HYDRODYNAMIC CHARACTERISTICS OF LIQUID-SOLID FLUIDIZATION OF BINARY MIXTURES IN TAPERED BEDS

Sankarshana Talapuru Dr* J S N Murthy† S Nandana‡
Phani Kiran S V G R** V Ramesh††

*University College of Technology, Osmania University, tsankarshana@yahoo.com
†University College of Technology, Osmania University
‡University College of Technology, Osmania University
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J S N Murthy, S Nandana, Phani Kiran S V G R, V Ramesh,
V V Basava Rao, T Sankarshana

Department of Chemical Engineering, University College of Technology,
Osmania University, Hyderabad - 500 007, A.P., INDIA

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 no systematic studies reported on fluidization behavior of binary mixtures wherein the effect of size ratio 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 fluidization behavior and hydrodynamic characteristics of liquid-solid fluidization of binary mixtures of size ratios ranging from 1.2 to 5.13 using sand of different sizes in tapered beds of apex angles 5^0, 10^0 and 15^0. Water has been used as the fluidizing medium. Three types of fluidization behavior have been observed which may be classified into (1) mono component behavior, (2) partially segregated behavior and (3) completely segregated behavior. The fluidization process is discussed in detail. Correlations have been presented for hydrodynamic characteristics.

Keywords: fluidization, tapered bed, critical fluidization velocity, peak pressure drop,

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 resulting in entrainment, limitation of operating velocity *etc*. These disadvantages are overcome by the use of tapered beds. The tapered liquid-solid fluidized beds are found to be suitable for biochemical reactions, biological treatment of waste water etc.

LITERATURE REVIEW

Koloini and Farkas (1) studied the pressure drop of fixed bed, minimum fluidization velocity and bed expansion in tapered beds of mono component particles. Scott, *et al* (2) have developed a reactor system based on a tapered fluidized bed for aqueous bioprocess. Pitt, *et al* (3) measured the expanded bed height and hydraulic pressure drop at several apex angles for mono component particles. Peng and Fan (4) 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 .There have been many investigations on fluidization behavior of binary mixtures in cylindrical columns (Pruden and Epstein (5) , Kennedy and Bretton (6) and Bruno Formisani, *et al* (7)).

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 detail. The variation of the hydrodynamic parameters with composition and particle size ratio has been clearly studied and correlations have also been proposed and 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 water and sand. The vessel has two walls made of 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 120 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 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 fluidization behavior of the system and the pressure drop across the bed are 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 below.

Scope of experimental data

Density (Kg/ m^3)	:	2600
Particle sizes(μm)	:	215, 275, 390, 550, 655, 780, 926.5, 1103.5
Weight of material(kg)	:	3
Size ratios(dimensionless)	:	1.19, 1.68, 2, 2.3, 2.83, 3.37, 3.63, 4.3, 5.13
Apex angles of vessels(^{0})	:	5,10,15

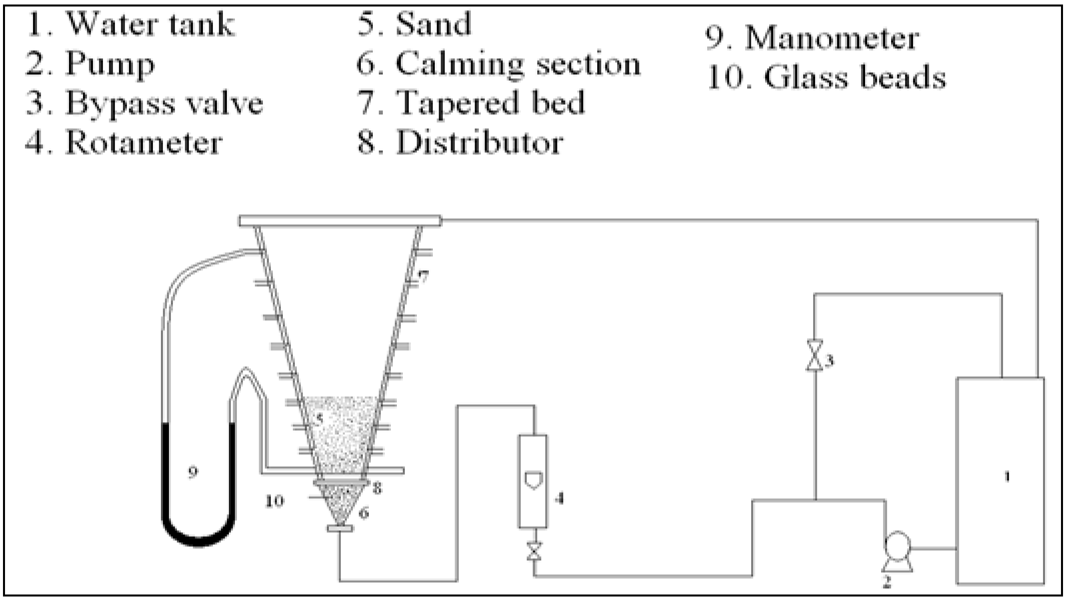

Figure 1.Schematic diagram of experimental set up.

FLUIDIZATION BEHAVIOR

Three types of fluidization behavior are observed with change in particle size ratio as mentioned below.

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.

(i) Mono component behavior:

A typical plot of pressure drop across the bed against superficial velocity of the fluid for binary mixtures exhibiting mono component behavior (size ratio 1.68) 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.

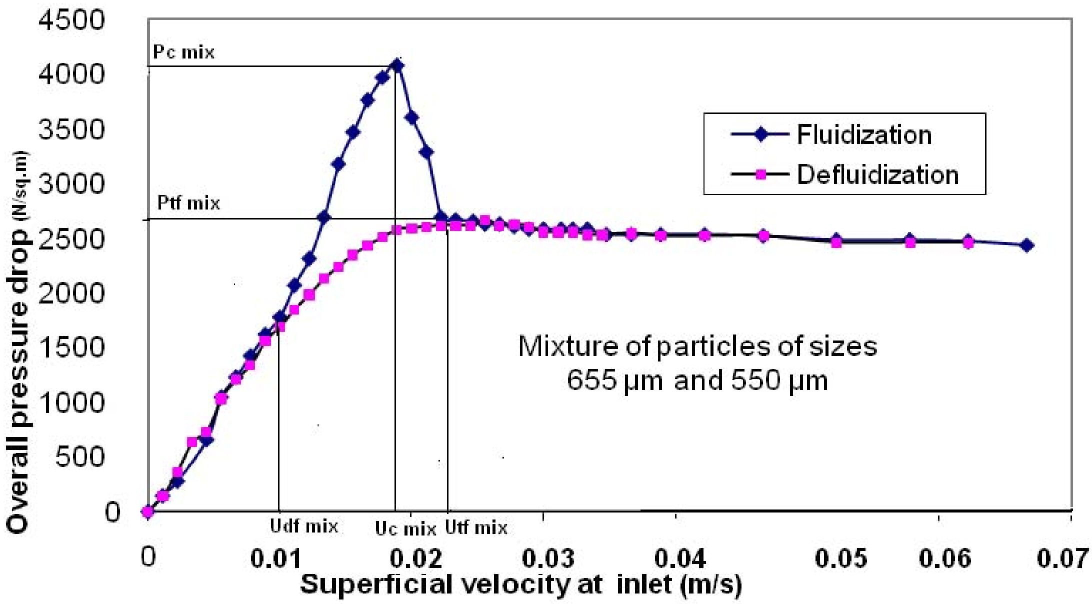

Figure 2. Characteristic plot of ΔP against superficial velocity at the entrance

(ii) **Partially segregated behavior**

The plot for a typical partially segregated systems (size ratio 2.83) is shown 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. 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. 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 between the bigger size particles.So, 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.

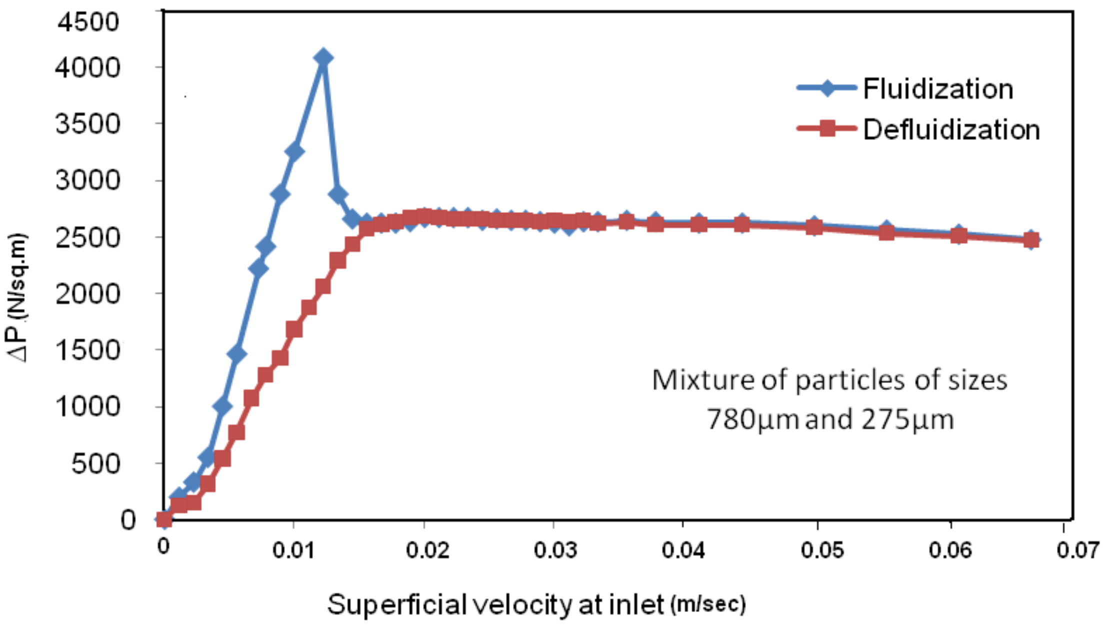

Figure 3 Characteristic plot of ΔP against superficial velocity

(iii) **Completely segregated behavior**

The hydrodynamic behavior for one of these systems (size ratio 4.3) is shown 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. 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.

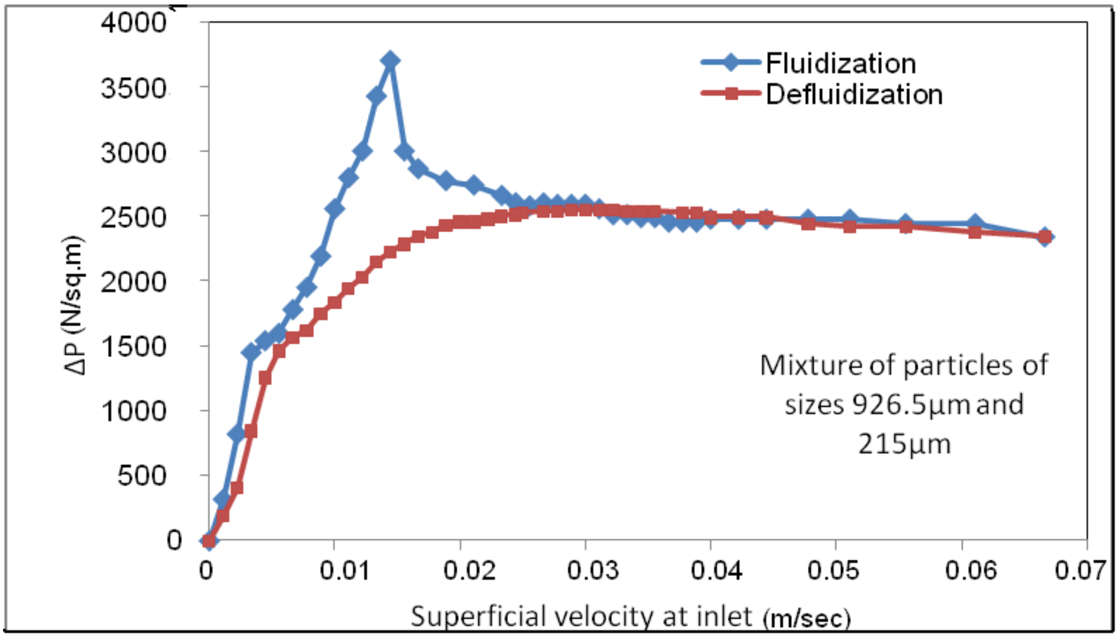

Figure 4 Characteristic plot of ΔP against superficial velocity

Behavior in cylindrical vessels

The fluidization behavior in cylindrical columns is vastly different from that in tapered vessels, the main feature being the absence of a peak pressure drop and a critical fluidization velocity. For segregating systems, the plot of pressure drop across the bed and superficial velocity at the entrance undergoes a change in slope at the point where the fluidization velocities of the two particle sizes is encountered. The absence of compressive force both while fluidization and defluidization is evident from the fact that there is no hysteresis in cylindrical columns. Also important to note is the absence of any formation of cavity near the distributor. For mono component systems, fluidization first starts near the distributor and gradually the entire bed gets fluidized. For partially segregating systems, the fine particles present near the distributor first get fluidized, while moving up for segregation and then as the flow rate of water is increased, the coarse particles displace the fines near the distributor and then start fluidizing, meanwhile the fine particles at the top of the bed attain completely fluidized state. The two distinct regions continue to fluidize without any lateral mixing. For segregating systems, the fluidization first starts at the interface of coarse and fine particles, when the fine particles begin to fluidize. With increase in the flow rate, coarse particles at the bottom of the bed also begin to fluidize. Mixing is another aspect that is not seen in cylindrical beds. Entrainment is one problem that cannot be avoided while fluidizing a mixture of different particles sizes resulting in restriction of the operating velocity.

RESULTS

The hydrodynamic behavior of fluidization in tapered beds is described by the plot of pressure drop across the bed against superficial velocity of the fluid at the entrance as shown in Figure 2. The hydrodynamic characteristics associated with the phenomenon are (i) critical fluidization velocity (ii) critical or peak pressure drop (iii) minimum velocity for full fluidization (iv) pressure drop at full fluidization (v) maximum velocity for full defluidization and (vi) hysteresis. The significance of each of the characteristics is explained by Peng and Fan (4).

CORRELATIONS

Correlations are proposed as a preliminary attempt for the prediction of the first three hydrodynamic characteristics for all particle size ratios in terms of corresponding single component values on the lines of equation suggested by Cheung *et al*(8) for fluidization of binary mixtures in cylindrical beds. They require further investigation.

Critical fluidization velocity:

$$(U_{c,mix}/U_{c_1}) = 1.079(U_{c_2}/U_{c_1})^{0.96x_2^2(\tan\alpha/2)^{-0.06}} \qquad 1<SR\leq 2 \qquad (1)$$

$$(U_{c,mix}/U_{c_1}) = 1.0(U_{c_2}/U_{c_1})^{0.51x_2^2(\tan\alpha/2)^{-0.16}} \qquad 2<SR\leq 3.3 \qquad (2)$$

$$(U_{c,mix}/U_{c_1}) = 1.56(U_{c_2}/U_{c_1})^{0.63x_2^2(\tan\alpha/2)^{-0.26}} \qquad SR>3.3 \qquad (3)$$

Critical pressure drop:

$$(P_{c,mix}/P_{c_1}) = 0.954(P_{c_2}/P_{c_1})^{0.75x_2^2(\tan\alpha/2)^{-0.19}} \qquad 1<SR\leq 2 \qquad (4)$$

$$(P_{c,mix}/P_{c_1}) = 0.929(P_{c_2}/P_{c_1})^{0.18x_2^2(\tan\alpha/2)^{-0.89}} \qquad 2<SR\leq 3.3 \qquad (5)$$

$$(P_{c,mix}/P_{c_1}) = 0.9188(P_{c_2}/P_{c_1})^{1.08x_2^2(\tan\alpha/2)^{-0.28}} \qquad SR>3.3 \qquad (6)$$

Minimum velocity for full fluidization:

$$(U_{tf,mix}/U_{tf_1}) = 1.32(U_{tf_2}/U_{tf_1})^{0.12x_2^2(\tan\alpha/2)^{-0.73}} \qquad 1<SR\leq 2 \qquad (7)$$

$$(U_{tf,mix}/U_{tf_1}) = 1.23(U_{tf_2}/U_{tf_1})^{1.32x_2^2(\tan\alpha/2)^{0.07}} \qquad 2<SR\leq 3.3 \qquad (8)$$

$$(U_{tf,mix}/U_{tf_1}) = 3.43(U_{tf_2}/U_{tf_1})^{1.2x_2^2(\tan\alpha/2)^{0.3}} \qquad SR>3.3 \qquad (9)$$

The correlations have been tested with experimental data and found to be in agreement within ±10%

DISCUSSION

Characteristic Plots of Pressure Drop against Superficial Velocity

The plot in Figure 2 for particle size ratios less than 2 indicates that the particles are completely mixed and hence the fluidization behavior of mixture is like that of mono components. For particle size ratios between 2 and 3.3, the plot shown in Figure 3 is more or less similar to that obtained for a mono component while increasing the flow rate of the fluidizing medium. While fluidizing, the segregation is not noticeable and formation of packed bed region does not take place. Only a small amount of flotsam particles tend to segregate at higher flow rates, whereas, while defluidization, the plot traces a separate path in the packed bed region. This behavior is attributed to the separation of particles during defluidization and gradual settling of heavier or larger particles, followed by that of lighter or smaller particles taking place, till the flow rate is reduced to zero. In the third case, wherein the particle size ratio is greater than 3.3, complete segregation is reported as is evident from the plot in Figure 4, where there is a large gap between the fluidization and defluidization curves. Also, clearly noticeable is the large change in slope of the curve, where the inflection point marks the flow rate at which the flotsam particles just begin to fluidize. This point occurs much before the critical fluidization velocity of the mixture, and for some compositions of particular particle size ratios, a clear peak is observed at the inflection point. The same phenomenon is observed to occur while defluidization too. Hysteresis is observed in mixtures of all size ratios.

Variation of Hydrodynamic Characteristics

Fluidization velocities

For all systems of mixtures for all particle size ratios, the critical fluidization velocity and minimum velocity for full fluidization increase with the fraction of jetsam, as higher velocities are required for fluidizing increased quantities of larger particles. These are also found to increase with the fraction of jetsam due to larger proportion of bigger size particles. It may be mentioned that the difference between their magnitudes is a function of the particle size ratio and weight fraction of jetsam.

Pressure Drop

Peak Pressure drop: For systems of mixtures with particle size ratios up to 2, the pressure drop across the bed is found to attain a maximum value for the pure jetsam feed. This is expected, as the highest amount of pressure drop would occur only when the bed comprises of large sized particles. For partially segregated systems, similar behavior was observed though further investigation is required before making any predictions. However, for completely segregated systems ranging from particle size ratios 3.3 onwards to 5.13, the behavior is quite complex and depends to a large extent on the extent of segregation.

Pressure drop at minimum velocity for full fluidization: This is found to remain approximately constant in a vessel of given apex angle, for the binary mixture systems of equal weight, as per the concept that in fluidized state, the force acting on the particles is equal to the net weight of the particles. However, a slight variation is possible due to different expanded bed heights during fluidization, because of change in particle sizes and composition.

CONCLUSIONS

The experimental study on fluidization of binary mixtures in a tapered vessel of apex angle 5^0, 10^0, 15^0 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 behave like a mono component. The mixtures with particle size ratio between 2 and 3.3 are observed to exhibit a partial segregation behavior. The third type of behavior exhibited by systems of particle size ratio 3.3 and above is termed as completely segregated behavior, in which the smaller size particles escape through the pores of the larger sized particles and fluidize independently on top. Also, the plot of overall pressure drop across the bed v/s superficial velocity shows a distinct change in slope, a phenomenon that is unique to systems of this type. Correlations have developed that allow the prediction of three hydrodynamic parameters. The range of particle size ratios over which each set of these correlations can be applied has been clearly brought out and has been justified based on the behavior of the three types of systems.

NOTATION

$U_{c,\,mix}$: critical fluidization velocity of binary mixture
U_{c1} : critical fluidization velocity of flotsam
U_{c2} : critical fluidization velocity of jetsam
$P_{c,\,mix}$: peak pressure drop of binary mixture
P_{c1} : peak pressure drop of flotsam
P_{c2} : peak pressure drop of jetsam
$U_{tf,\,mix}$: minimum velocity for full fluidization of binary mixture
U_{tf1} : minimum velocity for full fluidization of flotsam
U_{tf2} : minimum velocity for full fluidization of jetsam
x_2 : weight fraction of jetsam
SR : size ratio
α : apex angle of the tapered vessel
$U_{df,\,mix}$: maximum velocity for de-fluidization
$P_{tf,\,mix}$: pressure drop at total fluidization

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