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Studies on segregation of binary mixture of solids in continuous fast fluidized bed Part III. Quantification of performance of the segregator

K. Ganesh Palappan, P.S.T. Sai *

Department of Chemical Engineering, Indian Institute of Technology Madras, Chennai 600036, India

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ABSTRACT

Segregation of particles due to difference in either size or density was studied in a continuous fast fluidized bed of 69 mm ID and 3.65 m height [1]. Binary feed mixtures of either flotsam-rich or intermediary or jetsam-rich mixtures were utilized for the study. The influence of the operating variables on the particles segregation was examined. All the considered feed mixtures, showed similar segregation effect even though the fluidization behavior of the binary mixtures differ [1,2]. Empirical correlations were suggested for the entrainment of solids and purity of the top and bottom products for all the three categories of binary feed mixtures considered. The optimum gas velocity for maximum separation of the lighter/fine and heavier/coarse particles is identified. The effect of the operating variables on the identified optimum gas velocity and optimum purity/recovery is presented.

1. Introduction

The separation of binary mixture of particles by physical methods depends upon difference in properties of the solids. The important physical methods of separation used in the mineral process industries are: (1) mechanical separation (screens, jigs, fluidized beds), (2) magnetic separation (high gradient, open gradient) and (3) electrical separation (electrodynamic, triboelectric). Mechanical separation involves the response of the particles to drag force of the fluid and either gravitational or inertial or centrifugal force [3]. Separations which use differences in gravity are one of the most commonly used methods because of their effectiveness, low cost and operational simplicity. In some cases, combinations of two or more techniques are necessary to separate, concentrate and tailing economically.

Separation of particles can be done in a variety of process equipments. Equipment selection depends upon the properties of the material, the required purity, recovery and the process economics. Among gravitational type separators, fluidized bed based devices is the best which provides substantial advantages over other equipments when separation of heterogeneous mixtures into cleaner fractions of large quantities [3–5]. The throughput and power consumption figures for pre-cleaning equipment using fluidization are similar to those of other alternative methods, efficiency of separation can be far superior, compactness and precision of a continuous fluidizing cleaner makes it an attractive alternative to other precleaners [6]. Studies covering the applications and advantages of the fast fluidized beds segregation were presented in Part I of this study [1].

The fluidized bed separator can be used to remove lighter/fine particles from the binary mixture of solids while the main charge is merely suspended in a fluidized state. Fluidized bed air separators employ the principles of air drag, gravity and particle inertia, which depend upon particle size/density. The main forces acting on the elementary volume of the bed are gravitational forces which periodically compress it and hydrodynamic forces which expand it. The particle size, shape, and density, the fluid density and viscosity, the operating and design variables have an effect on the separation of the particles. An analysis of literature suggest that the investigation on quantification of the segregator in terms of purity and recovery of lighter/fine and heavier/coarse is not available in case of continuous fast fluidization. In addition, correlations to predict purity and recovery are not reported.

The single particle terminal settling velocity is the decisive parameter, which affects solids segregation in the fluidized beds [7]. Consider a binary mixture of solids of differing density/size are introduced into a fluidized bed operating at gas velocity greater than the terminal settling velocity of the lighter/fine flotsam particles and less than the terminal settling velocity heavier/coarse jetsam particles. There are four possible cases of particles distribution when the fluidized bed is operated at a

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* Corresponding author. Tel.: +91 44 2257 4163; fax: +91 44 2257 4152.
E-mail address: psts@iitm.ac.in (P.S.T. Sai).

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Nomenclature

A	coefficient defined in Eqs. (5)–(7)
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)
H	height of the column (m)
H_i	feed inlet height from the distributor (m)
R	recovery of the particles
U_mf	minimum fluidization velocity of particles (m/s)
U_t	terminal settling velocity of particles (m/s)
U_0	superficial gas velocity (m/s)
V	factor defined in Eq. (6).
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

f	lighter/fine flotsam particles
j	heavier/coarse jetsam particles

gas velocity intermediate between the terminal settling velocity of the lighter/fine and heavier/coarse particles. They are as follows:

1. Both lighter/fine and heavier/coarse particles appear in the bottom flow and only lighter/fine particles reports to the top flow, which occurs at, lower operating gas velocity.
2. Both lighter/fine and heavier/coarse particles appear in the bottom flow as well as top flow at intermediate gas velocity.
3. Both the lighter/fine and heavier/coarse particles appear in the top flow and no lighter/fine particles reports to the bottom flow at higher gas velocity.
4. Only lighter/fine particles report to the top flow and only heavier/coarse particles report to the bottom flow happens at ideal gas velocity.

The idea is to find the ideal gas velocity so that all the lighter/fine particles entering the fluidized bed overflow as the top product while all the heavier/coarse particles discharge as the bottom product. When the density/size of the lighter/fine and heavier/coarse particle is wider the terminal settling velocity of the particles gets wider and the ideal gas velocity is reachable. When the particles size/density ratio is close to one it is not possible to reach the ideal gas velocity. In such cases the maximum separation of the particles occurs when the maximum amount of the lighter/fine particles reports to the top product and maximum amount of the heavier/fine particles reports to the bottom product. The optimum gas velocity is the gas velocity at which maximum separation of the particles is occurs. The optimum gas velocity not only depends on the particle size or particle density but also on the operating variables such as solids feed rate, solids feed composition and feed inlet height.

The present study draws attention to the particles segregation of binary system in continuous mode of operation with the objective of understanding how the recovery of both the flotsam and jetsam particles and the purity of top and bottom products are influenced by the operating conditions. The operating variables tested were gas velocity, solids feed rate, feed composition, feed inlet height, particle size distribution, and particle size and density ratio. The aspects studied were the entrainment rate (kg/h) and discharge rate (kg/h), mass fraction of top and bottom products and bed pressure drop (mbar).

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

Material	d (μm)	ρ (kg/m^3)	U_mf[a] (m/s)	U_t[b] (m/s)	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 [8].

[b] Value calculated according to Haider and Levenspiel [9].

The present work is designed to sort out the existing discrepancies and to fill up the gap in the research in the area of continuous fast fluidization technique. Present study provides an apparent illustration of the continuous segregation phenomena of flotsam-rich, intermediary or jetsam-rich binary feed mixture of solids using gas–solid fast fluidization. The work identify the optimum conditions for maximum separation of the lighter/fine and heavier/coarse particles and analyze the effects of the operating variables such as solids feed rate, feed composition, feed inlet height and particle size ratio on the identified optimum gas velocity and optimum purity/recovery of the particles.

2. Experimental

The experimental set-up used and the experimental procedure employed in the present study is described in first part of this communication [1]. Table 1 reports the properties of solids used in the present study. All the selected particles fall in 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).

Three categories of particle feed mixtures have been examined in the continuous fast fluidized bed of varying density or size. First category has less composition of heavier/coarse particles in the feed mixture (flotsam-rich), second category of segregation has more concentration of heavier/coarse particles in the feed mixture (jetsam-rich) and the third category is the intermediary feed mixtures. Each category of mixture exhibited different fluidization behavior [1,2]. The particle density and size ratio selected is given in Table 2. The range of operating variables used in the present study is given in Table 3.

3. Results and discussion

A set of 1500 runs was performed to study the segregation of three categories of binary mixture of solids specifically, flotsam-rich, intermediary and jetsam-rich feed mixtures of solids of varying density and size in continuous fast fluidized bed. The influence of variables such as gas velocity, solids feed rate, feed composition, feed inlet position, particle size distribution and particle density/size ratio was studied to estimate the entrainment rate, discharge rate and, purity and recovery of the lighter/fine and heavier/coarse particles.

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

The purity of lighter/fine flotsam particles in the top product (Y_f) and purity of heavier/coarse jetsam particles in the bottom product (X_j) are defined as follows:

$$Y_f = \frac{\text{amount of lighter/fine particles in the sample collected}}{\text{total amount of sample collected in the overflow}} \quad (1)$$

$$X_j = \frac{\text{amount of heavier/coarse particles in the sample collected}}{\text{total amount of sample collected in the bottomflow}} \quad (2)$$

$(1-Y_f)$ gives the weight fraction of jetsam particles in the top product and $(1-X_j)$ gives the weight fraction of flotsam particles in the bottom product.

Although the exit concentrations presented above are a measure for design based on purity specifications, measure of recovery with operating conditions is additionally essential to analyze the performance of the separator. Recovery of flotsam particles (R_f) is the ratio of weight of lighter/fine particles in the overflow to the total weight of lighter/fine particles in the feed:

$$R_f = \frac{DY_f}{FZ_f} \quad (3)$$

Recovery of jetsam particles (R_j) is the ratio of weight of heavier/coarse particles in the bottom flow to the total weight of heavier/coarse particles in the feed:

$$R_j = \frac{B(1-X_f)}{F(1-Z_f)} \quad (4)$$

3.1. Effect of operating variables on purity and recovery of particles

3.1.1. Effect of gas velocity

The operating gas velocity strongly affects the quality of the products to be separated [10]. Fig. 1, typically, shows the effect of gas velocity on the purity of top and bottom products for size segregation of flotsam-rich mixture. At lower operating gas velocity, the drag force acting upon the particles is less. Most of the lighter/fine particles ejected from the bottom dense bed into the freeboard slow down after raising a certain height and returns back to the bottom dense bed along with the heavier/coarse particles. The amount of solids in the freeboard is found to decrease with height of the column. The upward airflow carries only the lighter/fine particles, if at all possible. Therefore only lighter/fine particles appear in the top product. So the purity of top product is maximum while the purity of bottom product is minimum. With further increase in gas velocity, the rate of material ejection from the bottom dense bed into the freeboard boosts up. The drag force acting on the particles increases. Few heavier/coarse particles are carried along with the lighter/fine particles to the top product. So the purity of top product starts dropping while the purity of bottom product increases due to decrease in the settling of the lighter/fine particles to the bottom of the bed. At higher gas velocity the purity of top product further reduces while the purity of bottom product attains maximum since there is no settling of the lighter/fine particles. It is clear from the experimental observations that the purity of lighter/fine particles in the top product decreases with increase in gas velocity whereas the purity of heavier/coarse particles in the bottom product increases with increase in gas velocity.

Table 3
Range of operation

Variable	Range
U_0 (m/s)	2–5.4
F (kg/h)	20–82
Z_j (%)	3–97
H_i (m)	0.3–2.1
PSD (μm)	+100–1000

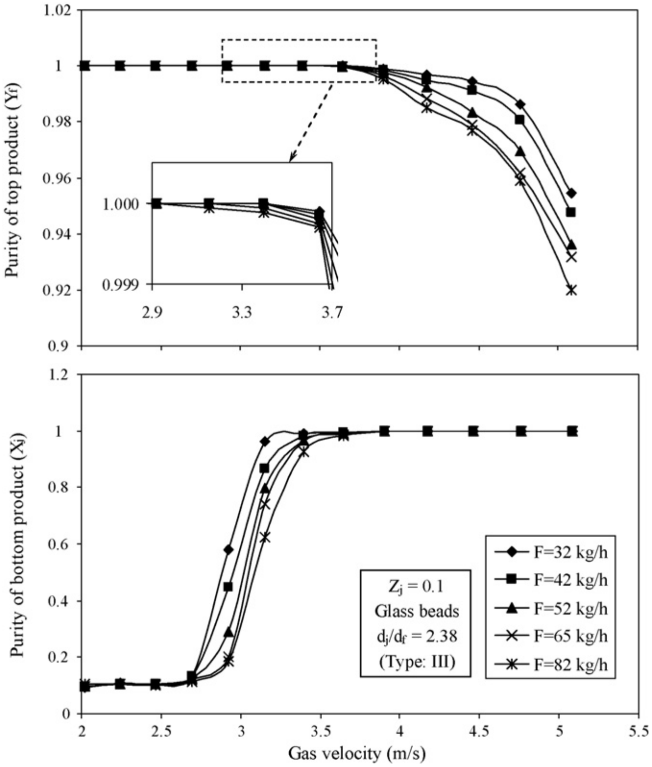

Fig. 1. Effect of gas velocity on the purity of top and bottom products for flotsam-rich mixture for size segregation of solids.

There is a threshold gas velocity beyond which the purity of lighter/fine particles in the top product is found to be dropping. The carryover of heavier/coarse particles to the top flow from the bed beyond the threshold velocity makes the concentration of lighter/fine particles in the top product to drop. The threshold velocity is found to decrease with increase in the solids feed rate. This makes a clear statement that the carryover of the heavier/coarse particles along with the lighter/fine particles occurs even at lower gas velocities for higher solids feed rate. For achieving maximum purity the fast fluidized bed has to operate below the threshold velocity.

Fig. 2, typically, shows the effect of gas velocity on the recovery of fine and coarse particles for flotsam-rich feed mixture for size segregation study. The entrainment of solids increases and the discharge of the solids decreases with the increase in the gas velocity for any category of feed mixtures [1,2]. At lower operating gas velocity, the recovery of the lighter/fine particles is less while the recovery of the heavier/coarse particles is maximum due to lesser entrainment rate and higher discharge rate of solids. With rise in

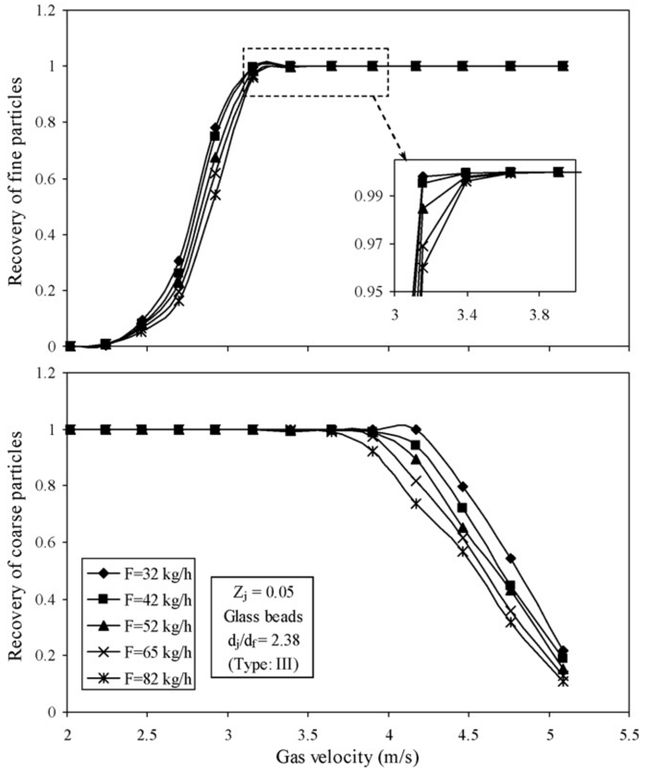

Fig. 2. Effect of gas velocity on the recovery of fine and coarse particles for flotsam-rich feed mixture for size segregation of solids.

gas velocity, the settling of the particles decreases and the discharge rate of the solids starts dropping. The entrainment rate and the recovery of lighter/fine particles in the top product increase while the recovery of the heavier/coarse particles in the bottom product starts decreasing. At higher operating gas velocity, the entrainment of solids is higher as lighter/fine particles do not settle at the bottom of the bed as well heavier/coarse particles are carried to the top product. As the outcome, the recovery of lighter/fine particles is complete but the recovery of the heavier/coarse particles is less.

Complete recovery of the lighter/fine particles is obtained only when all the lighter/fine particles in the feed reports to the top flow. At a given solids feed rate, there is a threshold gas velocity above which the recovery of lighter/fine particles is maximum. For obtaining maximum recovery of lighter/fine particles the system has to be operated just above the threshold velocity. The threshold gas velocity increases when the solids feed rate or the concentration of heavier/coarse particles in the feed increases. Finally it is concluded that for a given solids feed rate and feed composition, recovery of the lighter/fine particles increases whereas the recovery of the heavier/coarse particles decreases with the increase in the gas velocity. Similar result is noticed in the gas–solids bubbling fluidized beds [11,12] and liquid–solids fluidized bed separator [13].

3.1.2. *Effect of solids feed rate*

Solids feed rate is one of the important parameter in continuous fluidized beds [14]. Five feed rates in the range of 20–82 kg/h were tested for the selected feed composition and the results are presented, typically, in Figs. 3 and 4. It is found that the solids feed rate has less effect on the particle fluidization behavior [1,2] and considerable effect on the segregation in the range of the present study.

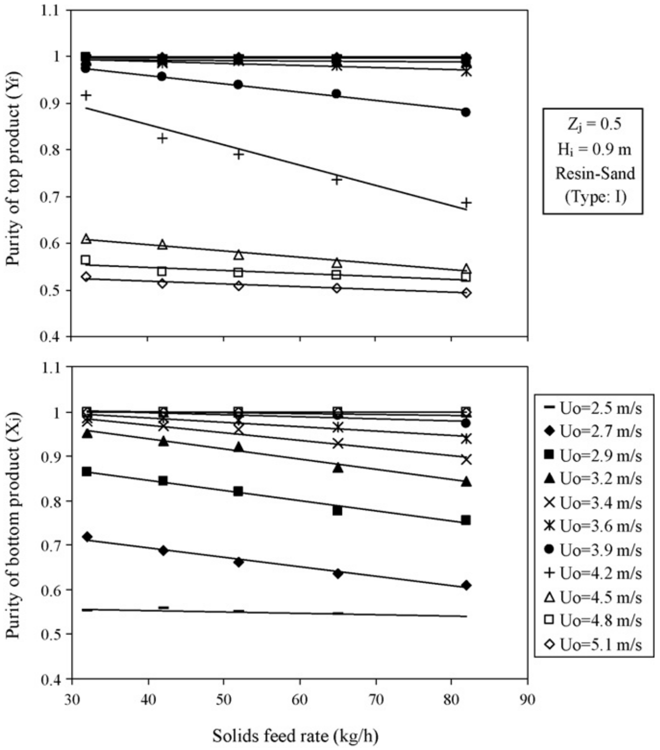

Fig. 3. Effect of solids feed rate on the purity of top and bottom products for intermediary feed mixture for density segregation of solids.

Fig. 3 shows the effect of the solids feed rate on the purity of top and bottom products for intermediary feed mixture for density segregation study. At higher solids feed rate and lower operating gas velocity, the holdup of solids inside the fluidized bed column

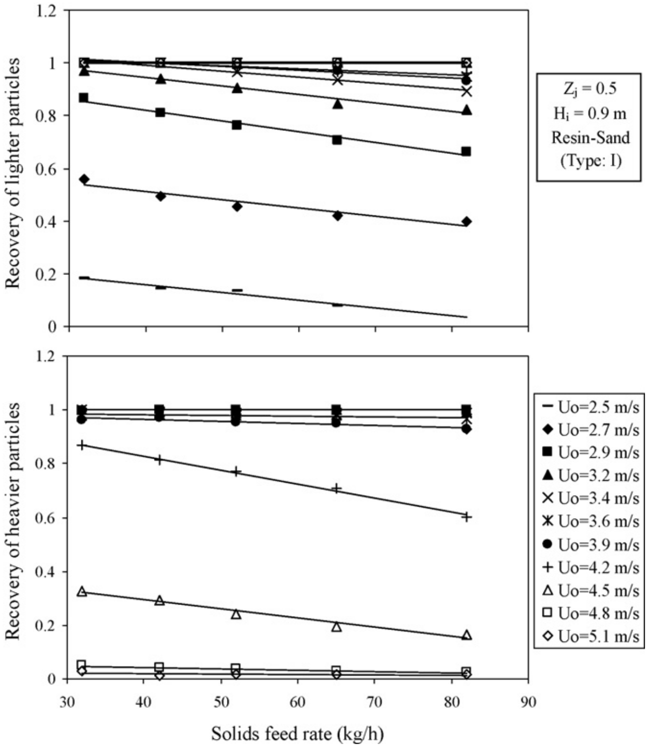

Fig. 4. Effect of solids feed rate on the recovery of lighter and heavier particles for intermediary feed mixture for density segregation of solids.

is more. It is understandable that the mobility of particles in the bed is affected due to the increase in particle–particle interactions [1,2]. As the result, some lighter/fine particles in the bed reports to the bottom flow along with the heavier/coarse particles while few heavier/coarse particles reports to the top flow along with the lighter/fine particles. The purity of bottom product reduces greatly whereas the purity of the top product is almost high.

At higher solids feed rate and higher operating gas velocity, the holdup of the solids inside the bed is less. The carryover of solids from the bed is more. Consequently more heavier/coarse particles report to the top flow along with the lighter/fine particles due to increase in the formation of the particles clusters [1,2]. As the result, the purity of top product reduces greatly but the purity of bottom product is almost high. Finally, it is affirmed that the purity of lighter/fine particles in the top product and purity of heavier/coarse particles in the bottom product decrease with increase in the solids feed rate [11,13].

Fig. 4 shows the effect of solids feed rate on the recovery of lighter and heavier particles for the intermediary feed mixture for density segregation study. The entrainment rate and discharge rate of solids increases with the increase in the solids feed rate [1,2]. Recovery of lighter/fine particles decreases with increase in the feed rate of solids. This effect is observed clearly at low operating gas velocities. The amount of particles ejected from the dense bed is higher for higher solids feed rates. Most of the ejected particles from the bed do not attain sufficient velocity to entrain along with the gas due to increase in inter-particle collisions. Therefore for higher solids feed rate and lower operating gas velocity, the recovery of lighter/fine particles is less. For higher solids feed rate and higher operating gas velocities, the recovery of the lighter/fine particles is found to be highest for the entire range of solids feed rate of the present study because of increase in the carryover of lighter/fine particles along with the gas.

The recovery of heavier/coarse particles is found to be decreasing with increase in the solids feed rate. At very low operating velocity, the recovery of heavier/coarse particles from the fluidized bed is less due to severe slugging in case of density segregation. But when the bed is in turbulent regime, the recovery of heavier/coarse particles is complete [1,2]. At higher gas velocities the recovery starts decreasing with increase in solids feed rate because of the carryover of heavier/coarse particles along with the lighter/fine particles to the top product.

3.1.3. *Effect of feed composition*

The study of the effect of feed composition on purity and recovery is important since the settling velocities also depend on the composition of solids. The classification driving force is proportional to the feed composition [15]. Generally the settling velocity decreases with increasing heavier/coarse solids composition due to hindered settling. This effect has been examined by increasing the composition of heavier/coarse particles in the feed mixture from 3% to 10% for the flotsam-rich mixture and 90–97% for the jetsam-rich mixture and 25–75% for intermediary mixture. The observed trends are presented, typically, in Figs. 5 and 6 for size segregation study.

The effect of the feed composition on the purity of top and bottom products is studied for flotsam-rich, intermediary and jetsam-rich mixtures and shown, typically, in Fig. 5 for jetsam-rich feed mixture. The holdup of heavier/coarse particles inside the column is comparatively more for higher feed composition of the heavier/coarse particles in the feed mixture. The bottom dense phase of the bed is found to be richer in heavier/coarse particles composition due to the increase in settling of the heavier/coarse particles. The jetsam-rich dense phase offers some mechanical force on the upper dilute phase and avoids the lighter/fine parti-

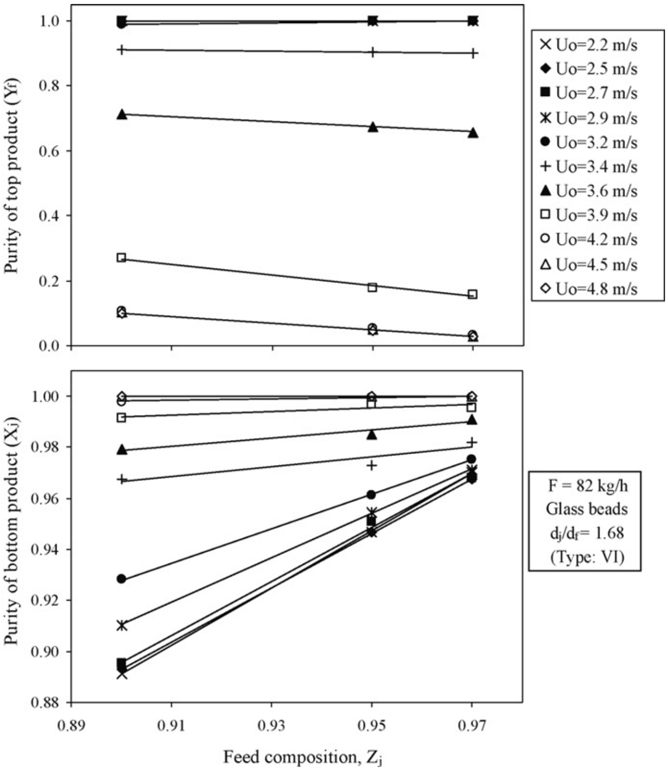

Fig. 5. Effect of solids feed composition on the purity of top and bottom products for jetsam-rich feed mixture for size segregation of solids.

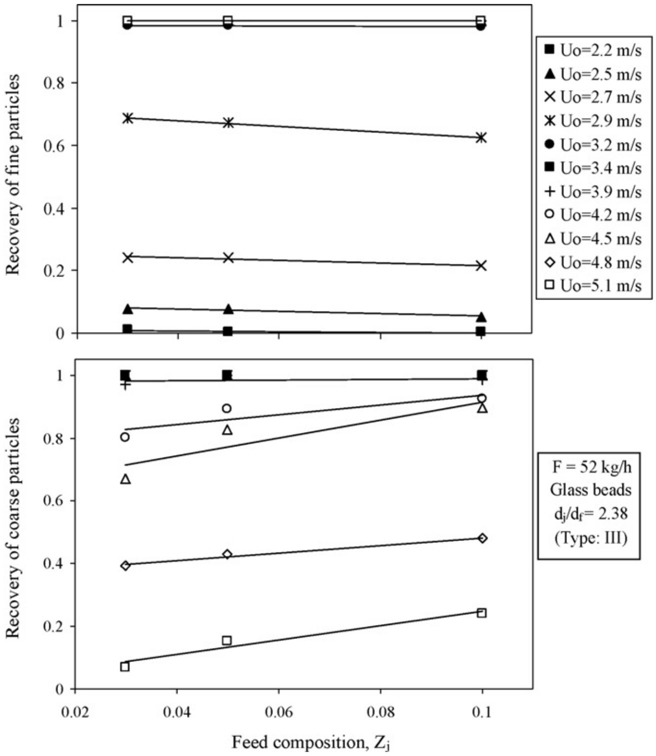

Fig. 6. Effect of solids feed composition on the recovery of fine and coarse particles for flotsam-rich feed mixture for size segregation of solids.

cles from the dilute phase entering the dense phase. The purity of bottom product increases as the outcome. Due to the increase in settling of the heavier/coarse particles and non-uniformity of the return flow, clusters are generated at the freeboard [1,2]. The size of the clusters is found to be larger for higher solids feed rate. The generated clusters of lighter/fine particles capture few heavier/coarse particles along with them to the top flow so the purity of top product decreases with increase in the feed composition of heavier/coarse particles. This phenomenon depends on the operating gas velocity. At higher gas velocities, the purity of the top product further reduces due to the entrainment of the heavier/coarse particles but the purity of the bottom product attains maximum. It is clear that the purity of lighter/fine particles in the top product decreases while the purity of heavier/coarse particles in the bottom product increases with increase in the feed composition of heavier/coarse particles.

The effect of feed composition on the recovery of fine particles and coarse particles is shown, typically, in Fig. 6 for flotsam-rich mixture. Increase in lighter/fine particles concentration in the feed mixture increases the carryover of heavier/coarse particles along with the lighter/fine particles to the top flow. The discharge rate from the column decreases and entrainment rate increases with increase in the lighter/fine particles concentration in the feed mixture. The recovery of lighter/fine particles in the top product increases and the recovery of heavier/coarse particles in the bottom product decreases with increase in the lighter/fine particles concentration in the feed mixtures. This effect is observed for jetsam-rich, intermediary, and flotsam-rich feed mixtures. The settling rate of solids increases with increase in the heavier/coarse particles concentration. Increase in the settling rate increases the recovery of heavier/coarse particles [13]. This effect is observed clearly even at higher gas velocities. The recovery of the lighter/fine particles is full at higher gas velocities because of complete entrainment of lighter/fine particles along with the some heavier/coarse particles to the top product. Looking at the observed results, it is concluded that the same trends on the variation of the purity of products and recovery of particles will result with changing either the gas velocity or solids feed rate.

3.1.4. Effect of the feed inlet height

The separation of particles in the continuous fast fluidized bed depends on the feed inlet position since the residence time of particles depends on feed inlet position [16]. Four different feed inlet positions are selected and tested for the present study. The experimental data is obtained for the resin-sand system of feed composition 10% for various gas velocities and solids feed rate.

When the feed inlet height is close to the distributor, the amount of lighter particles reporting to the bottom product along with the heavier particles is found to be higher. Since the settling heavier particles confine some lighter particles along with them to the bottom flow. So the purity of heavier particles is lesser when the feed inlet height is close to the distributor as presented, typically, in Fig. 7 for flotsam-rich mixture for density segregation study. The amount of particles ejected from the bed into the freeboard is higher when the feed inlet height is close to the distributor. Few of the ejected heavier particles from the dense bed are entrained out when the operating gas velocity is higher. As the outcome, the purity of lighter particles in the top product presented in Fig. 7 is found to be lesser. Particles' blocking in the feeding line is noted at very low operating gas velocity and higher solids feed rate when the feed inlet position is nearer to distributor ($H_i = 0.3$ m).

When the feed inlet height is far from the distributor, the amount of heavier particles reporting to the top product is more. It is well known that by increasing the feed inlet height the free board height decreases. The recovery of heavier particles decreases with increase in the feed inlet height as presented, typically, in Fig. 8 for flotsam-rich mixture for density segregation study. This effect is observed at higher operating gas velocities. At lower gas velocity, the recovery of heavier particles is found to be maximum for all the feed inlet heights in the range selected for the present study.

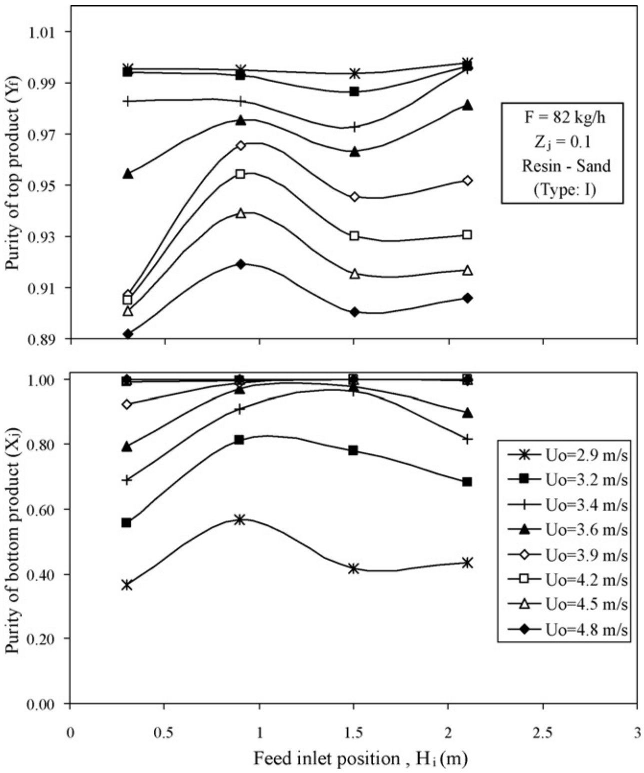

Fig. 7. Effect of feed inlet height on the purity of top and bottom products for flotsam-rich feed mixture for density segregation of solids.

The upward moving particles from the bottom dense bed collide with the particle's cloud created close to the feed inlet, by the feed flowing into the column from the hopper, slows down the lighter particles. The recovery of lighter particles and the purity of heavier particles are found to be lesser for a certain feed inlet ($H_i = 0.3$ and 2.1 m) selected for the present study. This effect is noted at lower operating gas velocities. At higher operating gas velocities, this effect disappears and the purity of heavier particles and the recovery of lighter particles are found to be maximum.

For the flotsam-rich feed mixture, the results confirmed that a better effectiveness of particle separation is attainable while the particles are fed at the mid-lower position of the bed. It is also understood that for a continuous process, a high feed inlet is not economically feasible for many practical applications because it includes conveying cost for lifting the amount of solids to be separated continuously.

Chyang et al. [16] reported that a better efficiency of particle segregation can be obtained when the particles are introduced at a lower position of the bed with a lowering solids feed rate. It is contrary to the results of Barari et al. [10]. They found that particle segregation could be increased when the particles are introduced into the higher position. This disagreement may possibly occur from the selection of the initial conditions such as feed composition and the operating gas velocity. Both the authors announced that increasing the particle residence time enhance the particle segregation, which dependent on feeding conditions. At higher operating gas velocity, lowering the feed inlet position increases the residence time of solids in the column. The results due to Gelperin et al.

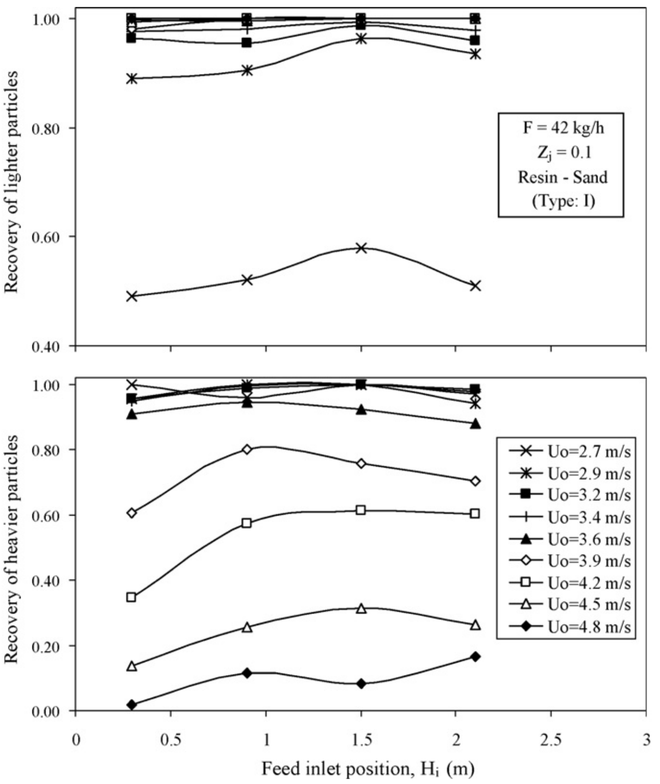

Fig. 8. Effect of feed inlet height on the recovery of lighter and heavier particles for flotsam-rich feed mixture for density segregation of solids.

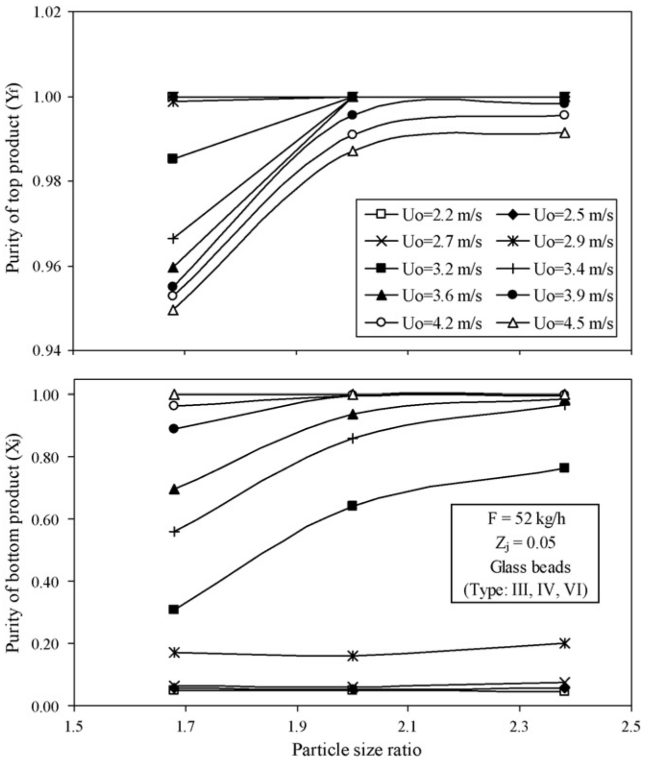

Fig. 9. Effect of particle size ratio on the purity of top and bottom products for flotsam-rich mixture for size segregation of solids.

[17] concerning feed inlet position are comparable to the present study.

3.1.5. *Effect of particle size/density ratio*

The particles size/density ratio is the major variable which affects the separation of any binary mixture of solids [18]. Three different size ratios of 2.3, 2 and 1.6 of mixture types III, IV and VI are tested in the present work. The fine particles used in all the three type of binary mixture is same. The coarse particles size is changed for getting required particle size ratio.

It is well known that when the particle size ratio is one, no separation of solids possible for the homogeneous mixture of solids. With increase in the particle size/density ratio, the separation of solids increases [10,17,18]. The purity of top product and the purity of bottom product increases with increase in the particle size ratio as presented, typically, in Fig. 9 for flotsam-rich mixture for size segregation study. The recovery of coarse particles and the recovery of fine particles increases with increase in particle size ratio as presented, typically, in Fig. 10 for flotsam-rich mixture for size segregation study. When the particle size ratio is less, the terminal settling velocity of fine and coarse particles becomes closer. The separation of particles decreases. Complete separation is achievable when the particle size ratio is greater than 2.4.

3.1.6. *Effect of particle size distribution*

Fluidized beds with widely sized particles commonly undergo segregation and results in bed de-fluidization. The operation of fluidized beds with heterogeneous mixture of particles with wide size distribution is very sensitive to the operating conditions. Experiments were conducted to find the size distribution of the particles collected in the top and bottom products for lignite-marcasite system with size range of 100–1000 μm. The lignite and marcasite particles collected in the top and bottom products are analyzed

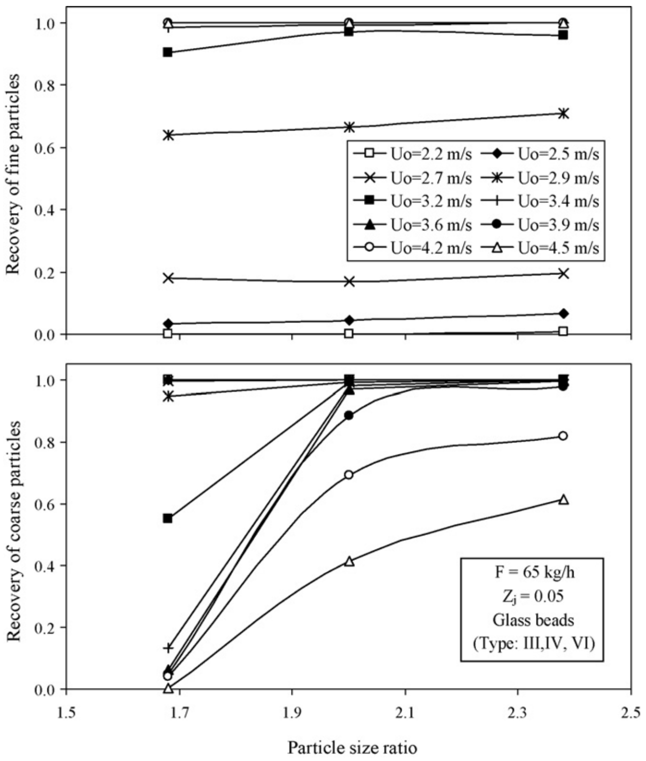

Fig. 10. Effect of particle size ratio on the recovery of fine and coarse particles for flotsam-rich mixture for size segregation of solids.

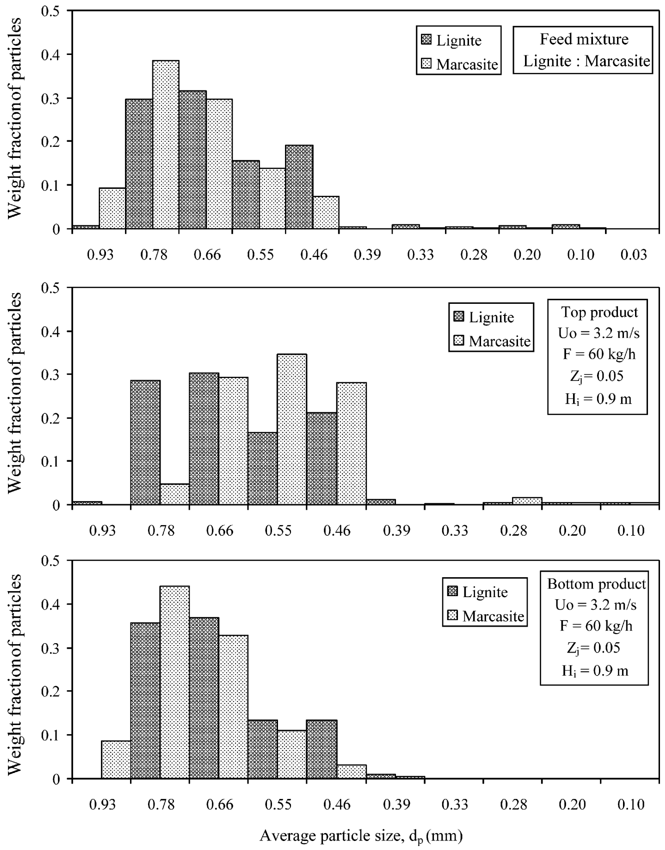

Fig. 11. Particle size distribution in the feed, top and bottom products.

using different test sieves. The size distribution of the particles in the feed, top flow and bottom flow for a particular gas velocity is presented, typically, in Fig. 11 for lignite-marcasite system. It is clear from the figure that the top flow is richer in smaller size lignite and marcasite particles and the bottom flow is richer in larger size lignite and marcasite particles. Fig. 12 shows the particle mean diameter of lignite and marcasite particles collected in the top and bottom products respectively. No lignite particles reports to the bottom flow when the velocity is greater than 4.17 m/s. Likewise, no marcasite particles are collected in the top flow when the velocity is lesser than 2.69 m/s. It is comprehensible from the figure that lignite and marcasite particles of smaller diameter go to the top product while the particles with the larger diameter comes in the bottom product if there is a broad size distribution of particles in the feed mixture. The mean diameter of lighter and heavier particles collected in the top and bottom products increases with increase in gas velocity. The effect is widely recognized and analyzed by many investigators in dissimilar field of gas–solids fluidization.

3.2. Empirical correlations

Based on the experimental data, correlations are developed for the continuous fast fluidization for different category of feed mixtures of the present study. The relationship of the entrainment rate, purity of top product and purity of bottom product with the system variables are expressed for density and size segregation of solids as follows:

1. Fractional entrainment:

$$\left(\frac{D}{F}\right) = A\left[\left(\frac{U_0}{U_{t,j}}\right)^a (Z_j)^b \left(\frac{H_i}{H}\right)^c \left(\frac{\rho_j}{\rho_f}\right)^d \left(\frac{d_j}{d_f}\right)^e\right] \tag{5}$$

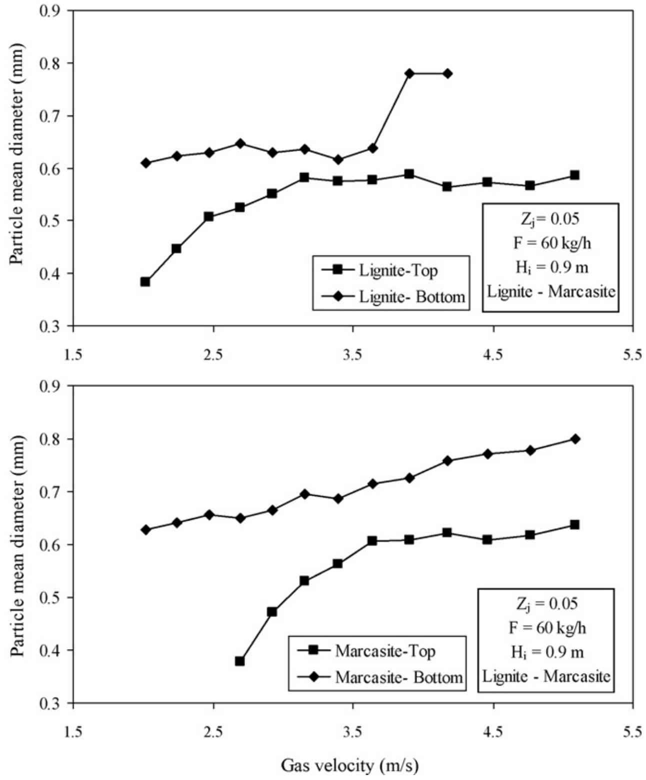

Fig. 12. Particle mean diameter of lignite and marcasite in the top and bottom products.

2. Purity of lighter/fine particles in the top product:

$$(V) = A\left[\left(\frac{U_0}{U_{t,j}}\right)^a (Z_f)^b (F)^c \left(\frac{H_i}{H}\right)^d \left(\frac{\rho_j}{\rho_f}\right)^e \left(\frac{d_j}{d_f}\right)^f\right] \tag{6}$$

3. Purity of heavier/coarse particles in the bottom product:

$$(X_j) = A\left[\left(\frac{U_0}{U_{t,j}}\right)^a (Z_j)^b (F)^c \left(\frac{H_i}{H}\right)^d \left(\frac{\rho_j}{\rho_f}\right)^e \left(\frac{d_j}{d_f}\right)^f\right] \tag{7}$$

Even though the studies are carried out in other regimes the correlations are only presented for the fast fluidization regime [1,2]. The exponents *a*, *b*, *c*, *d*, *e*, *f* as well as the coefficient *A* defined in Eqs. (5)–(7) are determined individually for each category of feed mixtures by regression analysis.

The entrainment of solids increases with increase in either gas velocity or solids feed rate or particle density/size ratio and decreases with increase in either feed inlet height or concentration of heavier/coarse particles in the feed for all the category of feed mixtures in the range selected for the present study. The calculated exponents *a*, *b*, *c*, *d*, *e* and the coefficient *A* defined in Eq. (5) is given in Table 4. The correlations are also developed by representing the equation by Z_f instead of Z_j in Eqs. (5) and (7). The exponents of the other parameters remain same when the correlations are represented with Z_f. The parity chart for entrainment of solids of flotsam-rich feed mixture is presented, typically, in Fig. 13 for size segregation study.

Purity of the top product decreases with increase in either gas velocity or solids feed rate and increases with increase in either concentration of lighter/fine particles in the feed or feed inlet height to a certain level or particle density/size ratio as per the experimental observations for all categories of the feed mixtures. The calculated

Table 4

Coefficient and exponents for the correlation of entrainment of solids defined in Eq. (5)

S. No.	Segregation	Category of feed mixture	*A*	*a*	*b*	*c*	*d*	*e*	No. of data points	RMS error[a] (%)
1	Density	Flotsam-rich	0.59	0.25	−0.036	−0.0058	0.55	0	276	2
2		Intermediary	0.28	0.82	−1	[b]	[b]	0	83	17
3		Jetsam-rich	1.05	2.61	−0.24	[b]	[b]	0	45	8.6
4	Size	Flotsam-rich	0.88	0.2	−0.038	[b]	0	0.055	339	2
5		Jetsam-rich	0.99	0.27	−0.09	[b]	0	[b]	43	1.2

[a] $\mathrm{RMS} = \left[\frac{1}{n}\sum_{i-1}^{n}\left(\frac{U_{\exp}-U_{\mathrm{cal}}}{U_{\exp}}\right)^2\right]^{1/2}$ where n is the number of experimental points, U_{cal} and $U_{\exp}$ are the calculated and measured experimental values, respectively.

[b] Variable not studied.

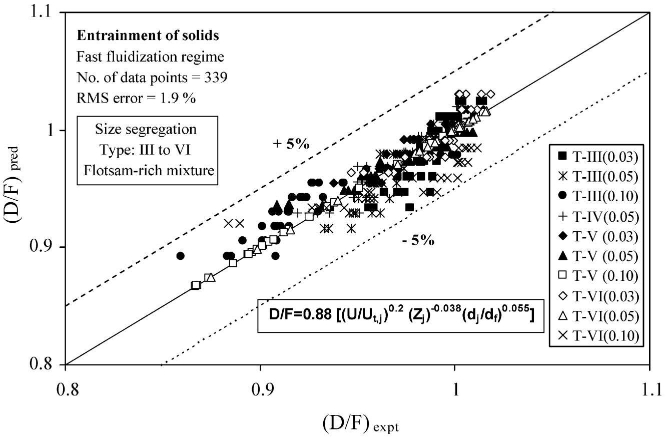

Fig. 13. Parity chart for entrainment of solids for flotsam-rich mixtures for size segregation of solids.

exponents *a*, *b*, *c*, *d*, *e*, *f* and the coefficient *A* defined in Eq. (6) is given in Table 5.

Purity of the bottom product increases with increase in either gas velocity or concentration of heavier/coarse particles in the feed or feed inlet height or particle density/size ratio and decreases with increase in solids feed rate for all categories of the feed mixtures as per the experimental observations. The calculated exponents *a*, *b*, *c*, *d*, *e*, *f* and the coefficient *A* defined in Eq. (7) is given in Table 6.

The discharge rate of solids can be calculated by drawing material balance for steady state operation. Recovery of the lighter/fine and heavier/coarse particles can be calculated using Eqs. (3) and (4) knowing the entrainment rate of solids, discharge rate of solids and the purity of top and bottom products. 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 Tables 4–6. The predicted data is satisfactorily compared with the experimental data for all the correlations proposed.

3.3. Identification of optimum gas velocity and optimum purity/recovery

The operating conditions that allow the best separation of two solids are found by relating the purity of the products and recovery of the particles. Fig. 14 shows the effect of gas velocity on the purity of products and recovery of particles for density segregation of solids for specified operating conditions. The purity of lighter/fine particles decreases with increase in gas velocity whereas the recovery of lighter particles increases with increase in gas velocity. The purity of heavier/coarse particles increases with increase in gas velocity whereas the recovery of heavier/coarse particles decreases with increase in gas velocity. The observed trend is similar for various operating conditions considered for the density and size segregation of solids of present study. Oshitani et al. [12] observed similar trends while separating non-spherical solids in the batch bubbling fluidized beds using a third material as the fluidizing agent.

To achieve complete separation both the purity of products as well as the recovery of particles should be one. At higher gas velocity, purity of the top product is less whereas the recovery of lighter particles is more and vice versa for lower gas velocity. Always there exists an optimum operating gas velocity corresponding to the point of intersection of the two lines. At this point, both the recovery of lighter/fine and heavier/coarse particles and both the purity of top and bottom products are maximum. The corresponding gas velocity is identified as the optimum gas velocity. At the optimum gas velocity, the purity of products and the recovery of particles are same for top product as well the bottom product. Therefore the optimum gas velocity can also be obtained by equating the purity of products and recovery of particles using Eqs. (1)–(7) and material balance for density and size segregation study. Six types of binary

Table 5

Coefficient and exponents for the correlation of purity of the top product defined in Eq. (6)

S. No.	Segregation	Category of feed mixture	*V*	*A*	*a*	*b*	*c*	*d*	*e*	*f*	No. of data points	RMS error[a] (%)
1	Density	Flotsam-rich	Y_f	0.75	−0.12	0.36	−0.01	0.01	0.36	0	345	1.6
2		Intermediary	Y_f	1.04	−0.44	0.011	−0.07	[b]	[b]	0	73	6
3		Jetsam-rich	$1-Y_f$	0.66	1.85	−0.06	0.09	[b]	[b]	0	45	6.5
4	Size	Flotsam-rich	Y_f	0.99	−0.055	0.21	−0.006	[b]	0	0.011	591	1.7
5		Jetsam-rich	Y_f	1.48	−1.05	1.02	−0.08	[b]	0	[b]	45	4.5

[a] $\mathrm{RMS} = \left[\frac{1}{n}\sum_{i-1}^{n}\left(\frac{U_{\exp}-U_{\mathrm{cal}}}{U_{\exp}}\right)^2\right]^{1/2}$ where n is the number of experimental points, U_{cal} and $U_{\exp}$ are the calculated and measured experimental values, respectively.

[b] Variable not studied.

Table 6
Coefficient and exponents for the correlation of purity of the bottom product defined in Eq. (7)

S. No.	Segregation	Category of feed mixture	*A*	*a*	*b*	*c*	*d*	*e*	*f*	No. of data points	RMS error[a] (%)
1	Density	Flotsam-rich	0.49	0.30	0.005	−0.014	0.01	1.02	0	256	3.7
2		Intermediary	1.22	0.32	0.016	−0.026	[b]	[b]	0	84	3
3		Jetsam-rich	1.01	0.012	0.007	−0.002	[b]	[b]	0	55	0.1
4	Size	Flotsam-rich	0.95	0.48	0.015	−0.03	[b]	0	0.402	308	8.4
5		Jetsam-rich	1	0.002	0.003	−0.0002	[b]	0	[b]	45	0.02

[a] $\mathrm{RMS} = \left[\frac{1}{n}\sum_{i-1}^{n}\left(\frac{U_{\mathrm{exp}}-U_{\mathrm{cal}}}{U_{\mathrm{exp}}}\right)^2\right]^{1/2}$ where n is the number of experimental points, U_{cal} and U_{exp} are the calculated and measured experimental values, respectively.

[b] Variable not studied.

systems were used considering, three categories of the mixture for obtaining the optimum gas velocity for various solids feed rate, feed inlet height and feed characteristics.

While operating closer to the optimum gas velocity, it is noted visually that most of the heavier/coarse particles entering the column sink down and the lighter/fine particles are pushed up by the heavier/coarse particles in the dense phase into the dilute phase. The upward moving gas applies additional force on the moving lighter/fine particles and carries them easily to the overflow. Few heavier/coarse particles rising from the dense bed slows down in the freeboard and sinks back into the bed close to the wall of the column and reaches the bottom flow.

In general, there is always a trade-off between quantity and concentration. Large the quantity of lighter/fine particles, poor the purity of lighter/fine particles in the top product. The quantity of heavier/coarse particles in the bottom product decreases as the result of increase in gas velocity. The gas velocity at which fluid beds particle classification can also be best performed depends on the demand. If a certain purity of the top layer is demanded, the gas velocity should be chosen in agreement with that demand [5]. Otherwise, the optimum gas velocity is at the point of intersection of the two lines where both the purity of the top and bottom products as well as the recovery of the lighter/fine and heavier/coarse particles is maximum.

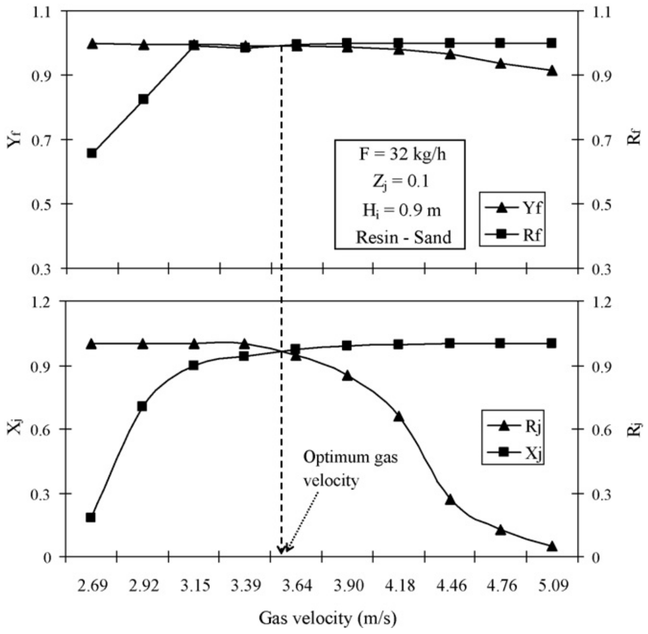

Fig. 14. Identification of the optimum gas velocity and optimum purity/recovery for density segregation of solids.

3.3.1. *Influence of solids feed rate*

The optimum operating gas velocity is the velocity at which the optimum purity/recovery exists. Figs. 15 and 16 shows the identified optimum operating gas velocity, optimum purity/recovery for various solids feed rates and feed compositions for density and size segregation of solids. The optimum operating gas velocity required for obtaining maximum separation is increasing marginally with solids feed rate and in some cases it is found to be decreasing marginally with solids feed rate. This opposing trend has occurred due to the variation of the fluidization behavior for different categories of the binary mixture of solids at different solids feed rates [1,2].

It is obvious from the figures that the optimum purity/recovery for maximum separation is decreasing with increase in the solids feed rate for the mixtures selected for the present study. Increase in solids feed rate decreases the concentration of the lighter/fine particles at the top product and heavier/coarse particles at the bottom product for density and size segregation of solids [1,2]. Thus by increasing the solids feed rate the maximum separation

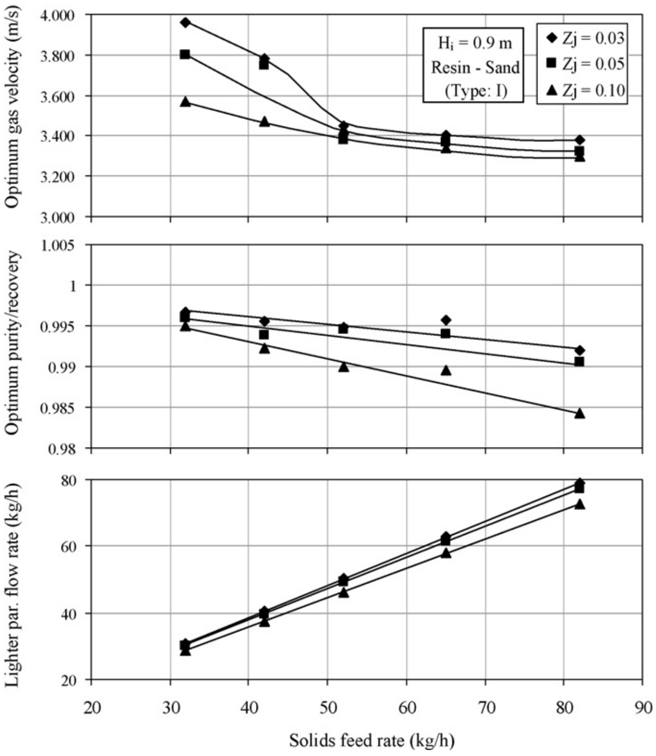

Fig. 15. Effect of solids feed rate and feed composition on the optimum gas velocity and optimum purity/recovery for density segregation of solids.

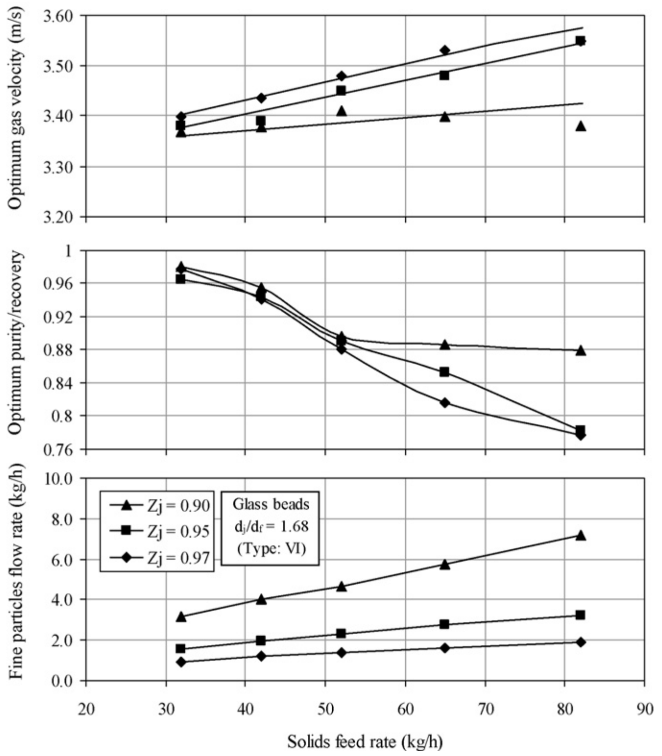

Fig. 16. Effect of solids feed rate and feed composition on the optimum gas velocity and optimum purity/recovery for size segregation of solids.

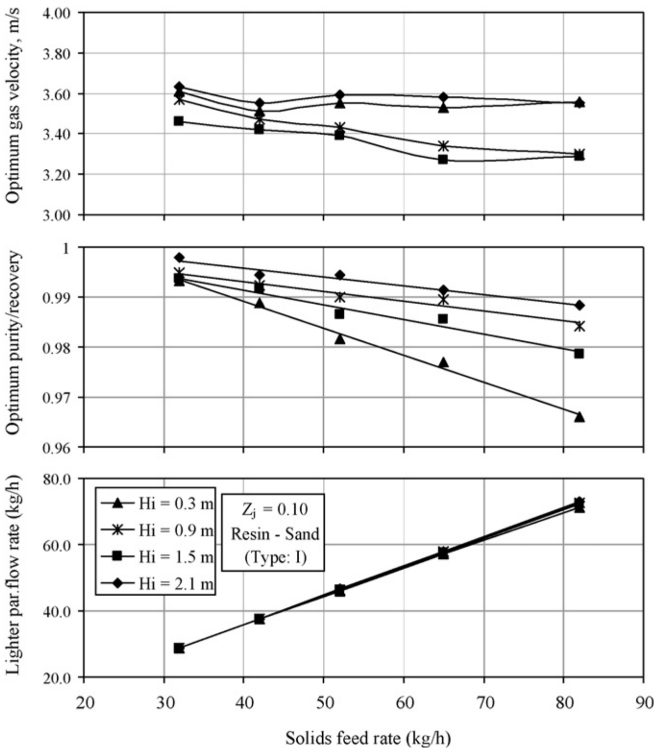

Fig. 17. Effect of solids feed rate and feed inlet height on the optimum gas velocity and optimum purity/recovery for density segregation of solids.

of the lighter/fine and heavier/coarse particles decreases even at the optimum gas velocity. The flow rate of the lighter/fine particles in the top product increases with the increase in the solids feed rate at optimum operating conditions. From the figures, it is comprehensible that the maximum separation of the binary mixture reduces with increase in the solids feed rate. The optimum gas velocity either increase or decrease marginally depending upon the fluidization behavior and the type of binary system selected.

3.3.2. *Influence of feed composition*

Figs. 15 and 16 shows the influence of solids feed composition on the optimum gas velocity and optimum purity/recovery for density and size segregation of solids. The optimum gas velocity increases marginally with increase in the heavier/coarse particles composition in the feed and some cases it decreases marginally with increase in the feed composition of heavier/coarse particles. Comparing the obtained data, it is identified that the optimum operating gas velocity is found to be higher when the heavier particles concentration is more in the feed mixture for the majority of the cases studied.

From the figures, it is evident that the optimum purity/recovery is higher when the lighter particles concentration is more in the feed mixture. But the observed trend varies marginally in some cases depending upon the category of the feed mixture selected for the present study. This crops up due to the dissimilarity of particles fluidization behavior due to the variation in the particles concentration [1,2]. Flow rate of the lighter/fine particles in the top product at optimum gas velocity increases with the increase in the feed composition of the lighter/fine particles.

3.3.3. *Influence of feed inlet height*

Fig. 17 shows the influence of feed inlet height on the optimum operating gas velocity and the optimum purity/recovery for the resin-sand system. The optimum operating gas velocity and the optimum purity/recovery are higher for the higher feed inlet height of 2.1 m. The optimum operating gas velocity is high while the optimum purity/recovery is low for the lower feed inlet height of 0.3 m. When the feed inlet height is close to the distributor lighter particles reporting to the bottom flow are more as well as air at high velocity is needed to push the gathered lighter particles from the bottom dense bed to the overflow. It is also clear from the figure that the amount of the lighter particles reporting to the top flow is less for the lower feed inlet height for higher solids feed rate. This occurs because of more gathering of the lighter particles in the bottom dense bed. The feed inlet height at mid-lower position of 0.9 m showing higher separation for different solids feed rates as well as utilize lower gas velocity compared to the other feed inlet height selected for the present study.

3.3.4. *Influence of particle size ratio*

Fig. 18 shows the influence of particle size ratio on the optimum gas velocity and optimum purity/recovery identified for the flotsam-rich feed mixture. The figure clearly states that the optimum gas velocity required for the separation is lower when the particle size ratio is less. The operating gas velocity increases with the increase in the particle size. When the particle size ratio is higher more velocity is therefore required to fluidize the coarse particles and to separate the fine particles.

The optimum purity/recovery increases with the increase in the particle size ratio. With increase in the particle size ratio the terminal settling velocity of the particles becomes wider and the particle segregation increases [2]. In the same way, the optimum purity/recovery is higher for higher particle size ratio. The amount of the fine particles reporting to the top flow increases with the increase in the particle size ratio.

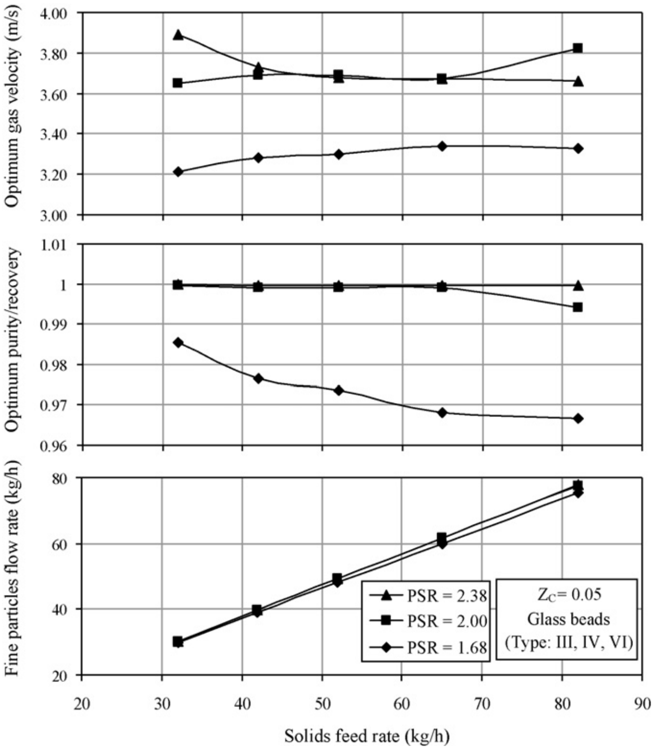

Fig. 18. Effect of solids feed rate and particle size ratio on optimum gas velocity and optimum purity/recovery for size segregation of solids.

4. Conclusions

Segregation of binary mixtures of solids in a continuous fast fluidized bed mainly depends upon the particles density and size. Density and size segregation of binary mixture of particles was experimentally studied for flotsam-rich, intermediary and jetsam-rich feed mixtures. The different sets of data obtained for the flotsam-rich, intermediary and jetsam-rich feed mixture showed identical trends even though the fluidization behavior of the mixture varies [1,2]. The performance of the separator is quantified by defining purity of products and recovery of particles. The gas velocity, solids feed rate, solids feed composition, feed inlet height, particle density/size ratio and particles size distribution in feed are the experimental factors which affects the purity of products and recovery of particles. Empirical correlations are proposed for the entrainment of solids, purity of top and bottom products and compared satisfactorily with the experimental data.

The gas velocity is the key parameter which affects the segregation of binary mixture of solids. The optimum gas velocity for maximum separation of the lighter/fine and heavier/coarse particles is identified for various operating conditions. The effect of the operating variables on the optimum gas velocity and optimum purity/recovery is presented.

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