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Studies on segregation of binary mixture of solids in a continuous fast-fluidized bed. Part IV. Total solids holdup, axial solids holdup and axial solids concentration

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ABSTRACT

The segregation pattern of a binary mixture of particles is studied in a continuous fast-fluidized bed of 3.65 m height and 69 mm ID. The influence of operating variables such as gas velocity, solids feed rate and feed composition on total solids holdup and axial solids holdup is studied. Empirical correlations are proposed for the total pressure drop in the fast fluidization regime when density and/or size segregation occur. The influence of the operating variables on the axial concentration of solids in both the dense and dilute phases is analyzed.

1. Introduction

When a binary mixture of solids of dissimilar density or size is fed into a fluidized bed, segregation of solids occurs. Most of the heavier/coarse particles descend to the bottom and most of the lighter/fine particles remain in the upper region depending on the operating variables. Studies on both axial solids holdup and solids concentration in bubbling fluidized beds have received much attention. The non-uniformity in axial solids distribution in circulating fast-fluidized beds for a binary mixture of dissimilar size and density has been recognized in earlier investigations. The majority of the researchers studied the influence of gas velocity and solids circulation rate on the axial distribution of solids. The dependence of axial distribution of solids on particle properties [1–3] and bed geometry such as inlet and exit structures, bed diameter and height was also established [3–5].

Several opinions still exist regarding the axial concentration and axial solids holdup profiles. Formerly, it has been shown that the solids distribution profile typically has a S-shape profile with a dense phase at the bottom followed by a dilute phase at top section and an interface in the profile dividing the two phases [5–7]. The interface point depends on the operating and design parameters. Following these observations, a cluster flow model was developed [6,8].

An alternate shape of solid distribution profiles was also noticed at some specified conditions when the average solid fraction was measured in fast-fluidized beds [5,9]. The profile existing in the riser depends mainly on combination of solids circulation rate and gas velocity. Examining the literature on high velocity fluidization, the axial solid profile can be classified into three types namely a dilute phase transport regime (exponential shape), the fast fluidization regime (S-Shape) and the dense transport regime (straight line). The existence of a S-shaped profile depends mainly on the design of the recycle loop and solids circulation rate [10].

At low gas velocity and high solids circulation rate, higher solids holdup exists in the bed and instabilities occur normally. Since the axial solids holdup was measured from the pressure drop in axial direction, the shape of the profile may be distorted because of neglecting the fluctuations. This may occur even because of the influence of the inlet and exit structures of fluidized bed. The conditions at which the flow corresponds to choking for solids holdup were described and correlations were proposed [11–13].

Investigators, knowing the solids holdup, examined the flow structures in circulating fast-fluidized beds with a mixture of solids that differ either in size or density [14–19]. Knowing the solids distribution at various gas velocities and solid circulation rates, the transition of the turbulent regime to fast fluidization and to pneumatic transport of binary systems of FCC and silica sand that differ in size was discussed [14].

S-shaped, linear and C-shaped axial solids holdup profiles were noticed in a 15.45 m long column using cork of 1170 μm as the feeding material. The C-shaped profile at high gas velocities in the dilute phase flow regime was due to the reflux of solid particles

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Nomenclature

B	flow rate of bottom particles (kg/h)
d	diameter of the particle (μm)
D	flow rate of overhead particles (kg/h)
F	flow rate of the feed particles (kg/h)
FR	flotsam-rich feed mixture
H	height of the column (m)
H_i	feed inlet height from the distributor (m)
IN	intermediary feed mixture
JR	jetsam-rich feed mixture
R	recovery of the particles
U_{mf}	minimum fluidization velocity of particles (m/s)
U_o	superficial gas velocity (m/s)
U_t	terminal settling velocity of particles (m/s)
X	weight fraction of particles in the bottom product
Y	weight fraction of particles in the top product
Z	weight fraction of particles in the feed

Greek letters

α	particle density/size ratio
Φ_s	sphericity of the particles
ρ	density of the particles (kg/m^3)

Subscripts

C	coarse particles
F	fine particles
H	heavier particles
L	lighter particles

in the abrupt T-exit. The linear profile was obtained at very low solids circulation rate and high gas velocity [15]. The C-shaped profile exists due to the accumulation of solids and the impact of the entrance and exit design [4]. Studies are available covering radial solids holdup profiles [17–23]. The effect of the secondary air inlet on the axial solids holdup distribution and entrainment of solids was studied [9,24]. Bai and Kato developed correlations for predicting the holdups and established the conditions for formation of a S-shaped profile [25].

A cluster based drag coefficient model for describing flows has been proposed. It predicts the axial pressure gradient of a fast-fluidized bed for uniform particles of Group-A [26]. Investigations on axial and radial segregation in the riser of a CFB for various sizes and densities of particles based on terminal settling velocities have been conducted and continuous classification of bed materials along the riser was identified. The core-annulus and dilute phase flows for binary mixtures were defined based on the superficial gas velocity [27,28]. Supplementary investigations illustrated the existence of core flow or core-annulus flow depending on the solids circulation rate and were independent of gas velocity [29,30]. Instantaneous velocity vector profiles of dense phase in turbulent regime showed rise as well as fall of both large and small particles at centre and wall of the riser respectively, in addition to vortex flow at the local position of the bed [31].

An examination of the literature indicates that the axial solids distribution and axial solids concentration in fast-fluidized beds are influenced by many factors. A more comprehensive study and careful analysis of the flow process are therefore needed to analyze the intricacy of the process. A rather large number of publications are available on the axial solids distribution and concentration in fast-fluidized bed for solid mixtures of varying size. But the analysis of the axial solids holdup and axial solids concentration with variables such as gas velocity, solids feed rate and feed composition for solid mixtures of varying density in a continuous fast-fluidized bed is limited. Moreover, empirical inputs are needed for scale up and modeling of continuous fast-fluidized beds for segregation of binary mixture of solids. Hence proper understanding of the solids behavior and mapping of solids flow in the column is necessary. The present study focuses on measurement of axial solids holdup and axial solids concentration in a continuous fast-fluidized bed with mixture of solids of dissimilar density and size. The total bed pressure drop is measured and empirical correlations are suggested for fast fluidization regime for density and size segregation studies.

Table 1
Properties of solids used for density and size segregation studies.

Material	d (μm)	ρ (kg/m^3)	U_{mf} (m/s)[a]	U_t (m/s)[b]	Φ_s	Category
Resin	780	1153	0.19	3.79	1.00	[S1]
Sand	780	2650	0.40	5.43	0.95	[S2]
Lignite	750	1540	0.24	2.63	0.73	[S3]
Marcasite	750	3345	0.46	4.90	0.85	[S4]
Glass beads	780	2500	0.38	5.92	1.00	[S5]
Glass beads	655	2500	0.29	5.22	1.00	[S6]
Glass beads	550	2500	0.21	4.56	1.00	[S7]
Glass beads	463	2500	0.15	3.94	1.00	[S8]
Glass beads	327	2500	0.08	2.82	1.00	[S9]

[a] Value calculated according to Wen and Yu [32].
[b] Value calculated according to Haider and Levenspiel [33].

2. Experimental

The experimental set-up used and the experimental procedure employed in the present study is described in first part of this communication [34]. The multi-limb manometer was connected to the eight pressure taps to measure the incremental pressure drops along the bed. The average of the absolute minimum and maximum readings on the manometer was considered in case of fluctuations in pressure, especially at the bottom of the bed. In addition, routine verification of the existence of steady state and sum of the incremental pressure drops across the column against an overall column pressure drop measurement using pressure transmitter was done.

Segregation patterns were described by the axial profiles of the mass fraction of heavier particles. Eight sampling ports were used for testing the axial solids concentration excluding the top and bottom flow. The axial concentration was obtained by collecting a small amount of bed material through the sampling ports installed at different positions along the column. The samples were separated using batch elutriator to find the concentrations of the lighter and heavier particles. Table 1 reports the properties of solids used in the present study. All the selected particles fall into the Geldart group B class. Reasonably close sized granular particles were obtained for each kind of solids by taking a single screen cut using the 'JAYANT' standard 'A' class test sieves. Particle density was measured using true density meter (Model: smart pycno 30).

The concentration of total solids in the bed and holdup was obtained by closing the airflow and solids feed flow into the column, and discharge of particles out of the column simultaneously after the steady state was reached. The measured total solids holdup was also verified with total bed pressure drop measured using the differential pressure transmitter.

Three categories of feed mixtures viz., flotsam-rich, jetsam-rich and intermediary of varying density or size were examined to study the total solids holdup. Each category of mixture exhibited different fluidization behavior [34,35]. The particle density and size ratios used are given in the Table 2. The operating variables were selected to cover the solids segregation in the entire flow regime. The range of operating variables used in the present study is given in Table 3.

Table 2
Density/size ratio used in the present study.

Type	α	Value	Ratio
I	[S1]/[S2]	2.29	Density
II	[S3]/[S4]	2.17	Density
III	[S5]/[S9]	2.39	Size
IV	[S6]/[S9]	2.00	Size
V	[S5]/[S8]	1.68	Size
VI	[S7]/[S9]	1.68	Size

Table 3
Range of operation.

Variable	Range
U_o, m/s	2–5.4
F, kg/h	20–82
Z_H and Z_C, %	3–97
H_i, m	0.3–2.1
PSD, μm	+100–1000

3. Results and discussion

3.1. Total solids holdup and concentration

Once the column attains the steady state, the concentration of total solids in the bed remains more or less constant and hence, the concentrations of top and bottom products remain nearly unchanged. The influence of gas velocity, solids feed rate and feed composition on the total solids concentration is studied and the results are presented for the resin–sand system.

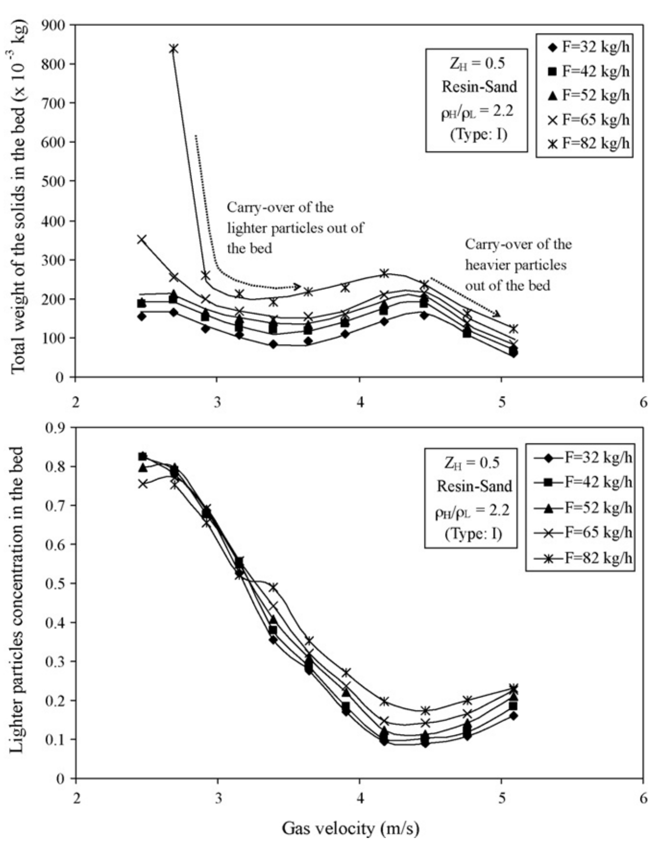

Fig. 1. Effect of gas velocity on the total solids holdup and lighter particles concentration in the total solids holdup for density difference mixture of resin–sand.

3.1.1. Influence of gas velocity

Fig. 1 shows the influence of the gas velocity on the concentration of lighter particles in the holdup. From the figure, it is clear that the concentration of lighter particles is higher and the concentration of heavier particles is less at low operating gas velocity. This is because of less entrainment of solids at low gas velocity [34–36]. Most of the heavier particles settle and discharge out of the column and hence the concentration of heavier particles is less. However, lighter particles expand through the entire height of the column since the gas velocity is not sufficient enough to carry all the lighter particles. With increase in gas velocity, the entrainment of solids increases and the carryover of lighter particles out of the column also increases. The accumulation of lighter particles in the column reduces and the concentration of lighter particles in the holdup drops. With further rise in gas velocity, the discharge of heavier particles decreases due to the expansion of the heavier particles and results in accumulation of heavier particles in the column. The concentration of heavier particles in the holdup attains a maximum at a particular gas velocity. At this gas velocity the heavier particles in the bed expand, but the velocity is not sufficient to entrain out. With further increase in gas velocity, the heavier particles entrain out of the column continuously. The holdup of the heavier/coarse particles in the column decreases with the increase in gas velocity [34–36]. The accumulation of heavier particles in the column is greatly reduced and results in decrease in the concentration of heavier particles in the holdup. At very high gas velocities, the concentration of lighter particles increases and equals the feed composition at complete pneumatic transport when there is no accumulation of solids in the column.

3.1.2. Influence of solids feed rate

It is clear from Fig. 2 that the solids holdup inside the column increases and with increase in solids feed rate and hence the voidage decreases. Decrease in the voidage increases the particle–particle collision and prevents few lighter particles moving out of the column. Hence concentration of lighter particles is more for high solids feed rate. This effect is apparent at high gas velocity. At low gas velocity, movement of the particles decreases and discharge of the solids increases. Tanaka et al. observed that the concentration of coarse particles in the bed increases with increase in solids feed rate in a continuous fluidized bed. The dissimilarity in the result is due to the position of the solids discharge pipe [37].

3.1.3. Influence of feed composition

Fig. 3 shows the effect of feed composition on the concentration of total solids holdup. With increase in the concentration of lighter particles in the feed, the particle–particle and particle–wall interaction becomes higher. The collision of lighter particles increases due to increase in the volume fraction of lighter particles inside the upper section of the column. As the result, accumulation of lighter particles in the column increases. The concentration of lighter particles in the total holdup increases with increase in the lighter particles composition in the feed.

3.1.4. Empirical correlations

The holdup of the solids inside the continuous gas–solids fluidized column decreases with increase in operating gas velocity in fast fluidization regime. From the experimental observations, it is clear that the holdup of the solids decreases with increase in either particle density/size ratio or feed inlet height due to the drop in accumulation of the particles [36]. For all the categories of feed mixtures it is noticed that the concentration of the heavier/coarse particles in the dense bed increases as a result of increase in concentration of heavier/coarse particles in the feed. This occurrence is due to the increase in the settling of the heavier particles [36].

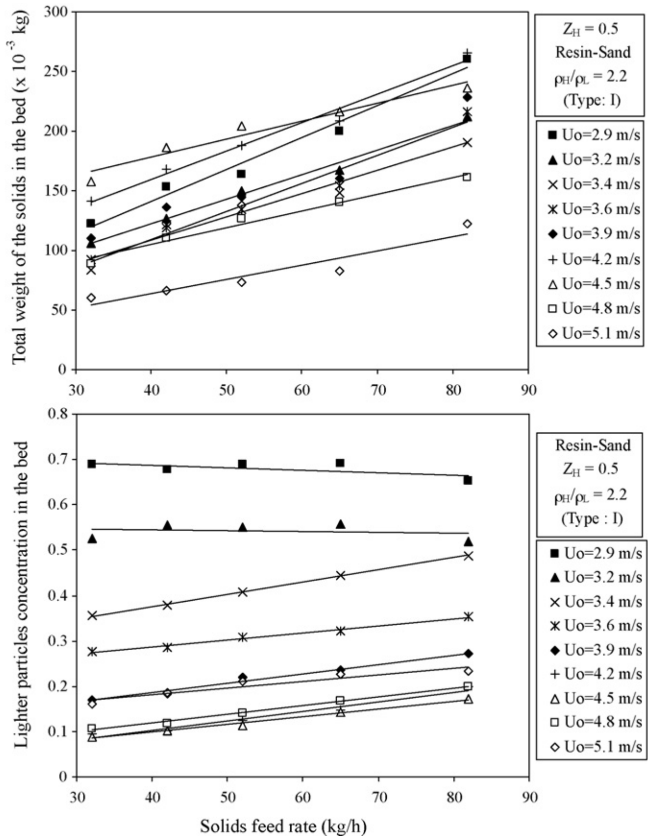

Fig. 2. Effect of solids feed rate on the total solids holdup and lighter particles concentration in the total solids holdup for density difference mixture of resin–sand.

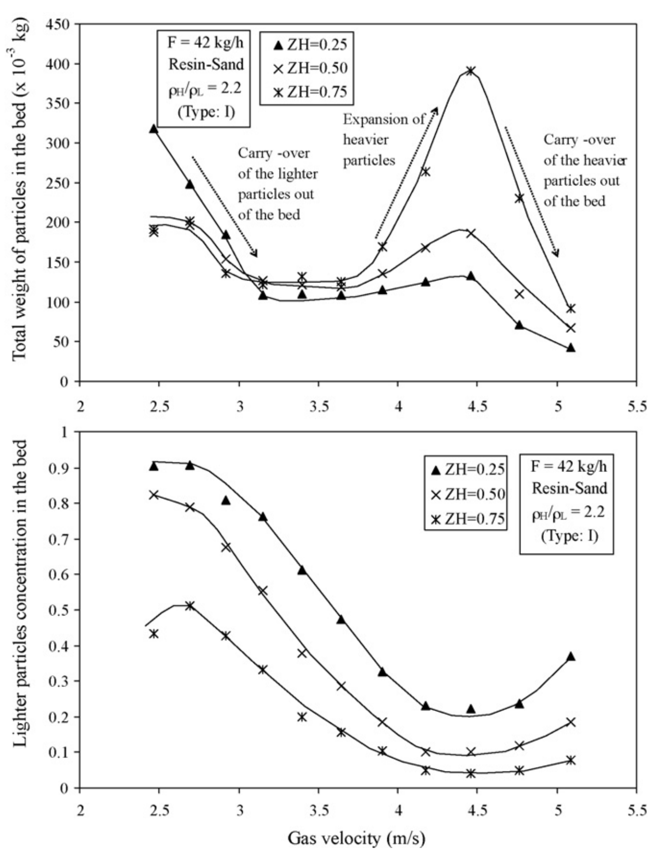

Fig. 3. Effect of feed concentration on the total solids holdup and lighter particles concentration in the total solids holdup for density difference mixture of resin–sand.

The correlations proposed for total bed pressure drop for density and size segregation are given below;

Density segregation:

$$(\Delta P)_{\text{bed}} = 0.12\left[\left(\frac{U}{U_{t,H}}\right)^{-1.81}(F)^{0.81}(Z_H)^{0.50}\left(\frac{H_i}{H}\right)^{-0.13}\left(\frac{\rho_H}{\rho_L}\right)^{-0.04}\right] \quad (1)$$

Size segregation:

$$(\Delta P)_{\text{bed}} = 0.38\left[\left(\frac{U}{U_{t,C}}\right)^{-3.03}(F)^{0.8}(Z_C)^{0.27}\left(\frac{d_C}{d_F}\right)^{-2.54}\right] \quad (2)$$

The proposed correlations are compared with 1500 experimental runs taken at various fluidization regimes. Even though studies were carried out in other regimes, correlations are presented only for the fast fluidization regime [34–36]. The experimental data obtained with all types and categories of feed mixtures are considered for developing the correlations. The predicted bed pressure drop is compared with experimental data in Figs. 4 and 5 for density and size segregation respectively. To establish the agreement of the equations proposed in the present study with the experimental data, the root mean square (RMS) deviation is calculated and reported in Figs. 4 and 5.

3.2. Axial solids holdup

It is known from the literature that axial solids holdup in fast-fluidized beds depends on gas velocity, solids feed rate, feed composition, feed inlet position, column geometry, and solid and gas properties. In fast-fluidized beds, the pressure gradient in lower dense phase is higher than in the upper dilute phase zone. The formation of a cloud of particles was noted in the region close to the feed inlet (0.9 m from the air distributor) in the continuous fast-fluidized bed of the present study . The formation of a cloud of particles is due to the contact of the flow of solids fed from the hopper into the column, downward flow of solids towards the dense phase from the dilute phase, and upward flow of solids from the dense phase towards dilute phase. As the outcome, an additional pressure drop occurs closer to the feed inlet in the continuous fast-fluidized bed column.

3.2.1. Influence of gas velocity

Fig. 6 shows the effect of gas velocity on axial solids holdup. From the figure it is obvious that there is a formation of bottom dense phase and an upper dilute phase. The segregation of the solids occurs in the upper half of the dense phase in the bottom of the column. The solids holdup in the bottom dense phase of the fluidized bed decreases with increase in the gas velocity due to bed expansion and an increased entrainment (carry over) of particles. The solids holdup near the feed inlet is identified to be comparatively higher due to the formation of cloud of particles.

At very low gas velocities, the holdup of solids is higher both in dense and dilute phases due to the formation of small slugs. When the bed is in turbulent regime, the solids holdup is much higher at the bottom of the column (dense-phase) than in high velocity fast fluidization regime. On the other hand, the solids holdup in turbulent regime is much lesser than high velocity fast fluidization regime at the upper part (dilute phase) of the column. This is due to increase in particle ejection from the bottom dense zone to the upper dilute zone.

With added gas velocity, the holdup of solids in the dense phase decreases while in the dilute phase it increases. In the resin–sand system, with 75% feed mixture and gas velocity of 4.46 m/s, the holdup of solids both in dilute and dense phases is more compared to other gas velocities due to the expansion of jetsam-rich dense phase and accumulation of dense solids in both the phases as reported in Fig. 3.

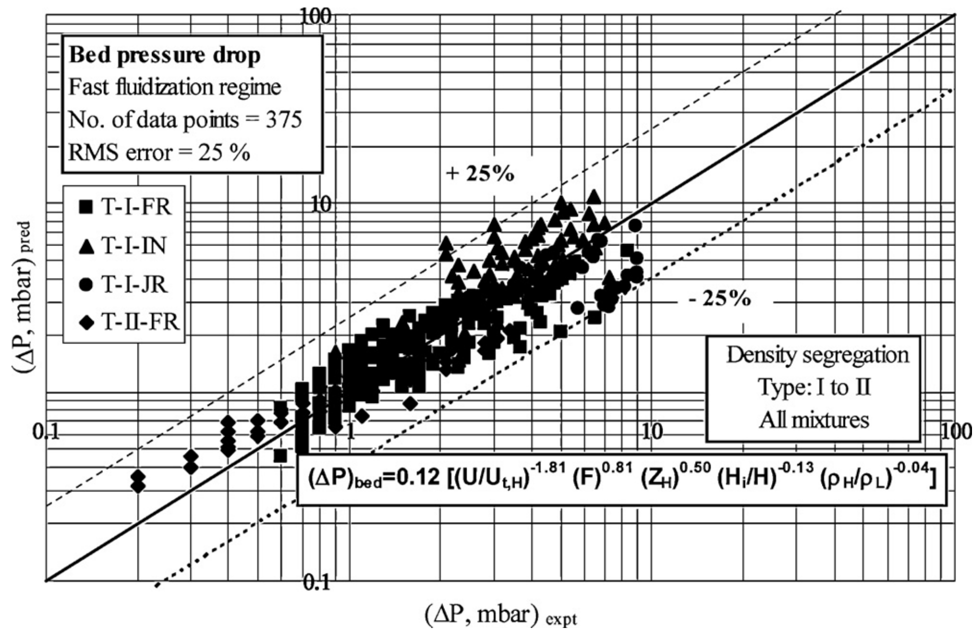

Fig. 4. Parity chart of total bed pressure drop in fast fluidization regime for all categories of the feed mixtures for density segregation study.

At elevated gas velocities, the solids holdup in the dense phase is more or less equal to the holdup in the dilute phase. The influence of the feed entry on axial solids holdup is found to be moderately dominant at higher gas velocity. Das et al. studied the influence of gas velocity in circulating fast-fluidized bed with binary mixture of smaller particles and reported constant voidage in the upper dilute phase [27].

3.2.2. Influence of solids feed rate

At a given gas velocity, the axial solids holdup in the fluidized bed column increases with increase in the solids feed rate. Fig. 7 shows the influence of solids feed rate on axial solids holdup. At higher solids feed rate, the gas velocity may be insufficient to carry all the entering particles without accumulation of solids at the bottom of the column to form a dense phase with additional solids. The dilute phase region with core-annulus structure forms above the dense phase bed [29,30]. The influence of feed rate of solids on the cloud of particles is minimum. The density of the cloud particles however increases with increase in solids feed rate at higher gas velocity.

Bai et al. and Namkung et al. investigated the axial pressure drop for circulating fast fluidized using a mono-component system of particles for various gas velocities and solids circulation rates [5,14]. Bai and Kato presented that the solids holdup in the upper dilute region and bottom dense region increases with increase in the solids circulation rate at lower G_s values [25]. Das et al. reported similar trend with binary mixture of small diameter particles of varying size in a circulating fast-fluidized bed [27].

3.2.3. Influence of feed composition

Fig. 8 shows the influence of feed composition on axial solids holdup. At lower operating gas velocity, for the 75% feed mixture,

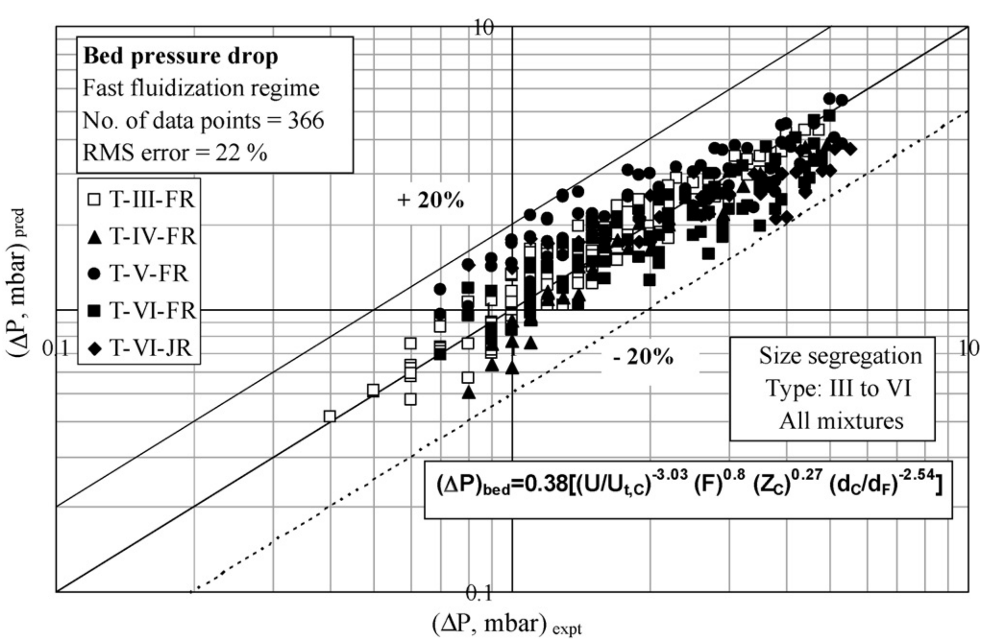

Fig. 5. Parity chart of total bed pressure drop in fast fluidization regime for both categories of the feed mixtures for size segregation study.

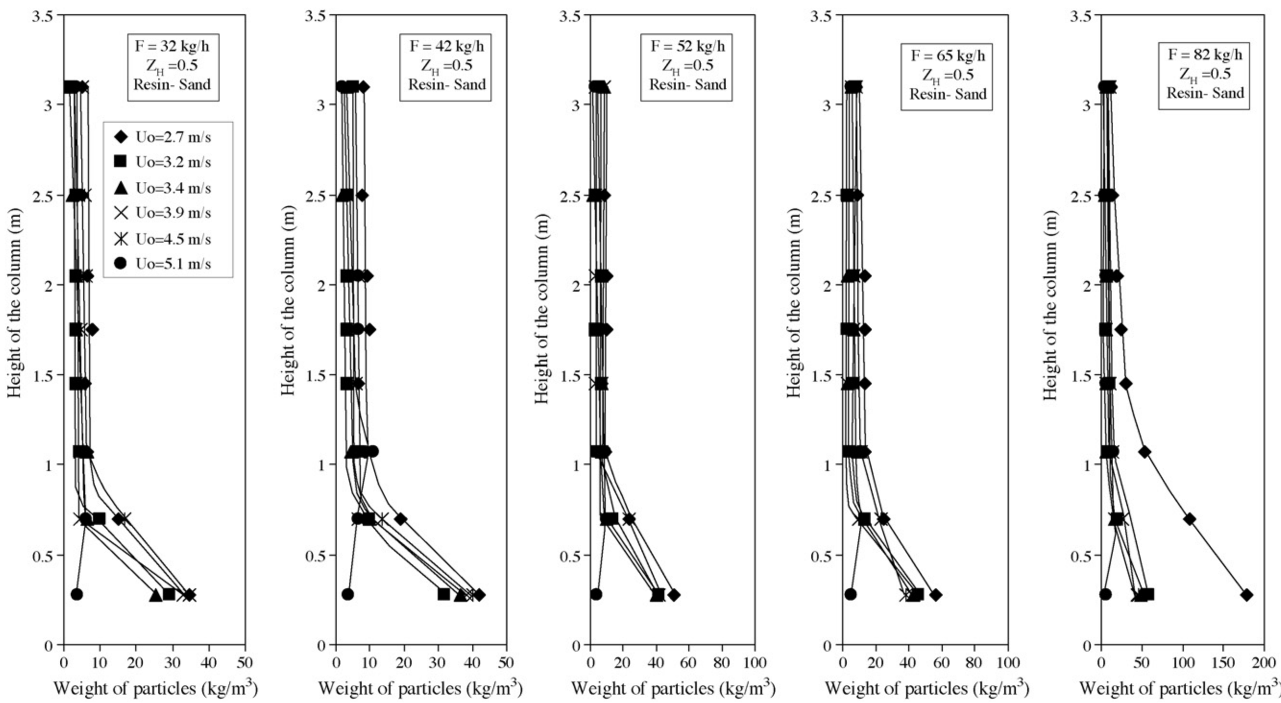

Fig. 6. Effect of gas velocity on the axial solids holdup for density difference mixture of resin–sand.

the holdup of solids is more in the bottom dense phase and less in upper dilute phase. Most of the particles in the feed mixture tend to settle and the holdup of solids in the bottom dense phase increases with increase in settling rate. For the 25% feed mixture, on the other hand, the holdup of solids is less in the dense phase and more in dilute phase. This happens because of the expansion of lighter particles in the feed mixture.

It is interesting to note that at intermediate operating gas velocities, the holdup of solids in the dense phase is higher for the 75% feed mixture as compared with the 25% feed mixture while the holdup of solids in the dilute phase is more or less equal for both kinds of feed mixtures. This occurs because of the beginning of expansion of heavier particles from the dense phase to the dilute phase along the column height and increase in entrainment of lighter particles.

At higher operating gas velocities, the holdup of solids both in the dense and dilute phases is higher for the 75% feed mixture as compared with the 25% feed mixture. This occurs because, for 75% feed mixture, the expansion of heavier particles throughout the column height is higher. At elevated gas velocities, the holdup of

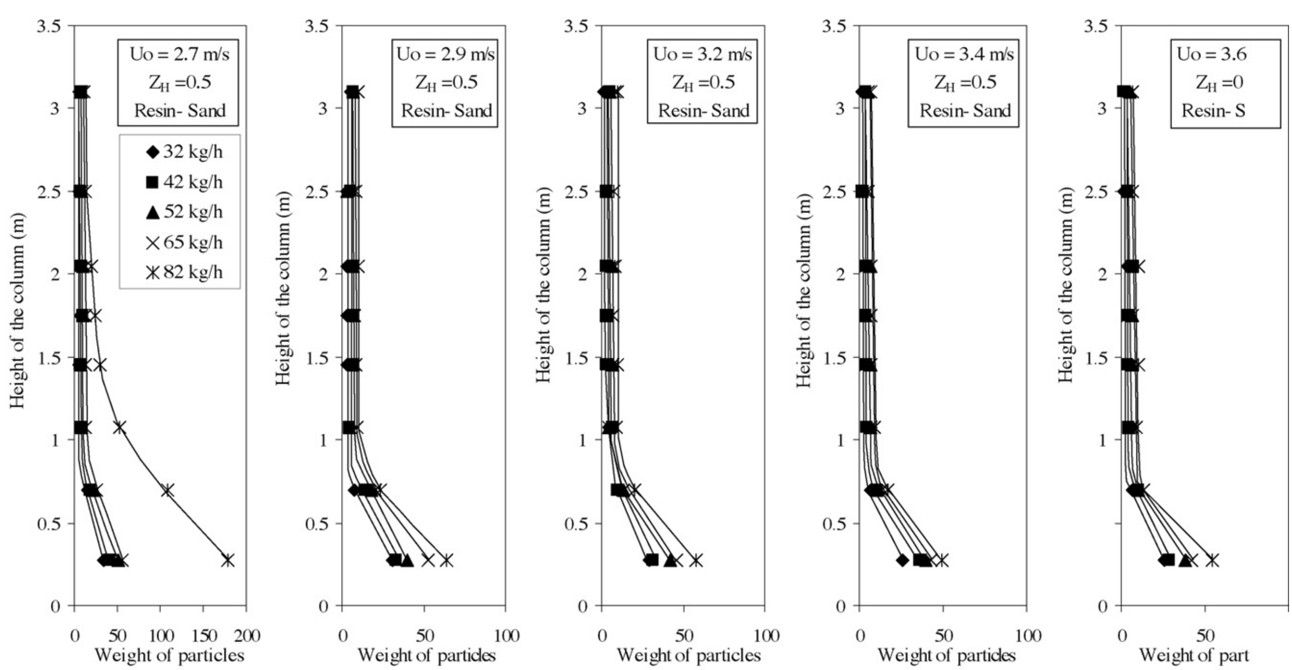

Fig. 7. Effect of solids feed rate on the axial solids holdup for density difference mixture of resin–sand.

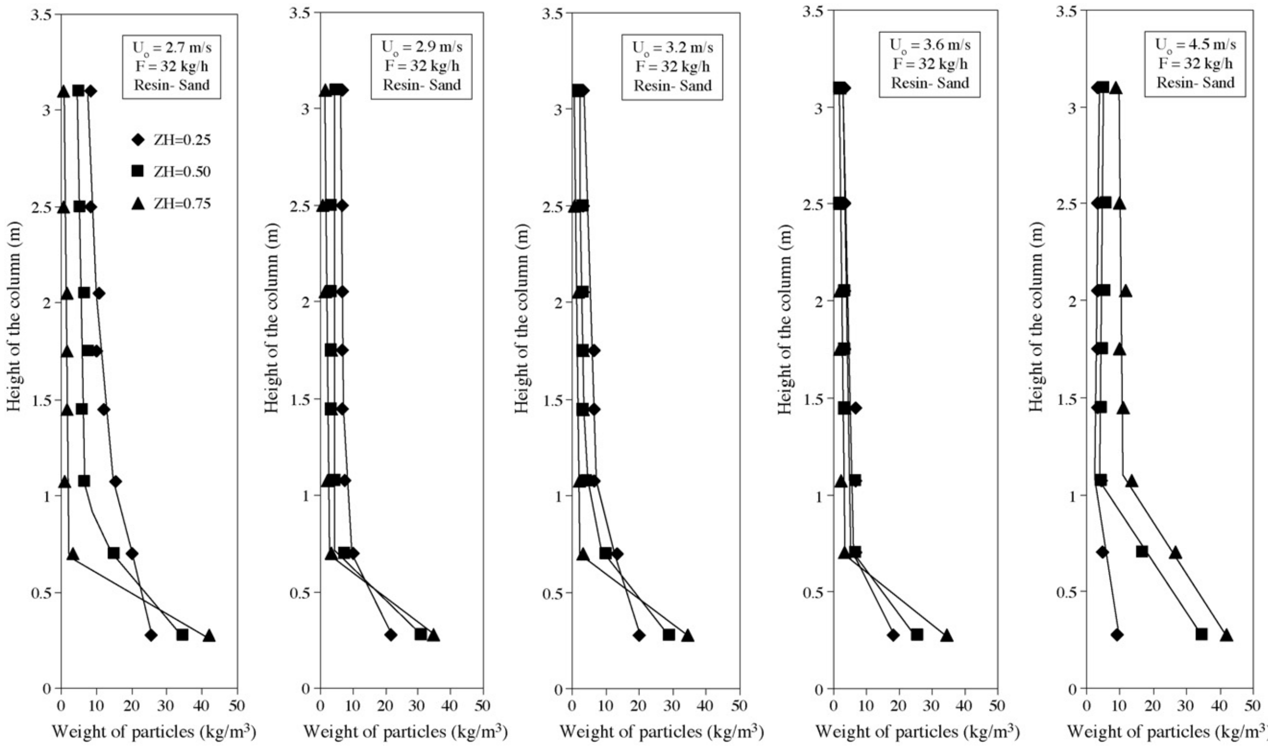

Fig. 8. Effect of feed composition on the axial solids holdup for density difference mixture of resin–sand.

solids in dense and dilute phases is least for both kinds of feed mixtures due to pneumatic transport of solids.

3.3. Axial solids concentration

Samples were collected along the column length to study the effect of the variables on axial solids concentration profiles. It is found that the axial solids concentration depends mainly on gas velocity, solids feed rate, feed composition and feed inlet height. Variation of solids concentration both in the dense and dilute phases is analyzed for different solids feed rate, feed composition and gas velocity.

3.3.1. Influence of gas velocity

Fig. 9 shows the influence of gas velocity on axial solids concentration. It is evident from the figure that the concentration of lighter particles in the bottom dense bed is less compared to upper dilute phase.

At lower operating gas velocity, the concentration of lighter as well as heavier particles in the bottom dense phase is higher while the dilute phase is identified to be richer in the lighter particles. At intermediate operating gas velocities, the concentrations of lighter particles both in the dilute and dense phases drop. At higher gas velocities, the bottom dense phase becomes more or less pure jetsam and the dilute phase becomes richer in the heavier particles.

The abnormal behaviour shown in Fig. 9 for higher gas velocities signify the influence of the feed entry. The rising heavier particles from the bottom dense to dilute phase and the dropping particles from the dilute to dense phase collides with the particles that enter from the solids feeder. This results in the drop of concentration of heavier particles and leads to divergence of the profile around that location.

Tanaka et al. [37] presented the axial distribution of the concentration of fines in a continuous fluidized bed with mixtures of particles of different size. The concentration of fines decreases with increase in gas velocity in the dense phase. These results are identical with the present study [37].

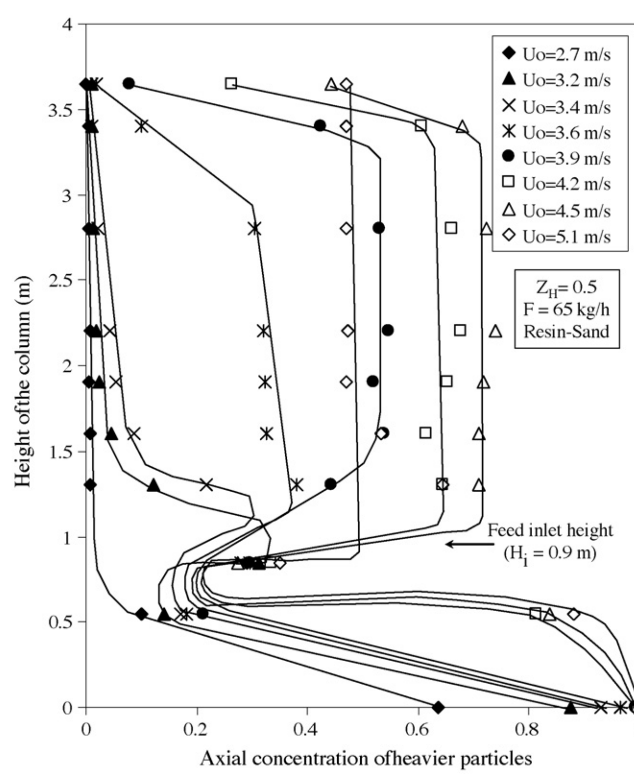

Fig. 9. Effect of gas velocity on the axial solids concentration for density difference mixture of resin–sand.

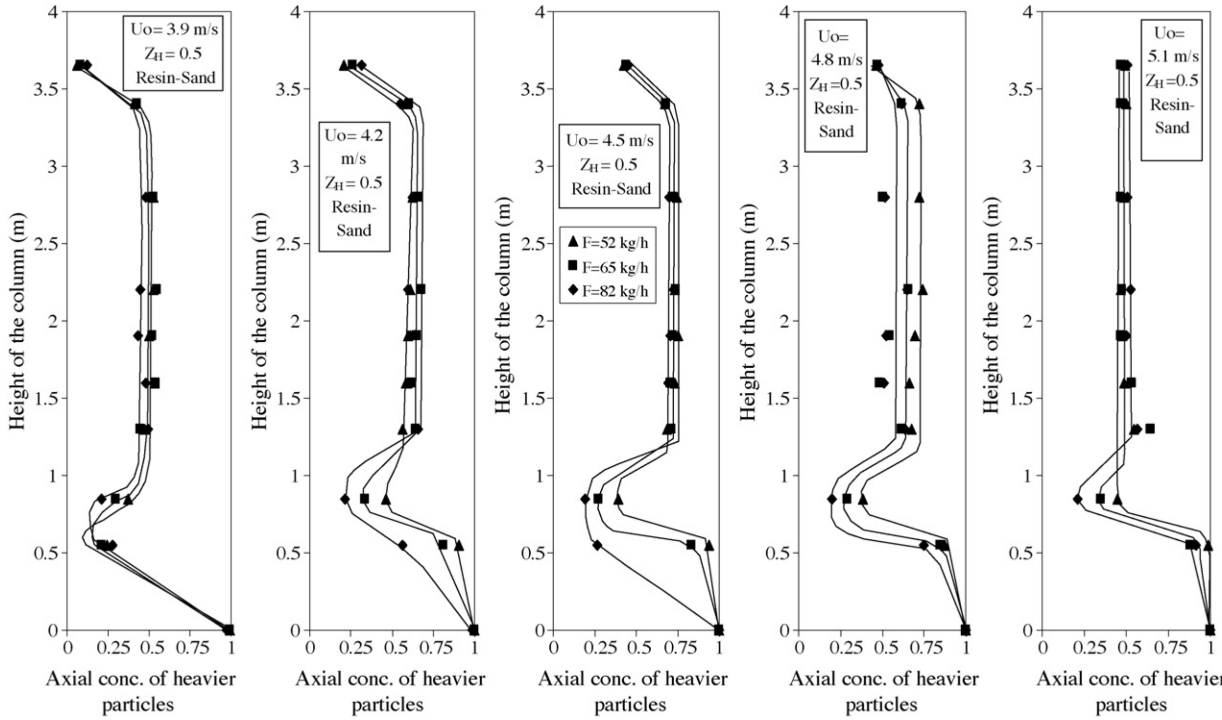

Fig. 10. Effect of solids feed rate on the axial solids concentration for density difference mixture of resin–sand.

3.3.2. Influence of solids feed rate

Fig. 10 shows the influence of solids feed rate on axial solids concentration. It clearly indicates that the concentration of lighter particles in the bottom dense phase increases and the concentration of lighter particles in the dilute upper phase decreases with increase in solids feed rate. This happens because of the arrival of heavier particles into the dilute phase due to decrease in the differential settling and collision of particles. The concentration of lighter particles near the feed inlet was found to be higher for higher solids feed rate because of the particles' cloud formation and movements of solids all over the place.

Tanaka et al. [37] noticed an increase in the concentration of fines in the dense phase with increase in solids feed rate for mixture of solids with size difference. Their results are comparable with the present study [37].

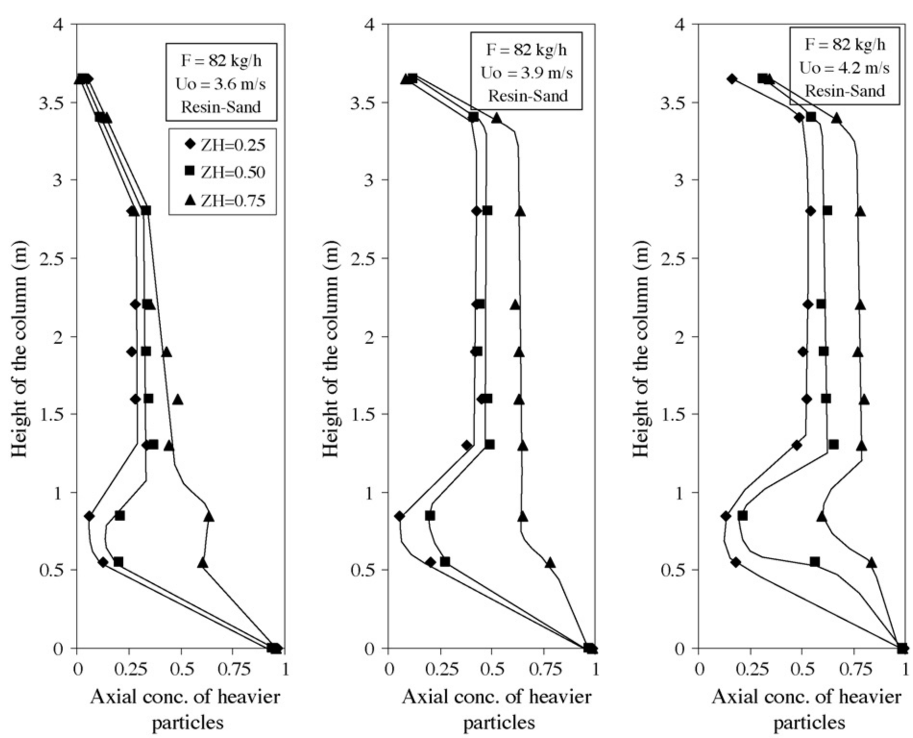

Fig. 11. Effect of feed composition on the axial solids concentration for density difference mixture of resin–sand.

3.3.3. Influence of feed composition

Fig. 11 shows the influence of feed composition on axial solids concentration. It is evident from the figure that the concentration of heavier particles in the bottom dense phase increases with increase in concentration of heavier particles in the feed. This occurs due to increase in settling of heavier particles which is due to increase in composition of heavier particles in the feed.

The ejection of solids into the freeboard from the dense phase and into the dilute phase is relatively lower for jetsam-rich mixture. As noted, the concentration of the lighter particles in the dilute phase is higher at lower operating gas velocity for the 75% feed composition. With increase in gas velocity, the ejection of solids from the dense phase to the dilute phase increases and hence the concentration of particles in the dilute phase drops. At elevated gas velocities, the concentration of lighter particles both in the dense and dilute phases is lower for the 75% feed composition. The deviation of the profile is because of the drop in concentration of heavier particles.

Similar studies are reported on adjoining fluidization regimes using a mixture with density difference in batch bubbling fluidized beds. Literature is also accessible on the studies counting the effect of gas velocity, feed composition, particle diameter ratio, bed diameter on axial solids concentration using a mixture with size difference in batch bubbling fluidized beds.

4. Conclusions

The total and axial variations of solids distribution and solids composition in a continuous fast-fluidized bed is analyzed for various solids feed rate, feed composition and gas velocity. A substantial rise in total solids holdup followed by a fall is noticed inside the bed at a certain higher gas velocity due to the influence of the feed composition. Empirical correlations for the pressure drop in fast fluidization of binary mixtures satisfactorily fit the experimental data.

With an increase in gas velocity, the holdup of solids decreases in the dense zone and increases in dilute zone. At any gas velocity, the solids holdup increases with an increase in solids feed rate both at the bottom dense and upper dilute regions. With an increase in solids feed rate, the concentration of the lighter particles increases in the bottom dense phase and decreases in upper dilute phase. At any solids feed rate and at lower velocity, an increase in feed composition of heavier particles results in an increase in density of the bottom dense zone. But at a higher velocity, the holdup of heavier particles increases both in the dense as well as dilute phase. The total concentration of lighter particles in the holdup increases with increase in either solids feed rate or feed composition of lighter particles, and decreases with increase in gas velocity. The formation of a particle cloud is noticed in the bed due to the influence of the feed. The effect of operating variables on the cloud is presented.

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References

[1] X. Ma, K. Kato, Effect of interparticle adhesion forces on elutriation of fine powders from a fluidized bed of a binary particle mixture, Powder Technol. 95 (1998) 93–101.

[2] H. Li, H. Tong, Multi-scale fluidization of ultrafine powders in a fast-bed-riser/conical-dipleg CFB loop, Chem. Eng. Sci. 59 (2004) 1897–1904.

[3] N. Nakagawa, D. Bai, E. Shibuya, H. Kinoshita, T. Takarada, K. Kato, Segregation of particles in binary solids circulating fluidized beds, J. Chem. Eng. Jpn. 27 (1994) 194–198.

[4] A. Luckos, P. den Hoed, A study into the hydrodynamic behavior of heavy minerals in a circulating fluidized bed, Industrial Fluidization South Africa, IFSA 2005, Johannesburg, South Africa, 2005, pp. 345–355.

[5] D. Bai, Y. Jin, Z.-Q. Yu, J.-X. Zhu, The axial distribution of the cross-sectionally averaged voidage in fast fluidized beds, Powder Technol. 71 (1992) 51–58.

[6] J. Adanez, P. Gayan, F. Garcia-Labiano, L.F. de Diego, Axial voidage profiles in fast fluidized beds, Powder Technol. 81 (1994) 259–268.

[7] M.J. Rhodes, M. Sollaart, X.S. Wang, F1ow structure in a fast f1uid bed, Powder Technol. 99 (1998) 194–200.

[8] D. Kunii, O. Levenspiel, Entrainment of solids from fluidized beds. I. Holdup of solids in the freeboard. II. Operation of fast fluidized bed, Powder Technol. 61 (1990) 193–206.

[9] Y.J. Cho, W. Namkung, S.D. Kim, S. Park, Effect of secondary air injection on axial solids holdup distribution in a circulating fluidized bed, J. Chem. Eng. Jpn. 27 (1994) 158–164.

[10] K. Smolders, J. Baeyens, Gas fluidized beds operating at high velocities: critical review of occurring regimes", Powder Technol. 119 (2001) 269–291.

[11] Y.O. Chong, L.S. Leung, Comparison of choking velocity correlations in vertical pneumatic conveying, Powder Technol. 47 (1986) 43–50.

[12] J. Biswas, L.S. Leung, Applicability of choking correlations for fast-fluid bed operation, Powder Technol. 51 (1987) 179–180.

[13] H.T. Bi, J.R. Grace, J.-X. Zhu, Types of choking in vertical pneumatic systems, Int. J. Multiphase Flow 19 (1993) 1077–1092.

[14] W. Namkung, S.W. Kim, S.D. Kim, Flow regimes and axial pressure profiles in a circulating fluidized bed, Chem. Eng. J. 72 (1999) 245–252.

[15] E.R. Monazam, L.J. Shadle, J.S. Mei, J. Spenik, Identification and characteristics of different flow regimes in a circulating fluidized bed, Powder Technol. 155 (2005) 17–25.

[16] S.W. Kim, G. Kirbas, H. Bi, C.J. Lim, J.R. Grace, Flow behavior and regime transition in a high-density circulating fluidized bed riser, Chem. Eng. Sci. 59 (2004) 3955–3963.

[17] H. Chen, H. Li, M. Kwauk, Two-phase structure in a high-density downer, Powder Technol. 158 (2005) 115–123.

[18] A. Yan, J. Ball, J. Zhu, Scale-up effect of riser reactors: axial and radial solids flux distribution and flow development, Chem. Eng. J. 109 (2005) 97–106.

[19] S. Bhusarapu, M.H. Al-Dahhan, M.P. Dudukovi, Solids flow mapping in a gas–solid riser: mean holdup and velocity fields, Powder Technol. 163 (2006) 98–123.

[20] R.J. Dry, Radial particle segregation in a fast fluidized bed, Powder Technol. 52 (1987) 7–16.

[21] M.J. Rhodes, Modeling the flow structure of upward-flowing gas–solids suspensions, Powder Technol. 60 (1990) 27–38.

[22] W. Zhang, Y. Tung, F. Johnsson, Radial voidage profiles in fast fluidized beds of different diameters, Chem. Eng. Sci. 46 (1991) 3045–3052.

[23] L.F.D. Diego, P. Gayan, J. Adanez, Modeling of the flow structure in circulating fluidized beds, Powder Technol. 85 (1995) 19–27.

[24] J.H. Choi, K.J. Kim, S.D. Kim, Effect of secondary gas injection on the particle entrainment rate in a gas fluidized bed, Powder Technol. 90 (1997) 227–233.

[25] D. Bai, K. Kato, Quantitative estimation of solids holdups at dense and dilute regions of circulating fluidized beds, Powder Technol. 101 (1999) 183–190.

[26] L.M. Zou, Y.C. Guo, C.K. Chan, Cluster-based drag coefficient model for simulating gas–solid flow in a fast-fluidized bed, Chem. Eng. Sci. 63 (2008) 1052–1061.

[27] M. Das, A. Bandyopadhyay, B.C. Meikap, R.K. Saha, Axial voidage profiles and identification of flow regimes in the riser of a circulating fluidized bed, Chem. Eng. J. 145 (2008) 249–258.

[28] M. Das, B.C. Meikap, R.K. Saha, 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, Chem. Eng. J. 145 (2008) 32–43.

[29] M. Van de Velden, J. Baeyens, K. Smolders, Solids mixing in the riser of a circulating fluidized bed, Chem. Eng. Sci. 62 (2007) 2139–2153.

[30] M. Van de Velden, J. Baeyens, J.P.K. Seville, X. Fan, The solids flow in the riser of a circulating fluidised bed (CFB) viewed by positron emission particle tracking (PEPT), Powder Technol. 183 (2008) 290–296.

[31] J. Gao, X. Lan, Y. Fan, J. Chang, G. Wang, C. Lu, C. Xu, Hydrodynamics of gas–solid fluidized bed of disparately sized binary particles, Chem. Eng. Sci. 64 (2009) 4302–4316.

[32] C.J. Wen, Y.H. Yu, A generalized method for predicting the minimum fluidization velocity, AIChE J. 12 (1966) 610–612.

[33] A. Haider, O. Levenspiel, Drag coefficient and terminal velocity of spherical and non-spherical particles, Powder Technol. 58 (1989) 63–70.

[34] K.G. Palappan, P.S.T. Sai, Studies on segregation of binary mixture of solids in continuous fast fluidized bed. Part I. Effect of particle density, Chem. Eng. J. 138 (2008) 358–366.

[35] K.G. Palappan, P.S.T. Sai, Studies on segregation of binary mixture of solids in continuous fast fluidized bed. Part II. Effect of particle size, Chem. Eng. J. 139 (2008) 330–338.

[36] K.G. Palappan, P.S.T. Sai, Studies on segregation of binary mixture of solids in continuous fast fluidized bed. Part III. Quantification of performance of the segregator, Chem. Eng. J. 145 (2008) 100–111.

[37] I. Tanaka, M. Koga, T. Akiyama, H. Shinohara, T. Ishikura, Solids separation in a continuous fluidized bed, Inst. Chem. Eng. Symp. Ser. 59 (1980), 4/2/1–4/2/8.