Factors Affecting Solids Segregation in Circulating Fluidized-Bed Riser

B. Hirschberg and J. Werther
Dept. of Chemical Engineering, Technical University Hamburg-Harburg, D-21071 Hamburg, Germany

Axial and radial segregation effects due to differences in particle sizes and solids densities were studied in a 0.2-m-dia. riser at gas velocities between 3.5 and 7 m/s and solids circulation rates between 8 and 40 kg/($m^2 \cdot s$). Two bed materials (a quartz sand/iron powder mixture and a quartz sand with a broad size distribution) with identical terminal velocity distributions were used. Local mean particle sizes and local mass fractions of the iron powder (for the mixture) decreased with height. Measurements of the solids streams revealed that the downflowing solids consist preferentially of large and/or heavy particles, while the reverse happens in the upward solids flow. The single particle terminal velocity is the decisive parameter affecting solids segregation. The comparison of both bed materials indicates that two bed materials will exhibit the same segregation patterns only if the distributions of the particles' terminal velocities in both materials are the same.

Introduction

When solids exhibiting a wide size distribution and/or different solids densities are fluidized in a circulating fluidized bed (CFB), segregation of solids will always occur. The solid particles that are easier to fluidize tend to be elutriated by the fluidization gas and the others tend to sink and remain at lower levels. Gas turbulence as well as interactions between individual particles and particularly the interaction of the upward flowing gas solids suspension with downward moving strands or clusters will on the other hand lead to mixing of the particles. As a result, a dynamic equilibrium is obtained between mixing and segregation tendencies.

Solids segregation is of great practical interest. In some CFB applications it is important that solids segregation is avoided; in others that segregation and thereby the separation of the different species be achieved. The CFB combustor is an example where solids segregation is generally observed. The inventory of a CFB coal combustor consists of various solids, that is, coal, ash, limestone and inert materials that are different in size and solids densities. Measurements of particles sizes in industrial combustors by Herbertz et al. (1989), Johnsson and Leckner (1995), and Na et al. (1996) have given indications that the bed material in the CFB riser is classified along the riser height. As a result, the bottom bed in the riser shows significantly larger particle sizes than the circulating material. Mainly ash, limestone, and small coke particles circulate through the CFB loop, while the large feed coal or coke particles remain preferentially in the bottom part of the riser.

A major feature of the CIRCOFER process where iron ore is directly reduced to metallic iron by char (Hirsch et al., 1985) is the continuous segregation with a separation of the char and iron ore particles in the CFB riser (Bresser et al., 1993; Reh, 1995). Mainly char particles are entrained by the gas and circulated through the CFB loop, while the heavy iron ore particles will preferentially remain in the riser.

A continuous solids separation of the bed material is also crucial for the performance of the multisolid fluidized bed (MSFB) combustor (Bai et al., 1994). In order to achieve high combustion efficiencies, the reducing zone in the bottom part of the MSFB riser contains coarse particles of up to 15 mm that should always remain in the bottom part of the riser and should not be elutriated. Thus, a stabilization of the combustion process is ensured that promotes the breakdown of large feed particles, enabling the use of large coal particles of up to 50 mm diameter (Nowak et al., 1993).

Solids segregation has received much attention in bubbling fluidized beds (such as Rowe et al., 1972; Nienow and Chiba, 1985; Baeyens and Geldart, 1986; Kunii and Levenspiel, 1991). In recent years there has been growing interest in segregation effects in CFBs and their segregation mechanisms (c.f. Werther and Hirschberg, 1997). However, there is only a limited database of detailed experimental investigations which are mainly restricted to binary mixtures.

Most authors have added coarse particles to a circulating fluidized bed of fine particles with a different solids density (Chesonis et al., 1990; Nowak, 1990; Bi et al., 1992; Ijichi et al., 1992; Bai et al., 1994; Jiang et al., 1994; Nakagawa et al., 1994). For a mixture of fine particles (FCC, 70 μm, 1,700 kg/m^3) and coarse particles (sand, 320 μm, 2,600 kg/m^3), Bai et al. (1994) have compared vertical profiles of local solids volume concentrations of the mixture with profiles of the local volume concentrations of the fine particles. They used risers of two different diameters under identical operating conditions. The enlargement of the column diameter leads to an increase of both the solids volume concentration and the fine solids volume concentration in the bottom section, and a corresponding decrease in the upper part of the riser. Generally, the addition of coarse particles leads to an increase of the holdup and thus of the residence time of the solids in the riser. In the case of a solid-catalyzed gas-phase reaction, this may increase the conversion (Bi et al., 1992). Nakagawa et al. (1994) found for a mixture of sand and FCC that solids segregation becomes less severe with increasing superficial gas velocity. Similar tendencies were reported by Ijichi et al. (1992) and Hirschberg et al. (1996) for binary mixtures of solids components having nearly identical particle sizes but different solids densities.

So far, only little attention was paid to radial segregation. In the recent studies by Na et al. (1996) and Liu et al. (1996) limited data are available on solids compositions and particle sizes in the up- and downflowing solids mass fluxes in CFB risers. Although both of the latter studies are conducted in very differently sized reactors, they show similar differences between the upward flux consisting preferentially of easier-to-fluidize particles and the downward flow containing larger and heavy particles.

Experimental Studies

Circulating fluidized-bed system

All experiments were carried out in a CFB unit that is shown in Figure 1. It mainly consists of a cylindrical riser, 0.2 m in diameter, and 12 m in height. Air is supplied by a roots blower at a rate of 0.05 to 1 m^3/s. In the riser the entrained solids are accelerated and carried upward by the gas. The solids leave the riser through an abrupt exit into the cyclones, where they are separated from the gas. The particles descend through the return leg into the L-valve where they are fed back to the riser. The dusty air exhausts through a bag filter. The solids circulation rate can be varied by regulating the gas fed to the L-valve. The solids circulation rate is measured by temporarily closing a valve in the primary return leg and timing the mass accumulation of solids above the closed valve. The inventory of solid particles in the L-valve guarantees that steady-state feeding into the riser is not interrupted during measuring of the solids circulation rate. Along the whole riser, 13 instrumentation ports are attached to the riser, where measuring probes can be introduced into the riser. They are located at $h = 0.2$ m, 0.5 m, 0.7 m, 1.1 m, 1.8 m, 2.6 m, 3.9 m, 4.9 m, 5.7 m, 7.1 m, 9.5 m, 10.3 m, and 11.3 m above the distributor plate.

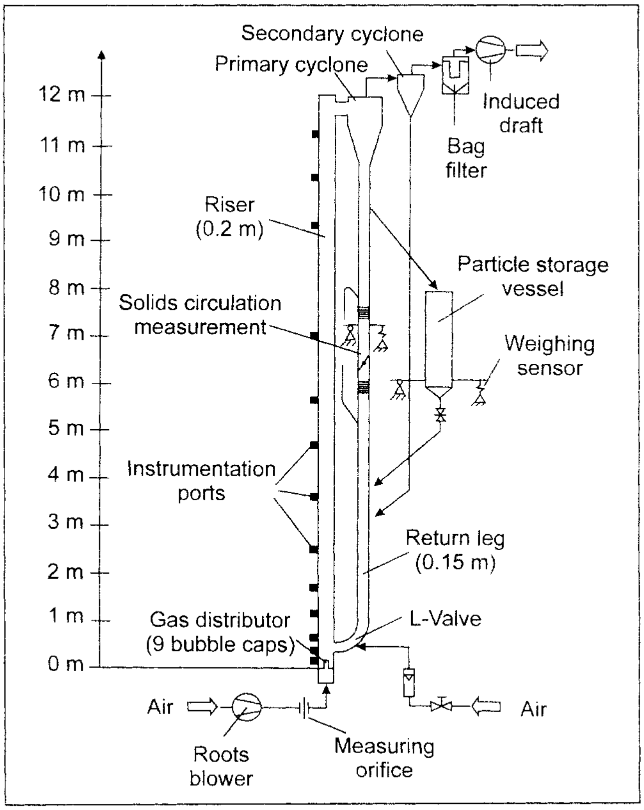

Figure 1. CFB test facility.

For pressure drop measurements, 32 pressure taps are installed along the CFB loop that are connected to pressure transducers. Their signals are transmitted to a PC that is equipped with a high-speed data acquisition board (Burr-Brown PCI-20098 C). The superficial gas velocity is measured by pressure drop measurements along an orifice (DIN 1952) that is installed in the air supply line between the roots blower and the gas distributor.

Experiments were carried out with two bed materials. The first bed material was a binary solid particle mixture consisting of 60 mass-% quartz sand (quartz sand I) and 40 mass-% iron powder. The second bed material consisted of quartz sand particles (quartz sand II) only (Table 1). The particle-size distributions $Q_3(d_p)$ of the different solids (Figure 2) were measured with a laser particle sizer (Malvern, type 2600 LC). The binary mixture represents the more general case of a mixture exhibiting different solids densities and overlapping broad distributions in particle sizes.

For sedimentation of single spheres in air at ambient conditions, the particle size may be converted into terminal velocities u_t. The resulting cumulative mass distributions of sin-

Table 1. Physical Properties of Bed Materials Used

Bed Materials	Solids Density ρ_s	Mean Particle Size $d_{p,50}$ (Sauter Dia.)	CFB Invent.	Init. Bed Comp. ξ_{tot}
Quartz sand I	2,650 kg/m^3	261 μm (236 μm)	60 kg	60 mass%
Iron powder	7,600 kg/m^3	202 μm (178 μm)	40 kg	40 mass%
Quartz sand II	2,650 kg/m^3	331 μm (312 μm)	100 kg	

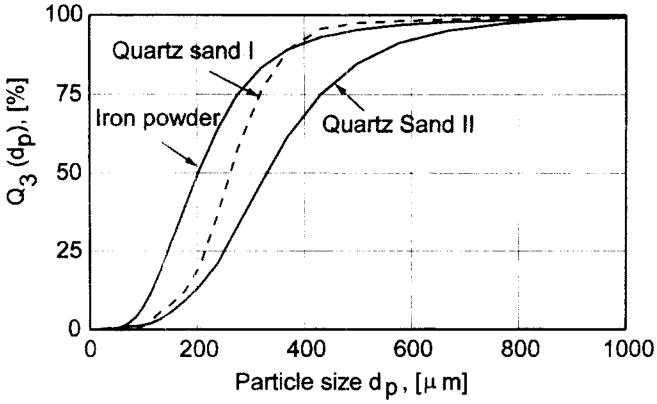

Figure 2. Cumulative mass density distributions of the particle sizes $Q_3(d_p)$ of the solids used.

gle-particle terminal velocities $Q_3(u_t)$ are shown in Figure 3. It is apparent that the distributions in single particle terminal velocity of the quartz sand II particles and of the iron powder/quartz sand I mixture are nearly identical.

The distribution of single particle terminal velocities allows a first common estimation of the mixing behavior of both mixtures. No segregation is expected above gas velocities of 7 or 8 m/s, where practically all particles can be elutriated. At lower gas velocities, segregation will lead to a separation of the particles. Primarily particles with lower terminal velocities are elutriated, while the others tend to sink and accumulate in the riser. In the case of the binary mixture a separation between the iron powder and sand particles is expected, while in the case of the quartz sand II particles the larger sand particles will primarily accumulate in the bottom region of the riser.

Measuring techniques

In this study the well-known sampling technique by suction probes (such as Rhodes et al., 1992; Kruse and Werther, 1995; Louge, 1997) was applied. The sampling unit consists basically of a probe (4-mm ID), that can be introduced into the bed at various axial locations, where instrumentation ports are attached to the riser. The probe tube is bent at the end in

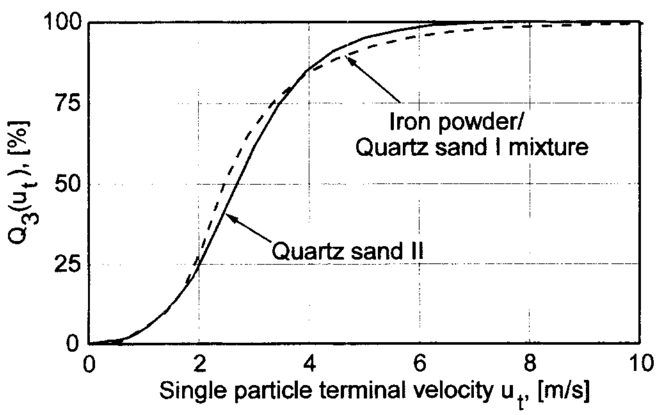

Figure 3. Cumulative mass density distributions of the particles' terminal velocities $Q_3(u_t)$.

the vertical direction which allows sampling of either the downflowing or upflowing suspension depending on the orientation of the probe tip. During measurements, solid particles are sucked through the tip of the probe and then collected by a sampling cyclone. By subsequent off-line analysis, the samples' characteristics, that is, the solids composition and the local particle-size distribution, are measured. The determination of local solids composition was determined by measurements of the solids density of the sampled solid particles mixtures in a helium pycnometer (Micromeritics, type 1305). The solids density of the sampled binary mixture $\rho_{s,\mathrm{mix}}$ (kg/m^3) consisting of solids components 1 and 2 can be expressed as a function of the mass fraction of solids component 1, ξ_1, if the solids densities of the pure solids components, $\rho_{s,1}$ and $\rho_{s,2}$, are known

$$\rho_{s,\mathrm{mix}} = \frac{m_{s,\mathrm{mix}}}{V_{s,\mathrm{mix}}} = \frac{m_{s,1}+m_{s,2}}{V_{s,1}+V_{s,2}} = \frac{m_{s,1}+m_{s,2}}{\dfrac{m_{s,1}}{\rho_{s,1}}+\dfrac{m_{s,2}}{\rho_{s,2}}} = \frac{1}{\dfrac{\xi_1}{\rho_{s,1}}+\dfrac{1-\xi_1}{\rho_{s,2}}} \quad (1)$$

The measurement of solids densities turned out to be a very reliable method that allowed to determine the composition of solid particle mixtures with a maximum error in mass fraction of 1%. The particle-size distributions of the sampled particles were measured with a laser particle sizer (Malvern, type 2600 LC). In the case of the binary mixture for each sample three particle-size distribution measurements were made, one of the sampled mixture and two of the subsequently magnetically separated solids.

It may be suspected that the nonisokinetic sampling with the suction probe gives biased information about the composition in the case of a segregating system in the sense that particles with smaller diameters and/or lower density might be sampled preferentially. The applicability of this technique was therefore investigated in a separate work (Reppenhagen, 1994). The result of extensive measurements with quartz sand/iron ore mixtures at various locations inside the CFB riser in both the upflow and downflow was that no significant influence of the suction conditions on the composition of the samples was observed. As an example, Figure 4 shows the composition of the sampled solids as a function of the suction velocity. Obviously, there are still so many interparticle collisions in the flowing suspension that no significant segregation occurs during the short duration of the suction process. The plot of Figure 4 may be taken as a justification for choosing the suction technique for the present investigation.

Results and Discussion

Overall system behavior

First nonsteady-state mixing experiments were carried out in such a way that the CFB was initially operated under conditions of steady state with quartz sand I particles only. The loop contained 72 kg sand. At a preselected time, the valve under the particle storage vessel (cf. Figure 1) was opened and a batch of iron powder of about 48 kg was suddenly released into the lower part of the downcomer. The mixing

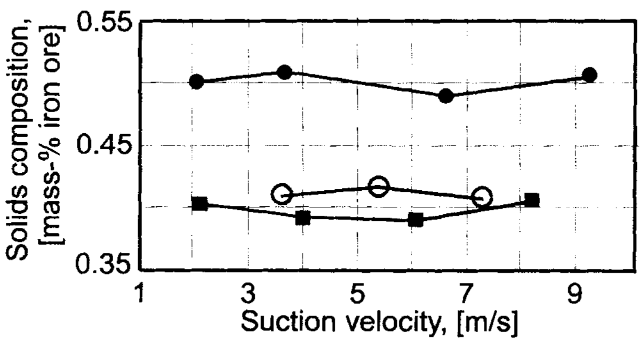

Figure 4. Influence of the suction velocity on the composition of samples obtained by nonisokinetic suction.

Mixture of quartz sand and iron ore in the 0.2-m-dia. riser, $u = 4.6$ m/s, $G_s = 13$ kg/m^2·s, sampling in the upflow on the riser axis, ● $h = 0.7$ m, ○ $h = 5.7$ m, ■ $h = 11.3$ m; from Reppenhagen, 1994.

process was monitored by taking samples in the upflow on the riser axis at 1.1 m above the distributor plate. Figure 5 shows the local solids compositions as a function of time. Obviously, the bed material has to be circulated for a minimum of 10 times the mean solids turnover time t_{circ} (s)

$$t_{circ} = \frac{m_{s,sand} + m_{s,iron}}{G_s A_t}, \tag{2}$$

before steady-state mixing conditions are achieved. All following experiments were carried out under conditions of steady-state solids mixing.

First insights into the overall flow behavior were obtained from measurements of the axial pressure profiles. Under the simplifying assumption that acceleration and deceleration effects are negligible, these profiles may be converted into axial profiles of the cross-sectional average solids volume concentration $\bar{c}_v$. Examples for quartz sand II are given in Figure 6. The concentration distributions are very similar to those observed in circulating fluidized combustors (such as Werther, 1993). Under all operating conditions, a dense bottom bed

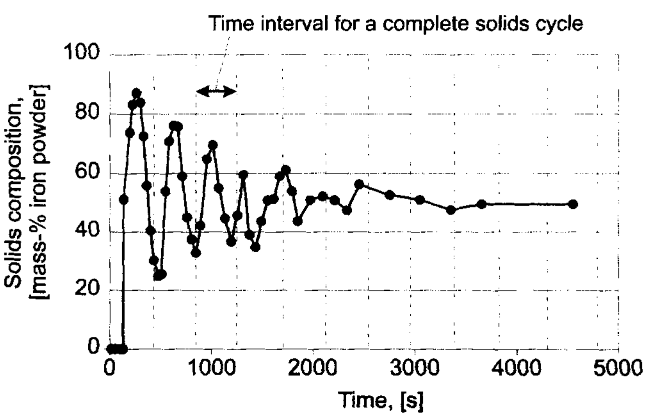

Figure 5. Nonsteady state mixing of quartz sand I and iron powder.

$u = 4.1$ m/s, $G_s = 9$ kg/m^2·s at $h = 1.1$ m, $r/R = 0$ in the upflow.

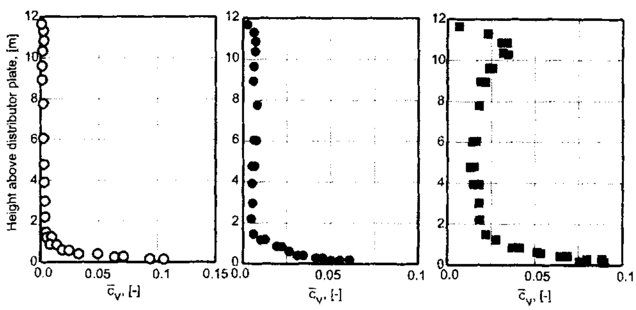

Figure 6. Axial solids volume concentrations calculated from differential pressure drop measurements for quartz sand.

○ $u = 3.5$ m/s, $G_s = 8$ kg/m^2·s, ● $u = 4.6$ m/s, $G_s = 13$ kg/m^2·s, ■ $u = 7.5$ m/s, $G_s = 40$ kg/m^2·s.

was observed. For the solids circulation rate of 40 kg/(m^2·s), a significant effect of the abrupt exit is reflected in the shape of the profile which is in agreement with experimental findings of other authors (such as Brereton and Grace, 1993). Further measurements of local solids fluxes which are not reported here in detail revealed the existence of the typical core-annulus flow structure in the upper dilute zone (such as Hartge et al., 1988; Wirth, 1991; Zhang et al., 1991). The central core region is dominated by a dilute upflowing suspension of solids, whereas the annulus is occupied by dense, downward traveling clusters or strands. The downflow is predominantly found in the region near the riser wall and shows solids concentrations which are significantly higher than in the lean phase. In the following detailed experimental investigations, local solids compositions and local particle sizes of the upflowing and downflowing solid particles are presented.

Axial segregation of iron powder/quartz sand I mixture

The segregation behavior of the quartz sand I and iron powder mixture has been investigated for three experimental conditions. In Figure 7 the local solids compositions along the riser are reported in terms of iron powder fractions of the samples, taken at different axial locations along the riser, but at one radial position of $r/R = 0$, that is, on the axis of the riser with the tip of the probe pointed downward to sample only the upward flowing solids. For the gas velocity of 3.5 m/s and a solids circulation rate of 8 kg/m^2·s, iron powder contents of the sampled mixtures were determined of almost 65 mass % at the bottom of the riser, which decrease with height and reach 40 mass % at the top. This indicates that there is segregation of iron powder particles along the riser. Preferentially large iron powder particles that are not elutriated by the fluidization gas at 3.5 m/s remain in the riser and lead to higher iron powder contents in the bottom part of the riser. Increasing the gas velocity and the solids circulation rate leads to less segregation. Nearly uniform solids compositions were observed at a gas velocity of 7.5 m/s and a solids circulation rate of 40 kg/m^2·s. The solids compositions varied only slightly around the overall solids composition in the CFB loop of 40 mass % iron powder. For this latter case, complete elutriation of all particles was obviously achieved.

Besides these variations of the local solids compositions along the riser height, differences of the local mean particle

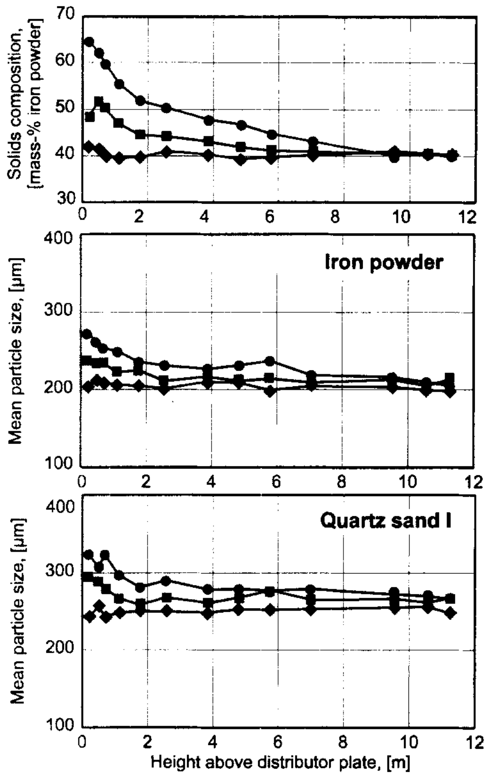

Figure 7. Local solids compositions (upper figure) and mean particle sizes (lower figures) in the upward flow (sampled at $r/R = 0$) for the binary mixture of iron powder and quartz sand I.

ξ_{tot} = 40 mass-% iron powder; ● u = 3.5 m/s, G_s = 8 kg/m^2·s; ■ u = 4.6 m/s, G_s = 13 kg/m^2·s; ♦ u = 7.5 m/s, G_s = 40 kg/m^2·s.

size have been observed. The 50% values of the local cumulative mass distributions of the particle sizes are also shown in Figure 7 for the sampled iron powder and quartz sand fractions. The curves of both solids components indicate that segregation causes a decrease of the mean particle size of each component along the riser height. Due to the larger mean particle size of quartz sand I particles and due to their lower solids density, the measured particle sizes of this fraction show higher values than the iron powder. In summary, it can be said that the axial variations in particle size show generally the same tendencies as the solids compositions.

Axial segregation of quartz sand II

Segregation patterns of the quartz sand II particles of a broad size distribution are presented in Figure 8. The variation of the mean particle sizes along the riser height is shown for the same experimental conditions as the results for the binary mixture shown above. At a low gas velocity of 3.5 m/s, the highest degree of segregation was observed with a strong decrease in mean particle size from 490 μm in the lower part of the riser to 310 μm at the riser top. A significant enrichment of the large particles is obviously observed in the bottom region of the riser, causing higher mean particle sizes at the riser bottom. At a gas velocity of 4.6 m/s, lower mean particle sizes were determined in the bottom region of the riser, indicating less segregation. The nearly constant mean

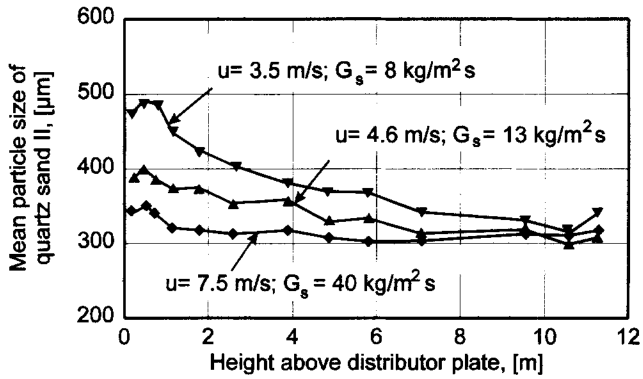

Figure 8. Local mean particle sizes in the upward flow (sampled at $r/R = 0$) for quartz sand II.

particle size experienced at a gas velocity of 7.5 m/s indicates a carry-over of all particles with negligible segregation in the riser.

Radial segregation of iron powder/quartz sand I mixture

Radial segregation is discussed for experiments conducted with the binary mixture of quartz sand I and iron powder at a gas velocity of 3.5 m/s and a G_s = 8 kg/m^2·s. Detailed measurements in the upflow as well as in the downflow are shown in the upper part of Figure 9 in terms of solids compositions along the riser radius. Samples were taken at three different heights of 0.7 m, 5.7 m and 11.3 m. The upward flow was detectable along the entire radius, while descending particles could only be sampled at radial positions from $r/R = 0.6$ to $r/R = 1$. Within this range, the samples taken at $h = 0.7$ m from the downward moving particle flux show always higher iron powder contents than the respective solids upflow. These differences are decreasing with height and at the riser top ($h = 11.3$ m) the samples of both flow directions show the same compositions. The corresponding radial profiles of the mean particle sizes of the two components show uniform particle sizes along the radius with significant differences between the upflow and downflow. The mean particle size of each component in the downflowing stream is always larger than in the upward flow. Based on these detailed measurements, it can be concluded that radial segregation within the respective flow direction is negligible. Therefore, the following discussion of the upflow and downflow is limited to a comparison of samples taken at two radial positions, that is, the upflow samples are taken at $r/R = 0$ on the riser axis and the downflow was sampled at $r/R = 0.97$ near the riser wall.

In Figure 10 the solids compositions and particle sizes, respectively, of the upward and downward flowing solids are compared. In accordance with the above discussed radial profiles, the downward moving solids show along the riser height higher iron powder fractions and larger mean particle sizes of each component. Following their individual flow direction, it can be said that the iron powder content and the particle sizes in the upflow are decreasing, while these characteristics of the downflow are increasing. Since the physical mechanisms of transfer between the upflowing and the downflowing solids are still unknown, one can only speculate whether large particles are segregating from the upflow into the downflow or whether finer particles are preferentially

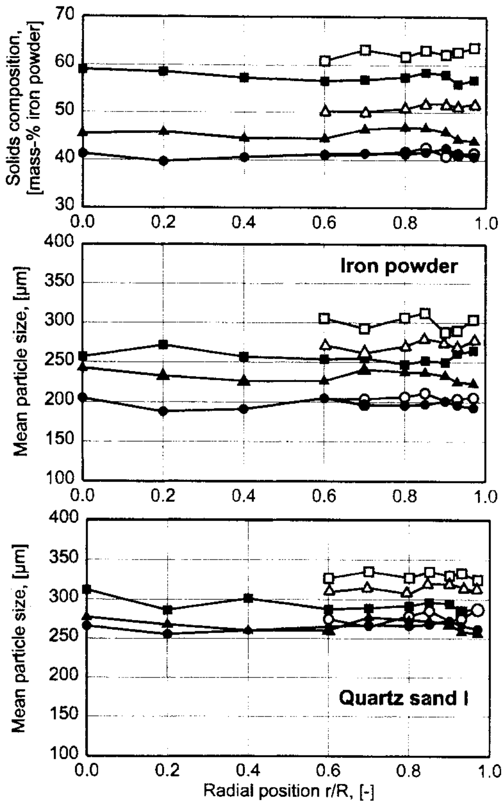

Figure 9. Local solids compositions (upper figure) and local mean particle sizes (lower figures) in the upward (solid symbols) and downward flow (open symbols) for the binary mixture of iron powder and quartz sand I.

ξ_{tot} = 40 mass% iron powder; u = 3.5 m/s; G_s = 8 kg/m²·s; ■ □ h = 0.7 m; △ h = 5.7 m; ● ○ h = 1.13 m.

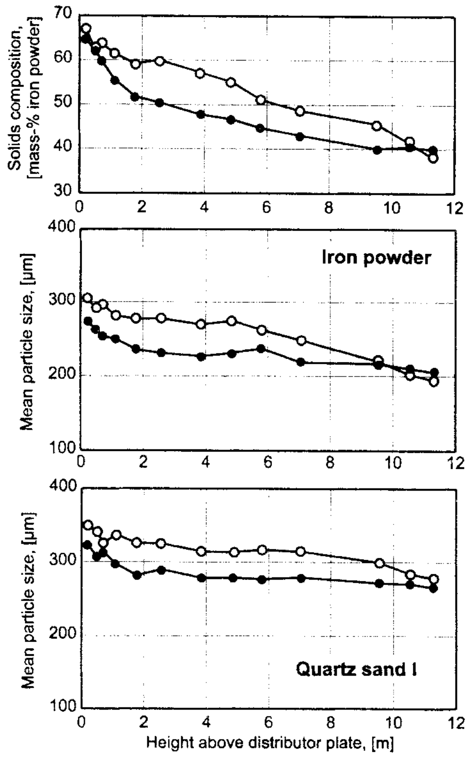

Figure 10. Comparison of local solids compositions (upper figure) and local mean particle size (lower figures) in the upward (●) and downward flow (○) for the binary mixture of iron powder and quartz sand I.

ξ_{tot} = 40 mass% iron powder; u = 3.5 m/s; G_s = 8 kg/m²·s.

stripped from the downflowing solids into the upflow stream. At the riser top, all profiles show nearly identical values which are indicative of an intensive solids mixing near the abrupt exit to the cyclone.

In summary, it can be concluded that radial solids segregation is negligible compared to axial segregation, but significant differences between the upflow and the downflow are found. The observed tendencies are in accordance with measurements of radial particle size profiles by Liu et al. (1996) and radial solids composition profiles by Na et al. (1996). Since the latter investigations are conducted in risers of different sizes [Liu et al. (1996) $H_t = 8$ m, 0.39×0.39 m^2 cross section; Na et al. (1996) $H_t = 13.5$ m, 1.7×1.4 m^2 cross section] with very different solid particle mixtures [Liu et al. (1996) used resins (691 μm; 1,152 kg/m^3) and sand (178 μm, 2,484 kg/m^3); Na et al. (1996) employed stones (5.4 mm, solids density not given by authors) and sand (290 μm, 2,600 kg/m^3)], these conclusions may be assumed to be of general validity.

Terminal velocity as the decisive parameter affecting solids segregation

So far, investigations on solids segregation in the literature (Bi et al., 1992; Bai et al., 1994; Jiang et al., 1994; Nakagawa et al., 1994) were mainly limited to binary mixtures consisting of coarse and fine particles. The observed segregation patterns are usually presented in terms of fractions of the coarse particles along the riser. In order to compare different segregation patterns for binary mixtures, Nakagawa et al. (1994) suggested a segregation intensity S based on the normalized differences between the local solids volume fractions of coarse particles $\mu(h)$ and the mean solids volume fraction of coarse particles in the riser, $\bar{\mu}_{riser}$. S is defined by

$$S = \frac{1}{H_t} \int_0^{H_t} \left[\frac{\mu(h) - \bar{\mu}_{riser}}{\bar{\mu}_{riser}} \right]^2 dh \tag{3}$$

and $\bar{\mu}_{riser}$ can be determined as follows

$$\bar{\mu}_{riser} = \frac{1}{H_t(1 - \bar{\epsilon}_{riser})} \int_0^{H_t} \mu(h)\, [1 - \epsilon(h)]\, dh \tag{4}$$

where $\epsilon(h)$ denotes the local cross-sectional average voidage and $\bar{\epsilon}_{riser}$ is the mean cross-sectional average voidage in the riser. S describes the degree of segregation according to the axial distribution of the coarse component in the riser. They applied such defined segregation intensity to compare experiments at varied operating conditions and discussed the effects of operating conditions on the quantity S.

Since the investigations cited above are limited to the description of solids compositions, they may strictly be applied only to particle mixtures of equal particle sizes or mixtures of two components with widely differing mean particle sizes. On the other hand, in reality CFB applications are operated with particle mixtures of continuous and broad particle-size distributions with two or more species of different solids densities, which exhibit axial variations of the particle size and solids compositions. So far, no tools are available to quantify the resulting segregation tendencies.

In order to describe the more general case of segregation of particle mixtures of different particle sizes and/or solids densities, it is proposed to use the single particle terminal velocity as the decisive segregation characteristic. The physical basis of this suggestion is that the circulating fluidized-bed risers which are considered here are characterized by very low solids volume concentrations. In the upper part of these risers solids volume concentrations are present of the order of 0.1–1% (such as Hartge et al., 1988; Svensson et al., 1993). According to Sinclair and Jackson (1989), the mean free path of the particles l_p (m) between two interparticle collisons may be calculated from kinetic theory using

$$l_p = \frac{d_p}{6\bar{c}_v\sqrt{2}} \tag{5}$$

This means that the ratio of the average center to center distance to particle diameter l_p/d_p (m) in the bed is between 12 and 120 for the above mentioned range of solid volume concentrations of 0.1 to 1%. Under these conditions, the particles have some freedom of individual movement although of course interparticle collisions will prevent them from moving as they would in isolation. Nevertheless, it is the particles' terminal velocity which gives rise to segregation in the flow. For the bed material which is characterized by different particle sizes and solids densities, its tendency towards segregation may conveniently be described by its distribution of single particle terminal velocity u_t.

In the present study the terminal velocity distributions are determined as follows for the binary mixture of iron powder and quartz sand I. As a first step, the samples taken from the riser are analyzed with respect to their solids composition, that is, by solids density measurements. Then the sample is separated into an iron powder fraction and a quartz sand I fraction and their respective particle-size distributions are measured. If sedimentation of single spheres in air at ambient conditions is assumed, the particle sizes d_p can be converted in single-particle terminal velocities u_t (m/s) according to

$$u_t = \sqrt{\frac{4(\rho_s - \rho_g)gd_p}{3c_w(Re_t)\rho_g}} \tag{6}$$

with the correlation of the drag coefficient suggested by Brauer (1971)

$$c_w(Re_t) = \frac{24}{Re_t} + \frac{4}{\sqrt{Re_t}} + 0.4 \tag{7}$$

Re_t is the particles' Reynolds number

$$Re_t = \frac{u_t d_p}{v} \tag{8}$$

Equations 6–8 have been used to determine the single-particle terminal velocity distributions $Q_{3,\text{sand}}(u_t)$ and $Q_{3,\text{iron}}(u_t)$, shown in Figure 11. The terminal velocity distribution of the sampled mixture $Q_{3,\text{mix}}(u_t)$ can be determined from

$$Q_{3,\text{mix}}(u_t) = \xi_{\text{iron}} Q_{3,\text{iron}}(u_t) + (1 - \xi_{\text{iron}}) Q_{3,\text{sand}}(u_t) \tag{9}$$

where ξ_{iron} denotes the local solids composition in terms of mass fractions of the iron powder. For the present example, the terminal velocity distribution of the mixture is also shown in Figure 11, which was determined with the measured $\xi_{\text{iron}} = 55$ mass %.

In accordance with the definition of the segregation intensity by Nakagawa et al. (1994) which is based on solids compositions, a modified definition of the segregation intensity may now be formulated, which is based on the terminal velocity. It is proposed to be used for the more general case of mixtures consisting of particles differing in particle size and solids density. If the solids compositions $\mu(h)$ and $\bar{\mu}_{\text{riser}}$ of Eq. 3 are replaced by the respective terminal velocities $u_{t,50}(h)$ and $\bar{u}_{t,\text{riser}}$, the following definition of the segregation intensity based on the terminal velocity is obtained.

$$S = \frac{1}{H_t}\int_0^{H_t}\left[\frac{u_{t,50}(h) - \bar{u}_{t,\text{riser}}}{\bar{u}_{t,\text{riser}}}\right]^2 dh \tag{10}$$

where $u_{t,50}(h)$ is the local mean terminal velocity (m/s) (50% value of the local u_t distribution) and $\bar{u}_{t,\text{riser}}$ denotes the average mean terminal velocity in the whole CFB riser. Following the proposed calculation of $\bar{\mu}_{\text{riser}}$ by Nakagawa et al. (1994) given by Eq. 4, $\bar{u}_{t,\text{riser}}$ can be calculated as follows

$$\bar{u}_{t,\text{riser}} = \frac{1}{H_t(1 - \bar{\epsilon}_{\text{riser}})}\int_0^{H_t} u_{t,50}(h)\,[1 - \epsilon(h)]\,dh \tag{11}$$

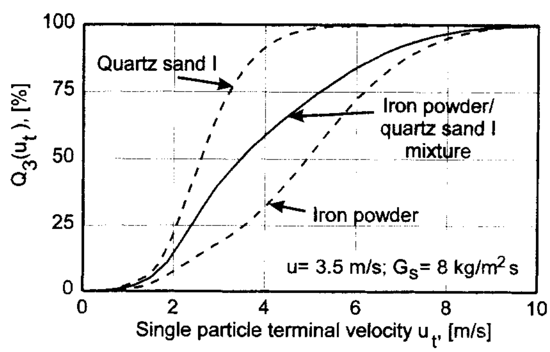

Figure 11. Example of local distributions in single particle terminal velocity $Q_3(u_t)$ in the upward flow (sampled at $r/R = 0$) for the binary mixture of quartz sand I and iron powder.

$h = 1.1$ m with $\xi_{\text{iron}} = 55$ mass% iron powder.

Similar to the definition of Nakagawa et al. (1994), the modified segregation intensity based on terminal velocities (Eq. 10) describes the degree of segregation. Perfect mixing is reached if every measured value of $u_{t,50}(h)$ along the riser height would be equal to $\bar{u}_{t,\text{riser}}$. When segregation occurs, the measured values $u_{t,50}(h)$ differ from $\bar{u}_{t,\text{riser}}$ and higher values of the segregation intensity indicate the degree of segregation. Therefore, the above shown modification of the segregation intensity can be considered as a generalization of the definition given by Nakagawa et al. (1994).

In the present study the axial profile of the local voidage $[1-\epsilon(h)]$ is determined by measurements of the axial pressure profile $\Delta p(h)$ (Pa) along the riser. Under the assumption that acceleration effects and wall friction are neglected, the local voidage $[1-\epsilon(h)]$ can be calculated from

$$[1-\epsilon(h)] = \frac{\Delta p(h)}{(\rho_s - \rho_g) g \Delta h} \tag{12}$$

and the respective mean cross-sectional averaged voidage in the riser $\bar{\epsilon}_{\text{riser}}$ is

$$(1-\bar{\epsilon}_{\text{riser}}) = \frac{\Delta P_{\text{riser}}}{(\rho_s - \rho_g) g H_t} \tag{13}$$

where ΔP_{riser} (Pa) is the total pressure drop along the entire riser length.

The values of S are a relative measure of segregation, valid for tests of particular mixtures in a specific CFB riser. As examples, experiments with the iron powder/quartz sand I mixture are compared in Figure 12 for varied operating conditions in terms of segregation intensity. It is apparent that increasing gas velocities and solids circulation rates decrease the degree of segregation. The present effects of the gas velocity confirm the observations reported in previous studies by Nakagawa et al. (1994), Bai et al. (1994), and Hirschberg et al. (1996). When the superficial gas velocities are increased, solids segregation becomes less severe. No segregation is apparent at gas velocities which exceed the terminal velocities of the largest and heaviest particles.

Axial segregation in terms of local terminal velocity distributions

In Figure 13 the local single-particle terminal velocity distributions are presented for four different axial positions along the riser. It is apparent that axial segregation causes a separation of the particles according to their terminal velocity. The degree of segregation over the entire riser length is indicated by the difference between the samples taken at the riser bottom ($h = 0.2$ m) and at the riser top ($h = 11.3$ m). If the 95% value is considered as the upper limit of the distribution, it can be concluded that in the bottom region of the riser ($h = 0.2$ m) particles are present with terminal velocities up to 8 m/s (95% value), while the samples taken at the riser top ($h = 11.3$ m) consist only of particles with lower terminal velocities up to 5 m/s (95% value). For comparison, the distribution of the CFB inventory is additionally shown in Figure 13. It is apparent that all samples taken in the riser show higher terminal velocities indicating an accumulation of these particles in the riser.

The observed segregation may be understood as a continuous classification occurring along the riser height. In the bottom region the particles will be carried upward by the gas, where due to the high solids concentrations with various particle interactions even particles with terminal velocities higher than the local gas velocity might be dragged up by elutriable solids. Above this bottom region continuous segregation occurs which is supported by decreasing solids concentrations and thus decreasing gas velocities. Preferentially particles with large terminal velocities may leave the upward flow and join the downward flow to be transported back in the bottom region of the riser. On the other hand, particles with lower terminal velocities may be entrained from the downfalling clusters into the upflow stream. At the riser top, solids segregation in the present study is affected by the abrupt exit. Particularly at high gas velocities and high solids circulation rates, the typical exit effect (Brereton and Grace, 1993; Kruse and Werther, 1995; Grace, 1996) with increased solids concentrations and enhanced solids downflow was observed. The exit's effect on the axial segregation was estimated by a comparison of samples taken at the riser top and in the return leg below the cyclone. The latter showed always lower terminal velocities (Figure 13) than the corresponding values at a height of

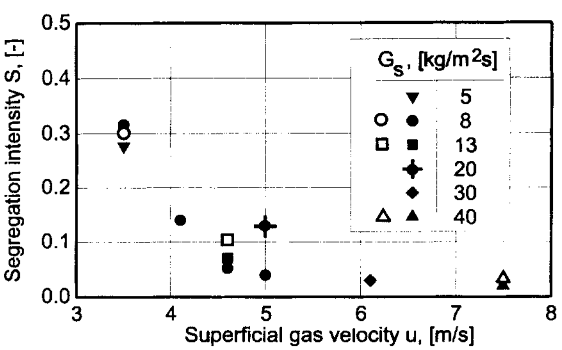

Figure 12. Effect of operating conditions on solids segregation for the binary mixture of quartz sand I and iron powder.

$\xi_{tot} = 40$ mass % iron powder (solid symbols); quartz sand II (open symbols).

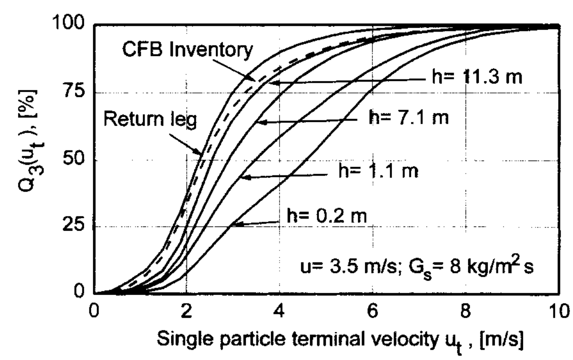

Figure 13. Local single-particle terminal velocity distributions $Q_3(u_t)$ in the upward flow (sampled at $r/R = 0$) for the binary mixture of quartz sand I and iron powder.

$\xi_{tot} = 40$ mass % iron powder.

11.3 m below the exit in the riser. It can therefore be assumed that the abrupt exit acts as an additional classifier, supporting the tendency towards segregation.

Comparison of segregation tendencies of both bed materials

A comparison of the observed segregation patterns of both bed materials is shown in Figure 14 for three different operating conditions at $h = 11.3$ m (riser top) and $h = 0.5$ m (bottom region). It is apparent that the locally measured terminal velocity distributions of both bed materials are nearly identical, indicating very similar segregation tendencies of both bed materials. Thus, the distributions in single particle terminal velocities seem to be decisive for the tendencies towards segregation independent of the selected mixture. In the case of $u = 7.5$ m/s and $G_s = 40$ kg/m^2·s, segregation was obviously avoided by the high gas velocity, which corresponds to the maximal terminal velocity of the largest sand particles (quartz sand II) and the largest iron powder particles in the binary mixture, respectively. Hence, the curves representing the two selected axial positions show almost no differences.

An additional comparison of the observed segregation patterns for both bed materials is obtained when the local distributions in terminal velocities are presented as segregation intensities. This is shown in Figure 12. It is apparent that both bed materials show roughly the same segregation intensities.

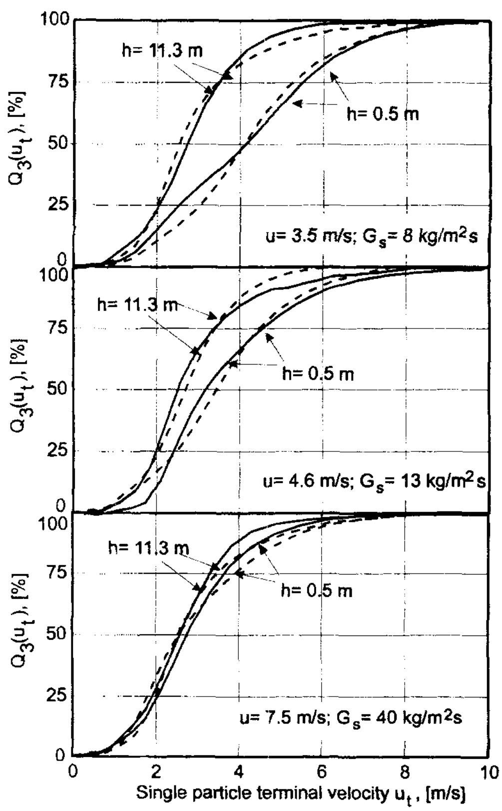

Figure 14. Local single particle terminal velocity distributions $Q_3(u_t)$ in the upward flow (sampled at $r/R = 0$) for the binary mixture of: quartz sand I and iron powder (dashed lines); quartz sand II (solid lines).

Conclusions

(1) Fluidization of a bed material consisting of particles differing in size causes axial segregation with decreasing particle sizes along the CFB riser. For binary mixtures consisting of species with different solids densities and different particle sizes, the segregation patterns are characterized by solid fractions of the heavier component and particle sizes decreasing with riser height. In general, the unelutriable solids are preferentially accumulated in the bottom region of the riser.

(2) Measurements of radial segregation showed constant solids compositions and particle sizes along the riser radius. However, the upflowing and downflowing solids at the same axial position in the riser exhibit significant differences in solids characteristics. Larger and/or heavier particles are preferentially found in the downflow near the riser wall and the upflow consists of those particles that are easier to fluidize.

(3) The single-particle terminal velocity is found to be the decisive parameter affecting solids segregation in CFB risers. For the general case of mixtures which are broadly distributed in size and/or density, it summarizes the effects of particle size and solids density.

(4) Based on the mean terminal velocities a modified definition of a segregation intensity is suggested which considers the uneven distribution of the bed mass in the riser. It may be used to quantify the extent of solids segregation in CFB risers for experiments conducted at varied operating conditions. Increasing superficial gas velocities are found to lead to less segregation in the riser.

(5) Two different bed materials will exhibit the same solids segregation patterns if the distributions of the particles' terminal velocities in both materials are the same.

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Notation

$d_{p,50}$ = 50% value of the cumulative particle size distribution, m
g = gravity acceleration, m^2/s
G_s = solids circulation rate, kg/m^2·s
h = vertical coordinate measured from the gas distributor, m
H_t = total height of riser, m
m_s = solids mass, kg
r = radial distance from riser axis, m
R = riser radius, m
u = superficial gas velocity, m/s
V_s = solids volume, m^3
υ = kinematic viscosity, m^2/s
ρ_g = gas density, kg/m^3
mix = mixture
sand = quartz sand
tot = total related to CFB inventory

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