14 m in diameter by applying a lateral flux probe and electrical capacitance tomography. The external solids mass flux was varied between 148 and 302 kg/(m^2·s), while the superficial gas velocity was varied between 3.7 and 4.7 m/s. Under these conditions, a dense bottom region and an upper dilute region coexisted in the riser. Lateral fluxes in the dense bottom region reached 100 kg/(m^2·s) at the wall, but fell to 14 kg/(m^2·s) at the wall in the upper dilute region. At both axial locations, a net deposition of solids from the core to the annulus occurred, indicating that fully developed flow was never established under these conditions. The lateral fluxes in the bottom region were significantly larger than those found in previous studies. It was further concluded that considering the lateral solids flux to be only a function of solids concentration is an over-simplification.

Les profils radiaux du flux massique de solides latéral et de la vitesse de solides latérale ont été déterminés pour des particules de FCC dans une colonne à lit fluidisé circulant de 7 m de hauteur et de 0,14 m de diamètre, en appliquant une sonde de flux latérale et la tomographie par capacitance électrique. On a fait varier d'une part le flux massique de solides externe entre 148 et 302 kg/(m^2·s) et d'autre part la vitesse de gaz superficielle entre 3,7 et 4,7 m/s. Dans ces conditions, une région inférieure dense et une région supérieure diluée coexistent dans la colonne. Les flux latéraux dans la région inférieure dense atteignent 100 kg/(m^2·s) à la paroi, mais tombent à 14 kg/(m^2·s) à la paroi dans la région supérieure diluée. Aux deux régions axiales, une déposition nette de solides se produit du coeur vers l'espace annulaire, indiquant qu'un écoulement pleinement développé n'a jamais été établi dans ces conditions. Les flux latéraux sont nettement plus importants que ceux trouvés dans les études antérieures. Il a en outre été conclu que le fait de considérer le flux de solides latéral uniquement comme étant fonction de la concentration de solides constituait une sur-simplification.

Keywords: circulating fluidized beds, lateral flux, high-density riser.

Circulating fluidized beds (CFBs) are generally operated in the fast fluidization regime. This regime is characterized by a dense-phase region in the lower part of the CFB riser coexisting with a dilute region in the upper portion of the riser (Li and Kwauk, 1980; Bi et al., 1993). Further, it is known that a dilute core region exists in the central portion of a circulating fluidized bed riser surrounded by a thin, relatively denser annular layer of solids at the wall. This core-annulus flow structure has been quantified by radial profiles of solids concentration, axial solids mass flux and axial solids velocity in numerous studies (Monceaux et al., 1986; Weinstein et al., 1986; Rhodes et al., 1988; Hartge et al., 1988). Depending on the applied solids mass flux and superficial gas velocity, solids in the annular layer can flow either upward or downward (Issangya et al., 1998; Karri and Knowlton, 1999).

While the axial components of the main flow parameters, i.e. the axial solids velocity and the axial solids mass flux, have gained a lot of research interest, very little research has been directed toward the radial components of solids mass flux and solids velocity. The lateral solids movement is important as it can quantify the solids mixing in a CFB riser. The degree of solids mixing influences the temperature control and the heat transfer from the suspension to heat exchange surfaces. Moreover, the solids residence time distribution is strongly affected by the lateral particle exchange between core and annulus.

Despite these important aspects of lateral particle flux, the first experimental work was not published until 1993 (Qi and Farag, 1993). Qi and Farag (1993) recorded their measurements at an external solids mass flux of 21.3 kg/m^2·s and a superficial gas velocity of 3.9 m/s using glass beads as solids. Their CFB riser consisted of a 0.089-m inner diameter and 3 m high primary combustion zone and a 0.14-m inner diameter secondary combustion zone of 3.4-m height. The authors took their measurements at an axial location 1.85 m above the secondary air intake, corresponding to an overall height of 4.85 m. Despite the fact that no profile of the apparent axial solids concentration was given it might be assumed that under the given operating conditions, the measurement height was within a region of dilute gas–solid flow (i.e. upper dilute region). The flux of solids moving from the wall to the centre was measured by the authors using a probe oriented 45° to the vertical and with a vertical opening in the end inserted into the riser. They observed a nearly

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constant lateral particle flux for inner radial locations ($r/R < 0.4$). Beyond this radial range a strong increase of the lateral flux with increasing radial position occurred. Close to the wall a lateral flux of 45.9 $kg/m^2 \cdot s$ was measured, which was roughly twice as high as the external solids recirculation rate. The maximum of the lateral solids mass flux appears at their largest dimensionless radial location, $r/R = 0.97$. In a later work, Qi and Farag (1995) stated that the lateral particle flux is strongly dependent on the particle concentration.

Zhou et al. (1995) investigated the particle cross-flow using a sampling probe similar to that of Qi and Farag (1993). They measured the lateral flow of sand particles with a mean diameter of 213 μm at different axial and radial locations in a CFB riser of square cross-section (146 mm x 146 mm) and 9.1 m height. Net riser solids mass fluxes of 40 and 60 $kg/(m^2 \cdot s)$ and riser superficial gas velocities of 5.5 and 7.0 m/s were adjusted. They found that even in the dense bottom region of the riser where the lateral fluxes were the highest, both the inward and outward lateral solids mass fluxes close to the wall were much lower than the external solids mass flux (the largest lateral flux recorded was 21 $kg/(m^2 \cdot s)$, compared to 40 $kg/(m^2 \cdot s)$ for the external solids mass flux). This contradicted the observations of Qi and Farag (1993) and Zhou et al. (1995) suggested that a leak in the sampling probe applied by Qi and Farag (1993) was responsible for the high lateral solids fluxes they measured. While Qi and Farag (1993) solely determined the lateral inward flux, from the wall to the centre, Zhou et al. (1995) also measured the outward lateral flux. Qualitatively, they observed the same shape of the radial profile of the lateral solids mass flux in both directions. As in the work of Qi and Farag (1993) for the lateral inward flux, the lateral flux in each direction increased continuously until the maximum was reached directly at the wall. For the net solids cross-flow flux, however, Zhou et al. (1995) recorded an increase of the flux to a maximum near the core-annulus boundary, before the flux decreased again. In the lower part of the riser, a net solids cross-flow outwards from axis to the wall was observed, while in the upper portion the net flow was inwards. Consistent with the statement of Qi and Farag (1995), Zhou et al. (1995) observed an increase of the lateral flux with increasing solids concentration. Zhou et al. (1995) further provided profiles of the lateral particle velocity by dividing the lateral solids momentum flux by the lateral solids mass flux. The authors observed an increase with height near the bottom of the column and then a decrease with height near the top. Absolute lateral solids velocities ranged up to a value of about 3 m/s.

Jiang and Fan (1999) studied the lateral solids motion of FCC particles in a 0.102 m diameter riser 6.3 m in height for a range of solids mass fluxes from 5 to 30 $kg/(m^2 \cdot s)$ and gas velocities from 1.7 to 3.0 m/s. They focused on the upper dilute region of the riser and also measured the lateral flux in both directions, inward and outward. The authors claimed that the lateral flux in both directions increased with radial location to a maximum between dimensionless radial locations of roughly 0.8 and 0.9, and then decreased. This contradicted the continuous increase of inward and outward solids mass flux claimed by Qi and Farag (1993) and Zhou et al. (1995).

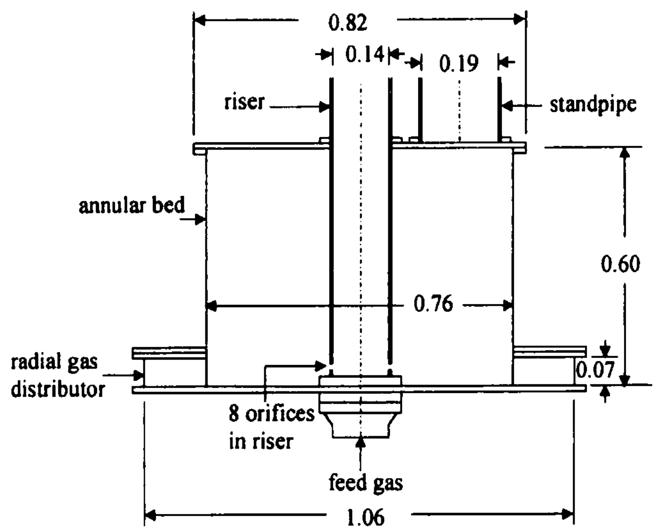

Figure 1. Detail drawing of the annular bed solids feeder.

The results on lateral solids mass fluxes in CFB risers reported to date do not provide a consistent or complete picture of its behaviour. There is a clear need to perform more research on the lateral solids mass flux and its dependency on operating conditions and riser geometry. The knowledge about the influence of the external solids mass flux on the lateral flow is still rather limited, as investigations have only been performed to a maximum solids mass flux of 60 $kg/(m^2 \cdot s)$. In the current study, we perform measurements up to an external solids mass flux of 302 $kg/(m^2 \cdot s)$ while varying the superficial gas velocity between 3.7 and 4.7 m/s. The solid material is FCC catalyst. Under these conditions, a very dense bed is formed at the base of the riser, which gives way to a dilute zone near the exit. Lateral fluxes and radial solids concentration profiles have been measured in both regions. Although Jiang and Fan (1999) provided the lateral solids mass flux and the solids concentration profile, they did not combine these profiles to supply the lateral solids velocity profile. In the present work we will introduce radial profiles of the lateral solids velocity based on the lateral solids mass flux and radial solids concentration profile measurements.

Experimental

Circulating Fluidized Bed Apparatus

The lateral solids flux measurements were carried out in a laboratory-scale CFB consisting of a 0.14-m inside diameter riser with a smooth elbow exit to the cyclone and a 0.19-m standpipe. The overall height of the unit is 7 m. The riser is designed with a scaled-up version of the annular bed solids feeder described by Pugsley et al. (1996). A detail drawing of the annular bed is given in Figure 1. Aeration air is introduced radially into the annular bed of solids that surrounds the bottom of the riser, pushing the solids inwards towards the riser. Eight equally spaced orifices of 1.5-cm diameter drilled into the riser at a height of 0.05 m allow the solids to re-enter the riser. The standpipe is uniformly aerated in order to realize a larger

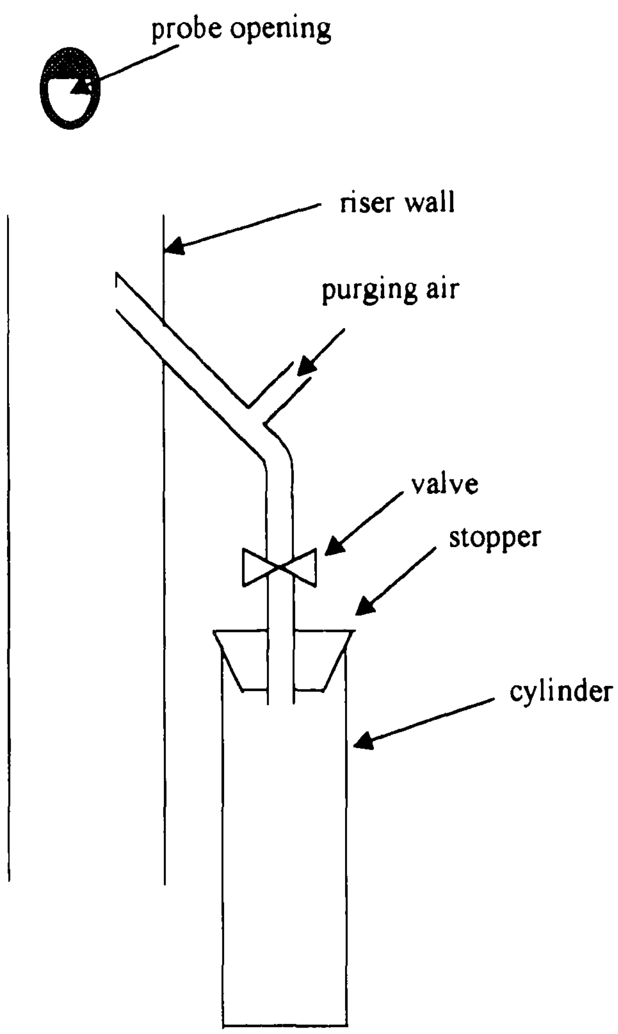

Figure 2. Schematic of the lateral solids mass flux probe.

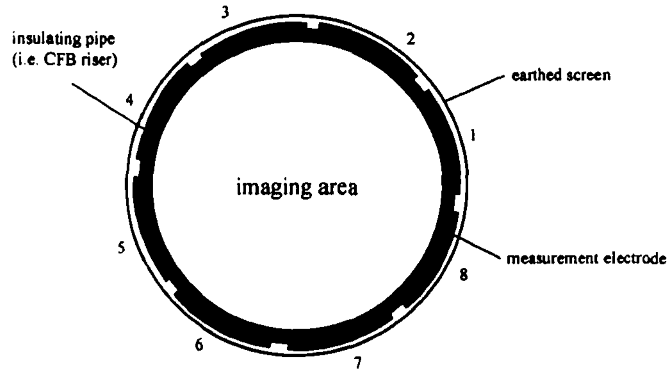

Figure 3. Schematic of the Electrical Capacitance Tomography sensors mounted on the outer wall of the CFB riser.

pressure gain in the return system and hence higher solids mass fluxes. The FCC catalyst used in the study has a Sauter mean diameter of 89 microns and particle density of 1740 kg/m^3. Air was used as the fluidizing gas. The riser is equipped with sixteen differential pressure transducers to measure the axial pressure gradient. Pressure taps are installed at a 45° angle and are fitted with a small piece of stainless steel mesh to prevent clogging of the taps by fine particles. The lateral flux probe and ECT system (see descriptions below) have been applied at two different axial locations. The first measurements were taken at a height of 1.55 m, which is in the lower dense region of the riser for most operating conditions, while the second axial location was at 5.90 m, which is in the upper dilute region of the CFB riser.

Lateral Solids Flux Probe

The design of the lateral solids flux probe is essentially identical to that of Zhou et al. (1995) and is schematically shown in Figure 2. A 6.35-mm i.d. stainless steel tube is introduced into the riser at an angle of 45°. The end of the tube is cut vertically so that the opening faces the lateral flow of solids. A small obstruction at the top of the opening prevents solids that enter the tube from bouncing back out. This obstruction leads to an open area of 28.3 mm^2. The probe is traversed from one side of the riser to the other. Thus, we measure the outward lateral flux between the entry port and the riser centreline and the inward flux between the centreline and the opposite wall. The effect of the slight variation in axial location due to its angle as the probe is traversed is assumed to have a negligible impact on the measurements. Purge air is supplied to the probe to maintain it free of solids prior to the actual measurement.

Electrical Capacitance Tomography System

Radial solids concentration profiles were measured with an Electrical Capacitance Tomography (ECT) system. A schematic of our ECT is provided in Figure 3. ECT is a non-intrusive measurement technique in which equally spaced capacitance electrodes are wrapped around the outer circumference of a vessel. The particular system used in this study consists of eight such electrodes, each having a length of 0.40 m. At any instant in time, one electrode discharges to the remaining seven electrodes. Then, through computer control, the next electrode discharges, and so on until capacitance measurements have been taken between all unique combinations of electrodes. Through an on-line reconstruction technique, the capacitance measurements are used to calculate the solids concentrations between electrodes. Hence a tomographic image of the solids distribution over the riser cross-section is generated. The ECT system is very fast; images of the cross-section are generated at a rate of one hundred per second. More details on the ECT system, its operation and the reconstruction technique can be found in the work of Malcus et al. (2000).

Results and Discussion

Lateral Solids Mass Flux

Dense Bottom Region

Figure 4 shows the apparent axial solids concentration profiles based on the axial pressure gradient under different external solids mass fluxes at a fixed superficial gas velocity of 4.7 m/s.

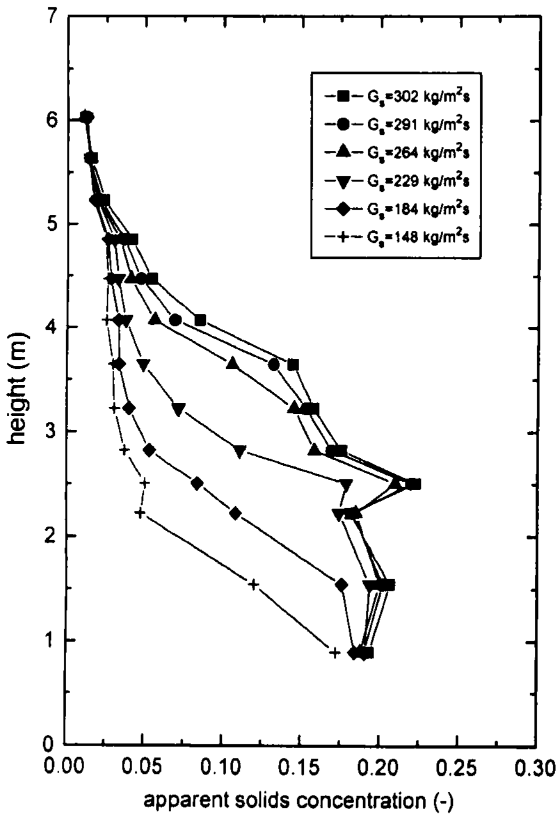

Figure 4. Axial profiles of the apparent solids concentration at a superficial gas velocity of 4.7m/s.

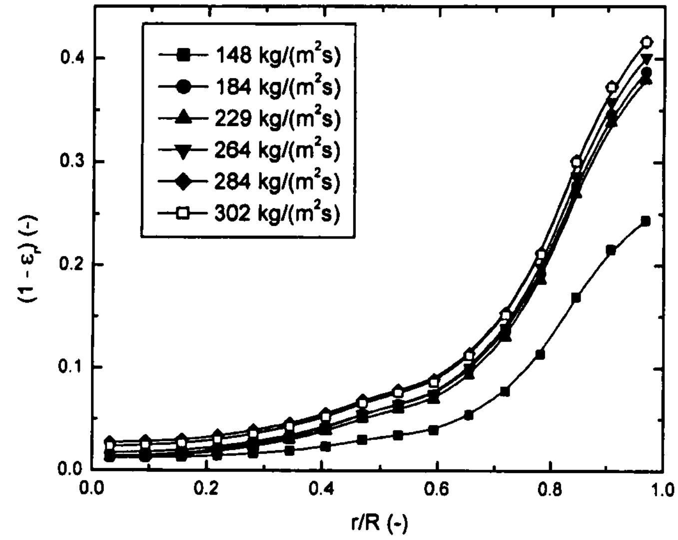

Figure 5. Radial profiles of solids concentration at a riser height of 1.55 m (dense region) and a superficial gas velocity of 4.7 m/s.

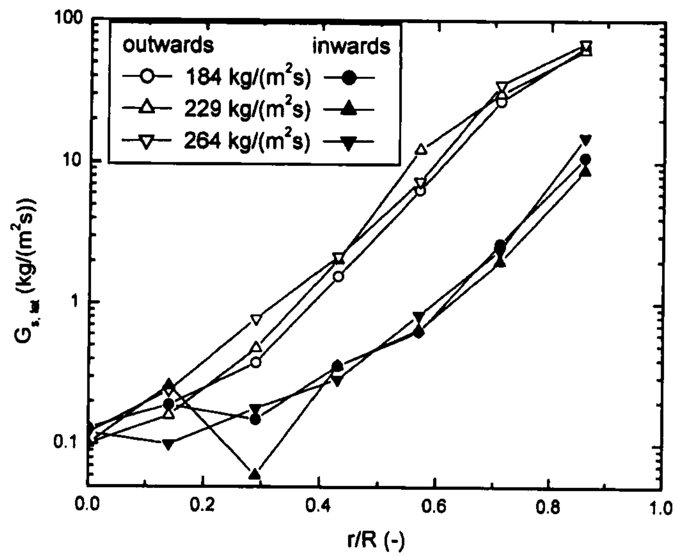

Figure 6. Lateral solids mass fluxes in the outward and inward directions at a riser height of 1.55 m (dense region) and a superficial gas velocity of 4.7 m/s.

It can be seen that, depending on the adjusted operating conditions, either an exponential profile or a profile with a dense bottom zone and an upper dilute region exists. Figure 4 indicates that the cross-sectionally averaged solids concentration in the dense region is independent of the adjusted external solids mass flux at a fixed superficial gas velocity.

Figure 5 provides radial profiles of solids concentration in the CFB riser at an axial location of 1.55 m, a superficial gas velocity of 4.7 m/s and solids mass fluxes varying between 148 and 302 kg/(m^2·s). Figure 5 illustrates that for the conditions in which the dense bottom bed of constant average solids concentration appeared in Figure 4, the radial solids concentration profiles essentially overlap. A lean core phase can be observed that is surrounded by an annular region of higher solids concentration. Figure 6 presents radial profiles of the outward and the inward lateral solids mass flux for three intermediate external solids mass fluxes. As was the case for the solids concentration, when a dense bottom zone is established, the radial profile of the lateral solids mass flux barely varies with a change in the external solids mass flux. At the centreline, lateral solids mass fluxes of about 0.1 kg/(m^2·s) occur. The lateral outward flux increases approximately exponentially with radial location. The lateral inward flux remains nearly constant for dimensionless radial locations below 0.3, before an exponential increase of the flux with radial location takes place. The outward flux reaches values of about 60 to 70 kg/(m^2·s) at a dimensionless radial location of 0.86, while the inward flux reaches values of only 15 kg/(m^2·s). Thus, the highest value of the lateral solids flux is below the external solids mass flux, agreeing with the findings of Zhou et al. (1995). The difference between the outward and inward flux indicates that a net outward flux of particles takes place in the bottom zone of the CFB riser. Zhou et al. (1995) also observed a net transfer of solids from the core to the annulus at the riser bottom. Brereton and Grace (1993) and Pugsley and Berruti (1996) stated as well that a net transfer of solids to the wall in the lower part of the riser occurs.

While a net outward flux of solids was confirmed in the bottom region in both our riser and the riser of Zhou et al. (1995), the

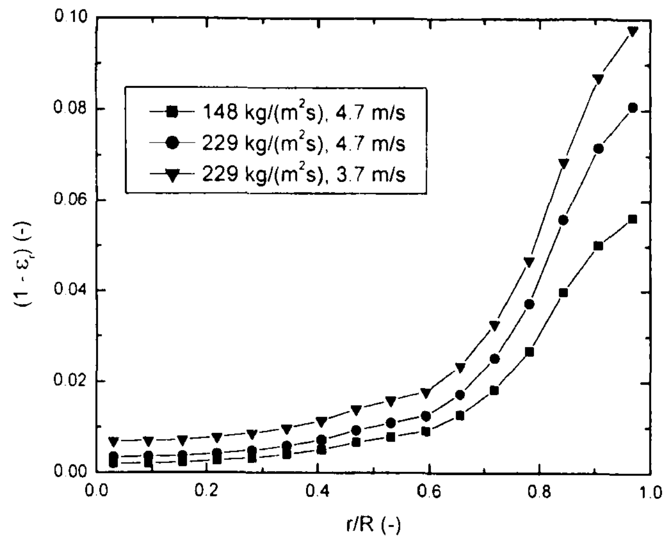

Figure 7. Radial profiles of solids concentration at a riser height of 5.90 m (dilute region).

magnitudes of the lateral fluxes differ. On the axis of their riser ($x/X = 0$, $y/Y = 0$), the lateral outward flux in the bottom region (i.e. below about 1.5 m) ranged from 0.5 to 3 kg/(m^2·s). At the wall of their riser at the location most remote from the corners ($x/X = 0$, $y/Y = 1$), the lateral flux reached 20 kg/(m^2·s) at the lowest measurement location and then rapidly decreased to less than 5 kg/(m^2·s) by a height of 1.5 m. Hence, their centreline lateral flux was slightly higher, but of the same order as that found in the bottom zone in the present work. Their wall fluxes, on the other hand, were noticeably lower.

In an earlier study, Zhou et al. (1994) investigated the local solids concentrations in the same CFB unit applying the same solids (sand) and the same range of operating conditions. The solids concentrations at the riser axis in their dense bottom region were higher than what we have measured in the present work. For instance, at a solids mass flux of 40 kg/(m^2·s) and a superficial gas velocity of 5.5 m/s, the solids concentration in the riser of Zhou et al. (1995) varied from 0.12 to 0.08. In the present work, a centreline solids concentration of about 0.012 to 0.027, as measured with the ECT system, occurred at a height of 1.55 m, depending on the adjusted operating conditions (see Figure 5). At the wall of their riser Zhou et al. (1994) measured solids concentrations in the range of 0.35 to 0.4 in the bottom region. Figure 5 shows a similar range of concentrations in the wall region of our riser. Considering the comparison at the axes of the two risers, the trend of increasing lateral solids flux with increasing solids concentration appears to be confirmed. Furthermore, Qi and Farag (1995) stated that at low solids concentrations (less than 5%), the lateral solids flux is greater for larger and denser particles than for lighter and smaller ones. The comparison at the centreline between the present work using FCC and the work of Zhou et al. (1995) with sand supports this statement as well. However, in the wall region, a much larger lateral flux was measured in the present work, even though the solids concentrations are similar to that of Zhou et al. (1994). One possible explanation for this difference might be that the riser of Zhou et al. (1994, 1995) was of square cross-section instead of circular. It is unknown how this difference might influence the lateral flux of particles. Moreover, Zhou et al. (1995, 1994) applied sand as solids instead of FCC catalyst, and operated at much lower external solids mass fluxes than those investigated in the present study. These points suggest that presenting the lateral solids flux as only a function of the solids concentration is an oversimplification. In the dense bottom zone established in the present work, the lateral flux may also depend on parameters like the particle density and mean diameter, riser geometry and the adjusted operating conditions.

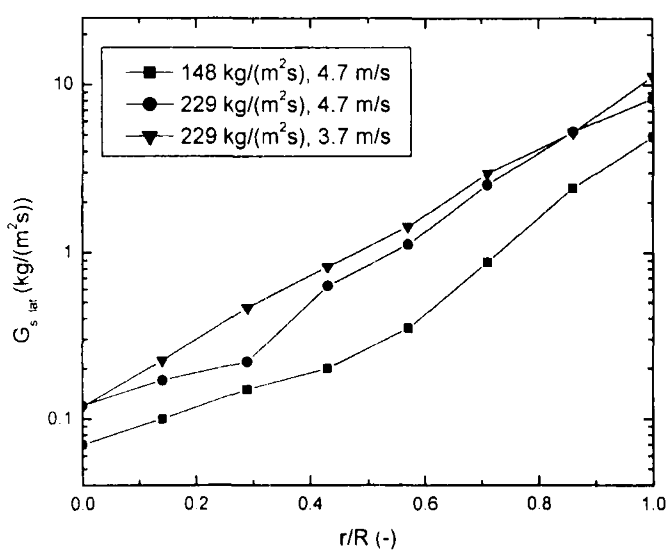

Figure 8a. Lateral outward solids mass fluxes at a riser height of 5.90 m (dilute region).

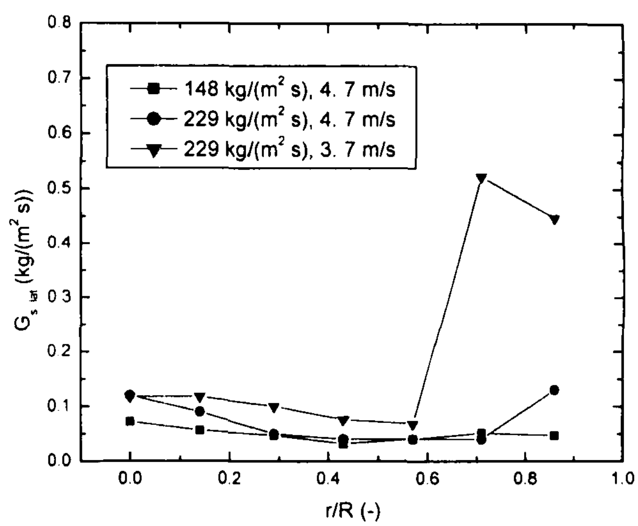

Figure 8b. Lateral inward solids mass fluxes at a riser height of 5.90 m (dilute region).

Upper Dilute Region

Figure 7 shows the radial profiles of solids concentration at a height of 5.9 m. This figure illustrates that an increase of the solids mass flux and a decrease of the superficial gas velocity causes an increase of the local solids concentrations. The corresponding outward solids mass fluxes at different external solids mass fluxes and superficial gas velocities at a height of 5.9 m are given in Figure 8a. At the centreline of the riser, the lateral solids mass flux varies between 0.07 and 0.12 kg/(m^2·s) and thus is effectively equal to the centreline values observed in the dense bottom region. Comparing Figures 5 and 7, we find that the solids concentration at the riser centreline changes with riser height, from values between 0.012 to 0.027 at a height of 1.55 m to values well below 0.01 at a height of 5.90 m. Thus, the centreline solids concentration increases down the riser while the centreline lateral solids mass flux remains nearly constant. Jiang and Fan (1999) suggested that the turbulent-particle interactions play a more important role for the lateral solids movement in the core region than the particle–particle collisions. The present findings are consistent with that postulation. Despite a significant increase in the core solids concentration when moving from the upper dilute region to the dense bottom region, which would tend to promote particle–particle collisions, the lateral flux stays the same. Thus some other mechanism, such as turbulent-particle interactions, must control the lateral motion of the particles.

An approximately exponential increase of the outward flux with increasing radial location can be seen, as was the case in the dense region of the CFB riser. However, this increase of the lateral flux is much slower at the higher axial location and results in lateral fluxes between only 5 and 14 kg/(m^2·s) at the wall. This is almost an order of magnitude lower than what was measured in the lower dense region. This indicates that solids mixing is more intense in the lower dense bed than in the upper dilute region. The sharp decrease of lateral flux with riser height corresponds to a sharp decline of local solids concentrations close to the wall with riser height. For instance, for a solids mass flux of 229 kg/(m^2·s) and a superficial gas velocity of 4.7 m/s, the solids concentration immediately at the wall declined from a value of about 38% in the dense bottom zone to a value of about 8% in the upper dilute region. Therefore, in the wall region, unlike at the centreline, the lateral outward flux does depend on the local solids concentration. The analysis of Jiang and Fan (1999) concluded that particle–particle collisions play a more important role in the lateral movement of solids near the wall of a CFB riser. The strong correlation between solids concentration and lateral solids flux at the riser wall found in the present work supports that theory.

The lateral outward solids flux at the centreline can be compared with the results obtained by Zhou et al. (1995) in the upper portion of their riser. Again, their lateral flux is slightly greater than that found in the present work (about 0.4 kg/(m^2·s) compared with values between 0.07 and 0.12 kg/(m^2·s) in the present work). Hence, the comparison at the riser centreline leads to the same conclusions as those arrived at in the dense bottom region. Similarly, a comparison of the wall regions in the upper dilute zones of the two risers shows that the wall solids concentrations are approximately the same, but the corresponding lateral outward fluxes are greater in the present work, as was the case for the wall region in the dense bottom zone. It is important to point out, however, that the difference between the lateral outward fluxes at the wall in the two studies is not as pronounced in the upper dilute region as it is in the dense bottom zone. Thus as the flow of the gas–solid suspension becomes more developed at the higher axial locations in the riser, it is possible that differences observed in the bottom regions and attributed to the differences in particle type, operating conditions and riser geometry become less important.

The lateral outward flux values in the upper dilute region can be further compared to the values measured by Jiang and Fan (1999). Like the present study, they carried out experiments with FCC particles in a riser of circular cross-section of similar diameter and height. They performed their experiments at operating conditions different from what we did (superficial gas velocity between 1.7 m/s and 3.0 m/s, solids mass flux between 5 and 30 kg/(m^2·s)), but the cross-sectionally averaged solids concentrations in the upper dilute region are comparable. For a cross-sectionally averaged solids concentration of 2.42%, Jiang and Fan (1999) measured a lateral outward flux of about 0.07 kg/(m^2·s) at the riser centreline and approximately 1.7 kg/(m^2·s) at a dimensionless radial location of 0.76. In the present work, based on the ECT measurements, an average solids concentration of 2.5% existed at a superficial gas velocity of 4.7 m/s and an external solids mass flux of 148 kg/(m^2·s). The measured lateral outward fluxes are very similar to the ones observed in the work of Jiang and Fan (1999). At the centreline, the value of the lateral flux amounted to 0.07 kg/(m^2·s), while at a dimensionless radial location of 0.71, the lateral outward flux was 0.88 kg/(m^2·s). The same comparison can be made with the data of Jiang and Fan (1999) at an average solids concentration of 4.36%. Applying a solids mass flux of 229 kg/(m^2·s) and a superficial gas velocity of 3.7 m/s in the present work resulted in a comparable average solids concentration of 4.1%. While the centreline value for the lateral outward flux amounted to 0.10 kg/(m^2·s) in the work of Jiang and Fan (1999), we measured a value of 0.12 kg/(m^2·s). At a dimensionless radial location of 0.88, Jiang and Fan (1999) reported a value of 5.8 kg/(m^2·s), which agrees very well with our value of 6.3 kg/(m^2·s) for a dimensionless radial location of 0.86. Considering the similarity of the lateral outward flux profiles despite the very different operating conditions, it appears that the lateral particle flux in the upper dilute zone is solely a function of the solids concentration in the case of comparable particles and riser dimensions.

There are some qualitative differences between our work and the work of Jiang and Fan (1999). They claimed that the lateral particle flux profile in both directions passes through a maximum and then decreases towards the wall. The results of the present work, in which the outward flux has been determined immediately at the wall, strongly suggest that there is a continuous increase of the lateral outward flux of solids towards the wall. In addition, the results of Jiang and Fan (1999) indicate fully developed flow in the upper dilute region of their riser, as their values of the local outward and inward fluxes were approximately equal. The results of the inward flux at an axial

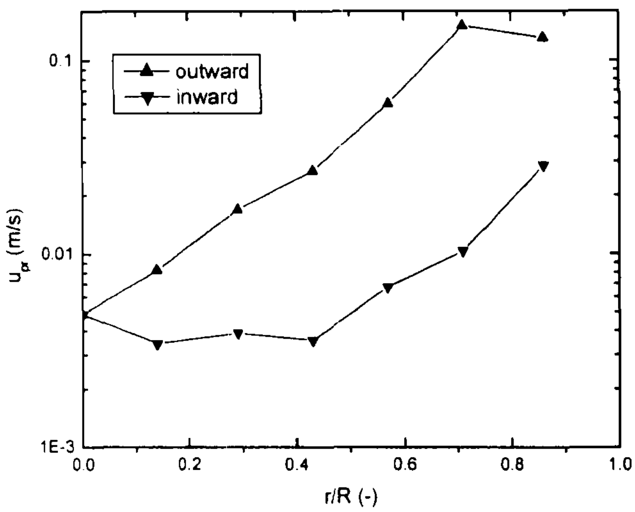

Figure 9. Lateral solids velocity in the outward and inward direction at a riser height of 1.55 m (dense region), a superficial gas velocity of 4.7 m/s, and an external solids mass flux of 264 kg/(m^2·s).

location of 5.9 m are depicted in Figure 8b. Combining the results of Figures 8a and 8b it can be seen that, even at an axial location of 5.9 m a net transfer of solids from the core region of the riser towards the wall exists. The net transfer of solids reveals that a fully developed region is still not reached at this axial location. Similar to the experimental results seen in the dense bottom zone of the riser, the net outward transfer of solids increases with radial location.

The net transfer of solids from the core into the annular region that we observe is in agreement with the statement of Rhodes et al. (1998). They stated that above the interface between the upper dilute region and the lower dense region in a CFB riser, the net radial transport of solids is from core to annulus. In a more recent paper, Wang et al. (1999) reported that inside the dense-dilute interface, the dominant flow direction near the wall is inward, while it is predominantly outward in the core region. In contrast to the present work and previous works referred to above, Zhou et al. (1995) observed a net solids transfer from the wall towards the centreline near the top of their riser. However, the CFB unit of Zhou et al. (1995) was equipped with an abrupt riser exit. This configuration causes an increase of the solids concentration at the top of the riser, as was shown in an earlier work of Zhou et al. (1994). The increased downflow of solids, bouncing off the riser exit, in the annular region might lead to an additional inward flow of particles towards the centreline.

Figure 8b also shows that the inward solids flux has a different profile than the outward flux. For most operating conditions the profile is very flat with values between 0.04 and 0.16 kg/(m^2·s). The profiles indicate that a slight decrease with radial location occurs first, followed by a small increase at higher radial locations. Only for a solids mass flux of 229 kg/(m^2·s) and a superficial gas velocity of 3.7 m/s is a strong increase of the lateral flux with radial location observed close to the wall. The significantly higher solids concentration at the wall under these conditions (see Figure 7) compared to the other conditions at the same height may cause this sharper increase in lateral flux. The inward flux profile at this higher axial location is also slightly different from the inward flux profile in the dense bottom zone, where an exponential increase of the lateral flux with radial location was observed from a dimensionless radial location of 0.3 outward.

Lateral Solids Velocity

The knowledge of the lateral solids mass flux and the local solids concentration allows the determination of the lateral solids velocity. This can be calculated based on the definition of the lateral solids mass flux:

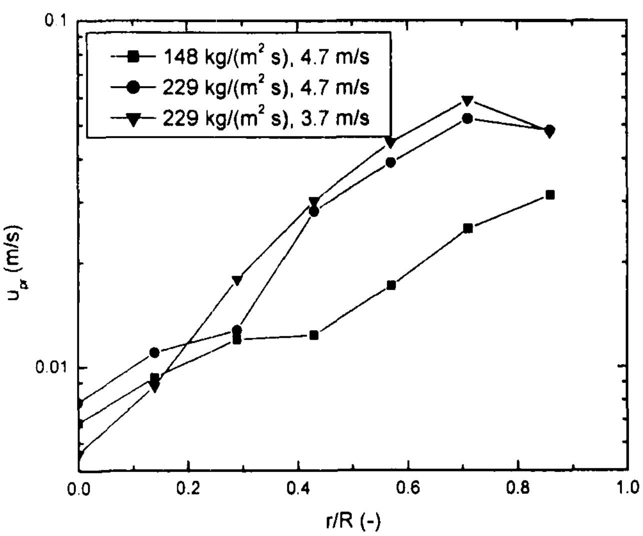

Figure 10a. Lateral outward solids velocity at a riser height of 5.90 m (dilute region).

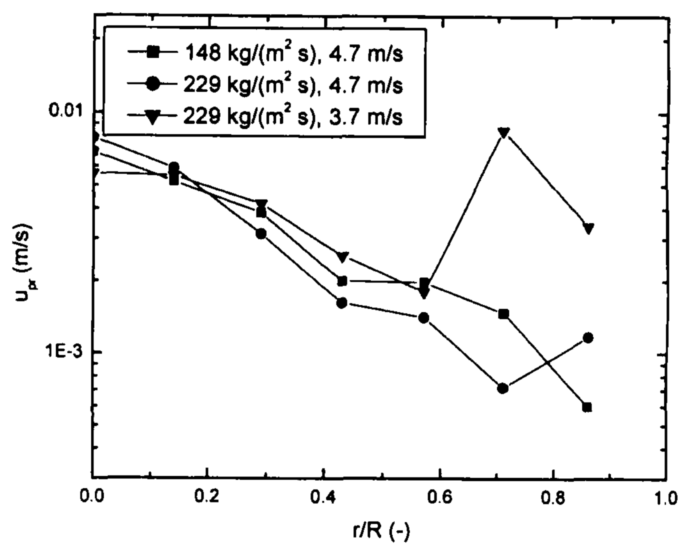

Figure 10b. Lateral inward solids velocity at a riser height of 5.90 m (dilute region).

$$G_{s,lat} = (1-\varepsilon_r)\cdot\rho_p\cdot u_{pr} \quad (1)$$

In this equation, $G_{s,lat}$ is the lateral solids mass flux, $(1 - \varepsilon_r)$ is the local solids concentration, ρ_p is the particle density, and u_{pr} is the local lateral solids velocity. As every parameter is known except for the solids velocity, the radial profile of the lateral solids velocity can be evaluated.

Dense Bottom Region

Due to the similarity of the solids concentration profiles and the lateral solids mass flux profiles in the dense bottom region of the riser, only the lateral velocity profile for a solids mass flux of 264 kg/(m^2·s) is given in Figure 9. The inward velocity remains nearly constant up to a dimensionless radial location of about 0.5. Over this range, the increase in solids concentration with radial location counteracts the increase in lateral solids mass flux. Beyond that radial position, a strong increase of the lateral velocity occurs. The inward lateral solids velocity increases from about 0.005 m/s to a value of about 0.03 m/s at a dimensionless radial location of 0.86. The outward lateral velocity, on the other hand, shows an exponential increase with radial location from the centreline to a dimensionless radial location of about 0.71. Beyond that point the outward lateral solids velocity levels off at its maximum value of 0.15 m/s. The centreline value of the lateral solids velocity in the present work is significantly lower than those reported by Zhou et al. (1995). At the very bottom of their riser, they observed a centreline lateral solids velocity of about 0.1-0.25 m/s, depending on the adjusted operating conditions. At an axial location of 1.4 m, the lateral particle velocity reached values of about 2 m/s. As mentioned earlier, Zhou et al. (1994) reported higher values of the solids concentration at the centreline than we observed in the present work. Thus, it may be suggested that it is partially the higher local solids concentration creating a larger lateral solids velocity. Also, Zhou et al. (1995) applied Ottawa sand as solids in their experiments. Thus, their particles were larger and heavier than the FCC particles employed in the current work.

Upper Dilute Region

Figure 10a shows the lateral outward solids velocity at the higher axial location. As in the dense bottom region, the lateral particle velocity first increases continuously with radial location and then levels off. Only for the lowest solids mass flux (148 kg/(m^2·s) is a continuous increase of the lateral solids velocity with radial location observed. An impact of the average solids concentration can be seen. Under higher solids concentration conditions, the lateral velocity appears to be slightly higher. Comparing the values of the outward lateral velocity at the higher axial location with those obtained in the dense bottom zone shows that the centreline values are rather similar or even slightly higher at the higher axial elevation. Applying the suggestion of Jiang and Fan (1999), that the turbulent-particle interactions are dominant in the core region of the riser, our results would indicate that the slightly lower solids concentration at the centreline in the upper dilute region allows a higher level of turbulence and thus slightly higher solids velocities in the radial direction. Close to the wall, though, the results clearly indicate that a higher lateral solids velocity occurs in the dense bottom region than in the dilute upper region. Assuming that particle–particle interactions are more important than turbulence-particle interactions in the dense annular region of a riser, it can be stated that the higher collision frequency in the denser annular bed at the riser bottom is responsible for higher lateral solids velocity in the annular region in the bottom zone compared to the upper dilute zone.

As Jiang and Fan (1999) gave both the profile of the lateral solids mass flux and the solids concentration distribution, we were able to calculate their corresponding lateral solids velocity profile for their experiments in the same manner as we did for our data. At the centreline, we evaluated lateral velocities slightly below 0.01 m/s for the work of Jiang and Fan (1999) while values at a radial location of $r/R = 0.76$ were between 0.05 and 0.07 m/s. These agree very well with the lateral outward solids velocities we determined from our experimental results.

Zhou et al. (1995), on the other hand, observed values for the lateral solids velocity of about 2 to 3 m/s at intermediate riser heights at the centreline. Thus, their values are much above the velocity values calculated in our work and the work of Jiang and Fan (1999). Zhou et al. (1995) chose a different way to determine the lateral solids velocity. Instead of combining lateral solids mass flux with the local solids concentration according to Equation (1), Zhou et al. (1995) divided the lateral solids momentum flux, which was experimentally measured, by the experimentally measured lateral solids mass flux. For example, at an axial location of 6.2 m, Zhou et al. (1995) measured a lateral solids momentum flux of 0.8 kg/(m^2·s) at the riser centreline and a lateral solids flux of about 0.4 kg/(m^2·s) for an external solids mass flux of 40 kg/(m^2·s) and a superficial gas velocity of 5.5 m/s. This gave them a lateral solids velocity of 2 m/s. As an alternative, we have combined the corresponding local solids concentration data from the work of Zhou et al. (1994) with the lateral solids mass flux to evaluate the lateral solids velocity. With this approach, a value of approximately 0.004 m/s is calculated, which agrees very well with the values evaluated for the present work and from the data of Jiang and Fan (1999). The reason for this discrepancy is not clear, but one possibility may be the particle size distribution. According to the size distribution given by Zhou et al. (1994), their sand contained some particles as large as 500 µm. It is possible that the lateral motion of the larger particles dominated the measured lateral momentum flux. On the contrary, lateral solids velocities determined from the lateral flux probe, would not be sensitive to the size distribution and could lead to the smaller values found here. In any event, this finding makes it clear that more investigations on the lateral solids momentum and mass fluxes are required in order to find an explanation for the discrepancy in the results for the lateral solids velocity depending on the method of calculation.

The results of our lateral inward solids velocities are depicted in Figure 10b. The results are significantly different from the ones observed in the dense bottom region of the riser. While in the dense region the lateral inward solids velocity profile showed an increase with raising radial location over most of the radial range, the opposite trend occurred in the upper dilute zone of the riser. This behaviour might be explained by the strong decrease of the solids concentration close to the wall with increasing axial elevation. The lateral outward solids velocity also showed much lower values close to the wall at the higher elevation compared to the one in the bottom zone. Only for a solids mass flux of 229 kg/(m^2·s) and a superficial gas velocity of 3.7 m/s, conditions at which the solids concentration at the wall is the highest, can a significant increase of the lateral inward velocity at the wall be observed.

In their work, Qi and Farag (1993) stated that the lateral solids velocity has the same value at each radial location and is about 0.26 m/s. Zhou et al. (1995) already doubted their high lateral solids mass fluxes, which led to the high value of the radial solids velocity. Our results and the results of Jiang and Fan (1999) further suggest that under most operating conditions, the lateral solids velocity varies with radial position.

Conclusion

This study measured the lateral solids mass flux of FCC particles in both the dense bottom region and the upper dilute region of a 0.14-m inside diameter CFB riser. External solids mass fluxes of 148 to 302 kg/(m^2·s) and superficial gas velocities of 3.7 to 4.7 m/s were investigated. The time-averaged radial solids concentration profiles, when combined with the lateral flux measurements, allowed the calculation of the corresponding lateral solids velocity profiles.

When a dense bottom zone is established, both the inward and outward lateral flux of solids is independent of the external solids mass flux. The outward flux exceeds the inward flux at all radial locations, indicating a net deposition of solids from the core to the annulus in the dense bottom region. The lateral outward flux approaches 100 kg/(m^2·s) at the wall, indicating a high degree of solids mixing, but for no operating conditions does the lateral flux exceed the external solids mass flux. In the upper dilute region, lateral solids mass fluxes are lower, coinciding with the reduced solids concentration at that elevation in the riser. The results still indicate, however, that a net flux of solids from core to annulus takes place. Thus fully developed flow is not established. The calculated lateral solids velocities exhibit trends similar to the lateral fluxes, with the exception of the inward velocity in the upper dilute zone. This quantity decreases from the riser axis to the wall.

A comparison with the limited number of previous studies on the lateral solids flux has also been undertaken in order to gain some insight into the parameters that influence the lateral flux. The results of this comparison suggest that considering the lateral solids flux to be only a function of solids concentration is an over-simplification. Particularly in the dense bottom region, particle size and density, riser geometry, and the imposed operating conditions of external solids mass flux and superficial gas velocity influence the lateral solids movement. More work is needed to elucidate the relative importance of these parameters.

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