Prediction of Fluctuation, Expansion Ratios and Gas Hold Up in a Three Stage Gas-solid Fluidized Bed – A Statistical Approach

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Abstract
Multistage fluidized bed has shown greater performance than the single stage in terms adsorption efficiency, recovery efficiency etc. Thus, experiments have been carried out in a three stage gas-solid fluidized bed. The hydrodynamic characteristicssuch as fluctuation ratio, expansion ratio and gas holdups have been studied. The dependency of these quantities with the system variables like particle size, initial static bed height and superficial gas velocity in each stage of a three-stage fluidized bed have been analyzed. It has been found that both fluctuation and expansion ratios are inverse functions of particle size and static bed height whereas a direct function of superficial gas velocity. However the gas holdup is a direct function of all the three operating parameter.It has also been observed that bed fluctuation and expansion goes on decreasing from lower bed to the upper bed. Further correlations have been developed for all the three stages for fluctuation ratio, expansion ratio and gas holdup using statistical analysis. It has been found that the experimental values of the responses agree well with the values predicted from the models.
Key Words: Holdup, fluctuation, expansion,ANOVA,Multistage

1.0 Introduction

The increasing population and rapid growing industrialization is leading lots of environmental issues by its uncontrolled polluted emission has been a major problem in developing country like India.Coal-fired thermal powerplant,roaster and smelter for copper, zinc and lead, petroleum refinery, fluidized bed catalytic cracking unit(FCC) and sulfuric acid plants are the main culprit for the emission of host of harmful substances like sulfur dioxides and many others. Therefore the control and abatement of these harmful pollutants has become a challenge for the day.Multistage fluidized bed reactors have been used in variety of industries to separate and concentrate solvents and to remove harmful pollutants from flue gas. The application of multistage fluidized beds has been extended for drying and adsorption due to its high capacity and high thermal efficiency.

The hydrodynamic characteristics of multistage fluidized beds are required for the designing and analyzing its performance. This includes mainly the bed fluctuation, bed expansion ratios and the phase hold up.Previousinvestigationsdeals with the quality of gas-solid fluidization and the development of correlations for fluctuation ratioin cylindrical (Agarwal and Roy, 1987 and Krishnamurthy et al., 1981) and conical beds (Singh and Roy, 2006 and Biswal et al., 1982).Sau et al. (2009) have investigated the bed fluctuation ratio for regular and irregular particles in a tapered fluidized bed. The minimum bubbling velocity, fluidizing index and range of particulate fluidization for gas-solid fluidization in cylindrical and non-cylindrical beds have been investigated by Singh and Roy (2005).Padhi et al., (2010) proposed that the introduction of twisted tape bafflesin gas-solid fluidized bedhas reduced the fluctuation ratio, thus increasing the quality of fluidization.Again, the distributor plate with 10% of open area has provided better expansion ratio as compared to 6%, 8% and 12% open areas (Mohanty et al., 2007).The gas hold up and expansion ratio have been investigated in a gas-liquid bubble column(Moshtari et al., 2009) and gas-solid fluidized bed (Hiligardt et al., 1986). The hydrodynamic characteristics in a three-phase fluidized bed with monosized (Sivalingam et al., 2009) and ternary mixture (Dora et al., 2015) of spherical glass bead particles have been investigated.Mahalik et al. (2015) have studied the bed pressure drop and minimum fluidization velocity in a three-stage gas-solid fluidized bed. Dimensional analysis (Kumar and Roy, 2004 and Dora et al., 2015), ANN approach (Kumar and Roy, 2004) and statistical approach (Kumar and Roy, 2005; Dora et al., 2015 and Mahalik et al., 2015) have been used for the development of correlations for the different hydrodynamic characteristics of a fluidized bed.

Available literatures mostly dealt with the study of bed fluctuations, bed expansion and gas holdups in a single stage fluidized bed.The multistage fluidized bed can perform better than the conventionally used single stage fluidized bed for the adsorption of gaseous pollutants from flue gas. But the use of multistage fluidized bed in the field of drying, cracking, adsorption has been a challenging job for the industries because of scarcity in literature in terms of hydrodynamics for its designing and analyzing its performance. Thus, the hydrodynamic characteristics in terms of fluctuation ratio, expansion ratio and gas holdups of multistage stage fluidized bed have been investigated in the present work. The fluctuation and expansion ratios are essential for predicting the size of the system and fluidization quality; while the phase hold up has its own importance in determining mixing and segregation characteristics. Thus, the study of these hydrodynamic characteristics helps in analyzing the performance of the fluidized bed. The effect of system parameters includes initial static bed height, particle size and superficial gas velocity. Correlations for prediction of fluctuation ratio, expansion ratio and gas holdup in each stage of multistage fluidized bed column have been developed using statistical analysis and compared with the experimental counterparts.

2.0 Materials and Methods

The details of experimental setup (fig. 1)used in the present work has been presented in the author's previous paper(Mahalik et al., 2015). It consists of three-stagesof fluidized bed column made up of Perspex sheet having same diameter and length for each stage. A multistage air compressor with a capacity of 1297 kg_f/cm^2has been used to supply air to the fluidizer through a silica gel column and rotameter. The silica gel column has been used to arrest moisture in the air. The flow rate of air from the silica gel column has been measured using a calibrated rotameter (capacity 120 m^3/h).

The bottom of the column is fixed to a Perspex flange. Air distributors made of perforated stainless steel plate, and having an 8% open area with respect to the column cross-section, have been placed between the columns to distribute air uniformly through the entire cross-section of the bed. The holes on the distributor plates are laid out in a triangular pitch manner. Two pressure tapings have been provided at each stage to measure the pressure drop through differential monometers, in which carbon tetrachloride (density 1.59 kg/m^3) has been used as the manometric fluid. A calming section has been placed just below the lower stage, and has been filled with glass beads to attain plug flow condition of air. Two short windows, one at the bottom and one at the top, have been made in each column for loading and unloading ofmaterials. After loading and unloading, the windows are closed by tightening a butterfly bolt with thegasket arrangement.

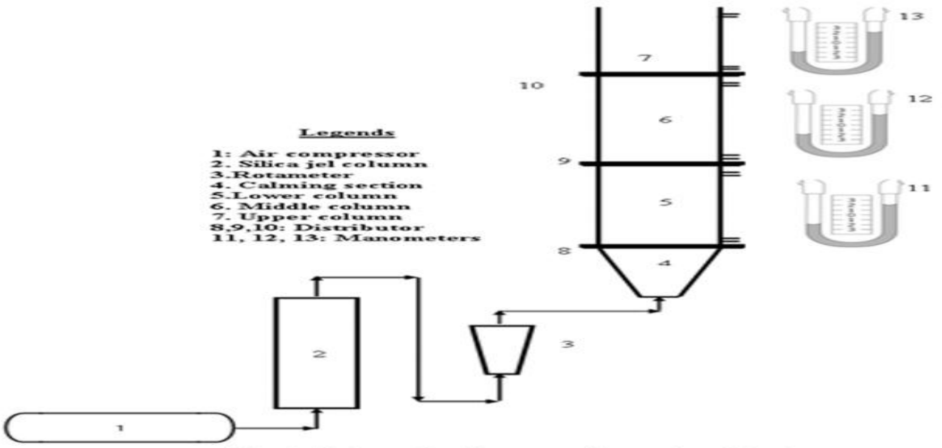

Fig. 1. Schematic diagram of experimetal set-up

The bed material used in this study is dolomite. Dolomite of different size ranges have been obtained by conventional sieve analysis. A particular size of dolomite has been poured in to each stage such that the static bed height remains same.To fluidize the entire bed material, air from the compressor is allowed to flow into the lower column through the silica gel column. The air flow rate is regulated by the calibrated rotameter. The fluctuation and expansion ratios have been calculated by noting the highest and lowest height attained by the particles during fluidization.From the volume of expanded bed, volume fraction of solid has been calculated. The gas hold ups has been calculated by subtracting the solid hold up from unity.The similar experimental procedure is followed for different particle size, static bed height and superficial gas velocity.

3.0 Result and Discussion

3.1 Study of bed fluctuation ratio

The variation of bed fluctuation ratio with particle size for different stages at constant static bed height of 10 cm and superficial gas velocity of 2.19m/s is shown in fig.2.It is observed that with decrease in particle size, the bed fluctuation ratio increases. This is owing to the fact that smaller particles due to their less density get carried easily by the air bubbles than that of larger particles, and are carried to a greater height in the bed, resulting increase in fluctuation ratio.It is also observed from the same figure that the bed fluctuation ratio decreases from the lower bed to the upper bed with an intermediate bed fluctuation in the middle bed. This phenomenon is due to the fact that as the gas moves from lower bed to the top one through the middle bed, a part of kinetic energy is lost to pressure energy. Therefore the bubbles donot get sufficient energy to lift the particles to a greater height, leading to decrease of bed fluctuation ratio.

The variation of bed fluctuation ratio with superficial gas velocity for various beds at constant particle size of 1.9mm and static bed height of 10cm is presented in fig.3.An increase in superficial gas velocity results in increase of number of bubble formation and energizing the bubbles which lift the particles to a greater height, which leads to increase in bed fluctuation ratio. Similarly fig.4 shows the variation of bed fluctuation ratio with static bed height for different beds at constant particle size and superficial velocity of 2.19m/s. It is evident from the figure that bed fluctuation ratio is an inverse function of static bed height. This may be due to the increase in weight of the bed(resulted owing to increase in static bed height)that results in considerable reduction of vertical lift of the particles and hence the fluctuation ratio.

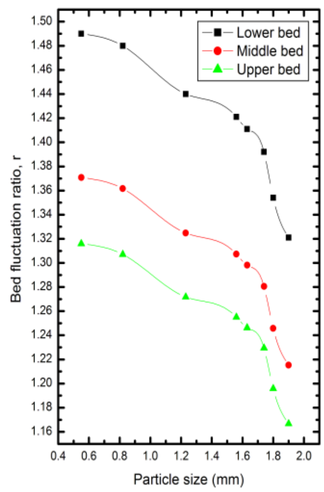

Fig. 2. variation of bed fluctuation ratio with particle size for different stages at constant static bed height of 10 cm and superficial gas velocity of 2.19m/s

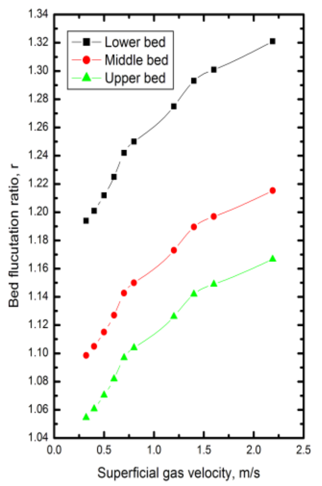

Fig. 3. Variation of bed fluctuation ratio with superficial gas velocity for various beds at constant particle size of 1.9mm and static bed height of 10cm

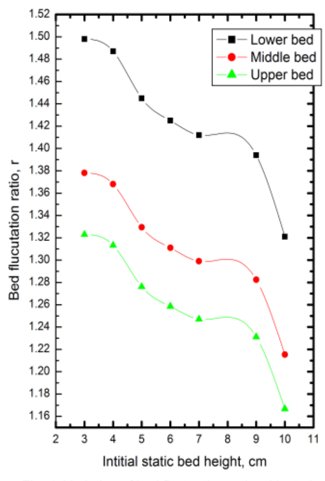

Fig. 4. Variation of bed fluctuation ratio with static bed height for different beds at constant particle size and superficial velocity of 2.19m/s

3.2 Study of bed expansion ratio

The effect of particle size on bed expansion ratio for different stages of three stage fluidized bed column at constant superficial gas velocity of 2.19 m/s and initial static bed height of 10 cm is presented in fig.5. It is observed from the figure that the bed expansion ratio is an inverse function of particle size, i.e. with increase in particle size the bed expansion ratio decreases. This may be due to the fact that smaller particles are easily carried to greater height by bubbles than that of the larger particles (vertical lift is reduced).

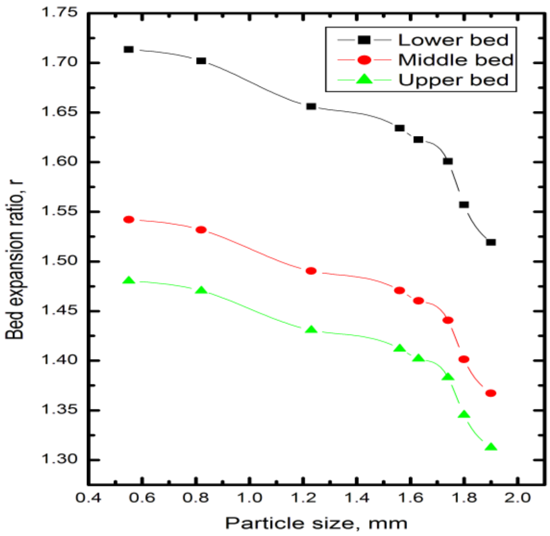

Fig. 5. Variation of bed expansion ratio with respect to particle size for different stages of multistage fluidized bed column at constant U_s of 2.19 m/s and H_s of 10 cm

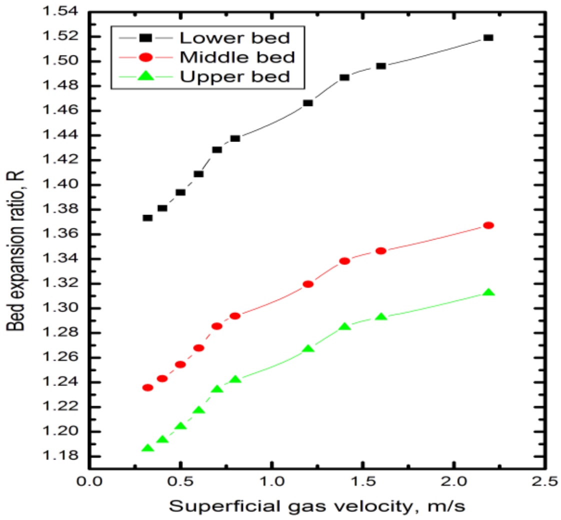

Fig. 6. Variation of bed expansion ratio with respect to superficial gas velocity for different stages of multistage fluidized column at constant H_s=10 cm and D_p=1.9mm

With increase in superficial gas velocity the bed expansion ratio increases (see fig.6).As the gas velocity increases thebubbles get sufficient energy that results in increase of bed volume, leading to high bed expansion ratio**.**The variation of bed expansion ratiowith initial static bed height for three different stages of fluidizer at constant superficial gas velocity 2.9 m/s of and particle size of 1.9 mmis shown in the fig.7. It is clear from the figure that bed expansion ratio decreases with an increase of static bed height. This is due to increase in the weight of the bed which in turns is due to the increase in static bed height. In this case the bubbles unable to overcome the force of gravity, that leads to decrease of vertical lift and hence the expansion ratio.Further it can be observed from the figures that the bed expansion decreases from the lower bed to the upper bed. In this case as the gas moves from the lower bed to the upper bed through the middle one, a part of kinetic energy is lost to pressure energy and the bubbles due to insufficient energy unable to expand the bed properly(due to decrease in vertical lift).

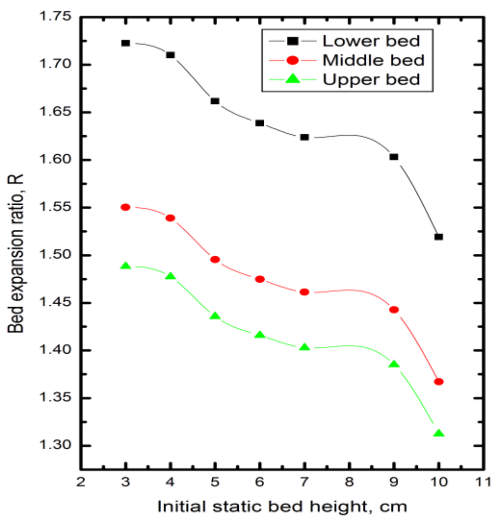

Fig. 7. Variation of bed expansion ratio with respect to initial static bed height for the three stages at a superficial gas velocity of 2.19m/s and particle size of 1.9mm

3.3 Study of gas holdups

Fig.8 shows the combined effect of particle size and static bed height on gas holdup at constant superficial gas velocity of 1.13m/s for all the three stages. Similarly the combined effect of particle size and superficial gas velocity on gas holdup at constant static bed height of 6.5cm is presented in fig.9. Further the combined effect of static bed height and superficial gas velocity on gas holdup at particle size of 1.225 mm for all the stages is shown in fig. 10.

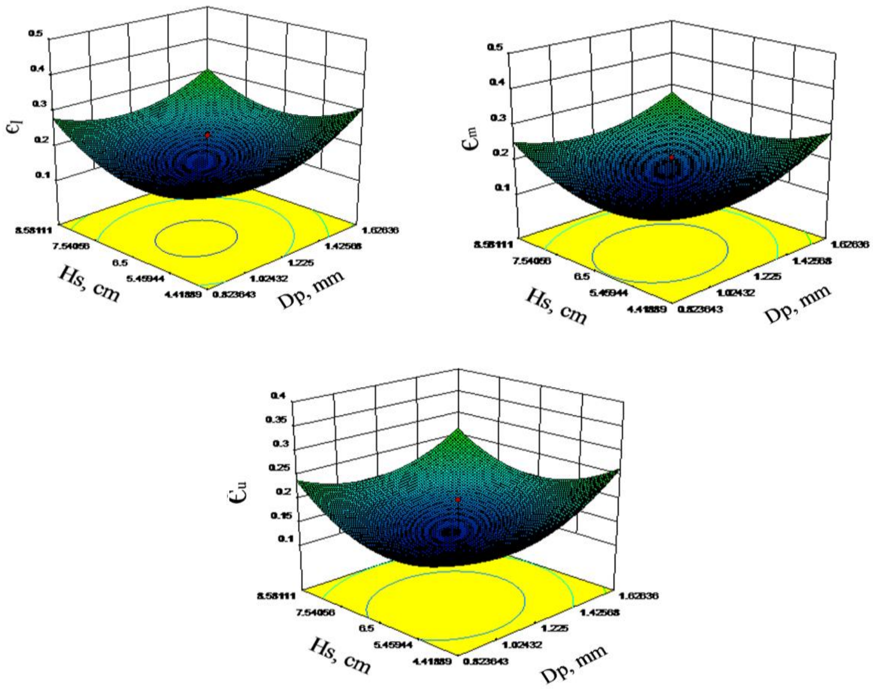

Fig.8 Combined effect of Particle size(Dp, mm) and Static bed height(hs, cm) on gas holdup for (a) lower bed (b)middle bed (c)upper bed

After careful observation of the above figures, it is revealed that the gas holdup is a direct function of all the three operating variables, such as particle size, static bed height and superficial gas velocity. With increase in particle size, the bed porosity increases and the gas finds more space to flow and thus the gas hold up increases. Again with increase in superficial gas velocity the bed volume increases. The increase in bed volume reduces the solid hold up, that results in increase of the gas holdups. Furthermore it is a well known fact that the gas holdup increases with increase in static bed height

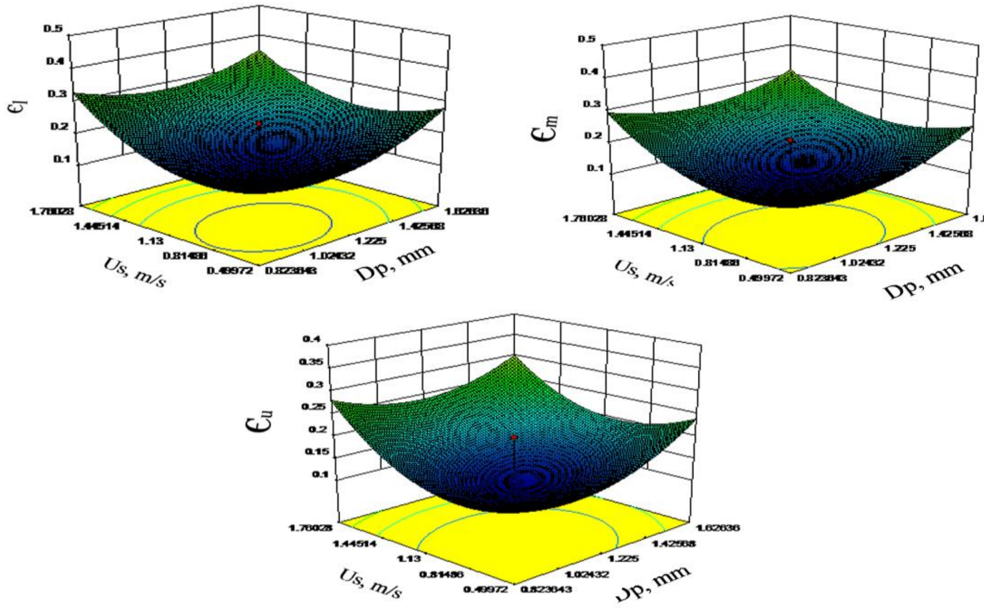

Fig.9 Combined effect of Particle size(Dp, mm) and superficial gas velocity(Us, m/s) on gas holdup for(a) lower bed (b)middle bed (c)upper bed

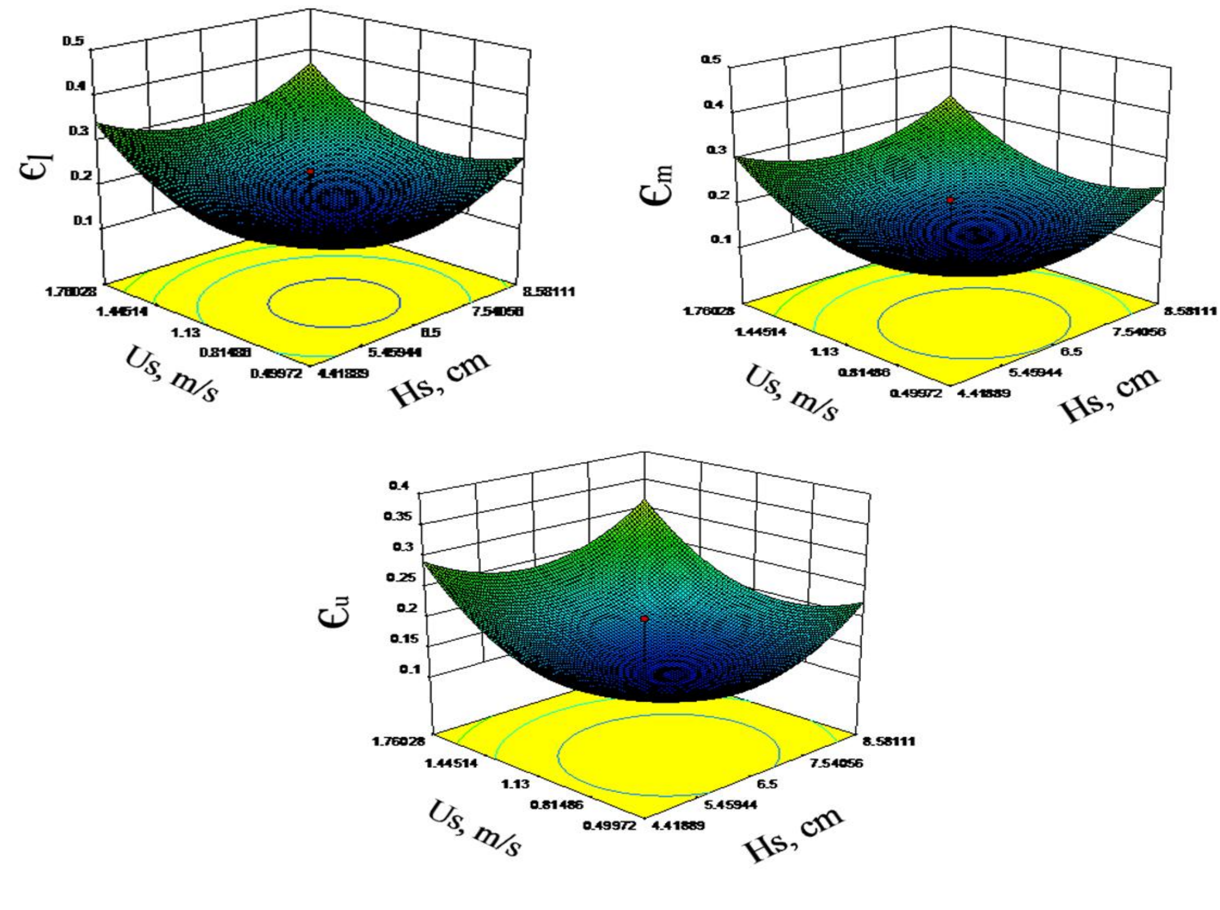

Fig.10 Combined effect of static bed height (hs, mm) and superficial gas velocity(Us, m/s) on gas holdup for(a) lower bed (b)middle bed (c)upper bed

3.4 Development of correlations for Fluctuation ratio, expansion ratio and gas holdup

Based on the experimental data,correlations have been developed by employing Response Surface modeling (RSM) based central composite design (CCD). Analysis of variance(ANOVA) has been used to estimate the contribution of individual, combined and square terms of the independent variables. From the experimental data it has been found that all the three responses, i.e. fluctuation ratio, expansion ratio and gas holdup are functions of particle size, initial static bed height and superficial velocity. The complete experimental range and the level of independent variables are given in table 1.The design of experiment together with the experimental results is given in table 2, table 3 and table 4 for fluctuation ratio, expansion ratio and gas holdup respectively.The experiments have been conducted in three level, i.e factorial run (runs 1-8), axial run(runs 9-14) and centre run(runs 15-20).The axial points are chosen in such a manner that they allowrotatability, which ensures that the variance of the model predictionis constant at all points equidistant from the design center(Dora et al., 2012).Replicates of the test at the center are very important as they providean independent estimate of the experimental error.

Table 1. Level of independent variables

Variables	**Symbol**	**-α**	**-1**	**0**	**+1**	**+α**
Dp, mm	A	0.055	0.824	1.225	1.626	1.9
Hs, cm	B	3.0	4.419	6.5	8.581	10.0
Us, m/s	C	0.070	0.481	1.085	1.689	2.1

Table 2. Design of experiments for bed fluctuation ratio

Run	Dp(mm)	Hs(cm)	Us(m/s)	Bed fluctuation ratio, r		
				Lower bed	Middle bed	Upper bed
1	0.824	4.419	0.481	1.468	1.395	1.353
2	1.626	4.419	0.481	1.351	1.283	1.245
3	0.824	8.581	0.481	1.294	1.229	1.000
4	1.626	8.581	0.481	1.201	1.141	1.107
5	0.824	4.419	1.689	1.442	1.370	1.329
6	1.626	4.419	1.689	1.301	1.236	1.199
7	0.824	8.581	1.689	1.281	1.217	1.180
8	1.626	8.581	1.689	1.365	1.297	1.258
9	0.550	6.500	1.085	1.412	1.341	1.301
10	1.900	6.500	1.085	1.099	1.044	1.013
11	1.225	3.000	1.085	1.545	1.468	1.424
12	1.225	10.000	1.085	1.113	1.057	1.026
13	1.225	6.500	0.070	1.425	1.354	1.313
14	1.225	6.500	2.100	1.498	1.423	1.380
15	1.225	6.500	1.085	1.145	1.088	1.055
16	1.225	6.500	1.085	1.145	1.088	1.055
17	1.225	6.500	1.085	1.145	1.088	1.055

18	1.225	6.500	1.085	1.145	1.088	1.055
19	1.225	6.500	1.085	1.145	1.088	1.055
20	1.225	6.500	1.085	1.145	1.088	1.000

Table 3.Design of experiments for bed expansion ratio

Run	Dp(mm)	Hs(cm)	Us(m/s)	Bed Expansion ratio, R		
				Lower bed	Middle bed	Upper bed
1	0.824	4.419	0.500	1.615	1.453	1.308
2	1.626	4.419	0.500	1.486	1.337	1.204
3	0.824	8.581	0.500	1.423	1.281	1.153
4	1.626	8.581	0.500	1.321	1.189	1.070
5	0.824	4.419	1.760	1.586	1.428	1.285
6	1.626	4.419	1.760	1.431	1.288	1.159
7	0.824	8.581	1.760	1.409	1.268	1.141
8	1.626	8.581	1.760	1.502	1.351	1.216
9	0.550	6.500	1.130	1.553	1.398	1.258
10	1.900	6.500	1.130	1.209	1.088	0.979
11	1.225	3.000	1.130	1.700	1.530	1.377
12	1.225	10.000	1.130	1.224	1.102	0.992
13	1.225	6.500	0.070	1.568	1.411	1.270
14	1.225	6.500	2.190	1.648	1.483	1.335
15	1.225	6.500	1.130	1.260	1.134	1.020
16	1.225	6.500	1.130	1.260	1.134	1.020
17	1.225	6.500	1.130	1.260	1.134	1.020
18	1.225	6.500	1.130	1.260	1.134	1.020
19	1.225	6.500	1.130	1.260	1.134	1.020
20	1.225	6.500	1.130	1.260	1.134	1.020

Eqs. 2-4 have been obtained for fluctuation ratio of lower middle and upper bed of the three stage fluidizer. Similarly,eqs 5-7 and eqs 8-10 have been developed for expansion ratio and gas holdup respectively.

Models for fluctuation ratio

$r_{l=}$ 1.15-0.058A-0.084B+0.014C+0.031AB+0.019AC+0.028BC+0.034A^2+0.060B^2+0.01C^2 (2)

r_m=1.09-0.055A-0.080B+0.014C+0.030AB+0.018AC+0.027BC+0.032A^2+0.057B^2+0.10C^2 (3)

r_u=1.05-0.039A-0.092B+0.027C+0.053AB-0.0064AC+0.050BC+0.030A^2+0.054B^2+0.097C^2 (4)

Models for Expansion ratio

R_l=1.26-0.046A-0.092B+0.016C+0.034AB+0.021AC+0.031BC+0.038A^2+0.066B^2+0.12C^2 (5)

R_m=1.13-0.058A-0.083B+0.014C+0.031AB+0.019AC+0.028BC+0.034A^2+0.060B^2+0.11C^2 (6)

R_u=1.02-0.052A-0.075B+0.013C+0.028AB+0.017AC+0.025BC+0.030A^2+0.054B^2+0.095C^2 (7)

Models for gas holdups

ϵ_l=0.15+0.032A+0.017B+0.056C-0.017AB-0.020AC-0.0031BC+0.059A^2+0.074B^2+0.081C^2 (8)

$\epsilon_{m=}$0.13+0.029A+0.015B+0.050C-0.015AB-0.018AC-0.0028BC+0.053A^2+0.067B^2+0.073C^2 (9)

ϵ_u= 0.12+0.027A+0.015B+0.048C-0.014AB-0.017AC-0.002BC+0.050A^2+0.063B^2+0.069C^2 10)

Table 4. Design of experiments for gas hold-up

Run	Dp (mm)	Hs (cm)	Us (m/s	Gas hold-up,		
				Lower bed	Middle bed	Upper bed
1	0.824	4.419	0.500	0.235	0.211	0.201
2	1.626	4.419	0.500	0.392	0.353	0.335
3	0.824	8.581	0.500	0.339	0.305	0.290
4	1.626	8.581	0.500	0.384	0.346	0.328
5	0.824	4.419	1.760	0.394	0.354	0.337
6	1.626	4.419	1.760	0.427	0.384	0.365
7	0.824	8.581	1.760	0.440	0.396	0.376
8	1.626	8.581	1.760	0.451	0.406	0.385
9	0.550	6.500	1.130	0.221	0.198	0.189
10	1.900	6.500	1.130	0.334	0.300	0.285
11	1.225	3.000	1.130	0.301	0.271	0.257
12	1.225	10.000	1.130	0.341	0.306	0.291
13	1.225	6.500	0.070	0.221	0.198	0.189
14	1.225	6.500	2.190	0.459	0.413	0.392
15	1.225	6.500	1.130	0.232	0.209	0.198
16	1.225	6.500	1.130	0.131	0.117	0.112
17	1.225	6.500	1.130	0.131	0.117	0.112
18	1.225	6.500	1.130	0.131	0.117	0.112
19	1.225	6.500	1.130	0.131	0.117	0.112
20	1.225	6.500	1.130	0.131	0.117	0.112

The positive sign in front of the terms indicate synergistic effect where as the negative sign indicates antagonistic effect. The various correlation coefficients (R^2, R^2_{adj} and R^2_{pred}) for all the models have been presented in table 5. It is observed that the predictetd $R^2$for all the responses are in reasonable agreement with R^2_{adj}.The value of the adequate precision is sufficiently more than 4 for all the models. The standard deviations of all the models are within 5%. Thus the correlations developed can be used within the design space.The fair correlation coefficient of table 5 may be due to insignificant model term and most likely due to three different variables selected in a wide ranges with a limited number of experiment as well as the non linear influence of investigated parameter on process response(Dora et al., 2012).

Table 5. Values of coefficient of correlations

Eq. No	R^2	R_{adj}^2	R_{pred}^2
1	92	89	85
2	92	89	85
3	92	89	85
4	92	89	85
5	92	89	85
6	92	89	85
7	92	89	85
8	92	89	85
9	92	89	85
10	92	89	85

ANOVA for eqs.8-10 is shown in tables 6-8respectively. The F-value of the models for gas holdup (eqs.8, 9, 10) are found to be 11.8795.This implies that the models are significant. There is only 0.01% chance that this large could occurs due to noise(Dora et al., 2012).Values of “probability >F” less than 0.0500 indicates that the model terms are significant.In this case A, C, A^2, B^2, C^2 are significant model terms.

4.0 Conclusion

In the present work fluctuation ratio, expansion ratio and gas holdups in a three stage fluidized bed have been studied. In this study RSM based CCD have been employed to evaluate the influence of three process parameter (particle size, static bed height and superficial gas velocity) on the three responses (Fluctuation ratio, Expansion ratio and gas hold up).Mathematical correlations have been derived by using sets of experimental data and ANOVA.The performance of multistage fluidized bed has been compared with respect to different stages. As fluctuation ratio and expansion ratio is related to quality of fluidization, less fluctuation ratio and bed expansion is desirable. In this study both fluctuation ratio and expansion ratio is greatly reduced from the lower bed to the upper bed with an intermediate one in middle bed. Similarly under identical conditions, the gas holdup is maximum at the lower bed and minimum at the upper bed. Thusthe result of this study can effectively be used for the design and fabrication of amultistage fluidized bed reactor for various industrial applications such as drying, adsorption etc.

Nomenclature

D_p Particle size, mm
h_s Static bed height, cm
U_s Superficial gas velocity, m/s
r_l Fluctuation ratio for lower bed
r_m Fluctuation ratio for middle bed
r_u Fluctuation ratio for upper bed
R_l Expansion ratio for lower bed

R_m Expansion ratio for middle bed
R_u Expansion ratio for upper bed
ϵ_l Gas hold up for lower bed
ϵ_m Gas hold up for middle bed
ϵ_u gas hold up for upper bed

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