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Studies on segregation of binary mixture of solids in a continuous fast fluidized bed Part I. Effect of particle density

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 binary mixture of solids was experimentally investigated in a continuous fast fluidized bed of 69 mm i.d. and 3.65 m high with air as the separation medium. The feed is a binary mixture of solid particles of same size, but different density. The variables include superficial gas velocity, solids feed rate and feed composition. It was observed that, at steady state, there exists physical equilibrium between the evolved flotsam and the residual jetsam when the granular solids are in fluid-like state. The phase diagram was constructed from the experimental observations. It shows the range for segregation, behavior of the fluidized bed and the distribution of the flotsam and jetsam, which can be understood by analogy with the distillation of the binary liquid mixture. The effect of the solids feed rate and feed composition on equilibrium distribution of the flotsam and jetsam was studied.

Keywords: Fast fluidization; Density segregation; Equilibrium phase diagram; Binary solids; Bed pressure drop

1. Introduction

In fast fluidization, solids entrain out of the bed along with the gas when the upward gas velocity exceeds the terminal velocity of the particles. If the solids in the bed are of different size and/or density, coarse and/or heavy particles sink to the bottom and fine and/or light particles entrain from the top of the bed. The particles that settle to the bottom are called as the jetsam phase and the entrained particles are termed as flotsam phase. Thus the differences in density or size of the individual particles can be exploited to effect segregation and concentrate the desired components [1].

Among the several classifiers, fluidized-bed based devices provide stable operation and sharp separation in the size range of 50–1000 μm [2]. Separation of the solids in a fluidized bed seems to be attractive since there are no moving parts in the separator, considerable reduction in space, simplicity in construction, operation and maintenance, consistency of products, easy installation, etc. This technique has wide applications in the areas of dry beneficiation of minerals and agriculture. Separation of the solids by fluidization provides higher separation efficiencies at higher velocities and is most suitable for separation of lean mixtures in spite of significant amount of energy is consumed in the form of supply of air. The best way to reduce the operating costs of existing units is to improve their efficiency and operation via process optimization and control. To achieve this improvement, a thorough understanding of fluidization principles and how fluidized-bed systems are designed is essential. The successful application of segregation in continuous fast fluidized bed depends on understanding the equilibrium existing between the flotsam and jetsam phases of the mixtures encountered.

Continuous separation of components from a solid mixture via fast fluidization depends not only on the differences in density and/or size of the individual components but also on the composition of the components present in the feed, the operating gas velocity and the solids flow rate into the fluidizing column. Many researchers have made remarkable effort to understand the segregation phenomena in fluidization of binary mixture of solids [3–19].

The important characteristics of fluid-like flow behavior of solids in gas–solid fluidized beds have been widely recognized and is used to analyze fluidized-bed behavior as the flowability

* Corresponding author.
E-mail address: psts@iitm.ac.in (P.S.T. Sai).

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Nomenclature

B	flow rate of bottom particles (kg/h)
D	flow rate of overflow particles (kg/h)
F	flow rate of the feed particles (kg/h)
U_O	superficial gas velocity (m/s)
X_H	weight fraction of heavier particles in bottom product
X_L	weight fraction of lighter particles in bottom product
Y_H	weight fraction of heavier particles in overhead product
Y_L	weight fraction of lighter particles in overhead product
Z_H	weight fraction of heavier particles in feed
Z_L	weight fraction of lighter particles in feed

of gas–solid mixtures [20,21], phase equilibrium [9,22], particle elutriation [23], apparent viscosity [20,21,24], particle mixing [25], bubble motion [21,26,27] and exchange of particles between the core and the annular regions in circulating fluidized beds [28,29,36]. There are analogies between flow patterns in regime transitions of gas-solids upward transport and gas–liquid upward transport [30]. The bubble-free fluidization regime is analogous to the dispersed bubble flow regime where small bubbles or 'voids' do not coalesce with each other. Such an analogy was examined by Krishna et al. [31]. Based on the hydrodynamic behavior of the fluidized beds and bubble columns, a unified model is also developed for the scaling up of the two reactors in either heterogeneous or homogeneous flow regimes [32]. Even the concept of theoretical plate is applied to the process of separating granular material in gas–solids fluidized bed with limited data and simplifying assumptions by the rectification method for the column design [33].

In distillation, a liquid or vapor mixture of two or more substances is separated into its component fractions of desired purity by the application and removal of energy. Similarly in fluidization, a mixture of two or more substances of solids is separated into its component fractions of desired purity by the application and removal of energy. The parameter of a fluidized bed that is analogous to temperature of a distillation is the fluidizing velocity [4,22,23]. In this connection it is assumed that certain physical properties of a fluidized bed depend on velocity in the same way as the corresponding properties of a liquid depend on temperature.

The entrainment of particles from the bed is analogous to transition of liquid to the vapor state [22]. The lighter particles have a lower minimum fluidization velocity than the heavier particles. Higher the fluidization velocity, greater the rate at which the lighter particles leave the bed. The free space height above the feed inlet serves like a rectification section; the elutriated heavier particles slow down and return to the bottom dense phase mixture. The greater the boiling rate, greater is the capacity needed of the rectification section and hence the greater the free space height which is similar to the increase in vapor pressure of a liquid with temperature. The cyclone separator in the system acts like condenser where the momentum of the particles is removed completely from the entrained particles [23]. After removal of the momentum, the particles are collected in the collection tank. The separated particles will be richer in lighter particles. Therefore, the upward gas velocity should exceed the terminal settling velocity of the lighter particles to separate the solids having particles of different size or density [1]. The existence of a liquid is limited by the critical temperature and similarly the upper limit of existence of a fluidized bed is close to the free falling velocity of heavier particles.

The present study relates the solids segregation in a continuous fast fluidized bed to the entrainment separation following distillation involving equilibrium considerations or phase change of any of the components. Phase distribution of the lighter and heavier particles in both jetsam and flotsam phases are investigated for various superficial gas velocities, solids feed rate and feed composition. The outcome of this research provides better guidelines for the design and selection of operating variables for the fast fluidized-bed operation. Whereas the present study reports the effect of particle density on segregation, the effect of particle size is reported in the second part of this communication.

2. Experimental

2.1. Apparatus

The schematic of the experimental set-up is shown in Fig. 1 and the details are described elsewhere [18]. The column (6) was made of Perspex with an i.d. of 69 mm and 3.65 m length from the distributor to the gas exit. A perforated distributor plate with free area of 13% (2 mm orifice diameter and 5 mm triangular pitch) was used. The distribution section (5) of 0.3 m high was filled with packing material of 2–3 mm spherical glass beads for uniform distribution of air. A fine mesh was fixed to the perforated plate to prevent the particle down flow through the perforations of the distributor plate. A bottom discharge pipe (12), placed above the distributor plate, was 12.2 mm in diameter. Cylindrical hopper (8) was used for feeding the binary mixture and pre-calibrated scales were used to control the solids flow rate from the hopper into the column. The feed inlet position was measured from the distributor plate in the fluidizing column.

Two pressure taps, one below the distributor plate and the other below the top product outlet were set to measure the total bed pressure drop of the column by the differential pressure transmitter (13). The data-acquisition unit (14) consists of PC (15) equipped with a 12-bit A/D card at a rate of 10 samples/s and for a fixed period of 0–10 min. The overhead product from the fluidized bed was separated by a cyclone separator (9) and was collected in collection tank 'A' (10). A fine mesh of 100 μm was fixed at the cyclone exit inorder to avoid the escape of the fine particles from the fluidized bed. The gangue particles in the bottom of the fluidized bed falls by gravity into the collection tank 'B' (11). Fluidizing medium was moisture free air from a high volume compressor (1) at a constant pressure using pressure regulator (3). Airflow rate was measured by the cali-

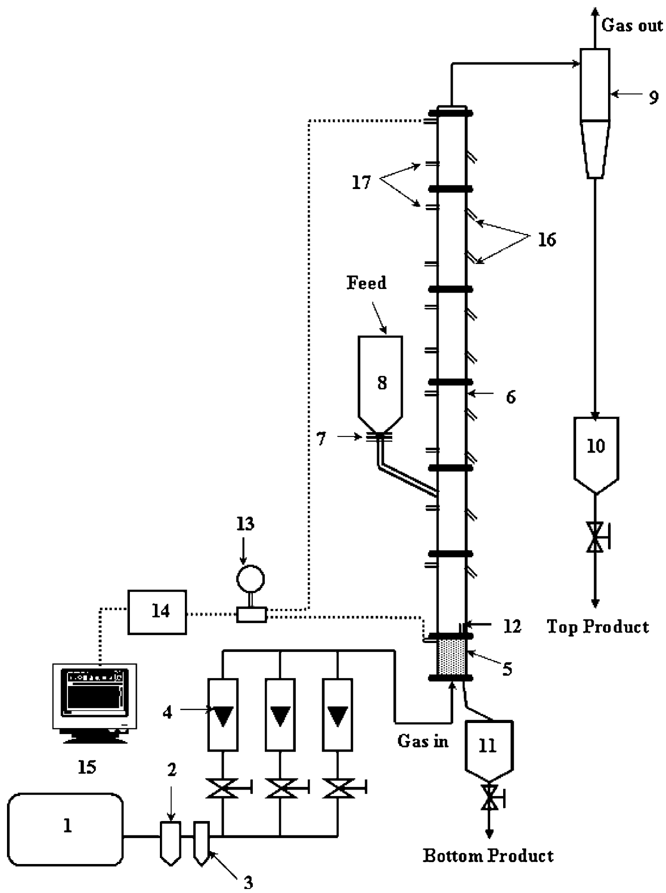

Fig. 1. Experimental setup of the continuous gas–solid fast fluidized bed: (1) compressor, (2) moisture separator, (3) pressure regulator, (4) rotameter, (5) plenum chamber, (6) fluidized bed column, (7) slide scale, (8) feed hopper, (9) cyclone separator, (10) collection tank ‘A’, (11) collection tank ‘B’, (12) discharge pipe, (13) pressure transmitter, (14) data acquisition system, (15) computer, (16) sampling ports and (17) pressure taps.

brated rotameters (4). The electrostatic forces generated among the particles were eliminated by earthing with copper wire.

2.2. Materials

Table 1 reports the properties of the solids used in the present study. Feed mixture of 780 μm resin (lighter)–sand (heavier) designated as type I mixture and 750 μm lignite (lighter)–marcasite (heavier) designated as type II mixture were used. The ratio of the density of the heavier to lighter particles was more than 2 for both the types. All the particles selected for the study falls in the Geldart group B class. Reasonably close sized granular particles were obtained for each mixture 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).

Table 2
Range of operating variables used in the present study

Variable	Range
U_O (m/s)	2.01–5.42
F (kg/h)	20–82
Z_H (%)	3, 5, 10, 25, 50, 75, 90, 95, 97

2.3. Experimental procedure

Air at a particular flow rate was introduced into the empty column, after choosing a composition of the solid mixture. Premixed solids were introduced from the hopper into the bed through the pre-calibrated slide scale at specified solids flow rate by gravity flow. The system was allowed to attain the steady state. The steady state was confirmed from the pressure drop data, which was monitored continuously by the differential pressure transmitter connected to data-acquisition. The steady state was verified by checking the mass flow of the material in the bottom and overhead products with the feed flow rate. After confirming the steady state operation to ensure steady entrainment and discharge rates, samples were collected for each run to find the composition of lighter and heavier particles. Flotsam and jetsam collected were analyzed by batch elutriation method using a small-fluidized bed for purity. Flow of the solids was visualized through the Perspex column and the identified particles flow structures were recorded. All the experiments were carried out with fixed column height and product discharge pipe diameter. The range of operating variables used in the present study is given in Table 2.

3. Results and discussion

The purity of flotsam is defined as the ratio of the amount of lighter particles in the sample to the total amount of the sample

Table 1
Physical properties of solids used in the present study

Material	Resin (lighter)	Sand (heavier)	Lignite (lighter)	Marcasite (heavier)
Type	I		II	
Average diameter (μm)	780	780	750	750
Size (μm)	+710–850	+710–850	+500–1000	+500–1000
Sphericity	1	0.95	0.73	0.85
Particle density (kg/m^3)	1153	2650	1540	3345
Geldart group	B	B	B	B
Terminal velocity[a] (m/s)	3.79	5.43	2.63	4.90
Minimum fluidization velocity[b] (m/s)	0.19	0.40	0.24	0.46

[a] Value calculated according to Haider and Levenspiel [37].
[b] Value calculated according to Wen and Yu [38].

collected in the top flow. The purity of jetsam is defined as the ratio of the amount of heavier particles in the sample to the total amount of the sample collected in the bottom flow. The superficial gas velocity is defined based on the cross sectional area of the empty column.

3.1. Fluidization behavior

Analysis of pressure fluctuations have been widely used to quantify the fluidization behavior of a gas–solid fluidized bed [34,35]. Fluidization behavior of the binary mixture of solids is strongly influenced by the variations of the gas velocity. The entrainment and discharge rates of solids depends on a number of factors such as gas velocity, particle-size distribution, column height, density of the particles and viscosity and density of the gas [12,13]. The fluidization behavior of the flotsam rich, intermediary and jetsam-rich feed mixture was studied individually in the present work for various solids feed rate and gas velocity.

3.1.1. Flotsam-rich feed mixture

Fig. 2 shows the discharge and entrainment rates, and the bed pressure drop for lignite–marcasite system of flotsam-rich mixture for different solids feed rates. It is evident from the figure that with increase in gas velocity, the entrainment rate increases

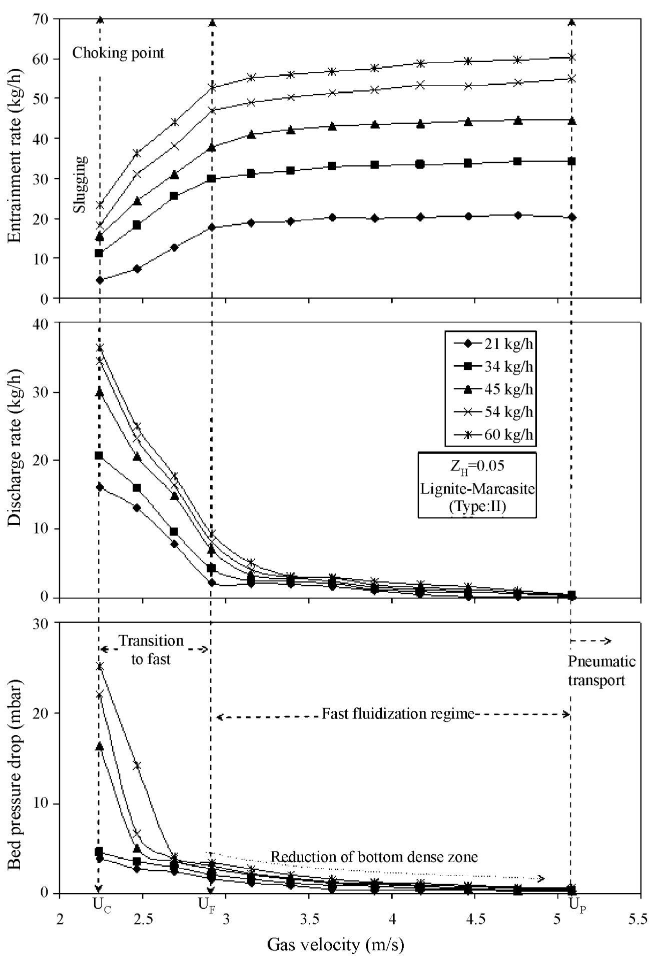

Fig. 2. Flow behavior of flotsam-rich feed mixture for lignite–marcasite system.

and the discharge rate decreases for any solids feed rate or feed composition. At gas velocities less than U_C, the entrainment rate from the fluidized bed is least. The particles fed into the bed do not attain sufficient velocity to entrain out of the bed. Most of the lighter particles rising from the bed slow down in the freeboard and return back to the distributor. At high solids feed rate, the discharge rate out of the column is not adequate and the holdup of the solids inside the column keeps on increasing because of steady accumulation of the solids. The dense bed above the distributor starts growing and the bed converts to slugging at one stage. The dramatic fluctuations in pressure were recorded because of the increase in the accumulation of the solids. Based on visual observation of flow patterns, it is believed that this phenomenon is very similar to the choking that occurs in the column for lower gas velocity or higher solids feed rate. The lower dense phase zone progressively extends upwards until the system becomes inoperable at the same solids feed rate. Due to severe slugging and accumulation of the solids, the feed rate of the solids from the hopper was not constant. A pulsed feed flow was noted from the hopper.

Choking was not observed for lower solids feed rates of 21 and 34 kg/h. At lower solids feed rate, the accumulation of the solids inside the column was less and as a result, the operation was steady. The transition from lean-phase conveying to fast fluidization is analogous to choking transition in vertical pneumatic conveying [35]. This transition should not be confused with the present observation. In the present study, choking was observed in the transition from slugging to turbulent regime.

If the operating gas velocity is between U_C and U_F, the entrainment rate increases and the discharge rate decreases with increase in gas velocity. The holdup of the solids inside the bed decreases. Considerable amount of the solids ejected from the bed do not attain the maximum velocity to entrain out. Many ejected solids from the bed slow down in the freeboard and falls back to the bed. There is quantitative indication of transition by the decrease in the pressure fluctuation and this extension of the slug flow is believed to be transition to fast. The flow is characterized by the breakdown of the smaller slugs due to slug–slug interactions. The material flow in the top and bottom products matches with the feed flow rate. The time taken for attaining equilibrium in case of transition to fast is more because of the upward and down ward flow of the solids similar to counter diffusion.

At $U_O = U_F$, a steady increase in the entrainment rate and a drop in the discharge rate were noted. This is believed to be the beginning of fast fluidization regime. The holdup of the solids was minimum compared to that of the transitional regime. The fast fluidized bed was characterized by the presence of bottom dense zone followed by upper dilute zone [34]. The bottom dense zone was found to be richer in the heavier particles. The amount of the solids in the dilute phase was higher compared to the transitional regime. With further increase in the gas velocity, the bottom dense phase starts decreasing. The carry-over of the solids increases and the discharge rate reduces. Furthermore, due to the decrease in the cluster formation, the differential pressure fluctuations become smaller and smaller and solids holdup decreases, giving an indication of increase in the bed homogeneity. For a given solids feed rate, U_F and U_P respectively are the lower and upper critical gas velocities for operation in fast fluidization mode. When $U_O > U_P$, all the particles entering the bed from the hopper were entrained out of the column and the column acts like a pneumatic transport line. The bottom dense bed disappears and the discharge rate becomes zero. This velocity is identified to be the termination of the fast fluidization regime or transition to pneumatic transport. The holdup of the solids in the fluidized bed was least. Gas–solid flow in the free board showed similarities to a fast bed or a pneumatic transport line.

3.1.2. *Intermediary feed mixture*

The flow regime map of resin–sand mixture of 50% feed composition is shown in Fig. 3. As observed in the case of flotsam-rich mixtures, choking occurs at low gas velocity and high solids feed rates as a result of collapse of free suspension of particles. Choking of solids results when the gas velocity is less than U_C and the bed is in slugging mode. The operation of the column with less than U_C is not stable and not feasible for solids separation. The velocity U_C is identified to be choking point.

When the gas velocity is between U_C and U_F, the bed is in transition to fast. The entrainment rate increases and the discharge rate decreases as the bed becomes stable. The holdup of the solids was higher compared to the flotsam-rich feed mixtures. The structure of the transitional bed is made of two phases: a dense phase of solids with closely packed clusters and streams of solids moving up and down, and a dilute phase with individual particles and small clusters. As can be seen from the figure, the captive fast fluidized bed exists between the bed of transitional and pneumatic transport. The fast fluidized-bed regime occurs when significant amount of particles entrained from the fluidized bed. The existence of the bottom dense region and upper dilute region was noticed as commonly noticed in the flotsam-rich mixtures. The holdup of the solids in the dilute phase is more in case of fast fluidization than the transitional regime. The recorded peak at the termination of the fast fluidization regime corresponds to the carry-over of the heavier particles from the bed. The rise of the peak indicates the expansion of the heavier particles from the bottom dense bed and the decline of the peak indicates the carry over of the heavier solids out of the column. Similar peak was not observed clearly incase of the flotsam-rich mixtures. The velocity between U_{FP} and U_P corresponds to the transition of the fast fluidization regime to the pneumatic transport of the solids. The transport of the heavier particles out of the bed increases with increase in the gas velocity in this region. When the gas velocity is above U_P, the entrainment attains maximum while the discharge of the solids is zero and the bed behaves like the pneumatic transport line.

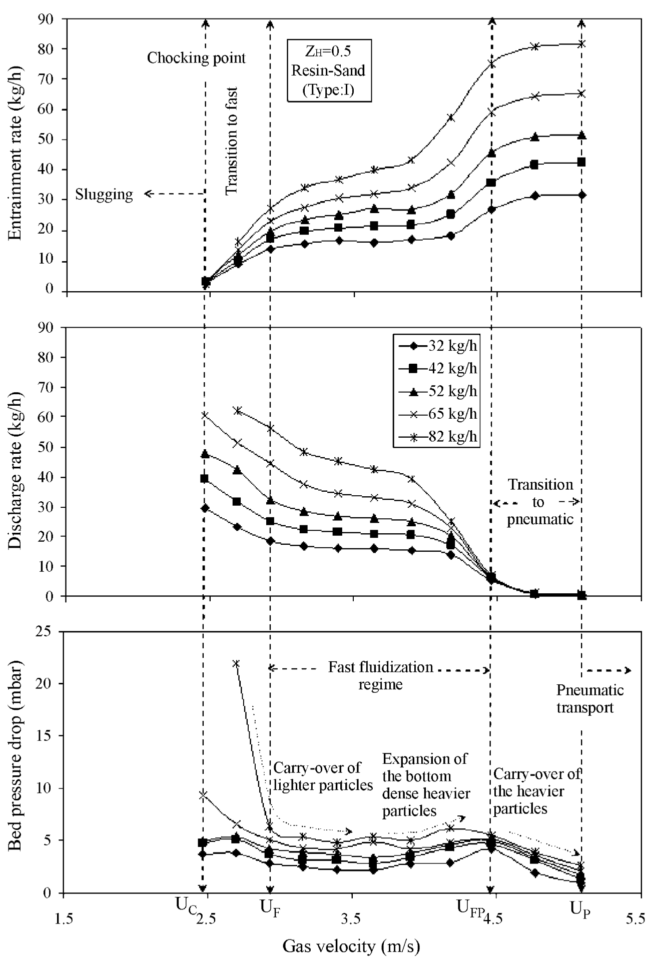

Fig. 3. Flow behavior of intermediary feed mixture for resin–sand system.

3.1.3. *Jetsam-rich feed mixture*

Fig. 4 shows the effect of the gas velocity on the entrainment rate, discharge rate and bed pressure drop for the jetsam-rich feed mixture for resin–sand system. It is comprehensible from the figure that with increase in the gas velocity, the rate of entrainment increases and the rate of discharge decreases for any operating feed rate. When the operating gas velocity is less than U_T, all the solids entering the column are discharged out. Small bubbles rising from the distributor carries some solids along with them and ejects the solids in the freeboard. All the ejected solids in the freeboard return back to the bed. There will be no carry-over of solids out of the column. The entrainment rate is zero and separation of the particles does not exist. When the gas velocity is at U_T, the solids start entraining. At this gas velocity, the entrainment rate is very small but the discharge rate is highest. This velocity appears to be the beginning of the turbulent fluidization.

When the operating gas velocity is between U_T and U_F, the bed starts expanding; the entrainment rate increases and the discharge rate decreases. The entrained solids are found to be richer in the lighter particles. The bubble size and coalescence is higher and the bed is vigorous. This region is believed to be turbulent regime. For higher solids feed rate, notably for 65 kg/h and 82 kg/h, a de-fluidized bottom layer was formed in the bottom of the bed. As a result, the bed pressure drop rises. It is evident from the figure that from point 1 to 2, the accumulated de-fluidized layer at the bottom of the bed and the bed pressure are more. From point 2 to 3, there is a drop in the bed pressure drop because of the decrease in the volume of the de-fluidized bottom layer due to increase in the entrainment rate of the solids. For lower solids feed rate, these effects were not observed since

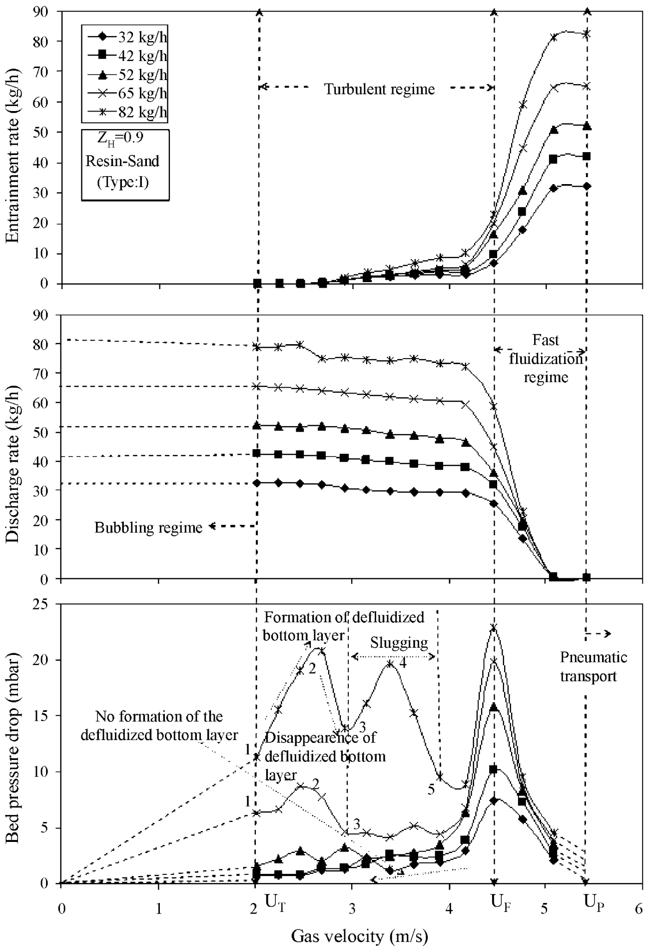

Fig. 4. Flow behavior of jetsam-rich feed mixture for resin–sand system.

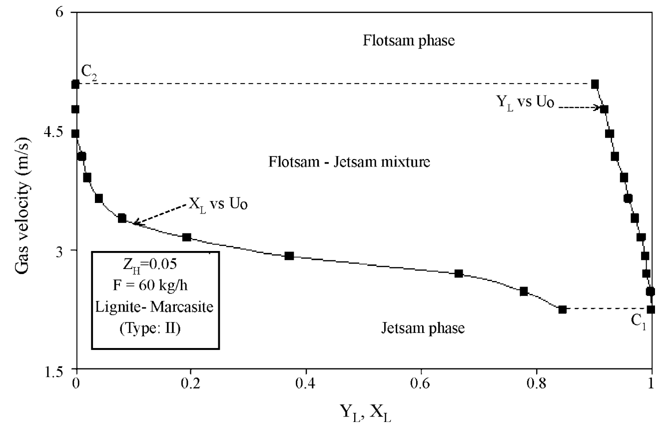

Fig. 5. Velocity concentration phase diagram for lignite–marcasite system.

there was no accumulation of the solids. From point 3 to 4, the bed pressure drop rises because the bed is in slugging mode for higher solids feed rate of 82 kg/h. This happens because of minimum or no carry-over of the heavier particles from the bed. For lower solids feed rate of 65 kg/h, the slugging was noticed but not severe. At these operating gas velocities, the bed is highly unstable. But for very low feed rate slugging was not observed.

With further increase in gas velocity, the carry-over of the heavier particles begins and the stability of the bed increases. The follow-on peak in Fig. 4 corresponds to the expansion and the carry-over of the heavier particles from the bed. When the gas velocity is at U_F, a sudden increase in the entrainment rate and drop in discharge rate were noted. There was a bottom dense phase zone and upper dilute zone. The bottom dense phase zone was richer in heavier particles and the dilute phase zone was of lighter and the heavier solids. When the operating gas velocity is increased from U_F and U_P, the entrainment rate increases and discharge rate further reduces. The carry-over of the heavier particles is very high. The holdup of the solids inside the column is least. When the operating gas velocity exceeds U_P, the entrainment rate attains the maximum and the bed behaves like a pneumatic transport of the solids.

Comparing the flow behaviors of flotsam-rich and jetsam-rich feed mixtures, it is obvious that the range of existence of the fast fluidization regime reduces with the increase in the heavier particles composition in the feed mixture.

3.2. Velocity–composition phase diagram

Fig. 5 shows the velocity–composition phase diagram for the lignite–marcasite system. The U_O–Y_L–X_L diagram shows the variation of the equilibrium composition of the components in the solid mixture with the velocity. The entire diagram can be divided into three different regions, viz., jetsam phase, jetsam–flotsam mixture and flotsam phase.

The upper curve provides the velocity–flotsam composition (U_O–Y_L) relationship, i.e., the carry over of the solids. The lower curve provides the velocity–jetsam composition (U_O–X_L), i.e., the settling of the solids. When the fluidized bed is operated below the point C_1, the separation of the particles from the bed is ineffective. There will be bottom product flow alone and no entrainment of the solids. All the solids behave like jetsam. The holdup of the solids in the fluidized bed increases, resulting in choking of solids. The observed regime is slugging and the material flow from the bed is not stable. The composition of the solids in the discharge is close to the feed composition. When the fluidized bed is operated above the point C_2, all the solids of the binary mixture behave like flotsam. The discharge rate is zero. The segregation of particles is unsuccessful. The holdup of the solids in the fluidized bed is least. The composition of the top product is equivalent to the feed composition. The column acts like a pneumatic transport of the solids. The velocity of the complete entrainment U_{C_2} is less than the terminal settling velocity of the heavier particles because of the mechanical action of the fluidized lighter particles on the heavier ones.

Segregation of the binary mixture begins at point C_1 when the gas velocity is sufficiently large to fluidize the entire height of the column. The entrainment rate from the fluidized bed at this point is lowest while the discharge rate is highest. The top flow is pure flotsam ($Y_L = 1$). The holdup of the solids in the fluidized bed is more. Segregation of the solids ends at the point C_2. At this point the entrainment of the solids from the fluidized bed is highest while the discharge of the solids is least. The bottom product is pure jetsam ($X_L = 0$). The points C_1 and C_2

are therefore critical points. For separating any binary system, the points C_1 and C_2 must be known.

In designing an equilibrium segregation process, it is necessary that conditions be selected such that both flotsam and jetsam phases co-exist. The condition of the two-phase region lies between the points C_1 and C_2. Mixture of heavier and lighter particles is found in both top as well as bottom products. This region is the operating regime for segregation of binary mixture in the continuous fast fluidized bed. As the gas flow rate increases, segregation occurs over a range of velocity. At any velocity, the line U_O–Y_L gives the composition of the top flow and the line U_O–X_L gives the composition of the bottom flow.

When the bed is operated in-between the points C_1 and C_2, there is both entrainment and discharge of the solids. The entrainment rate is fixed by the mass fraction of the lighter or heavier particles in the overhead and the bottom product.

3.3. Effect of feed rate

The effect of solids feed rate on the performance of the column is of interest as the throughput can be increased by increasing the feed rate [3,5]. The influence of solids feed rate on the phase diagram was investigated for different gas velocities and feed composition of the solids and is presented, typically, in Fig. 6. The entrainment and the discharge rates from the column increase with increase in the feed rate of the solids. The volume of the dense phase in the bottom of the column increases with increase in the solids feed rate. The volume fraction of the solids inside the column increases due to the increase in the holdup of the solids. The mobility of the particles reduces as the result of domination of inter-particle friction. The bottom dense phase in the fast fluidized bed becomes wealthier in the lighter particles. Due to this reason the composition of the heavier particles in the discharge decreases with the increase in solids feed rate. This effect in normally noticed in the lower operating gas velocity because of the decreased differential settling of the solids since the voidage drops off.

At higher gas velocities, the inter-particle friction greatly reduces and the upward flow of the particles increases. The holdup of the solids decreases because of the decrease in the downward flow of the particles towards the distributor and the bottom dense zone becomes richer in the heavier particles. The particles are entrained out of the column mostly in the form of clusters. The size of the cluster increases with the increase in the solids feed rate. The generated clusters carry some heavier particles along with them to the top product. Therefore, carryover of the heavier particles along with the lighter particles increases with the increase in the solids feed rate. So at higher gas velocity, the composition of the heavier particles in the bottom product increases and the composition of the lighter particles in the top product decreases. For higher solids feed rate, the purity of the lighter particles and the purity of the heavier particles decrease. The area of the flotsam-jetsam coexistence curves decreases as the result with increase in the solids feed rate. For this reason, the co-existence of the jetsam and flotsam phase decreases in the phase diagram presented. The critical points C_1 and C_2 remains constant for any solids feed rate.

The equilibrium curves of the fluidized bed are obtained for different solids feed rates from the composition of the entrained and discharged material. The curved line shown in Fig. 7 is the equilibrium lines for the resin–sand system for 5% feed composition. The solids feed rate has minimum effect on the bed behavior and considerable effect on the segregation in the range selected for the present study. The map provides a rapid, graphical means to visualize the separation possibilities and constraints of binary system. The line describes the compositions of lighter and heavier components in equilibrium [9,22]. The y–x equilibrium diagrams for binary mixtures constructed from the experimental data confirms the conclusion that the entrained material is enriched with the lighter particles. Greater the distance between the equilibrium curve and the diagonal, the difference in the lighter and heavier compositions is more and the separation by the fluidization technique is easier. At higher solids feed rate, the equilibrium lines approach the diagonal indicating that the separation efficiency of the fluidized bed reduces with increase in the solids feed rate.

3.4. Effect of feed composition

Composition of the overflow and discharge are affected by changes in composition of the initial mixture supplied to the

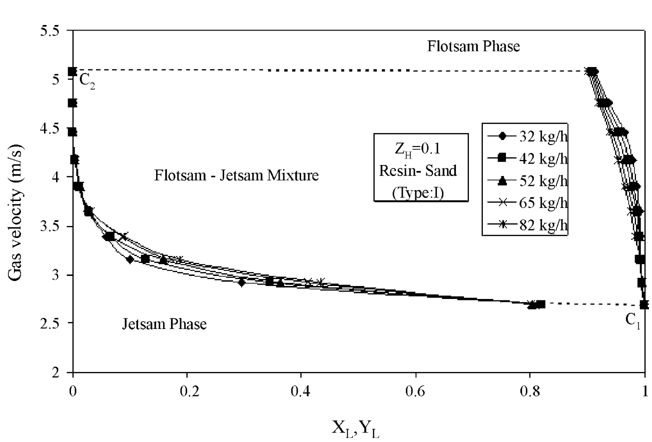

Fig. 6. Effect of feed rate on the phase diagram for flotsam-rich mixture.

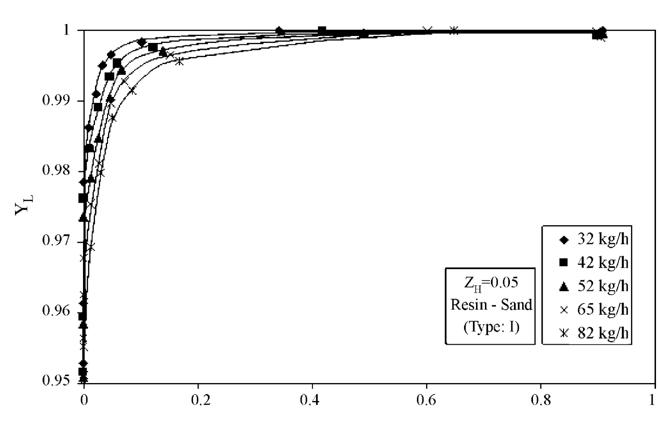

Fig. 7. Effect of feed rate on the equilibrium diagram for flotsam-rich feed mixture.

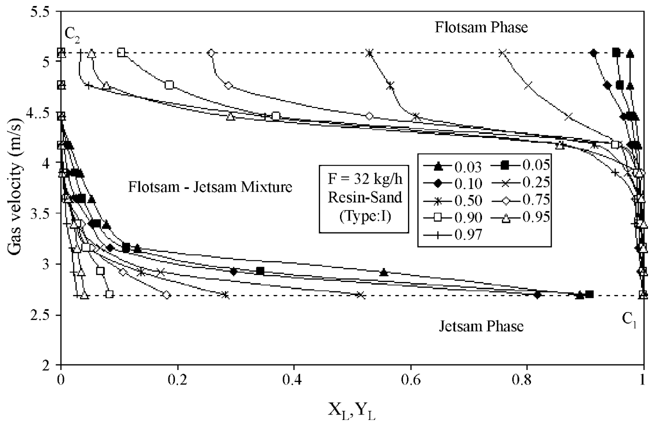

Fig. 8. Effect of feed concentration on the phase diagram.

column. The discharge rate decreases and entrainment rate increases with decrease in the heavier particles composition in the feed mixture for a constant gas velocity and solids feed rate.

The effect of the feed composition on the phase diagram is presented, typically, in Fig. 8. For high feed composition of the heavier particles, the volume fraction of the solids in the bottom dense phase increases. The dense phase is richer in the heavier particles for any constant solids feed rate. The composition of the heavier particles in the bottom flow therefore increases with increase in the heavier particles composition in the feed. The decrease in the void fraction decreases the settling velocity due to hindered settling. This effect disappears at elevated gas flow rate because of the increase in carry over of the heavier particles along with the lighter particles to the top product. The composition of heavier particles discharged in the bottom product attains extreme and the holdup of the solids inside the column becomes minimum. Therefore, the co-existence of the jetsam and flotsam phase changes. The area of the curve remains unaltered since the composition of the heavier particles in the bottom flow increases and the composition of the lighter particles in the top flow decreases with increase in the feed composition of the heavier particles. It is notable that the generated curves shift to the left with increase in the feed composition of the heavier particles. The critical points C_1 and C_2 remain unaltered for any feed composition of the solids.

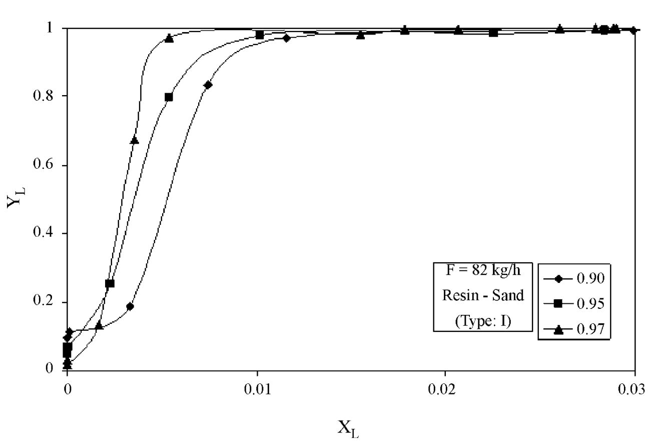

Fig. 9. Effect of feed concentration on the equilibrium diagram for jetsam-rich mixture.

The classification driving force is proportional to the lighter particles composition. The effect of the feed composition on the binary system equilibrium is presented, typically, in Fig. 9 for jetsam-rich feed mixture. The equilibrium line approaches close to the diagonal for higher feed composition of the heavier particles. Since the top product is richer in the lighter particles for lower feed composition of heavier particles, the equilibrium line is away from the diagonal. As per the observations, the figures clearly bear out the consequences of higher heavier particles feed composition in poorer separation.

4. Conclusions

The segregation behavior of a binary mixture differing in particle density with the same size is studied for flotsam rich, jetsam rich and intermediary feed mixtures and the results are reported through of a novel approach. The column pressure drop, entrainment and discharge rates and, mass fraction distribution of lighter and heavier particles in the overflow and bottom flows are obtained. Analysis of the experimental results shows that the nature of the influence of process parameters on the sharpness of separation is identical for mixtures of granular materials and mixtures of liquids. The velocity–composition phase diagram is presented for the flotsam and the jetsam phases in equilibrium. The diagram composed of three regions and the behavior of the fluidized bed in each region is explained. The effect of the solids feed rate and feed composition on the velocity–composition diagram is identified. The equilibrium diagram for the binary systems is presented. The equilibrium diagram helps to describe the separation possibilities and constraints of the lighter and heavier particles mixture.

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References

[1] D. Kunii, O. Levenspiel, Fluidization Engineering, 2nd ed., Butterworth-Heinemann, Boston, 1991.

[2] M. Shapiro, V. Galperin, Air classification of solid particles: a review, Chem. Eng. Process. 44 (2005) 279–285.

[3] N.G. Krishna, M.N. Rao, Continuous air classification of materials of mixed sizes, Ind. Chem. Eng. (1963) 45–54.

[4] N.I. Gelperin, V.G. Ainshtein, V.B. Kvasha, A.S. Kogan, S.A. Vilnits, Apparatus for classification of free-flowing materials in a fluidized bed, Int. Chem. Eng. 4 (1964) 198–203.

[5] H.B. Barari, D.D. Kar, P.S. Gupta, Performance of a continuous fluidized bed classifier, Ind. J. Tech. 16 (1978) 343–346.

[6] 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.

[7] D. Geldart, J. Baeyens, D.J. Pope, P. Van De Wijer, Segregation in beds of large particles at high velocities, Powder Technol. 30 (1981) 195–205.
[8] J.M. Beeckmans, L. Bergstrom, J.F. Large, Segregation mechanism in gas fluidized beds, Chem. Eng. J. 28 (1984) 1–11.
[9] M. Carsky, J. Pata, V. Vesely, M. Hartman, Binary system fluidized bed equilibrium, Powder Technol. 51 (1987) 237–242.
[10] F. Garcia-Ochoa, A. Romero, J.C. Villa, A. Bello, A study of segregation in a gas–solid fluidized bed: particles of different density, Powder Technol. 58 (1989) 169–174.
[11] A.C. Hoffmann, L.P.B.M. Janssen, J. Prins, Particle segregation in fluidized binary mixtures, Chem. Eng. Sci. 48 (1993) 1583–1592.
[12] D. Bai, N. Nakagawa, E. Shibuya, H. Kinoshita, K. Kato, Axial distribution of solid holdups in binary solids circulating fluidized beds, J. Chem. Eng. Jpn. 27 (1994) 271–275.
[13] B. Hirschberg, J. Werther, Factors affecting solids segregation in circulating fluidized bed riser, AIChE J. 44 (1998) 25–34.
[14] M.A. Gilbertson, I. Eames, Segregation pattern in gas-fluidized systems, J. Fluid Mech. 433 (2001) 347–356.
[15] B. Formisani, G.D. Cristofaro, R. Girimonte, A fundamental approach to the phenomenology of fluidization of size segregating binary mixtures of solids, Chem. Eng. Sci. 56 (2001) 109–119.
[16] C.-S. Chyang, K.-T. Wu, T.-T. Ma, Particle segregation in a screen baffle packed fluidized bed, Powder Technol. 126 (2002) 59–64.
[17] G. Olivieri, A. Marzocchella, P. Salatino, Segregation of fluidized binary mixtures of granular solids, AIChE J. 50 (2004) 3095–3106.
[18] M. Prasada Babu, Continuous segregation of binary heterogeneous solids in the gas-solids fluidized bed, PhD Thesis, IIT Madras, 2005.
[19] L. Huilin, Z. Yunhua, J. Ding, D. Gidaspow, L. Wei, Investigation of mixing/segregation of mixture particles in gas–solid fluidized beds, Chem. Eng. Sci. 62 (2007) 301–317.
[20] J. Furukawa, T. Ohmae, Liquid like properties of fluidized systems, Ind. Eng. Chem. 50 (1958) 821–828.
[21] J.F. Davidson, D. Harrison, J.R.F. Guedes de Carvalho, On the liquid like behavior of fluidized beds, Ann. Rev. Fluid Mech. 9 (1977) 55–86.
[22] J.F. Davidson, D. Harrison (Eds.), Fluidization, Academic Press, London, 1971, pp. 541–568.
[23] F.A. Zenz, Particulate solids: the third fluid phase in chemical engineering, Chem. Eng. 28 (1983) 61–67.
[24] Y. Zhao, L. Wei, Rheology of gas–solid fluidized bed, Fuel Process. Technol. 68 (2000) 153–160.
[25] M. Puncochar, J. Drahos, Entropy of fluidized bed—a measure of particles mixing, Chem. Eng. Sci. 58 (2003) 2515–2518.
[26] Yu.S. Teplitskiy, Similarity of transport processes in fluidized beds, Int. J. Heat Mass Transfer 42 (1999) 3887–3899.
[27] J.M. Schweitzer, J. Bayle, T. Gauthier, Local gas hold-up measurements in fluidized bed and slurry bubble column, Chem. Eng. Sci. 56 (2001) 1103–1110.
[28] J.F. Davidson, Circulating fluidized bed hydrodynamics, Powder Technol. 113 (2000) 249–260.
[29] 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.
[30] H.T. Bi, J.R. Grace, Regime transitions: analogy between gas-liquid co-current upward flow and gas–solids upward transport, Int. J. Multiphase Flow 22 (1996) 1–19.
[31] R. Krishna, J. Ellenberger, D.E. Hennephof, Analogous description of the hydrodynamics of gas–solid fluidized beds and bubble columns, Chem. Eng. J. 53 (1993) 89–101.
[32] J. Ellenberger, R. Krishna, A unified approach to the scale-up of gas–solid fluidized and gas–liquid bubble column reactors, Chem. Eng. Sci. 49 (1994) 5391–5411.
[33] P.P. Rumps Jr., Equilibrium relationships in elutriating columns, Resour. Rec. Conserv. 2 (1976/1977) 337–347.
[34] Mooson, Kwauk (Eds.), Fast Fluidization, Advances in Chemical Engineering, vol. 20, Academic Press, Inc., USA, 1994.
[35] K. Smolders, J. Baeyens, Gas fluidized beds operating at high velocities: a critical review of occurring regimes, Powder Technol. 119 (2001) 269–291.
[36] S. Bhusarapu, M.H. Al-Dahhan, M.P. Dudukovic, Solids flow mapping in a gas–solid riser: mean holdup and velocity fields, Powder Technol. 163 (2006) 98–123.
[37] A. Haider, O. Levenspiel, Drag coefficient and terminal velocity of spherical and non-spherical particles, Powder Technol. 58 (1989) 63–70.
[38] C.J. Wen, Y.H. Yu, A generalized method for predicting the minimum fluidization velocity, AIChE J. 12 (1966) 610–612.