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Characteristics of axial and radial segregation of single and mixed particle system based on terminal settling velocity in the riser of a circulating fluidized bed

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ABSTRACT

Axial and radial segregation and mixing of single and mixed particle systems were studied for the various sizes and densities in a 10.16 cm diameter riser of a circulating fluidized bed (CFB) based on terminal settling velocity of particles. The gas velocities were maintained in the range of 2.01–4.681 m/s and solid circulation rate between 12.5 and 50 kg/m^{2}s. Three quartz sand–FCC catalyst mixtures with different initial weight % of sand and two coal–iron ore mixtures were used. The difference in local mean particle sizes of the components of the binary mixture has been observed in the riser of a CFB. Due to the larger mean particle size of sand and due to their lower solid density, the measured particle sizes of this fraction show higher values than FCC. For the same size of bed materials consisting of coal and iron ore mixture the variation of the mean particle size for both has been found to be very narrow. Again the axial segregation for the coal/iron ore mixture has been studied in terms of terminal settling velocity of the particles. The result showed a continuous classification of bed materials along the riser of a CFB.

1. Introduction

The advantages of circulating fluidized bed (CFB) reactors like high gas–solid mass transfer and low-pressure drop helps to use them in many chemical processes industries. Among them the applications for non-catalytic gas–solid reactions and the solid-catalyzed gas-phase reactions have to be distinguished due to their different solid characteristics and their significantly operating characteristics. The common feature in this CFB application is that they are operated with bed solids that are not identical. When dissimilar solids with wide size distribution and/or different solid densities are fluidized, segregation of solids occur. The fluidizing gas elutriates the lighter and smaller particles, while the denser and heavier particles sink at the lower level. Gas turbulences as well as interaction of the upward flowing gas solid suspensions with the downward moving solids in the form of strands or clusters lead to mixing of particles. Due to this opposing tendencies a dynamic equilibrium forms.

The growing interest on CFB technology needs the knowledge of radial and axial segregation based on terminal settling velocity. Sometimes in CFB applications solid segregation is ignored and in others it is desirable to achieve complete segregation and mixing in different parts of the equipment, e.g. CFB combustors, CIRCOFER iron ore reduction process, Bressar et al. [1]. The inventory of a CFB coal combustor consists of various solids like coal, ash, limestone and inert materials of various sizes and densities. Measurements of particles sizes in industrial combustors by Herbertz et al. [2], Johnsson and Leckner [3], and Na et al. [4] 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 larger feed coal or coke particles remain preferentially in the bottom part of the riser. Werther and Hirschberg [5] analyzing their experimental data of iron ore powder/quartz sand mixture in the CFB suggested that terminal velocity distribution of the bed material is the most decisive parameter for segregation effects.

In this work, the mixing and segregation pattern in circulating fluidized bed consisting of (FCC catalyst—Geldart's group A type) and (coal, iron ore and sand—Geldart's group B type) particles having different density, size distributions and terminal settling velocity were investigated using a 0.1016 m ID and 5.62 m height riser of CFB system. Attention has been focused on understanding the interaction and mechanism between the particles and the conditions in which complete mixing or segregation is possible in

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Nomenclature

c_w	drag coefficient
$\overline{c_v}$	cross-sectional averaged solid volume concentration
d_p	diameter (m)
g	gravity acceleration (m^2/s)
G_s	solid circulation rate (kg/m^3)
h	vertical coordinate measured from the gas distributor (m)
H	vertical location measured from the gas distributor (m)
L_p	mean free path between two inter-particle collisions (m)
m	mass (kg)
Δp	pressure drop (Pa)
Δp_{riser}	total pressure drop along the riser length (Pa)
$Q_3(d_p)$	cumulative particle size distribution in mass
$Q_3(U_t)$	cumulative single-particle terminal velocity distribution
r	radial distance from riser axis (m)
R	riser distance (m)
Re_t	Reynolds number of particle
S	segregation intensity
U	superficial gas velocity (m/s)
U_t	single-particle terminal velocity (m/s)
$U_{t,50}$	ocal mean terminal velocity (50% value of the $Q_3(U_t)$ distribution (m/s)
V	volume (kg/m^3)
x	the ratio of coarse particle to mixed particles in volume

Greek letters

ε	cross-sectional averaged voidage
$\overline{\varepsilon_{riser}}$	mean cross-sectional averaged voidage in the riser
μ	solid volume fraction
$\overline{\mu_{riser}}$	mean solid volume fraction averaged long the riser
ξ_1	mass fraction of component 1
ρ	density (kg/m^3)

Subscripts

0	loading at the beginning of operation
c	coarse particles
f	fine particles
g	gas particle
mix	mixture
S	solids
t	total

CFB's. Axial and radial solid segregation is investigated in details. Segregation studies were carried out in terms of:

(i) Mean particle size distribution.
(ii) Terminal settling velocity.

2. Experimental set-up and techniques

2.1. Details of set-up and experimental procedure

The schematic diagram of the experimental set-up is shown in Fig. 1. A circulating fluidized bed made of perspex tube was fabricated and used as the experimental apparatus. The detailed equipment characteristic is listed in Table 1. It consisted of a riser, a cyclone and a bag filter to separate the fines, a down comer, a slow bed and the transfer line connecting the slow and fast bed. The solid after passing through the fast bed in the riser gets separated in the cyclone and bag filter, descend downwards through the down comer and are collected in the slow bed and then transferred back into the riser. Air, at controlled rates, is supplied to the fast bed (0.1015 m diameter × 5.83 m in height) from a root blower through a multi hole distributor plate having 12-percentage open area. A small amount of air from a bypass line is also sent to the slow bed to keep it at minimum fluidizing condition. For smooth transfer of aerated solids into the riser back, a transfer line inclined at 60° with the horizontal and having a control valve to regulate the flow of solids independently, have been used. In most of the work reported earlier L valve has been used; this however used to give a large variation in the pressure drop compared to the smooth flow reported here. Various procedures have been reported in the literature to measure the solids circulation rate but in the present case a butter fly valve is used for obvious reasons like simplicity in operation and no loss in the solids that are circulated back into the riser. For pressure drop measurements 24 pressure taps are located along the CFB loop. The superficial gas velocities into the riser and slow beds are measured by pressure drop measurements across standard calibrated orifice meters installed in the air supply lines. Solid sampling probes are installed at heights (h = 0.67, 1.20, 1.79, 3.66, 4.3, 4.77 and 5.09 m) above the distributor. Non-isokinetic sampling technique was adopted to withdraw samples using probes similar in construction as reported by Rhodes et al. [6]. The probe is made of steel tube of 4 mm in diameter and its long end is threaded so that it can be moved forward and backward in to the bed to permit solid collections at various radial positions. Solids are generally withdrawn by suction through a vacuum pump and a calibrated rotameter and collected in a sampling vessel for subsequent off-line detailed analysis, i.e. the solid composition and the local particle size distribution. The schematic diagram of the probe assembly is shown in Fig. 2. Das et al. [7] reported the works with sand and FCC particles having wide size distribution with the sampling probe pointed both upwards and downwards and at different axial position of riser collected solid samples and concluded that suction condition does not have any significant influence on the compositions of the samples collected. A photographic view of the experimental set-up of CFB riser is shown in Fig. 3.

2.2. Radial and axial segregation experimental methods and operating conditions

Experiments were conducted for five different bed materials that are presented in Table 2. To carryout the segregation and mixing experiments solid sampling probes are installed at heights 0.67, 1.20, 1.79, 3.66, 4.3, 4.77 and 5.09 m above the distributor. The probe is made of steel tube of 4 mm in diameter and its one end is threaded for 5.08 cm so that it can be moved forward and backward into the bed to for collection of solids at various radial positions. Solids are generally withdrawn by suction through a vacuum pump and a calibrated rotameter and collected in a sampling vessel for subsequent off-line detailed solid composition and the local particle size distribution analysis.

Experiments were carried out with five different bed materials. The desired fractions of sample are prepared by grinding and screening the materials through the various wire mesh sieves. The first class of bed material is composed of quarts sand and spent FCC catalyst. Three samples of sand–spent FCC mixture each of 18.0 kg inventory with various mass percentage of sand ranging from 20 to 80% were used. Two class of bed material each of 18.0 kg comprises of a binary mixture of coal (80% by weight) and iron ore

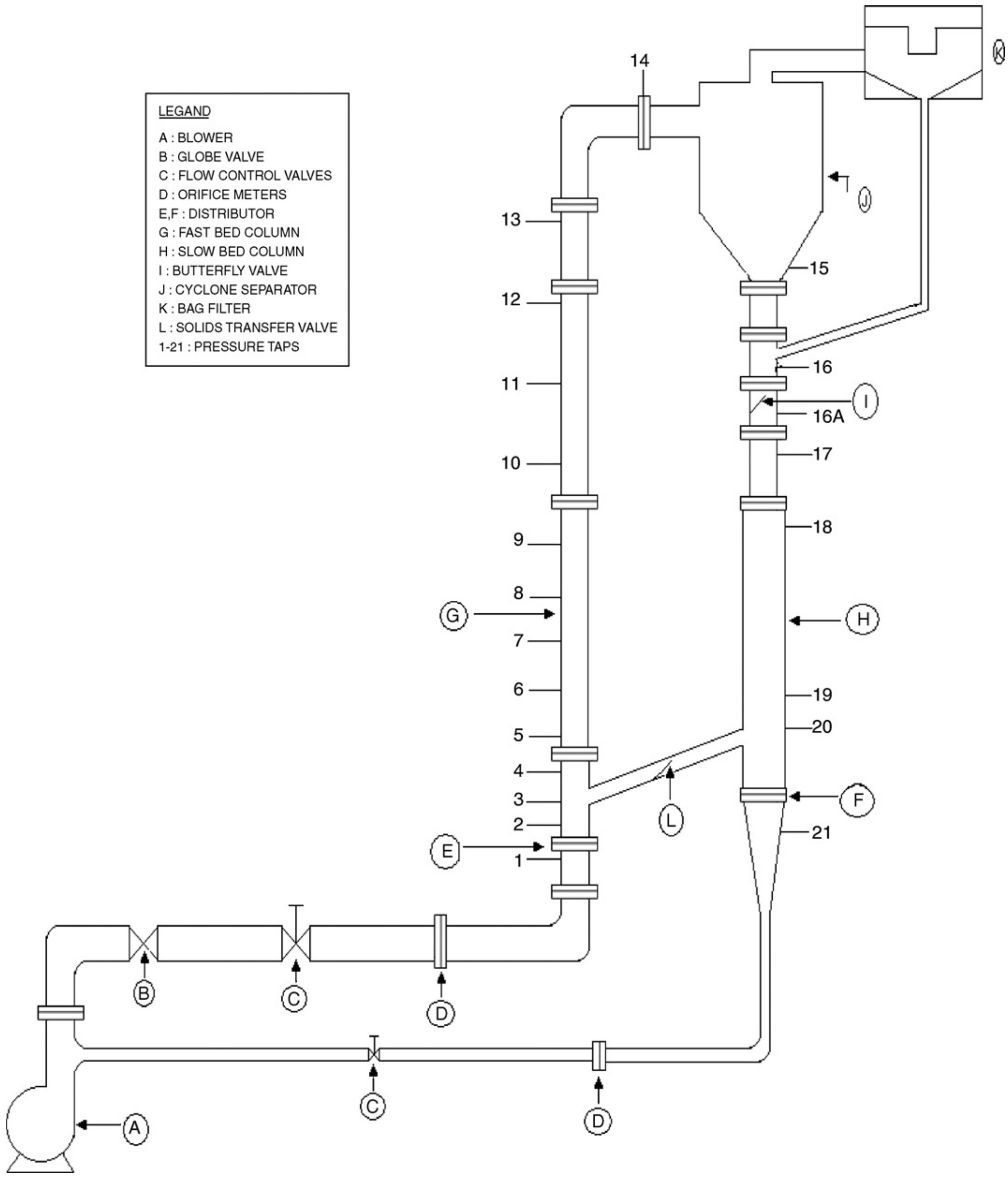

Fig. 1. Schematic of the experimental set-up.

(20% by weight). The later class of bed material thus has differences both in sizes and densities and the same size but different in densities. The cumulative particle size distributions in mass of the different solids were measured with a laser particle sizer (Malvern, type 3600). In the present study the solid compositions for both binary mixtures are given in terms of mass fractions of the heavier component, i.e. wt% of sand of the sand–spent FCC catalyst mixture. For the iron ore–coal mixture wt% of iron ore of iron ore–coal mixture was taken. The solid compositions of the sand–spent FCC catalyst were determined by measurements of solid density of the sampled solid particles in a helium pyconometer. The solid compositions of iron ore and coal mixtures were determined by separating them in a float and sink test using bromoform–CCl_4 mixture of appropriate density and taking weight of each separated fractions. All experiments were carried out at a steady state conditions. The total inventory of 18.0 kg of solids was put into the slow bed and the air is allowed to pass through the beds by keeping solid transfer line open at a known calibrated position. The mixing process was monitored by continuous sampling of solids at a given location of height = 0.67 m above the distributor plate at a radial position of $r/R = 0$, i.e. on the central axis of the riser. It was found that the local solid compositions in terms of heavier mass fractions remain constant after 30 min of operation of the apparatus. All data in the present study were taken only after that stipulated period to overcome the fluctuations of solid composition and the system attained a steady state.

Table 1
Equipment characteristics

	Riser column	Slow bed column	Solid transfer line	Cyclone	Re-circulating column
Diameter (m)	0.1016	0.2032	0.1016	0.258	0.1016
Height (m)	5.62	1.88	0.42	0.99	2.22

Table 2
Physical properties of bed material used

Bed materials	Solid density (kg/m^3)	Mean particle size $d_{p,50}$ (μm) (Sauter diameter, μm)	CFB inventory (kg)	Initial bed composition (ξ_{tot}) (mass%)	Superficial gas velocity range (m/s)	Solids circulation rate range, (kg/m^2 s)	Geldart type
Sand	2668	480 (471.2)	3.60	20	2.907–4.681	24.75–50	B
FCC	1672	135 (119.6)	14.40	80			A
Sand	2668	480 (471.2)	9.00	50	2.907–4.681	24.75–50	B
FCC	1672	135 (119.6)	9.00	50			A
Sand	2668	480 (471.2)	3.60	75	2.907–4.681	24.75–50	B
FCC	1672	135 (119.6)	14.40	25			A
Coal	1530	348 (335.33)	14.4	80	2.01–3.48	23–44	B
Iron ore	5192	165 (140.48)	3.6	20			B
Coal	1530	242 (168)	14.4	80	2.01–4.02	12.5–42	B
Iron ore	5192	198 (166)	3.6	20			B

The solid densities of the sampled binary mixture can be expressed as a function of mass fraction of individual components and their pure component densities according to the following relations:

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

Both the % mass axial composition of the mixtures as well as their size distribution were determined. The ranges of experimental conditions are given in Table 2 for each material tested. The cumulative particle size distribution in mass of the different solid (Figs. 4 and 5) was measured with a laser particle sizer (Malvern, type 3601). If sedimentation of single spheres in air at ambient conditions is assumed, the particle size d_p can be converted to single-particle terminal velocities U_t (m/s) according to

$$U_t = \sqrt{\frac{4(\rho_s-\rho_g)gd_p}{3c_w(Re_t)\rho_g}} \quad (2)$$

with the correlation of the drag coefficient suggested by Brauer [8]

$$C_w(Re_t) = \frac{24}{Re_t} + \frac{4}{\sqrt{Re_t}} + 0.4 \quad (3)$$

Re_t is the particles' Reynolds number

$$Re_t = \frac{U_t d_p}{\nu} \quad (4)$$

Eqs. (2)–(4) have been used to determine the single-particle terminal velocity distributions $Q_{3sand}(U_t)$, $Q_{3FCC}(U_t)$, $Q_{3coal}(U_t)$ and $Q_{3iron}(U_t)$ shown in Figs. 6–10. The terminal velocity distribution of the sampled mixture $Q_{3,mix}(U_t)$ can be determined from

$$Q_{3,mix}(U_t) = \xi_{iron}Q_{3,iron}(U_t) + (1-\xi_{iron})Q_{3,coal}(U_t) \quad (5)$$

where ξ_{iron} denotes the local solid composition in terms of mass fractions of iron ore powder. For the present case, the terminal velocity distribution of the mixture (coal-iron ore) determined with the measure ξ_{iron} = 20 mass% is shown in Figs. 9 and 10.

All experiments were carried out at steady state conditions. The total inventory of 18 kg of solids was put into the slow bed and the blower started with solid transfer line kept opened at a known calibrated position. The mixing process was monitored by continuous sampling of solids at a given location of h = 0.67 m above the distributor plate at one radial position of r/R = 0, i.e. on the axis of the riser with the tip of the probe pointed downwards to collect only

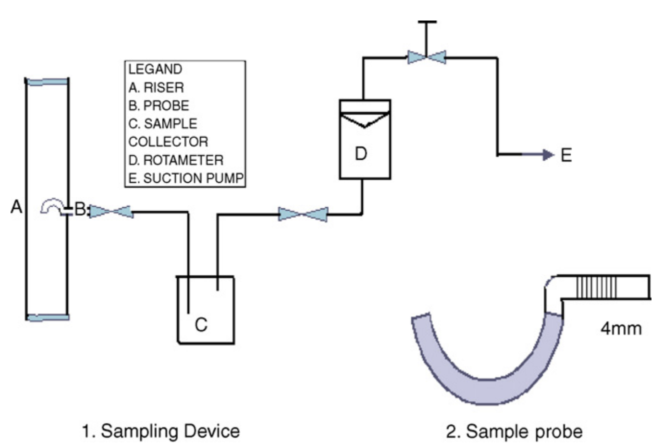

Fig. 2. Schematic diagram of sampling system in measuring radial solid flux.

Fig. 3. Photographic view of the experimental set-up of the riser of a circulating fluidized bed.

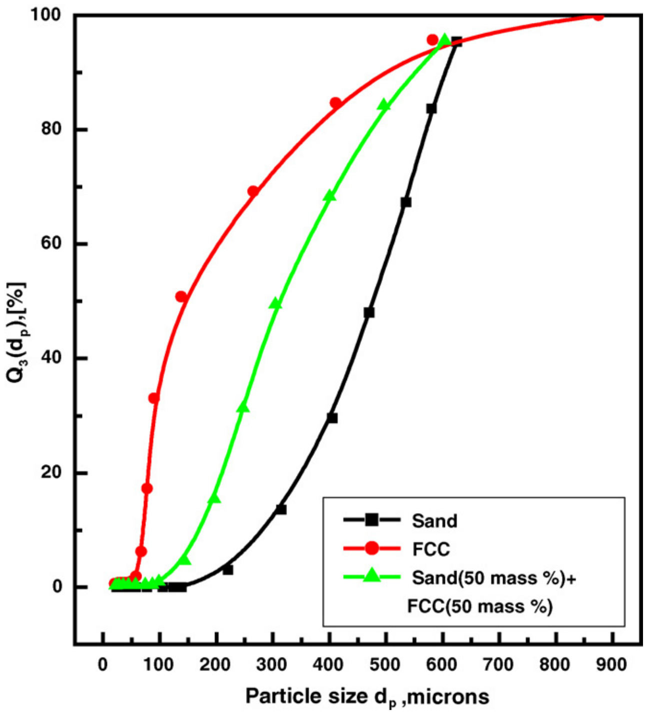

Fig. 4. Cumulative particle size distribution, $Q_3(d_P)$, of the FCC/sand mixture (ξ_{tot} = 50 mass% sand).

the upward flowing solids. It was found that the local solid compositions in terms of the heavier mass fractions remain constant after 30 min of operation of the apparatus. All data in the present study were taken only after that stipulated period was over and the system attained a steady state.

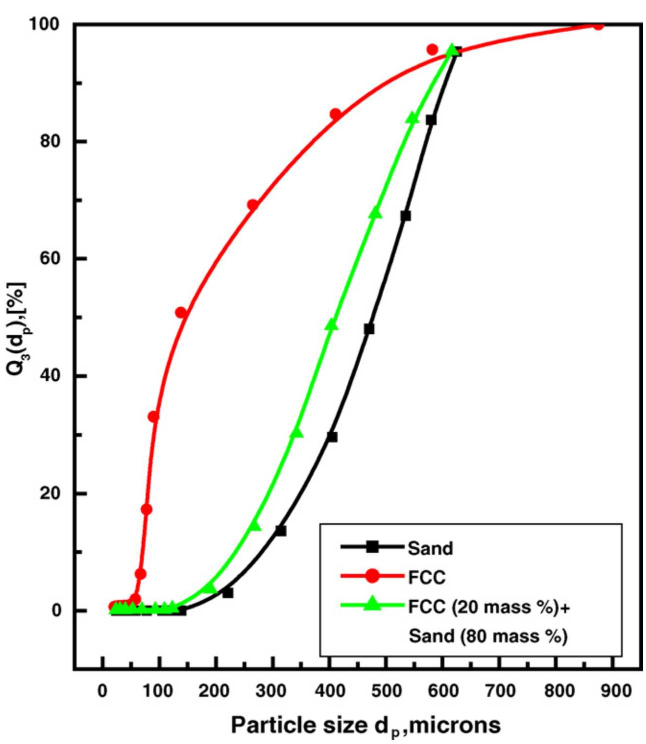

Fig. 5. Cumulative particle size distribution, $Q_3(d_P)$, of the FCC/sand mixture (ξ_{tot} = 80 mass% sand).

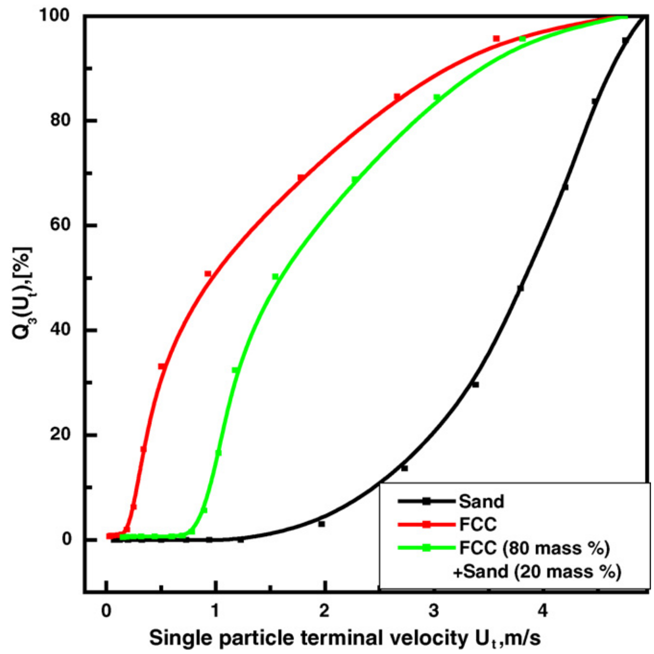

Fig. 6. Cumulative terminal velocity distribution, $Q_3(u_t)$, of the FCC/sand mixture (ξ_{tot} = 20 mass% sand).

3. Results and discussions

3.1. Segregation in terms of mean particle size distribution

Beside the variation of the local solids composition along the riser height, differences of the local mean particle size have been observed. They are separately shown in Figs. 11–16 for the sampled FCC–sand and iron ore powder–coal of same as

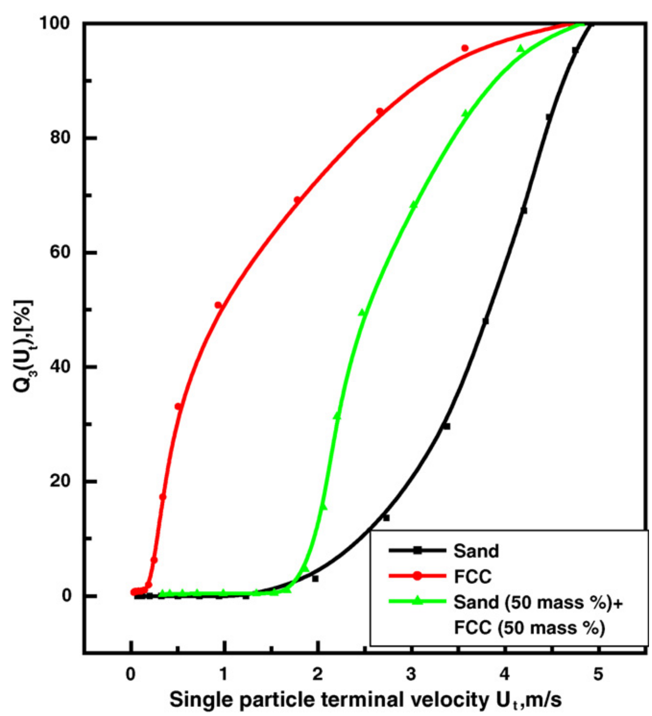

Fig. 7. Cumulative terminal velocity distribution, $Q_3(u_t)$, of the FCC/sand mixture (ξ_{tot} = 50 mass% sand).

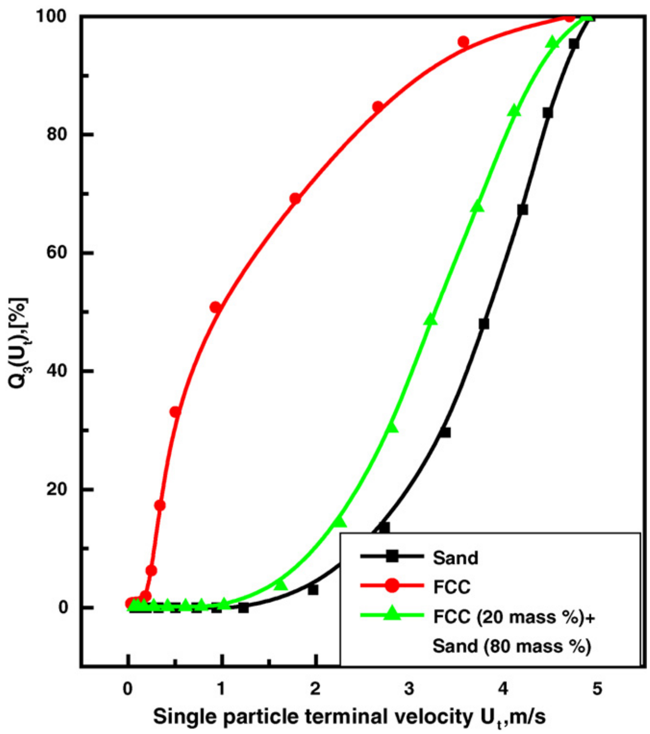

Fig. 8. Cumulative terminal velocity distribution, $Q_3(u_t)$, of the FCC/sand mixture (ξ_{tot} = 80 mass% sand).

well as varied size distributions. Due to the larger mean particle size of sand and due to their higher solids density, the measured particle sizes of this fraction show higher values than FCC.

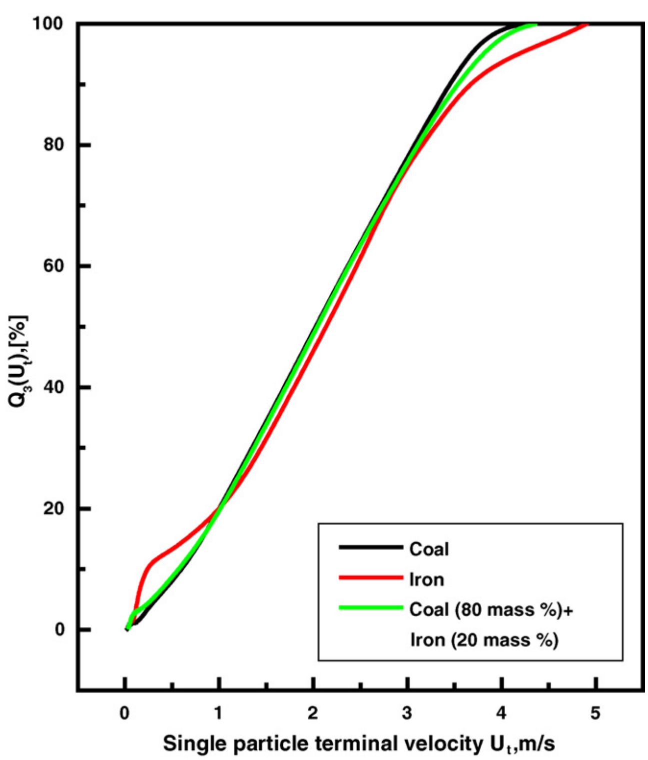

Fig. 9. Cumulative terminal velocity distribution, $Q_3(u_t)$, of the coal/iron ore mixture (ξ_{tot} = 20 mass% iron ore,$d_{p,iron}$ = 140.84 μm).

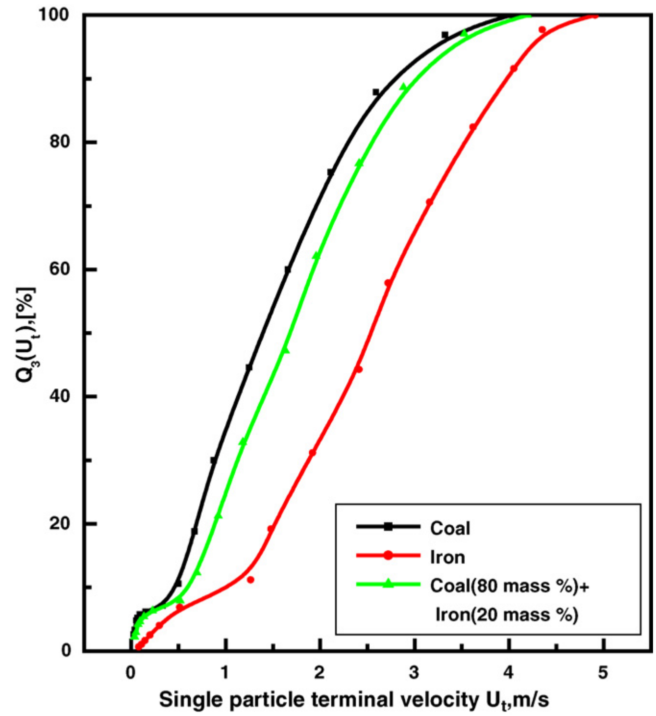

Fig. 10. Cumulative terminal velocity distribution, $Q_3(u_t)$, of the coal/iron ore mixture (ξ_{tot} = 20 mass% iron ore,$d_{p,iron}$ = 166 μm).

3.2. Axial segregation of coal/iron ore mixture in terms of terminal settling velocity

To study the axial segregation in terms of the terminal settling velocity, the separated components of iron ore and coal were treated in a laser particle sizer (Malvern Instrument, type 3601). It is seen that there is a significant variation in the local mean particle size along the riser. These mean particle sizes are then converted to

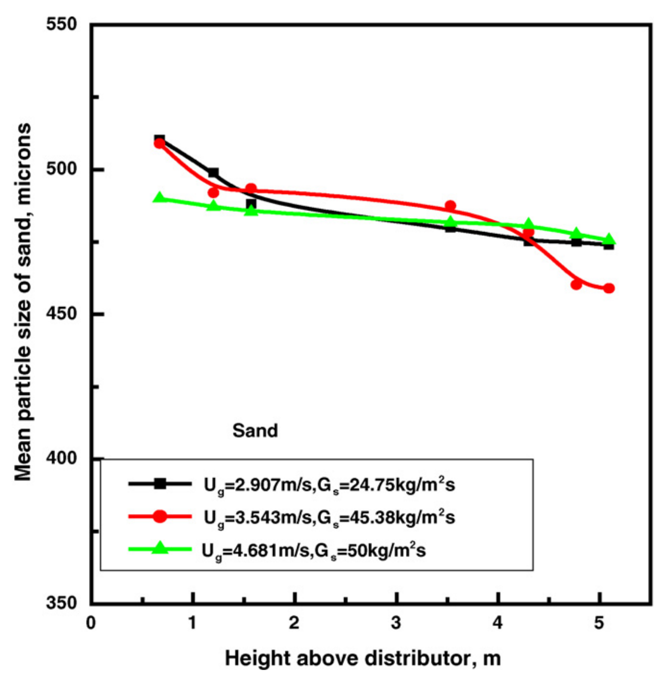

Fig. 11. Local mean particle size of sand in the upflow (sampled at r/R = 0) for the binary mixture of FCC and sand.

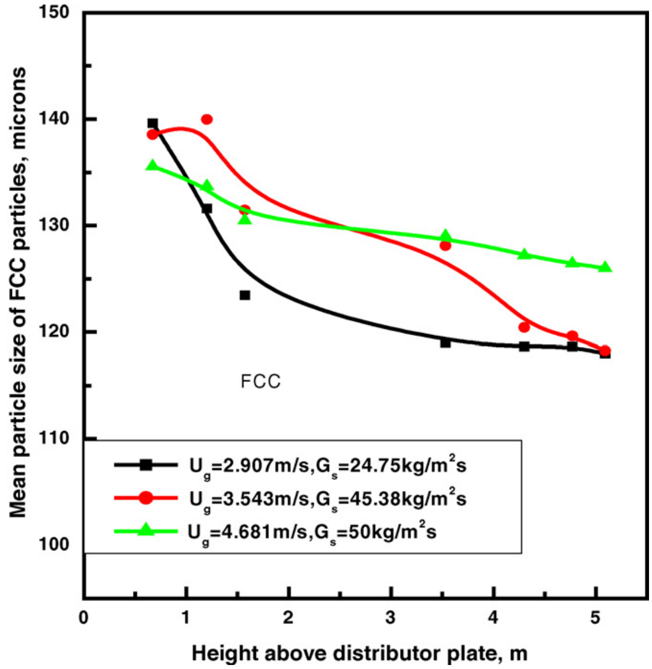

Fig. 12. Local mean particle size of FCC in the upflow (sampled at $r/R = 0$) for the binary mixture of FCC and sand.

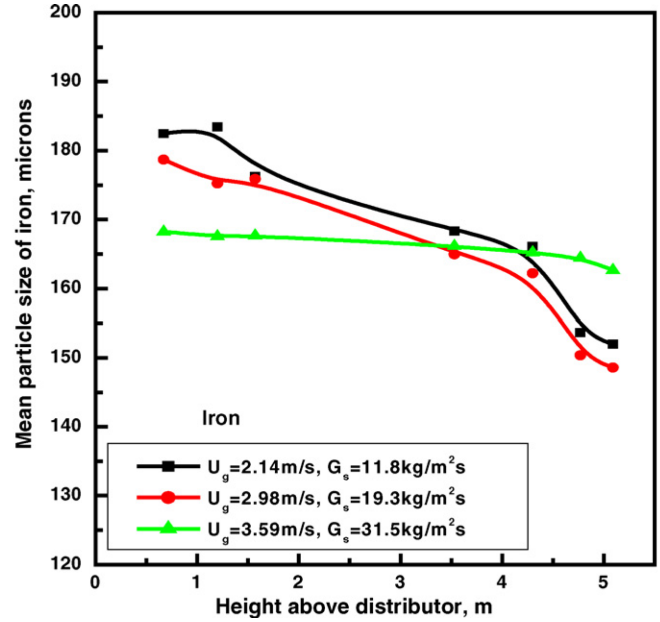

Fig. 14. Local mean particle sizes of iron ore in the upward flow (sampled at $r/R = 0$) for the binary mixture of coal and iron ore ($\xi_{\text{iron}} = 20$ mass%,$d_{\text{p,iron}} = 140.84\,\mu$m).

cumulative single-particle terminal velocity distribution in mass, $Q_3(U_t)$, by applying Eqs. (2)–(4).

The local single-particle terminal velocity distributions for seven different axial positions along with the inventory are presented in Fig. 17. It is apparent that axial segregation causes separation of 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 ($h = 0.67$ m) and at the riser top ($h = 5.09$ m). In Fig. 17 if 95% value is considered as the upper limit of the distribution, it can be concluded that in the bottom region of the riser ($h = 0.67$ m) particles are present with terminal velocity up to 3.97 m/s (95% value), while the samples taken at the top ($h = 5.09$ m) consist only of 2.04 m/s (95% value). 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 high

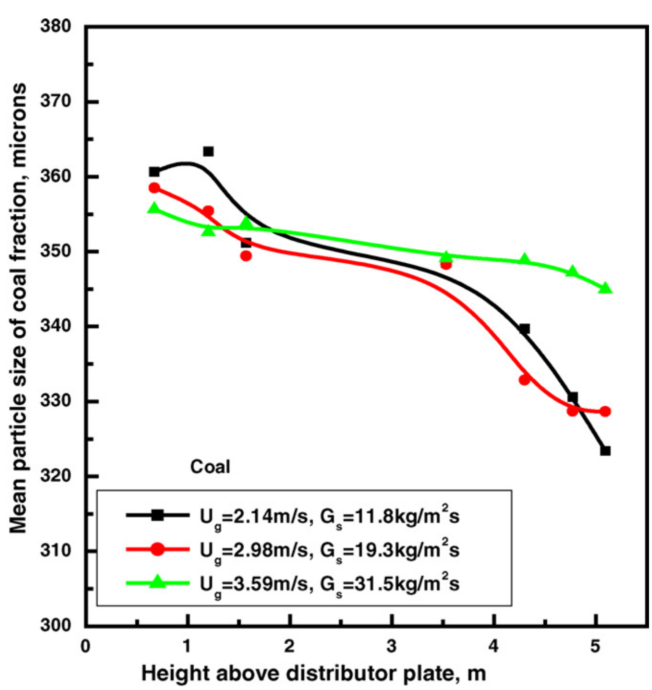

Fig. 13. Local mean particle sizes of coal in the upward flow (sampled at $r/R = 0$) for the binary mixture of coal and iron ore ($\xi_{\text{iron}} = 20$ mass%,$d_{\text{p,iron}} = 140.84\,\mu$m).

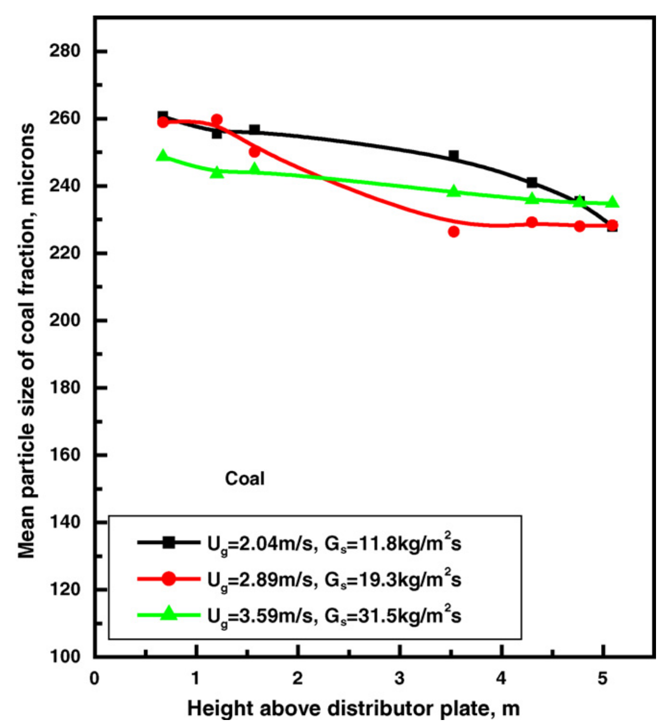

Fig. 15. Local mean particle sizes of coal in the upward flow (sampled at $r/R = 0$) for the binary mixture of coal and iron ore ($\xi_{\text{iron}} = 20$ mass%,$d_{\text{p,iron}} = 168\,\mu$m).

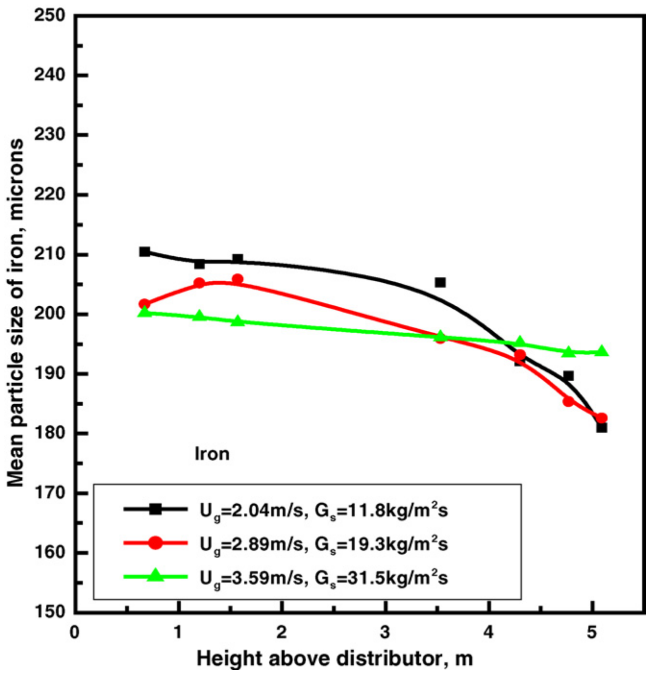

Fig. 16. Local mean particle sizes of iron ore in the upward flow (sampled at $r/R = 0$) for the binary mixture of coal and iron ore ($\xi_{iron} = 20$ mass%, $d_{p,iron} = 168$ μm).

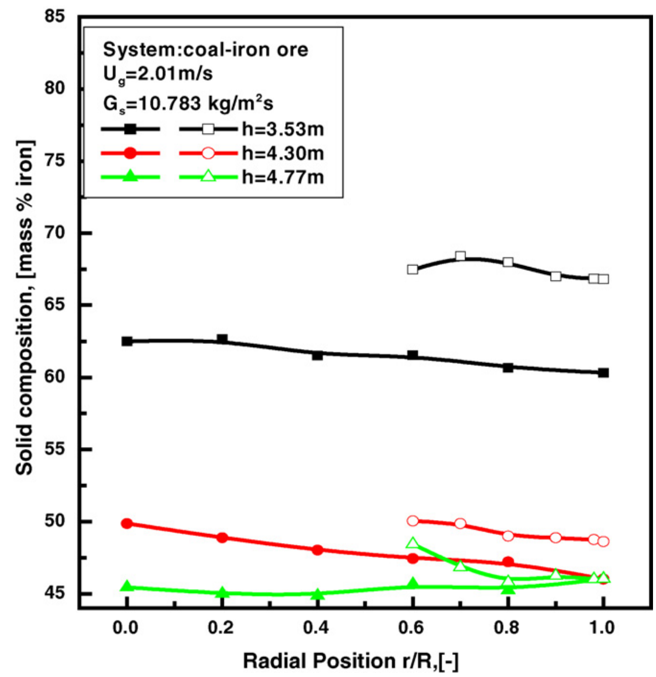

Fig. 18. Local solids compositions, ξ_{iron}, in the upward (solids symbols) and downward flow (open symbols) for the binary mixture of coal/iron ore mixture ($\xi_{iron} = 20$ mass%).

solid concentration and interaction with various particles even particles with terminal velocity 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 solid concentration and thus decreasing gas velocities. Preferentially particles with large terminal velocities may leave the upward 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 down flowing clusters into the upflow stream.

4. Segregation intensity based on solid composition

Investigation on solids segregation in the literature (Rowe et al. [9], Nienow et al. [10], Baeyens and Galdart [11], Hofman and Romp [12], Hofman et al. [13]) involving batch FB and CFBs is mainly limited to binary mixtures consisting of coarse and fine particles. The observed segregation tendencies are usually presented in terms of fractions of the coarse particles along the riser. Bai et al. [14] defined

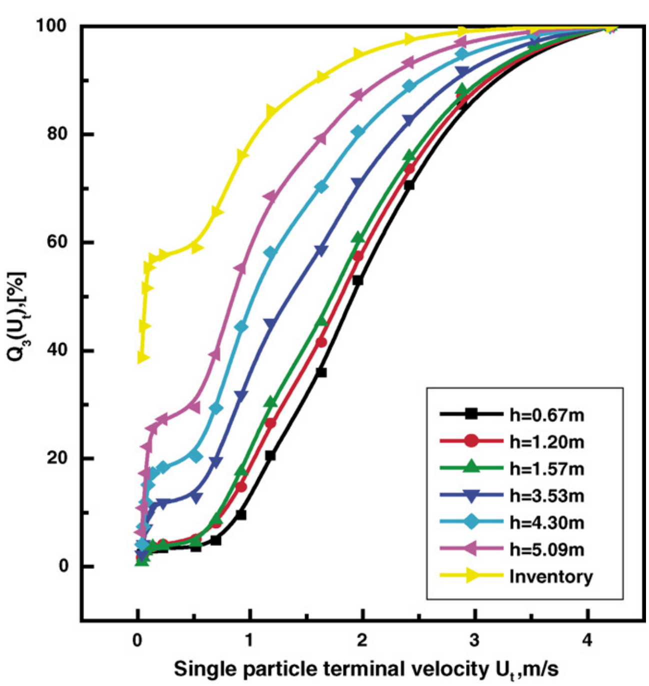

Fig. 17. Local single-particle terminal velocity distribution, $Q_3U(t)$ of a binary mixture of 80% coal and 20% iron ore at ($r/R = 0$) at $U = 1.27$ m/s and $G = 5.5$ kg/(m^2 s).

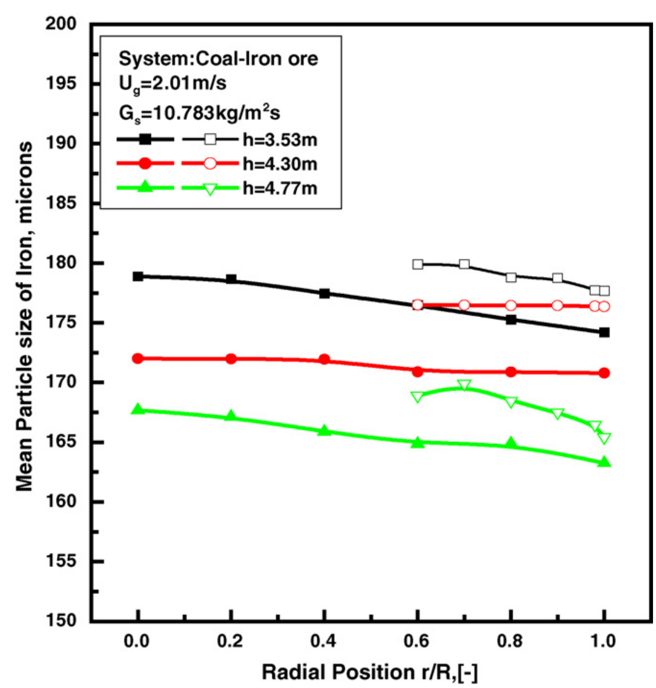

Fig. 19. Local mean particle size of iron ore, ξ_{iron}, in the upward (solids symbols) and downward flow (open symbols) for the binary mixture of coal/iron ore mixture.

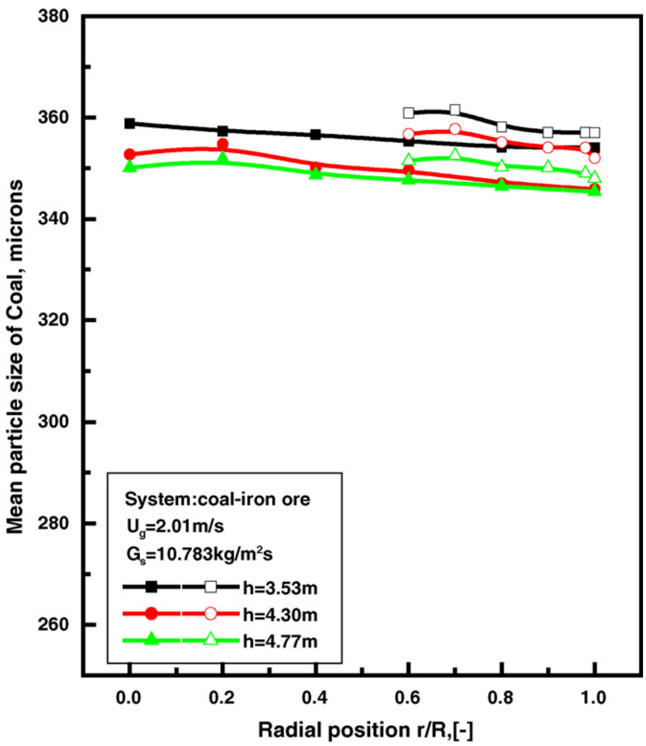

Fig. 20. Local mean particle size of coal in the upward (solids symbols) and downward flow (open symbols) for the binary mixture of coal/iron ore mixture.

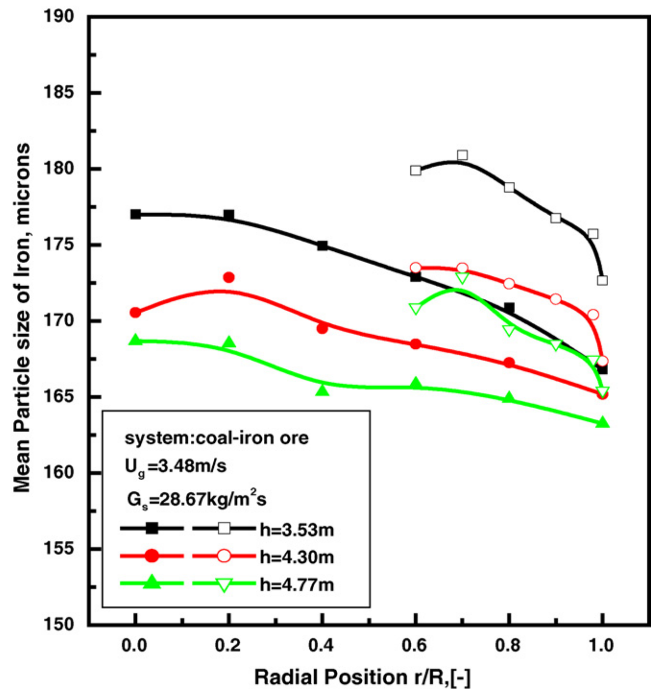

Fig. 22. Local mean particle size of iron ore, ξ_{iron}, in the upward (solids symbols) and downward flow (open symbols) for the binary mixture of coal/iron ore mixture ($\xi_{\text{iron}} = 20$ mass%).

the segregation intensity as the integral along the riser height of the normalized differences between the local volume fractions of coarse particle, $\mu(h)$, and the mean volume fraction of coarse particles in the whole CFB riser, μ_{riser}. Mathematically S, is defined by:

$$S = \frac{1}{H_t}\int_0^{H_t}\left(\frac{\mu(h)-\mu_{\text{riser}}}{\mu_{\text{riser}}}\right)^2 \mathrm{d}h \quad (6)$$

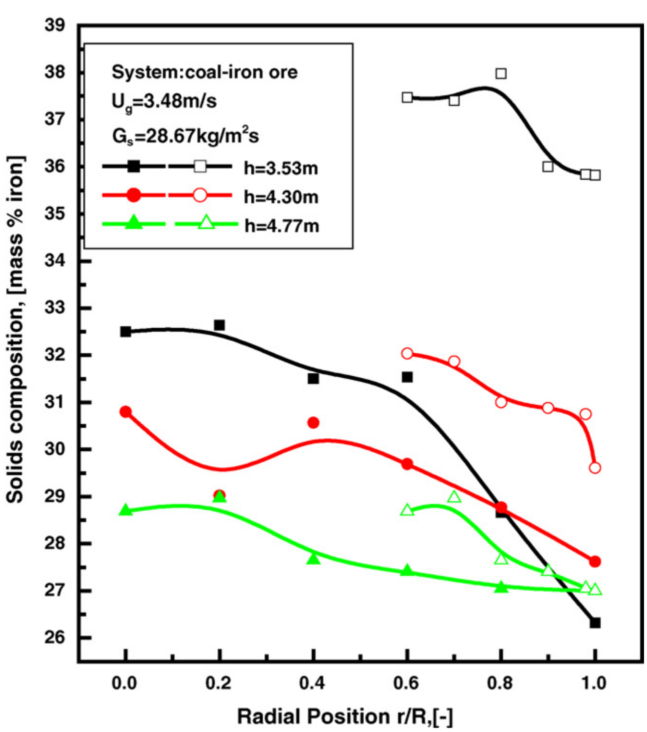

Fig. 21. Local solids compositions, ξ_{iron}, in the upward (solids symbols) and downward flow (open symbols) for the binary mixture of coal/iron ore mixture ($\xi_{\text{iron}} = 20$ mass%).

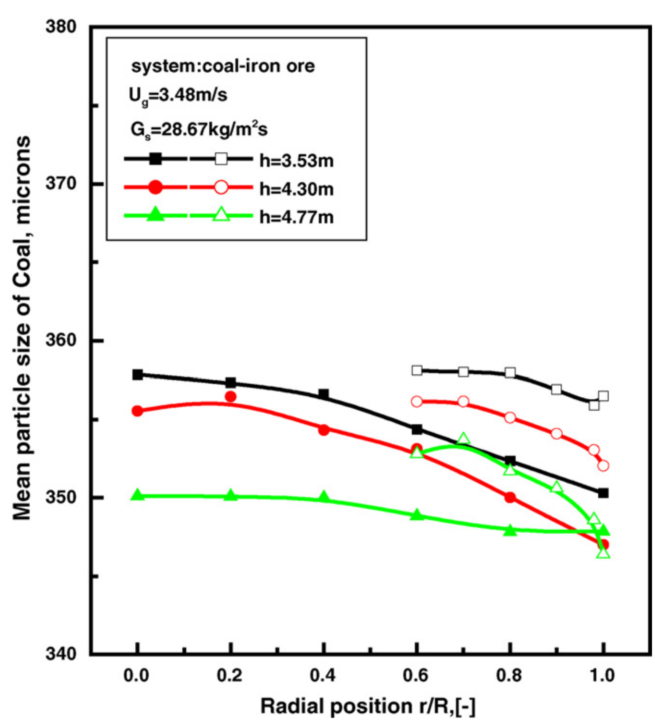

Fig. 23. Local mean particle size of coal in the upward (solids symbols) and downward flow (open symbols) for the binary mixture of coal/iron ore mixture ($\xi_{\text{iron}} = 20$ mass%).

and μ_{riser} can be determined as

$$\mu_{\text{riser}} = \frac{V_{\text{coarse,riser}}}{V_{\text{s,riser}}} = \frac{1}{H_t(1-\varepsilon_{\text{riser}})}\int_0^{H_t} \mu(h)\{1-\varepsilon(h)\}\,dh \quad (7)$$

The local cross-sectional averaged voidage $\varepsilon(h)$ is determined by measurement of the axial pressure profile, $\Delta P(h)$, along the riser. Under the assumption that acceleration effects and wall friction are neglected the local voidage can be calculated as follows:

$$1-\varepsilon(h) = \frac{\Delta P(h)}{(\rho_s-\rho_g)g\Delta h} \quad (8)$$

and the respective mean cross-sectional average voidage in the riser, $\varepsilon_{\text{riser,}}$ can be calculated by:

$$1-\varepsilon_{\text{riser}} = \frac{\Delta P_{\text{riser}}}{(\rho_s-\rho_g)gH_t} \quad (9)$$

where ΔP_{riser} is the total pressure drop along the entire riser length. S describes the degree of segregation according to the axial distribution of the coarse component of the riser. Thus, perfect mixing is reached when S equals to 0 and higher values indicate more segregation. Here S describes the segregation according to the presence of coarser fraction particles in the riser. The definition is better applicable to particle mixtures of equal particle sizes or mixtures of two components with widely differing mean particle sizes. A practical CFB is usually operated with particle mixtures of continuous and broad particle distribution with two or more species of different solid densities that exhibit axial segregation depending on size and density. Werther and Hirschberg [5] however, used bed materials having variations both in size and density, which are likely to be prevalent in industrial CFBs. To consider the cases more appropriate to their experimental conditions they suggested the single-particle terminal velocity as the decisive parameter in determining the segregation characteristics in the riser. The physical basis of this suggestion is that CFB riser, which is considered here, is characterized by very low solids volume concentrations. In the upper part of the riser solids volume concentrations, mixtures of C_v, are present of the order of 0.1–1%. According to Sinclair and Jackson [15], the mean free path of the particles $l_p(m)$ between two inter-particle collisions may be calculated from kinetic theory using

$$l_p = \frac{d_p}{6\bar{c_v}\sqrt{2}} \quad (10)$$

This means that the ratio of the average centre to centre 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 0.1–1%. Under these conditions, the particles have some freedom of individual movement along the course of inter-particle collisions which 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 FCC and sand and coal and iron ore of same and different size distributions. By subsequent off-line analysis, the samples' characteristics, that is, the solids composition and local particle size distribution, are measured. In accordance with the modified definition of the segregation intensity may now be used, 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 solid density. If the solid composition, $\mu(h)$, and μ_{riser} of Eq. (6) are replaced by the respective terminal velocities, $U_{t,50(h)}$ and $U_{\text{t,riser,}}$ the segregation intensity (Das et al. [16]))based on terminal velocity would be given by:

$$S = \frac{1}{H_t}\int_0^{H_t}\left(\frac{U_{t,50(h)}-U_{\text{t,riser}}}{U_{\text{t,riser}}}\right)^2 dh \quad (11)$$

where $U_{t,50(h)}$ is the local mean terminal velocity and $U_{\text{t,riser}}$ is the average mean terminal velocity in the whole CFB riser.

The equation for calculation of $U_{\text{t,riser}}$ by Bai et al. [14] is modified as:

$$U_{\text{t,riser}} = \frac{1}{H_t(1-\varepsilon_{\text{riser}})}\int_0^{H_t} U_{t,50(h)}\{1-\varepsilon(h)\}\,dh \quad (12)$$

The above Eq. (12) presents the segregation intensity based on terminal velocity. Perfect mixing is reached if every measured value of $U_{t,50(h)}$ along the riser would equal to $U_{\text{t,riser.}}$ When segregation occurs, the measured values, $U_{t,50(h)}$ differ from $U_{\text{t,riser}}$ and higher values of the segregation intensity indicate the degree of segregation.

5. Radial segregation of coal and iron ore

Radial segregation is discussed for experiments with the binary mixture of coal and iron ore at a gas velocity of 2.01 and 3.48 m/s and a G_s = 10.783 and 28.67 kg/(m^2 s), respectively. Detailed measurements in the upflow as well as in the downflow are shown in Fig. 18 in terms of solid compositions, ξ_{iron}, along the riser radius samples were taken at three different heights of 3.53, 4.30 and 4.77 m. The upflow was detectable along the entire radius, while descending particles could only be sampled at radial positions from r/R = 0.6 to r/R = 1.0. Within this range, the samples taken at h = 3.53 m from the downward moving particle flux show always higher iron contents than the respective solids upflow. These differences are decreasing with height and at the riser top (h = 4.77 m) samples of both flow directions show almost the same compositions. The corresponding

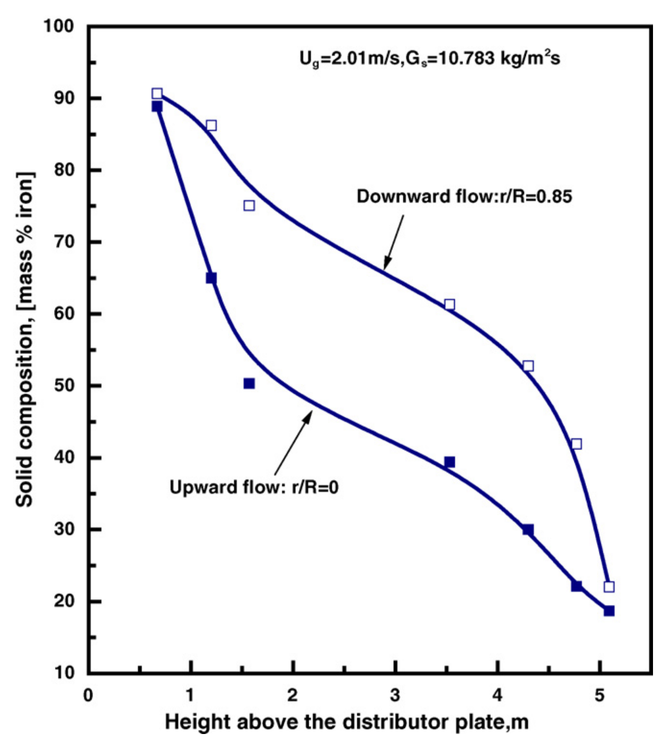

Fig. 24. Comparison of local solids compositions, ξ_{iron}, in the upward (solid symbol, sampled at r/R = 0) and downward flow (open symbol, sampled at r/R = 0.85) for the binary mixture of coal/iron ore mixture (ξ_{tot} = 20 mass% iron ore).

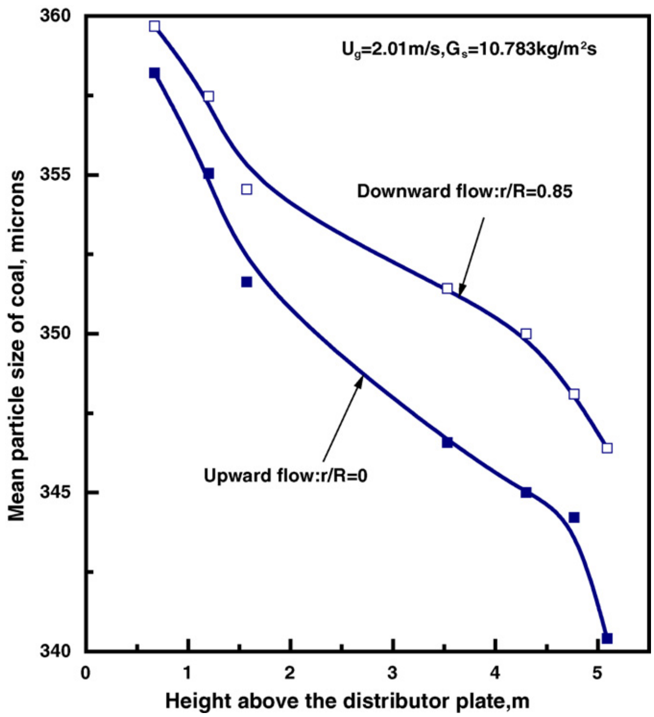

Fig. 25. Comparison of mean particle size of coal in the upward (solid symbol, sampled at $r/R = 0$) and downward flow (open symbol, sampled at $r/R = 0.6$) for the binary mixture of coal/iron mixture (ξ_{tot} = 20 mass% iron ore).

radial profiles of the mean particle sizes of the two components are separately presented in Fig. 19 for the iron ore and coal in Fig. 20. They show uniform particle sizes along the radius, with significant differences between the up- and downflow. The mean particle size of each component in the down flowing stream is always larger than in the upward flow as shown in Figs. 21–23. 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 up- and downflow is limited to a comparison of samples taken at two radial positions, i.e. the upflow samples are taken at $r/R = 0$ on the riser axis and the downflow was sampled at $r/R = 0.85$ near the riser wall. In Figs. 24–26 the solid compositions and particle sizes, respectively, in the upward and downward flowing solids are compared. In accordance with the above-discussed profiles, the downward moving solids show along the riser height higher iron ore powder fractions (Fig. 24) and larger mean particle sizes of each component (Figs. 25 and 26). Following their individual flow direction it can be said that the iron ore powder content and the particle sizes in the upflow are decreasing, while these characteristics of the downflow are increasing. Hence, there must be continuous transfer of large particles and preferentially iron ore powder particles, from the upflow region to the downflow region. Thus, the downflow is fed by segregating particles that are not elutriated by the gas flow in the up flowing core region. 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. The observed segregation tendencies are in accordance with measurements of radial particle size profiles and radial solids composition profiles as reported by Na et al. [4].

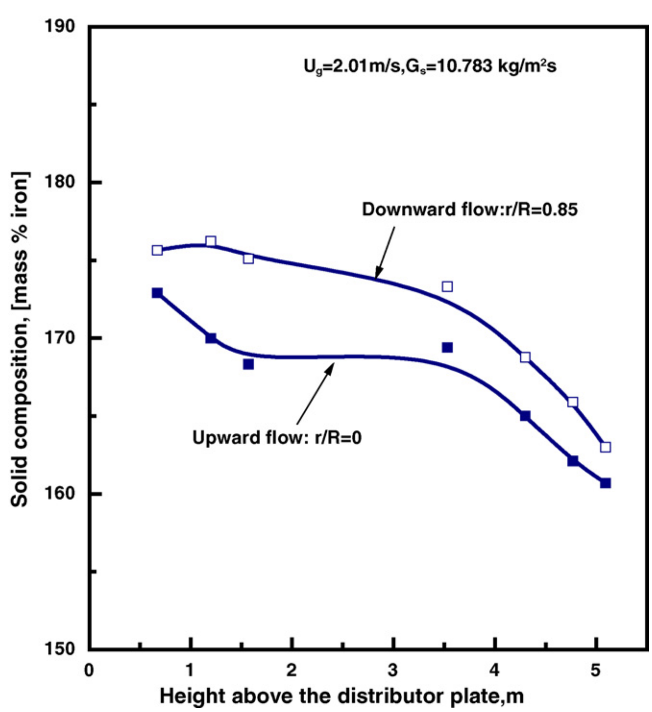

Fig. 26. Comparison of mean particle size of iron ore in the upward (solid symbol, sampled at $r/R = 0$) and downward flow (open symbol, sampled at $r/R = 0.6$) for the binary mixture of coal/iron ore mixture (ξ_{tot} = 20 mass% iron ore).

6. Conclusions

Axial and radial segregation effects were studied based on terminal settling velocity of the particles. In the riser of a CFB with mixture of solid particles the coarse particle settling at the bottom and finer moving upwards. For mixtures of particles with differences in sizes and/or densities, segregation effects are determined by mean particle size distribution. It has been observed that due to the larger mean particle size of sand and higher solids density, the measured particle size of this fraction display higher value at the bottom of the riser than FCC. The similar trend has been observed for the other group B particle mixture, i.e. coal and iron ore. In the first group of bed material where both the density and size varies considerably between coal and iron ore the mean particle size distribution for iron ore shows lower particle size compared to coal at the bottom of the riser. In the other group of bed material where the size is same for both coal and iron ore shows almost same particle size distribution along the riser for both. Axial segregation in terms of the terminal velocity distribution shows a continuous classification along the riser at different superficial gas velocities and solid circulation rate. Radial solids segregation is negligible compared to axial segregation, but significant differences between both flow directions are found.

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