Research Article

HYDRODYNAMICS OF LIQUID-SOLID FLUIDIZATION OF BINARY MIXTURES IN TAPERED BED

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ABSTRACT

The problems associated with fluidization in cylindrical beds like entrainment of particles, limitation of operating velocity could be overcome by adopting tapered beds. There have been many investigations on hydrodynamics of single size particles and also of binary mixtures up to small size ratios, but there have been comparatively fewer studies, wherein the effect of higher size ratios is considered on the hydrodynamic characteristics of liquid-solid fluidization in tapered beds. In the present work, an attempt has been made to study the hydrodynamic characteristics of liquid-solid fluidization of binary mixtures of size ratio up to 5 using sand of different sizes in a tapered bed with apex angle of 10^0. The process of fluidization behavior is observed to be drastically changing with particle size ratio and composition and also very much different from that of monocomponent systems. This process is discussed in detail. Similar studies have not been reported in literature. The variation of hydrodynamic characteristics with composition and size ratio is presented. Correlations have also been presented for these mixtures for critical fluidization velocity and minimum velocity for full fluidization in terms of single component characteristics. The correlations have been validated through experimental data.

KEYWORDS: fluidization, tapered bed, hydrodynamics, critical fluidization velocity, minimum velocity for full fluidization.

INTRODUCTION

Fluidization operations in cylindrical columns are extensively used in process industries. But, in a number of these operations, the particles are generally not of uniform size or there may be reduction in size due to chemical reactions like combustion or gasification, or attrition. In cylindrical beds, the particle size reduction results in entrainment, limitation of operating velocity in addition to the other demerits like slugging, non-uniform fluidization *etc*. These disadvantages are overcome by the use of tapered beds for fluidization operation, because of the gradual reduction in superficial velocity of the fluid with height. Also, recently, the use of tapered beds has begun to receive much attention for several applications because of several advantages, like (i) the operation of fluidization over a wide range of superficial velocity, (ii) the possibility of fluidizing a wide range of wide range of particles of different sizes or densities, and (iii) intensive particle mixing. The tapered liquid-solid beds are found to be suitable for biochemical reactions and biological treatment of waste water. These beds also have both laboratory and industrial applications as crystallizers.

LITERATURE REVIEW

The flow characteristics of the cylindrical fluidized bed have been studied by many investigators. Of the equations proposed to predict the bed voidage, those of Richardson and Zaki [1], and Wen and Yu [2] have gained widespread recognition and use. Koloini and Farkas [3] studied the pressure drop of fixed bed, minimum fluidization velocity and bed expansion in tapered beds of mono component particles. Kolar [4] correlated overall bed voidage for a conical bed of apex angle $\theta=10^0$ and 20^0 as a function of the liquid velocity for mono component particles. Scott, *et al* [5] have developed a reactor system based on a tapered fluidized bed for aqueous bioprocess. Pitt, *et al* [6] measured the expanded bed height and hydraulic pressure drop at several apex angles for mono component particles. Peng and Fan [7] were the first to explore various flow regimes in tapered beds at various flow rates of fluidizing liquid using different tapering angles of bed and have also developed equations for hydrodynamic characteristics based on several assumptions. Pruden and Epstein [8] have studied liquid-solid fluidization of binary mixtures and found that layer inversion would occur at a critical liquid velocity where both monocomponent beds have identical bulk bed density. Kennedy and Bretton [9] have proposed a mechanism of mixing and segregation in fluidization of binary mixtures. Malone, *et al* [10] investigated the layer-inversion phenomenon in binary solid liquid fluidized beds using a combined continuum and discrete model and observed varying degrees of segregation and mixing for a range of liquid velocities. Bruno Formisani, *et al* [11] have experimentally studied the effect of density difference on the segregating fluidization process of two-solid beds.

In the present work, an attempt has been made to experimentally study the hydrodynamics of liquid-solid fluidization of binary mixtures of solids in tapered beds covering a wide range of particle size ratio and composition. The phenomenon of fluidization has been reported in extensive detail. The variation of the hydrodynamic parameters with composition and particle size ratio has been clearly studied and correlations have also been proposed which have been validated through experimental data.

EXPERIMENTAL

Experiments have been performed in tapered vessels of square cross section (5cm x 5cm) size at the entrance and 1 m in height. The studies have been made using a system of water and sand. The vessel has two walls made of Plexi Glass for visual observation and the other two made of GI sheet. The distributor is made of brass plate of 3 mm thickness with 41 holes of 1.5 mm diameter. A 400 stainless steel wire mesh is placed over the distributor plate for uniform flow of water and also to act as support for bed material. The flow rate of water is measured by a rotameter and the pressure drop across the bed is measured by a manometer using carbon tetrachloride as manometric liquid. The schematic diagram of the experimental setup is shown in Figure 1.

The vessel is charged with a weighed amount of sand consisting of desired particle sizes in required ratio. The static bed height of the charged material is noted. Water is passed through the distributor at the required flow rate and the pressure drop across the bed is measured. At every flow-rate, the behavior of the system in the vessel is noted. The flow rate is increased gradually and the pressure drop across the bed is noted until the bed attains complete fluidized state. The flow rate is then decreased gradually to zero and the pressure drop is noted at each flow rate. The scope of experimental data is shown in Table 1.

Table 1:Scope of experimental data

Density	:	2600 kg/m^3
Particle sizes, µm	:	215, 275, 390, 550, 655, 780, 926.5. 1103.5
Weight of material, kg	:	3
Particle size ratios	:	1.19 to 5.13

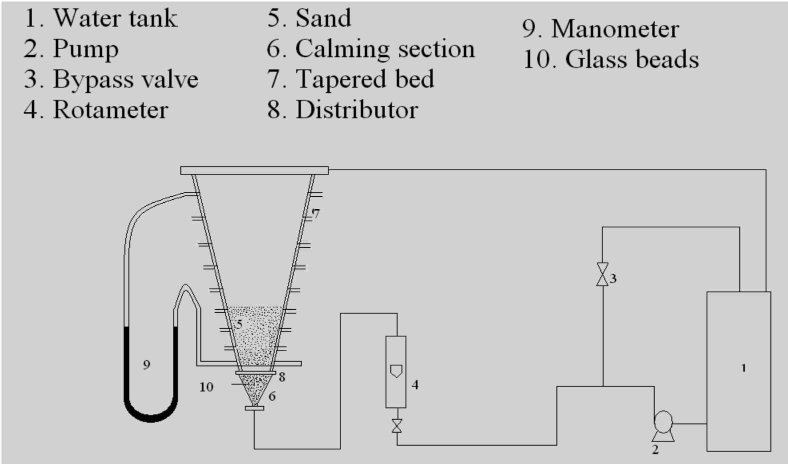

Figure 1: Schematic diagram of tapered liquid solid fluidized bed

FLUIDIZATION BEHAVIOR

Fluidization behavior is observed to be drastically changing with particle size ratio and is also very much different from that of mono component systems.

Three types of behavior have been observed. They are:

(i) Mono component behavior
(ii) Partially segregated behavior
(iii) Completely segregated behavior

The system exhibits mono component behavior for particle size ratios up to 2. The systems with particle size ratio above 2 and up to 3.3 show a partially segregated behavior while the systems with particle size ratio above 3.3 show complete segregation.

The fluidization behavior of the above systems is described as follows:

(i) Mono component behavior:

The plot of pressure drop across the bed against superficial velocity of the fluid indicating the hydrodynamic characteristics is shown in Figure 2. Fluidization first starts at the bottom near the distributor with the formation of a small cavity that gradually rises up with increase in the flow rate of water. At critical fluidization velocity, the bed is just lifted creating a narrow space for a few particles to fluidize in the cavity formed near the distributor. This height of fluidized region increases with flow rate of water. With further increase in flow rate, the bed attains complete fluidized state and the particles of both the sizes are distributed uniformly throughout the bed.

(ii) Partially segregated behavior:

The plot showing the hydrodynamic characteristics of partially segregated systems is shown schematically in Figure 3. At low flow rates of water, no segregation is observed for these systems. At a particular flow rate, bed gets lifted resulting in the formation of a cavity near the distributor. Most of the smaller size particles segregate from the bed and start fluidizing in the cavity. As the flow rate is increased further, these particles escape through the pores of bed and fluidize at the top.

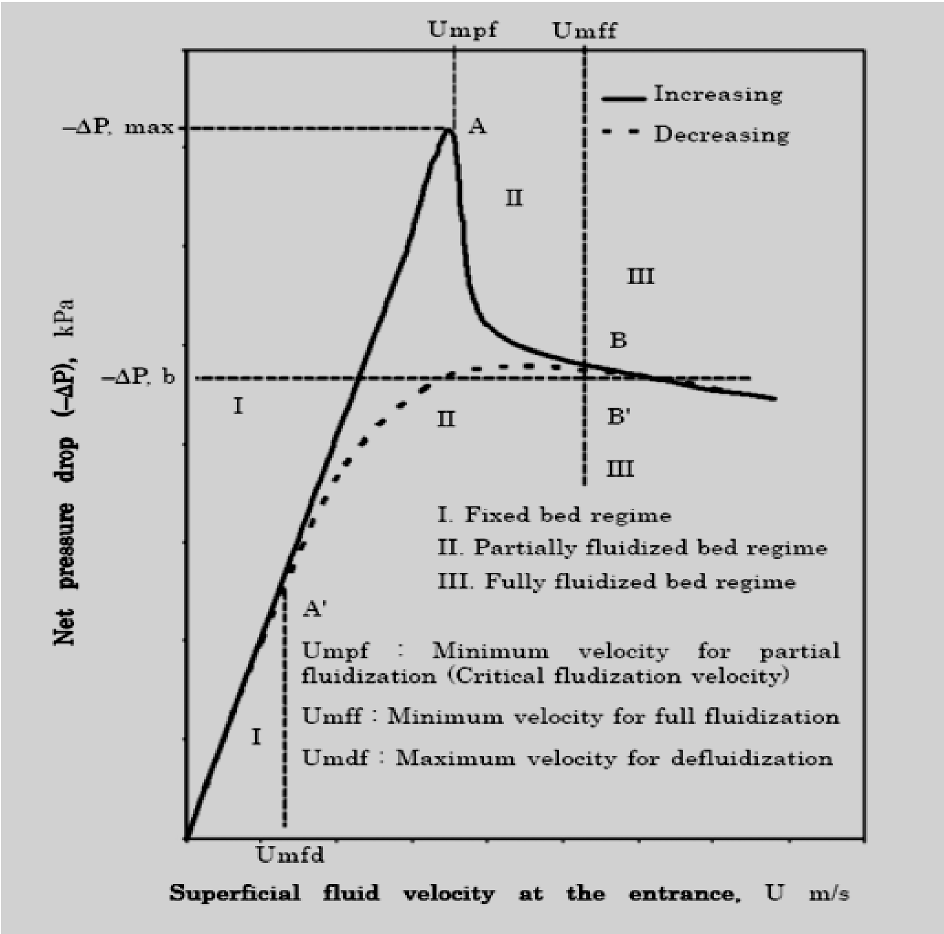

Figure 2: Characteristic plot of pressure drop as a function of the superficial velocity at the inlet of the tapered bed

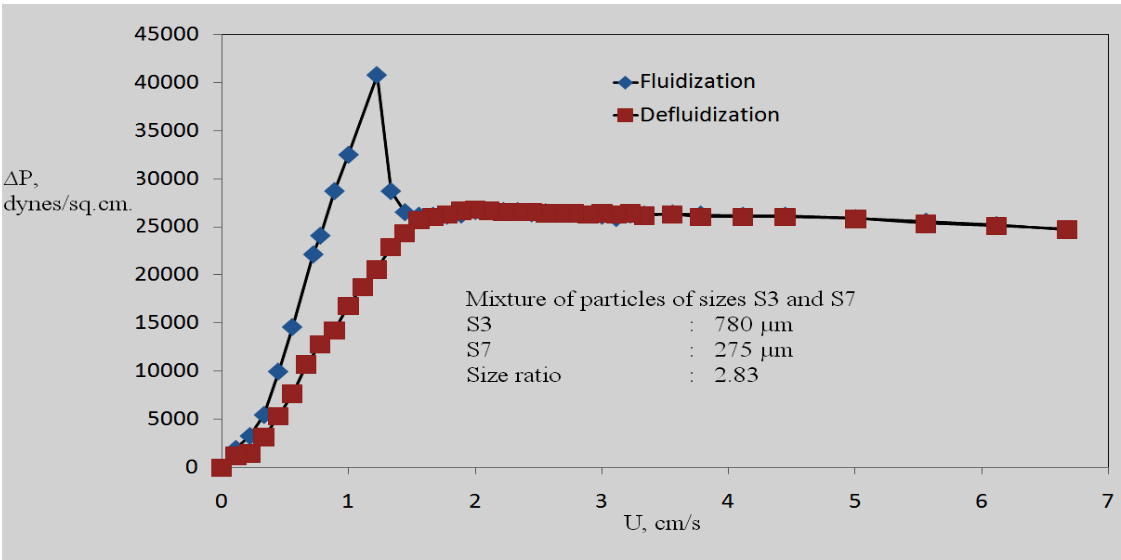

Figure 3: Characteristic plot of ΔP against superficial velocity at the entrance for mixtures of particles of sizes S_3 and S_7

The bigger size particles which were static until the segregation of the smaller size particles now get displaced and start falling down into the cavity. With increase in flow rate of water, the bigger size particles also begin to fluidize near the distributor, thus resulting in two distinct regions of fluidization, one at the top of the bed and the other near the distributor with the existence of a packed bed between them. This packed bed is a mixture of particles consisting of a small fraction of smaller size particles, clearly showing that segregation is not complete for these systems. With further increase in flow rate, the extent of fluidization of the particles in the packed bed increases from the bottom till all the particles in the packed bed attain complete fluidization state. The two fluidizing regions begin to mix with each other with the smaller size particles starting to go down through the fluidized bed. This phenomenon may be termed as inversion and the corresponding velocity of the fluid as the critical velocity for inversion. The height of mixing zone increases with the flow rate. As the flow rate is further increased, the whole bed gets mixed up with uniform distribution of particles of both sizes. During defluidization, most of the smaller size particles move up through the pores of the bed but some of them are entrapped in the bigger size particles, thus, the segregation is not complete. With a decrease in flow rate of water, the bed near the distributor reaches static condition while the bed consisting of smaller size particles continues to fluidize on top until when it reaches a static state too with continuing decrease in flow rate.

(iii) Completely segregated behavior:

The hydrodynamic behavior for these systems is shown schematically in Figure 4. In this case, when the feed is initially introduced into the tapered vessel, the smaller size particles move up through the pores of the bigger size particles and segregate completely forming two static bed regions. As the flow rate of liquid is further increased, fluidization of fine particles starts at the top of the bed while the coarse particles at the bottom are in static condition. It is observed that at the point of fluidization of fine particles, there is sudden decrease in the slope of the plot of pressure drop versus superficial velocity. The fine particles begin to fluidize much before the critical fluidization velocity. At the critical fluidization velocity, the bed is lifted and the coarse particles at the bottom begin to fluidize in the cavity near the distributor with the existence of a packed bed region between the two fluidizing regions. With subsequent increase in flow rate, mixing starts, first at the interface of the two regions and then gradually the height of mixing increases. The two fluidizing regions begin to mix with each other with the smaller size particles starting to go down through the fluidized bed. This phenomenon may be termed as inversion and the corresponding velocity of the fluid as the critical velocity for inversion. The height of mixing zone increases with the flow rate. As the flow rate is further increased, the whole bed gets mixed up with uniform distribution of particles of both sizes.

As the flow rate of water is decreased, the fine particles segregate from the coarse particles and fluidize independently at the top. As the flow rate is further decreased, a point is reached when mixing stops completely and a packed bed region is formed between the two fluidizing regions. As the flow rate is further decreased, the coarse particles become static while the fine particles continue to fluidize on top. With further decrease in flow rate, even the bed of fine particles becomes static.

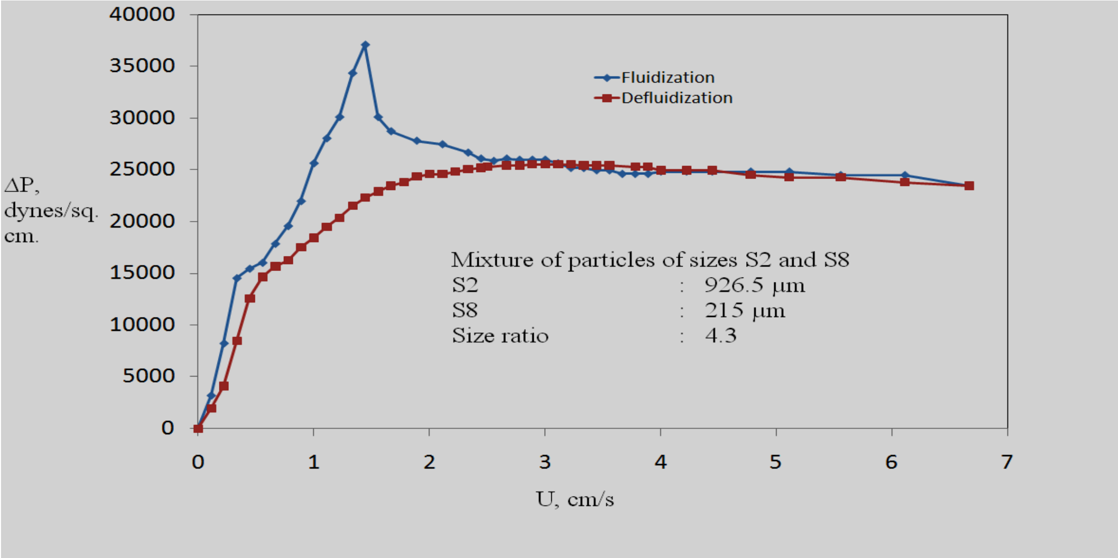

Figure 4: Characteristic plot of ΔP against superficial velocity at the entrance for mixtures of particles of sizes S_2 and S_8

RESULTS

The hydrodynamic characteristics of the fluidization phenomenon studied for the above systems are (i) critical fluidization velocity (minimum velocity for partial fluidization) (ii) critical or peak pressure drop (iii) minimum velocity for full fluidization. The significance of each of the characteristics is explained by Peng, *et al* [7]. Critical fluidization velocity is the velocity at which the bed is just lifted and the particles at the bottom begin to fluidize, while the rest of the bed is in static condition, resulting in partial fluidization. The pressure drop across the bed at this velocity is called critical pressure drop. At minimum velocity for full fluidization, the whole bed is just brought into fluidized state.

CORRELATIONS

Correlations are proposed for the prediction of critical fluidization velocity, minimum velocity for full fluidization and critical pressure drop of binary mixtures of all particle size ratio mixtures in terms of corresponding single component values in the lines of equation suggested by Cheung, *et al* [12] for fluidization of binary mixtures in cylindrical beds.

Depending on the type of behavior *viz.,* monocomponent, partially segregated or completely segregated exhibited by the system, the hydrodynamic characteristics mentioned above have been correlated in a form similar to that proposed by Cheung, *et al* [12].

The correlations are presented as below.

Critical fluidization velocity:

$$(U_{c,\,mix}/U_{c_1}) = 1.12(U_{c_2}/U_{c_1})^{1.18x_2^2} \quad SR > 1 \text{ and } \leq 2 \qquad (1)$$

$$(U_{c,\,mix}/U_{c_1}) = 1.14(U_{c_2}/U_{c_1})^{1.07x_2^2} \quad SR > 2 \text{ and } \leq 3.3 \qquad (2)$$

$$(U_{c,\,mix}/U_{c_1}) = 3.57(U_{c_2}/U_{c_1})^{0.6x_2^2} \quad SR > 3.3 \qquad (3)$$

Critical pressure drop:

$$(P_{c,\,mix}/P_{c_1}) = 1.01(P_{c_2}/P_{c_1})^{1.23x_2^2} \quad SR > 1 \text{ and } \leq 2 \qquad (4)$$

$$(P_{c,\,mix}/P_{c_1}) = 0.94(P_{c_2}/P_{c_1})^{2.23x_2^2} \quad SR > 2 \text{ and } \leq 3.3 \qquad (5)$$

$$(P_{c,\,mix}/P_{c_1}) = 1.04(P_{c_2}/P_{c_1})^{1.2x_2^2} \quad SR > 3.3 \qquad (6)$$

Minimum velocity for full fluidization:

$(U_{tf, mix}/U_{tf_1}) = 1.11(U_{tf_2}/U_{tf_1})^{0.79x_2^2}$

SR >1 and ≤2 (7)

$(U_{tf, mix}/U_{tf_1}) = 1.05(U_{tf_2}/U_{tf_1})^{0.77x_2^2}$

SR>2 and ≤3.3 (8)

$(U_{tf, mix}/U_{tf_1}) = 4.14(U_{tf_2}/U_{tf_1})^{0.33x_2^2}$

SR>3.3 (9)

Additional experiments have been performed to verify the validity of the above correlations. Most of the experimental data are found to agree with values predicted by the correlations within ±10%. The comparison is presented in Tables 3, 4 and 5.

Table 2: Data of hydrodynamic characteristics for mono components

Particle size, µm	Critical fluidization velocity, cm/s	Critical pressure drop, dynes/sq.cm.	Minimum velocity for full fluidization, cm/s
215	0.31	28265	0.52
275	0.56	29626	0.88
390	0.78	31714	1.16
550	1.36	35673	1.52
655	1.72	38854	2.11
780	2.29	41818	3.78
926.5	3.66	44441	4.22
1103.5	3.88	47917	5.13

Table 3: Comparison of experimental data with correlated data for critical fluidization velocity

Mixture of particles	Size ratio	Weight fraction of jetsam	Experimental value, cm/s	Predicted value, cm/s	Error, %
$S_4 + S_5$	1.19	0.2	1.69	1.82	7.7
$S_4 + S_5$	1.19	0.4	1.65	1.69	2.4
$S_4 + S_5$	1.19	0.6	1.61	1.59	-1.2
$S_4 + S_5$	1.19	0.8	1.48	1.54	4.1
$S_1 + S_4$	1.68	0.2	3.67	3.57	-2.7
$S_1 + S_4$	1.68	0.4	2.78	2.73	-1.8
$S_1 + S_4$	1.68	0.6	2.13	2.25	5.6
$S_1 + S_4$	1.68	0.8	2	2.01	0.5
$S_3 + S_6$	2	0.2	1.89	1.98	4.8
$S_3 + S_6$	2	0.4	1.45	1.39	-4.1
$S_3 + S_6$	2	0.6	1.17	1.08	-7.7
$S_3 + S_6$	2	0.8	1	0.92	-8
$S_4 + S_7$	2.38	0.4	1.11	0.87	-21.6
$S_3 + S_7$	2.83	0.8	1.56	1.56	0
$S_3 + S_7$	2.83	0.6	1.22	1.15	-5.7
$S_2 + S_7$	3.37	0.4	2	2.4	20
$S_3 + S_8$	3.63	0.8	2.06	2.39	16
$S_3 + S_8$	3.63	0.6	1.83	1.7	-7.1
$S_2 + S_8$	4.3	0.8	3	2.86	-4.7
$S_2 + S_8$	4.3	0.4	1.53	1.4	-8.5
$S_2 + S_8$	4.3	0.2	1.06	1.17	10.4
$S_1 + S_8$	5.13	0.8	3.21	2.92	-9
$S_1 + S_8$	5.13	0.6	2.31	1.91	-17.3
$S_1 + S_8$	5.13	0.2	1.2	1.18	-1.7

Table 4: Comparison of experimental data with correlated data for critical pressure drop

Mixture of particles	Size ratio	Weight fraction of jetsam	Experimental value, dynes/sq. cm.	Predicted value, dynes/sq. cm.	Error, %
$S_4 + S_5$	1.19	0.2	37770	38690	2.4
$S_4 + S_5$	1.19	0.4	36755	37568	2.2
$S_4 + S_5$	1.19	0.6	36424	36786	1
$S_4 + S_5$	1.19	0.8	36000	36325	0.9
$S_1 + S_4$	1.68	0.4	42600	43234	1.5
$S_1 + S_4$	1.68	0.6	40500	41059	1.4
$S_1 + S_4$	1.68	0.8	40000	39807	-0.5
$S_3 + S_6$	2	0.2	41177	39987	-2.9
$S_3 + S_6$	2	0.4	38158	36351	-4.7
$S_3 + S_6$	2	0.6	35526	33958	-4.4
$S_3 + S_6$	2	0.8	33800	32599	-3.6
$S_4 + S_7$	2.38	0.4	27252	30612	12.3
$S_3 + S_7$	2.83	0.8	41899	43194	3.1
$S_3 + S_7$	2.83	0.6	40803	37519	-8
$S_3 + S_7$	2.83	0.4	35809	33928	-5.3
$S_2 + S_7$	3.37	0.8	40200	42058	4.6
$S_2 + S_7$	3.37	0.6	36000	36705	2
$S_2 + S_7$	3.37	0.4	32060	33304	3.9
$S_2 + S_7$	3.37	0.2	30750	31416	2.2
$S_3 + S_8$	3.63	0.8	43117	39703	-7.9
$S_2 + S_8$	4.3	0.8	40000	41600	4
$S_2 + S_8$	4.3	0.6	37105	35737	-3.7
$S_2 + S_8$	4.3	0.2	31155	30041	-3.6
$S_1 + S_8$	5.13	0.8	43226	44075	2
$S_1 + S_8$	5.13	0.6	36500	36917	1.1
$S_1 + S_8$	5.13	0.2	28833	30149	4.6

Table 5: Comparison of experimental data with correlated data for minimum velocity for full fluidization

Mixture of particles	Size ratio	Weight fraction of jetsam	Experimental value, cm/s	Predicted value, cm/s	Error, %
$S_4 + S_5$	1.19	0.2	2.05	2	-2.4
$S_4 + S_5$	1.19	0.4	2	1.86	-7
$S_4 + S_5$	1.19	0.6	1.85	1.77	-4.3
$S_4 + S_5$	1.19	0.8	1.68	1.71	1.8
$S_1 + S_4$	1.68	0.2	4	3.68	-8
$S_1 + S_4$	1.68	0.4	3	3	0
$S_1 + S_4$	1.68	0.6	2.5	2.63	5.2
$S_1 + S_4$	1.68	0.8	2.3	2.42	5.2
$S_3 + S_6$	2	0.2	2.16	2.35	8.8
$S_3 + S_6$	2	0.4	1.86	1.81	-2.7
$S_3 + S_6$	2	0.6	1.56	1.5	-3.9
$S_3 + S_6$	2	0.8	1.26	1.34	6.3
$S_4 + S_7$	2.38	0.4	1.11	1.03	-7.2
$S_3 + S_7$	2.83	0.8	1.89	1.9	0.5
$S_3 + S_7$	2.83	0.6	1.44	1.39	-3.5
$S_3 + S_7$	2.83	0.4	1	1.11	11
$S_2 + S_8$	4.3	0.8	3.7	3.36	-9.2
$S_2 + S_8$	4.3	0.2	2.38	2.21	-7.1
$S_1 + S_8$	5.13	0.2	2.47	2.2	-10.9

CONCLUSIONS

The experimental study on fluidization of binary mixtures in a tapered vessel of apex angle 10^0 has shown that the hydrodynamic characteristics are dependent on size ratio of the particles. The systems of mixtures having a particle size ratio less than 2 exhibit monocomponent behavior. The mixtures with particle size ratio between 2 and 3.3 are observed to show partial segregation. For systems of particle size ratio greater than 3.3, completely segregated behavior is observed. Correlations developed for the three hydrodynamic parameters, *viz,* critical fluidization velocity, minimum velocity for full fluidization and critical pressure drop across the bed are found to be in agreement with the experimental data within ±10% for most of the observations.

NOMENCLATURE

P_c: peak pressure drop

$P_{c, mix}$: peak pressure drop of binary mixture

P_{c1}: peak pressure drop of fine particles

P_{c2}: peak pressure drop of coarse particles

S_1: sand of particle size 1103.5 µm

S_2: sand of particle size 926.5 µm

S_3: sand of particle size 780 µm

S_4: sand of particle size 655 µm

S_5: sand of particle size 550 µm

S_6: sand of particle size 390 µm

S_7: sand of particle size 275 µm

S_8: sand of particle size 215 µm

SR: particle size ratio

U_c: critical fluidization velocity

$U_{c, mix}$: critical fluidization velocity of binary mixture

U_{c1}: critical fluidization velocity of fine particles

U_{c2}: critical fluidization velocity of coarse particles

U_{tf}: minimum velocity for full fluidization

$U_{tf, mix}$:minimum velocity for full fluidization of binary mixture

U_{tf1}: minimum velocity for full fluidization of fine particles

U_{tf2}: minimum velocity for full fluidization of coarse particles

U_{mfd}: maximum velocity for full defluidization

x_2: weight fraction of coarse particles

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