Hydrodynamic Behaviour of Spouted Bed using Coarse / Fine Particles

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Abstract - **The characteristics of coarse / fine particles have been studied using a cylindrical spouted bed. The effects of different system parameters (viz. static bed height, particle size, particle density and superficial velocity of the medium) have been analysed to study the bed dynamics such as bed expansion / fluctuation ratio, bed pressure drop and fluidization index of coarse / fine particles. Mathematical expressions have been developed on the basis of dimensionless analysis. Finally calculated values of these bed dynamics have been compared against the experimentally observed values. The comparison results show very good agreement between the experimental and calculated values thereby indicating the application of these correlations over a wide range of parameters.**

Keywords- Spouted bed, Coarse particles, Fine particles, Hydrodynamic studies, Dimensionless analysis

INTRODUCTION

The spouted bed is one of the best known contacting methods used in process industries. The solid particles are transformed to fluid – like state through the contact with fluid i.e. gas or liquid or both which is allowed to pass through a distributor plate. A spouted bed has three different regions, each with its own specific flow behaviours: the annulus, the spout and the fountain as shown in **Fig.-1**. At stable spouting process, a spout appears in the center, a fountain above the bed surface and an annulus between the spout and the wall [1].

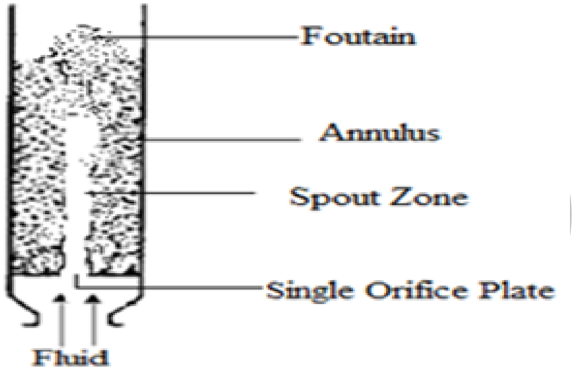


Fig. – 1: Different Regions of Spouted Bed

The spout and the fountain are similar to fluidized beds with particles dynamically suspended, while the annulus region is more like a packed bed or moving bed. At partial spouting, there are only two distinct regions, an internal spout that is similar to a fluidized bed and the surrounding packed particle region which is similar to a packed bed. Spouted beds have found extensive industrial applications as compared to fluidized / fixed beds. Due to the advantage of better fluid-solid contact, low inter particle diffusion resistance and low gas – solid mass transfer resistance, the spouted beds are used in chemical, biochemical, pharmaceutical, nuclear power plants, agricultural industries and metallurgical industries [1]. The advantages of spouted beds over the conventional fluidized bed are its ability to process coarse, sticky and heat sensitive materials.

The spouting and its stability, operating condition, spouting bed height along with the changing phenomenon from spouting to bubbling, slugging etc. depends on many factors like particle size, orifice size of spouting, flow rate of fluidizing fluid, bed height and the density of particles used proposed by [1, 2]. For a given solid material contacted by a specific fluid in a vessel of fixed geometry, there exists a maximum spoutable bed depth, beyond which the spouting action does not exists but it is replaced by a poor quality fluidization. The minimum spouting velocity at this bed depth can be 1.25 to 1.5 times the corresponding minimum fluidization velocity, U_{mf} [3]. Hydrodynamic behaviors of spouted beds of sand particles studied [4] and concluded that this is strongly dependent on the diameter of the inlet orifice. [5 - 7] explained different bed regimes for Geldart-A and D particles with the increase in superficial gas velocity. The effects of particle size, spout nozzle size, cone angle and fluidizing gas flow rate on the maximum spoutable bed height for Geldart group D particles has been studied by [8 – 10].

The bed expansion ratio (R) is quantitatively defined as the ratio of the average expanded bed height to the initial static bed height at any particular gas flow rate.

$$R = \left(\frac{H_{avg}}{H_{static}}\right) = \left(\frac{H_{\max} + H_{\min}}{2 * H_s}\right) \qquad (1)$$

The bed fluctuation ratio (r) is defined as the ratio of the maximum expanded bed height to the minimum expanded bed height at any particular gas flow rate within which the bed fluctuates.

$$r = \left(\frac{H_{\max}}{H_{\min}}\right) \qquad (2)$$

Fluidization index is the ratio of bed pressure drop to the weight of the bed materials per unit area of cross-section of the column. It is a measure of the degree of uniformity of fluidization.

$$F.I. = \left[\frac{\Delta P}{W/A}\right] \qquad (3)$$

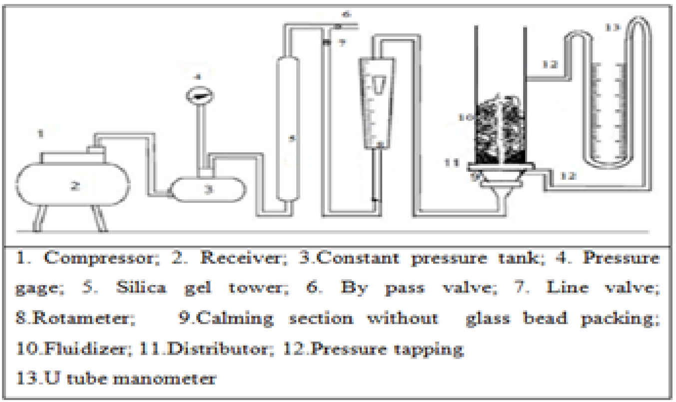
In the present work, the bed dynamics of coarse and fine particles have been studied through the bed pressure drop, bed expansion ratio, bed fluctuation ratio and fluidization index in a spouted bed. But the bed behaviour is unpredictable in case of fine particles, for which study of the bed dynamics for fine particles in a spouted bed is the point of focus in the present work by using mini aperture size / minimum diameter of spout.

MATERIALS AND METHODS

Materials

The hydrodynamic characteristics of coarse and fine particles are studied in a cylindrical column (made up of Perspex material) of 10 cm inside diameter and 100 cm high. An 80 mesh screen and a filter cloth (orifice size is approx. 40 microns) is placed just above the distributor plate between the lower flange of the fluidizer and the conical air distributor to prevent the backflow of bed materials for coarse and fine particles respectively. This is tightly attached to the column with the help of a gasket, so that there is no leakage of air. The calming section is without any packing material for spouted bed for allowing a jet of fluid to pass through the central hole of the distributor. The spout diameter is varied within 2.5 – 4 cm for coarse regular/ irregular particles and within 1-4 mm for fine particles. The Rotameter and U-tube manometer are connected to the cylindrical column for measuring the flow rate of air and the pressure drop across the bed respectively where Mercury (Hg) is used as the manometric fluid.

The spout diameter, D_i was selected according to particle size of bed materials. Then with the help of a rounder a circle of diameter equal to D_i was drawn on the card board sheet. Inner portion of the circle was cut to make it open for flow of air. The average particle size, d_p was determined by sieve analysis and the particle density is measured by specific gravity bottle for the present work.



1. Compressor; 2. Receiver; 3.Constant pressure tank; 4. Pressure gage; 5. Silica gel tower; 6. By pass valve; 7. Line valve; 8.Rotameter; 9.Calming section without glass bead packing; 10.Fluidizer; 11.Distributor; 12.Pressure tapping 13.U tube manometer

Fig. 2 (A): Schematic View of the Experimental Set-up

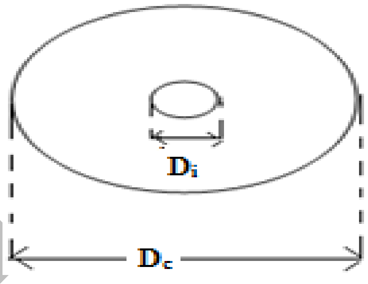


Fig. 2 (B): Schematic View of the Distributor

Methods

A known weight of material was taken in cylindrical column. Air is then supplied from the bottom of the column through a distributor till all the bed materials fluidize. The air flow through the bed was increased gradually causing the bed to expand. After crossing the minimum spouting velocity, the bed spouts suddenly. Flow rate of air was noted corresponding to steady spouting condition. The pressure drop and the expanded bed heights (maximum and minimum heights within which the bed fluctuates) were noted against each air flow rate. The same procedure is repeated by varying the different system parameters as discussed in scope of the experiment (**Table -1 (A), (B), (C)**). Bed fluctuation /expansion ratio and fluidization index were calculated as per equation (1), (2), and (3) respectively. Schematic diagram of the experimental set-up and distributor are shown in **Fig. - 2 (A) and (B)**.

TABLE – 1 (A): SCOPE OF EXPERIMENT FOR COARSE IRREGULAR PARTICLES IN SPOUTING PROCESS

SL.NO.	MATERIALS	HS, cm	dp, mm	Di, cm	ρs, g/cc	U0/Umf
1	Dolomite	8	3.325	2.5	2.89	1
2	Dolomite	12	3.325	2.5	2.89	1
3	Dolomite	16	3.325	2.5	2.89	1
4	Dolomite	20	3.325	2.5	2.89	1
5	Dolomite	8	2.58	2.5	2.89	1
6	Dolomite	8	2.18	2.5	2.89	1
7	Dolomite	8	1.7	2.5	2.89	1
8	Dolomite	8	3.325	3	2.89	1
9	Dolomite	8	3.325	3.5	2.89	1
10	Dolomite	8	3.325	4	2.89	1
11	Brick	8	3.325	2.5	1.92	1
12	Marble	8	3.325	2.5	1.39	1
13	Coal	8	3.325	2.5	1.57	1
14	Dolomite	8	3.325	2.5	2.89	1.1
15	Dolomite	8	3.325	2.5	2.89	1.2
16	Dolomite	8	3.325	2.5	2.89	1.3

TABLE – 1 (B): SCOPE OF EXPERIMENT FOR COARSE REGULAR PARTICLES IN SPOUTING PROCESS

SL. NO	**MATERIALS**	**H_S, cm**	**d_p, mm**	**D_i, cm**	**ρ_s, g/cc**	**U_0/ U_{mf}**
1	Glass Beads	8	3.325	2.5	2.8	1
2	Glass Beads	12	3.325	2.5	2.8	1
3	Glass Beads	16	3.325	2.5	2.8	1
4	Glass Beads	20	3.325	2.5	2.8	1
5	Glass Beads	8	2.58	2.5	2.8	1
6	Glass Beads	8	2.18	2.5	2.8	1
7	Glass Beads	8	1.7	2.5	2.8	1
8	Glass Beads	8	3.325	3	2.8	1
9	Glass Beads	8	3.325	3.5	2.8	1
10	Glass Beads	8	3.325	4	2.8	1
11	Aluminum Balls	8	3.325	2.5	3.21	1
12	Mustard Seeds	8	3.325	2.5	1.3	1
13	Sago	8	3.325	2.5	1.59	1
14	Glass Beads	8	3.325	2.5	2.8	1.1
15	Glass Beads	8	3.325	2.5	2.8	1.2
16	Glass Beads	8	3.325	2.5	2.8	1.3

TABLE – 1 (C): SCOPE OF EXPERIMENT FOR FINE PARTICLES IN SPOUTING PROCESS

SL.NO	MATERIALS	H_S, cm	d_p, microns	D_i, mm	ρ_s, g/cc	U_0/U_{mf}
1	Dolomite	8	63	3	1.15	1
2	Dolomite	12	63	3	1.15	1
3	Dolomite	16	63	3	1.1	1

					5	
4	Dolomite	20	63	3	1.15	1
5	Dolomite	8	125	3	1.15	1
6	Dolomite	8	90	3	1.15	1
7	Dolomite	8	45	3	1.15	1
8	Dolomite	8	63	1	1.15	1
9	Dolomite	8	63	2	1.15	1
10	Dolomite	8	63	4	1.15	1
11	Alumina	8	63	3	0.64	1
12	Marble	8	63	3	1.39	1
13	Sand	8	63	3	1.14	1
14	Dolomite	8	63	3	1.15	1.25
15	Dolomite	8	63	3	1.15	1.5
16	Dolomite	8	63	3	1.15	1.75

RESULTS AND DISCUSSION

The hydrodynamic study of the spouted bed has been carried out by analyzing the bed dynamics for coarse (regular / irregular) and fine particles. The following bed dynamics have been analyzed in a spouting process:

- Bed Pressure Drop (Δp)
- Bed Expansion Ratio (R)
- Bed Fluctuation Ratio (r)
- Fluidization Index (FI)

Bed Pressure Drop

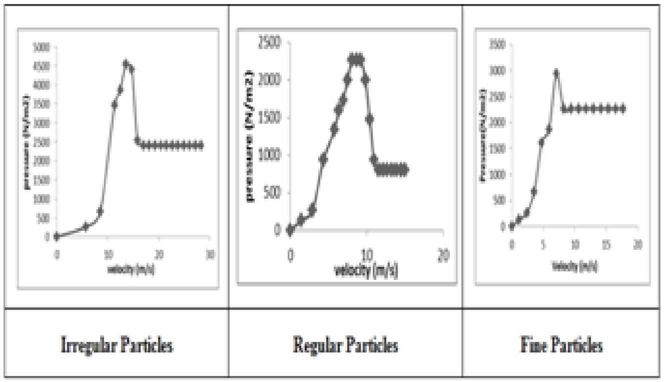
As per [1], the overall changes in values of bed pressure drop for coarse (regular / irregular) and fine particles were observed to increase with the increase in superficial spout velocity (U_o) up to certain point after which it decreases suddenly up to a point and then remains constant. Such variation of pressure drop with the velocity for the spouted bed has been shown in **Fig. - 3**. The reasons behind this may be due to the following facts.

(1). Initially at low air flow rates, the air simply passes up without disturbing the solid particles. The pressure drop is observed to be a linear function of the air flow rate showing packed bed behaviour.

(2). Again with the further increase in air flow rate, an empty cavity is formed just above the inlet point at the base of the bed. The particles surrounding the cavity are compressed and form a compacted arch which offers a greater resistance to air flow. As a result the total pressure drop across the bed continues to rise.

(3). With further increase in air flow, the cavity elongates to form an internal spout and the arch of compacted solids still exists above the internal spout so that the pressure drop across the bed rises further until it reaches a maximum value.

(4). As the air flow rate is increased further, the height of the hollow internal spout becomes large in comparison with the packed solids i.e. the resistance offered by arched solids is exceeded by air velocity and fountain forms. Then the pressure drop decreases to a certain point. Further increase in the air flow rate breaks the spout causing the fluidization of solids for which the pressure drop remains constant. The corresponding velocity at which the pressure drop is constant is called as the minimum spout velocity.



Irregular Particles

Regular Particles

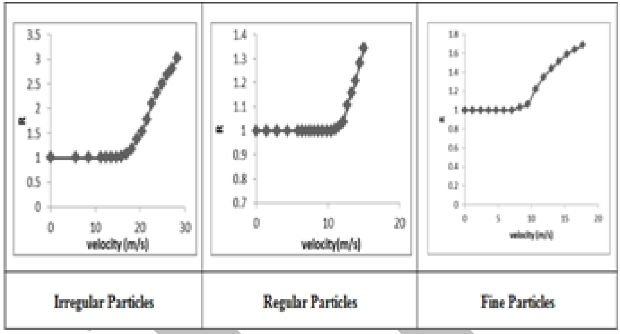
Fine Particles

Fig. – 3: Comparison Plot of Bed Pressure Drop Profiles for coarse / fine Particles

In case of coarse irregular, the pressure drop increases sharply with increase in spouting velocity as compared to coarse regular and fine particles. This is due to the presence of more number of air bubbles in coarse irregular particles. Thus the bed pressure drop increases with increase in superficial velocity of air as size of air bubbles also increases. In case of fine, the pressure drop is more as compared to coarse regular particles. This is due to less void spaces among the particles thereby causing less number of air bubbles to form with the fine particles.

Bed Expansion Ratio

The values of bed expansion ratio of coarse (regular/ irregular) and fine particles are also observed to increase with the increase in superficial velocity (U_o) for spouted bed (**Fig. – 4**). This may be due to the fact that superficial velocity of air exceeds minimum spout velocity. As a result more number of bubbles forms thereby causing bed expansion. As air bubble size increases with increase in spouting velocity, the bed expansion ratio increases. Again with increase in initial static bed height (H_s) and spout diameter (D_i) the bed expansion ratio are observed to decrease. This may be due to the breaking up of air bubbles with increase in initial static bed height. The bed expansion ratio is also observed to increase with the increased particle density (ρ_s) and particle size (d_p).



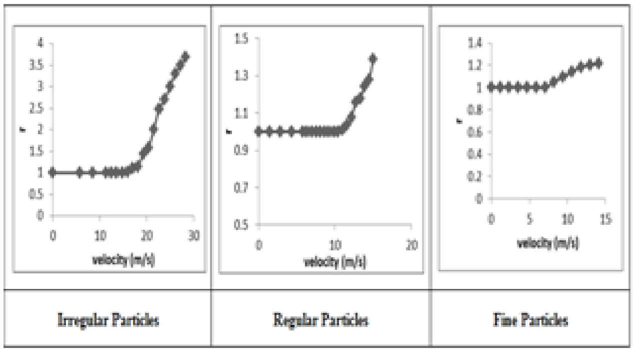
Irregular Particles | Regular Particles | Fine Particles

Fig. – 4: Comparison Plot of Bed Expansion Ratio for Coarse / Fine Particles

With the irregular particles, bed expansion ratio is observed to be more in comparison with coarse regular and fine particles. This may be due to the presence of more number of air bubbles with irregular particles. Thus the initial bed height for irregular particles expands more as compared to regular and fine particles. With the fine particles, the bed expansion ratio is also found to be more as compared to coarse regular particles. This may be due to minimum aperture size of spout, less amount of air passes through the bed materials with fine particles in comparison of regular coarse particles.

Bed Fluctuation Ratio

The values of bed fluctuation ratio for coarse (regular/ irregular) and fine particles are observed to increase with the increase in superficial velocity (U_o) for spouted bed (**Fig. – 5**). With an increase in initial static bed height (H_s) and spout diameter (D_i), the bed fluctuation ratio decrease. This may be due to the more weight of bed materials with increased initial static bed height which restrict the movement of materials at a constant velocity. The bed fluctuation ratio is also observed to increase with the increased density of the particles (ρ_s). This may be due to the fact that the minimum expanded height of bed (H_{min}) reduces to minimum due to heaviness of the particles thereby increasing the bed fluctuation ratio. Again the bed fluctuation ratio increase with increased particle size (d_p), where less number of air bubbles present and also minimum expanded height of bed (H_{min}) reduces due to breakage of air bubbles. Thus the bed fluctuation ratio increases. In case of irregular particles, bed fluctuation ratio is more as compared to coarse regular and fine particles. This may be due to the breakage of more number of bubbles with irregular particles as a result the minimum expanded height of bed (H_{min}) reduces thereby increasing the bed fluctuation ratio. In case of fine, bed fluctuation ratio is less as compared to coarse particles. This may be due to the presence of high inter-particle force of attraction / more cohesiveness of fine particles for which minimum expanded height of bed (H_{min}) does not reduce to much extent.

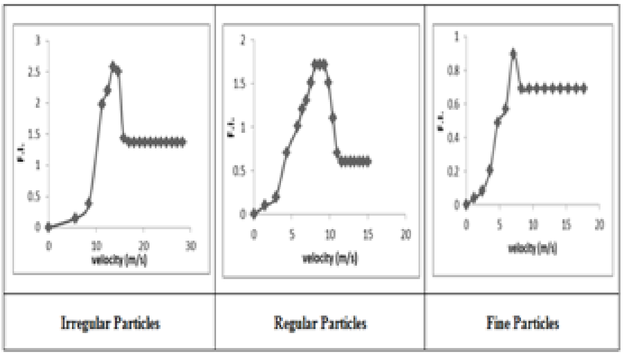


Irregular Particles | Regular Particles | Fine Particles

Fig. – 5: Comparison Plot of Bed Fluctuation Ratio for Coarse / Fine Particles

Fluidization Index

The fluidization index of coarse (regular / irregular) and fine particles are observed to increase initially with the increase in superficial velocity (U_o) up to certain point then decrease suddenly and after that remain constant. Profile of fluidization index is similar to that of bed pressure drop for spouted bed (**Fig. - 6**). A high value of fluidization index (F.I. > 1) is observed for glass beads, marble and bricks indicating that the fluidization quality is poor which further implies that the bed can hold more gas between the minimum fluidization and bubbling point. A low value of fluidization index (F.I. < 1) is observed for the mustard seeds, sago and coal implying that less gas is held between the minimum fluidization and bubbling point, because of better quality fluidization but away from the ideal value. The fluidization index of aluminium balls and dolomite is approximately one indicating the case of ideal fluidization.



Irregular Particles
Regular Particles
Fine Particles

Fig. – 6: Comparison Plot of Fluidisation Index for Coarse / Fine Particles

Fluidization index in spouting process always deviates from the fluidization process. Fluidization index directly depends on pressure drop. In case of spouting process, pressure drop is more at the time of spout formation when compared to fluidized bed. In the case of coarse irregular particles, fluidization index is found to be more in comparison with the coarse regular and fine particles. This may be due to the fact that bed pressure drop is more in irregular particles than those for the regular and fine particles because of the surface irregularies. This may be due to light weight of bed materials with fine particles in comparison with the higher weight of coarse particles That is why Fluidization index is more (i.e. >1) in the case of coarse particles in spouting process.

CORRELATION PLOTS

Correlations have been developed for the bed expansion / fluctuation ratio, fluidization Index by varying different system parameters on the basis of dimensionless analysis. The calculated values of these bed dynamics thus obtained through these correlation equations have been compared with the experimentally observed values. The correlation plots of bed expansion / fluctuation ratio and fluidization index for coarse (regular / irregular) and fine particles in a spouted bed are shown in **Fig. - 7, 8 and 9**. The observed and calculated values of these bed dynamics have been compared for regular, irregular and fine particles respectively in spouted bed. The standard and mean deviations of comparison of regular, irregular and fine particles in spouted bed are listed in **Table– 2**.

TABLE-2: COMPARISON RESULTS OF BED DYNAMICS FOR COARSE / FINE PARTICLES IN SPOUTED BED

Items	R			r			FI		
	Reg.	Irreg.	Fine	Reg.	Irreg.	Fine	Reg.	Irreg.	Fine
σ	-11 to +7	-5 to +10	-11 to +5	-13 to +8	-2 to +15	- 4 to +9	-10 to +15	-18to +11	-8to +11
M	1.05	6.07	0.04	3.95	3.79	0.02	4.62	1.28	0.05

Bed Expansion Ratio

The correlations developed for bed expansion ratio of coarse / fine particles on the basis of dimensionless analysis are as follows

(i) For Irregular Coarse Particles

$$R = 1.1707\left(\frac{H_s}{D_C}\right)^{-0.027}\left(\frac{\rho_S}{\rho_f}\right)^{0.001}\left(\frac{d_p}{D_C}\right)^{0.112}\left(\frac{D_i}{D_C}\right)^{-0.052}\left(\frac{U_0}{U_{mf}}\right)^{2.11}$$

(4)

(ii) For Regular Coarse Particles

$$R = 0.0271\left(\frac{H_S}{D_C}\right)^{-0.009}\left[\frac{\rho_S}{\rho_f}\right]^{0.364}\left(\frac{d_P}{D_C}\right)^{0.4}\left(\frac{D_i}{D_C}\right)^{-0.3}\left(\frac{U_0}{U_{mf}}\right)^{0.09}$$

(5)

(iii) For Fine Particles

$$R = 0.838\left(\frac{H_S}{D_C}\right)^{-0.01}\left(\frac{\rho_S}{\rho_f}\right)^{0.021}\left(\frac{d_P}{D_C}\right)^{-0.009}\left(\frac{D_i}{D_C}\right)^{-0.008}\left(\frac{U_0}{U_{mf}}\right)^{0.609}$$

(6)

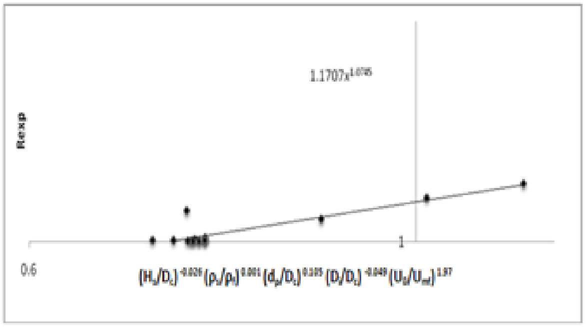


Fig. – 7 (A): Correlation Plots of Bed Expansion Ratio against System Parameters for Coarse Irregular Particles

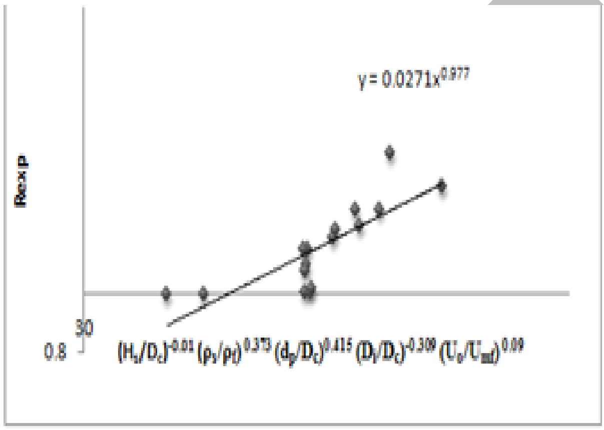


Fig. – 7 (B): Correlation Plots of Bed Expansion Ratio against System Parameters for Coarse Regular Particles

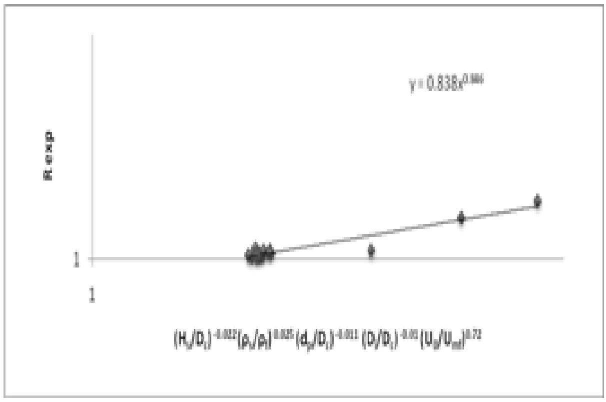


Fig. – 7 (C): Correlation Plots of Bed Expansion Ratio against System Parameters for Fine Particles

Bed Fluctuation Ratio

The correlations developed for bed fluctuation ratio of coarse / fine particles on the basis of dimensionless analysis are as follow

(i) For Irregular Particles

$$r = 1.648\left(\frac{H_S}{D_C}\right)^{-0.05}\left(\frac{\rho_S}{\rho_f}\right)^{0.002}\left(\frac{d_P}{D_C}\right)^{0.206}\left(\frac{D_i}{D_C}\right)^{-0.001}\left(\frac{U_0}{U_{mf}}\right)^{2.99} \qquad (7)$$

(ii) For Regular Particles

$$r = 0.006\left(\frac{H_S}{D_C}\right)^{-0.08}\left(\frac{\rho_S}{\rho_f}\right)^{0.44}\left(\frac{d_p}{D_C}\right)^{-0.69}\left(\frac{D_i}{D_C}\right)^{0.38}\left(\frac{U_0}{U_{mf}}\right)^{0.2} \qquad (8)$$

(iii) For Fine Particles

$$r = 0.674\left(\frac{H_s}{D_C}\right)^{-0.036}\left(\frac{\rho_s}{\rho_f}\right)^{0.043}\left(\frac{d_p}{D_C}\right)^{-0.019}\left(\frac{D_i}{D_C}\right)^{-0.031}\left(\frac{U_0}{U_{mf}}\right)^{0.412} \qquad (9)$$

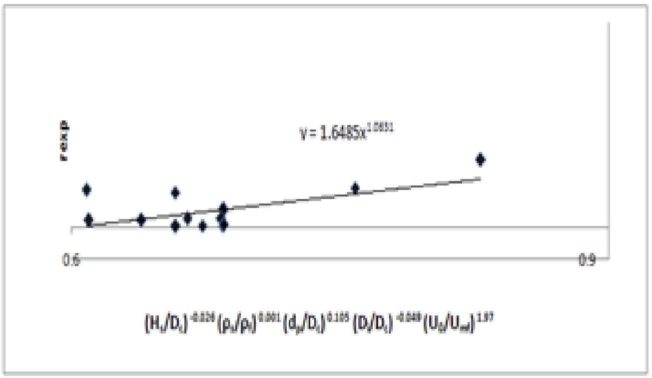


Fig. – 8 (A): Correlation Plot of Bed fluctuation Ratio against System Parameters for Coarse Irregular Particles

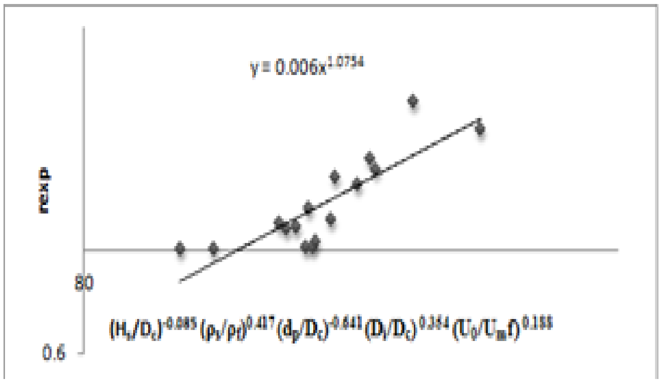


Fig. – 8 (B): Correlation Plot of Bed fluctuation Ratio against System Parameters for Coarse Regular Particles

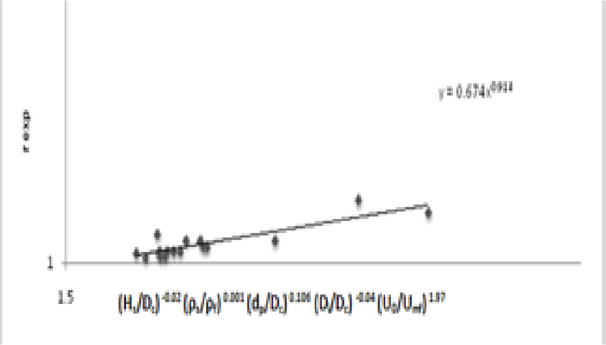


Fig. – 8 (C): Correlation Plot of Bed fluctuation Ratio against System Parameters for Fine Particles

Fluidization Index

The correlations developed for fluidization index of coarse/ fine particles on the basis of dimensionless analysis are as follows

(i) For Irregular Coarse Particle

$$FI = 0.0096\left(\frac{H_S}{D_C}\right)^{-0.155}\left(\frac{\rho_S}{\rho_f}\right)^{0.521}\left(\frac{d_p}{D_C}\right)^{-0.354}\left(\frac{D_i}{D_c}\right)^{0.321}\left(\frac{U_0}{U_{mf}}\right)^{-0.189} \quad (10)$$

(ii) For regular coarse Particle

$$FI = 0.0313\left(\frac{H_S}{D_C}\right)^{-0.084}\left(\frac{\rho_S}{\rho_f}\right)^{0.528}\left(\frac{d_P}{D_C}\right)^{0.646}\left(\frac{D_i}{D_C}\right)^{-0.628}\left(\frac{U_0}{U_{mf}}\right)^{0.463} \quad (11)$$

(iii) For fine Particles

$$FI = 168.69\left(\frac{H_S}{D_C}\right)^{-0.06}\left(\frac{\rho_S}{\rho_f}\right)^{-0.45}\left(\frac{d_P}{D_C}\right)^{0.46}\left(\frac{D_i}{D_C}\right)^{-0.08}\left(\frac{U_0}{U_{mf}}\right)^{-0.36} \quad (12)$$

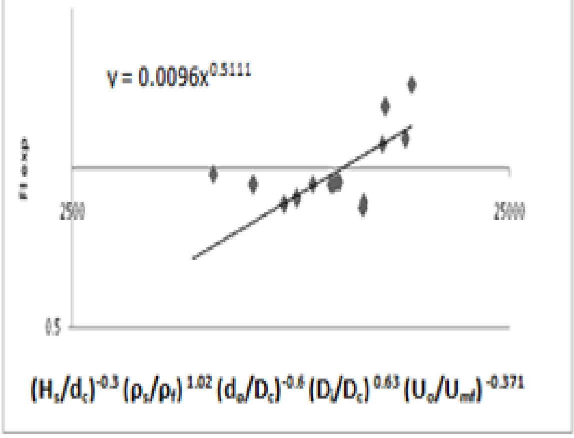


Fig. – 9 (A): Correlation Plot of Bed Fluidization Index against System Parameters Coarse Irregular Particles

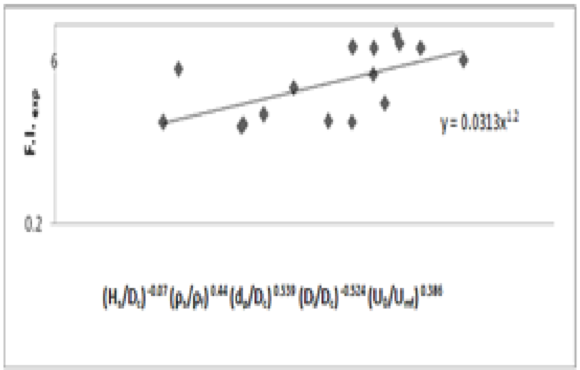


Fig. – 9 (B): Correlation Plot of Bed Fluidization Index against System Parameters Coarse Regular Particles

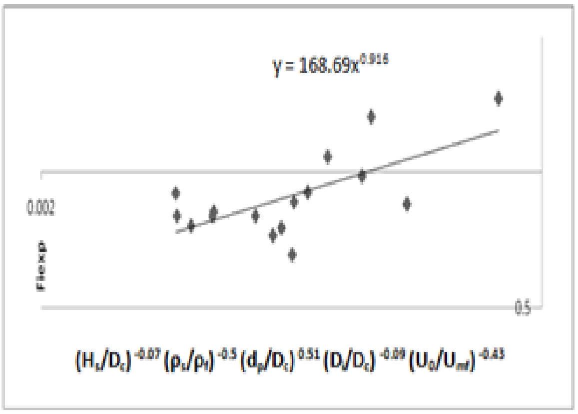


Fig. – 9 (C): Correlation Plot of Bed Fluidization Index against System Parameters for Fine Particles

It was oserved that increase of spout diameter decreases the bed expansion/ fluctuation ratio and fluidization index because of more amount of air passing in the central region only in case of spouted bed. The calculated values of the bed expansion / fluctuation ratio, fluidization index obtained through dimensional analysis are compared with the experimentally observed values. The deviations of calculated values are found to be within +15% to -15% and mean deviation within 1 to 7% for coarse and -1 to 5% for fine particles.

CONCLUSION

The calculated values of the bed dynamics obtained through the dimensionless analysis are observed to be agreed well with the respective experimental values of bed dynamics. The spouted bed can be well designed with these correlations especially in the fixation of bed heights. This indicates that the developed correlations can suitably be scaled up for pilot plant units or for industrial uses for handling fine particles in the fluidization process for example in the design of industrial fluidized bed reactors, especially in the pharmaceutical industries. This design with the provision of employing some force to break the cohesive forces among the particles can also be extended to nano scale.

NOMENCLATURE

ΔP : Pressure drop, N/m^2
d : Particle diameter, microns
H : Bed height, cm
r : Fluctuation ratio
R : Expansion ratio
U : Velocity of air, m/s
M : Mean deviation

Greek Symbols

ρ : Density, gm/cc
σ : Standard deviation

Subscripts

avg : Average
C : Column
max : Maximum
ms : Minimum spout
min : Minimum
o : Superficial
p : Particle
S : Static
i : Spout

Abbreviations

cal : Calculated
exp : Experimental
F.I. : Fluidization Index

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