

Mixing and Segregation Characteristics of Multistage Fluidized Bed Reactor-Statistical Approach

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ABSTRACT: The present paper describes statistical modeling of multistage fluidized bed for control of hazardous pollutant present in flue gas. The hydrodynamic studies relating to mixing index has been studied and compared between the lower, middle and upper bed of the multistage fluidized column. A 2^4 full factorial central composite design (CCD) has been employed and quadratic model equations of mixing index has been developed. The values of mixing index obtained through the developed models are found to agree well with their corresponding experimental counterparts with a very good correlation coefficient of 93%. From the experimental data it is revealed that simultaneously both mixing and segregation takes place in lower and middle and upper bed respectively.

KEYWORDS: ANOVA, Jetsam, Flotsam, Mixing Index, Multistage, hazardous

I. INTRODUCTION

Particle separation phenomenon is not uncommon in industrial fluidized beds, where particles of widely different sizes or densities are handled. It has been studied that the fluidized bed reactors can be operated in different modes either to promote the particle mixing or to enhance the particle segregation. It is also not unusual to have one part of the fluidized bed reactor operated in a mixing mode while the other in a segregation mode. A typical example of this kind of reactor is the fluidized bed agglomerating combustor or gasifier developed by Westinghouse [1] In the upper part of the reactor, where combustion or gasification occurs, a solid mixing between the combustion and gasification zones is essential

II. RELATED WORK

Nienow et al. [2] studied the role of particle size, density and air flow rate on the segregation or de-mixing behaviour in a gas-solid fluidized bed, and concluded that a fairly wide particle size difference can be tolerated, while small density difference leads to ready settling of denser particles

Chen et al. [3] presented a limited amount of data on the rate of separation in a char-dolomite system with an unmixed starting mixture. Kondukov and Sosna[4] and Gelperin et al. [5] suggested a phase equilibrium diagram for a segregating mixture. Using the analogy between a fluidized bed and a liquid, they suggested that a segregating mixture in a fluidized bed resembled a liquid-solid system. Yang and Keairns [6] studied the rate of particle separation in a fluidized bed 7.0 cm in diameter, using crushed acrylic plastic particles as flotsam and dolomite particles as jetsam, and concluded that for mixtures of different jetsam concentrations, the rate and degree of particle separation were different but generally completed in less than 15 sec. in all cases

Miyauchi [7] studied the vertical mixing of solids in vigorously fluidized beds ($u_0 > 10$ cm/s) of fine Geldart -A solids and found that the mixing data could reasonably be represented by the dispersion model.

$$D_{sv} = 12 u_0^{1/2} d_t^{0.9} \quad \dots (1)$$

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Avidan and Yerushalmi [8] found that the dispersion model better represented the mixing during turbulent fluidization, where the bed looked close to homogeneous, but fitted the data poorly when the bed was in the bubbling regime.

Quin et al. [9] studied particle mixing in rotating fluidized beds and concluded that for particles of the same material, the two layers of particles do not mix until bubbles appear. This result was similar to that of Menon and Durian [10] who concluded that bubbles are responsible for the bulk motion of particles in a conventional fluidized bed. After the critical minimum fluidization velocity, particles inside the bed start to move radially, and mixing occurs rapidly. Bubbles are a strong source of particle motion, and the bed becomes totally fluid-like. It was also found by Quin et al. [9] that the minimum bubbling velocity is dependent on the size and density of the particles. For Geldart-B particles, the minimum bubbling velocity is equal to the minimum fluidization velocity, whereas for Geldart-A particles, the minimum bubbling velocity is larger than the minimum fluidization velocity. Mixing occurs due to the difference in densities and fluidization properties of the two layers.

Fan et al. [11] reviewed the major developments in solid mixing since 1976 (170 articles), in three categories: characterization of states of solid mixtures, rates and mechanism of solid mixing processes and design and scale-up of mixers or blenders. Mixtures can be classified in to two major groups, one only involves free- flowing particles and the other contains cohesive or interactive constituent(s). The mixing indexes can only depict the macroscopic behaviour of a solid mixture. Three major mechanisms, diffusion, convection and diffusion-convection have been proposed for solid mixing.

Cooper and Coronella [12] studied fluidization of dissimilar material, i.e., coke and rutile in a fluidized bed and found that particle mixing and segregation phenomena are dominated by bubble activity.

Sahoo and Roy [13] studied the mixing characteristics of homogeneous binary mixture of regular particles (Geldart BD type) in a cylindrical gas-solid fluidized bed and developed a mathematical model for calculation of mixing index (I_M):

$$I_M = 0.3725 \times \left(\frac{dp}{d_F} \right)^{0.3679} \times \left(\frac{h_B}{D_c} \right)^{-0.4864} \times \left(\frac{H_s}{D_c} \right)^{0.8258} \times \left(\frac{U}{U - U_F} \right)^{0.3084} \quad \dots (2)$$

Patil et al. [14] studied the influence of internal baffles on mixing characteristics and found that the bed without baffles showed distinctive segregation nature. Internal baffles were effective in altering the fluidization of biomass-sand mixtures. Of the baffles tested, the annular plate showed the best performance as compared to coil and half-circle plate baffles.

Bosma and Hoffmann [15] studied the effectiveness of baffles and found that the baffles are most effective in systems that tend to segregate but do actually hardly segregate without baffles.

Majumdar et al. [16] investigated the mixing and segregation behaviour of granular flow in a sectorial container. The effect of different operating parameter such as frequency of oscillations, amplitude of oscillation, volume fraction and the size ratio of particle were studied and concluded that the mixing and segregation of particle takes place in a particular range of frequency zone.

Literature survey reveals that lot of works related to mixing index have been reported but in a single stage fluidized bed. But in this present work, attempt has been made to study the mixing index of a multistage fluidized bed and the same has been compared in different stages of the column. knowing the percentage of jetsam at different heights of the bed, the experimental values for the mixing index (I_M) at different heights have been calculated with the help of the following expression [17]:

$$I_M = \frac{X^*}{X_{bed}} \quad \dots (3)$$

III. METHODOLOGY AND DISCUSSION

The experimental setup (Fig. 1) consists of a three-stage fluidized bed column made of Perspex having different diameters and lengths for each stage. 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 columnar cross-section, are 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 are provided in each stage measure the pressure

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drop through a differential manometer, in which carbon tetrachloride (density 1.59 kg/m³) is used as the manometric fluid. A calming section is placed just below the lower stage, and is filled with glass beads to ensure a uniform distribution of air. Two short windows, one at the bottom and one at the top, are cut into the column walls to load and unload materials to and from the column. After loading and unloading, the windows are closed by tightening a butterfly bolt. A multistage air compressor with a capacity of 1297 kg/cm² is used to supply air to the fluidizer through a silica gel column and rotameter. The silica gel column is used to arrest moisture in the air. The calibrated rotameter (capacity 120 m³/h) is used to measure the flow rate of air from the silica gel column.

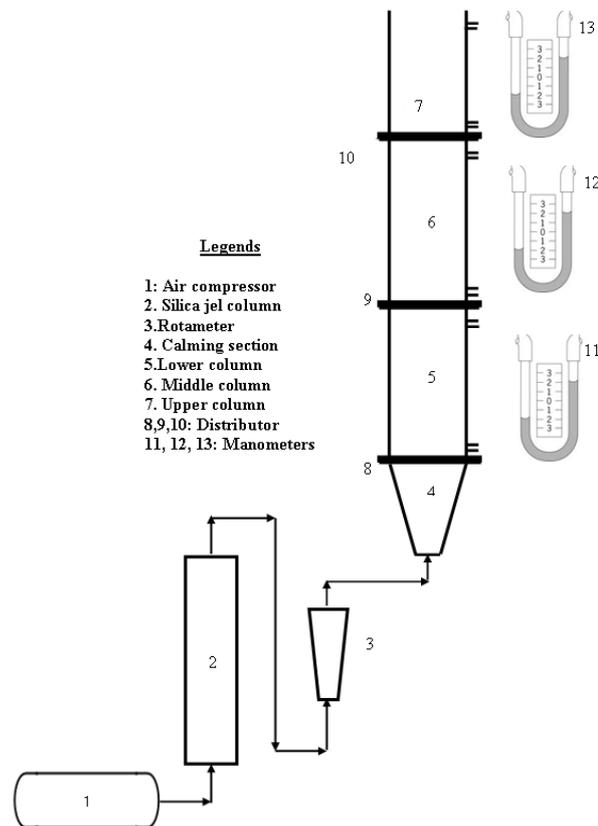


Fig. 1. Schematic diagram of experimetal set-up

To determine the mixing index of a multistage fluidized bed column and 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 variables affecting the mixing index are the static bed height, superficial gas velocity, particle size, and column diameter. We examine four different column sizes and four static bed heights, with varying gas flow rates.

Experiments have been carried out by taking two different bed materials, viz, iron, and dolomite . Iron has been considered as the base material due to its separability through a magnetic separator. A 50:50 mixture (by weight) has been taken for experimentation. The mixture is initially well mixed and then charged into the column, and then fluidized at varying air flow rates. The variables taken are different static bed heights, particle sizes, column diameter and gas velocities.

During fluidization, the samples have been drawn from the side ports made on either side of the column and have been analysed on the basis of the assumption of uniform concentration for a particular layer of particles across the cross-section of the column at any height. Then the samples have been separated through a magnetic separator and then the weights of the flotsam and jetsam particles taken in an electronic digital balance

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IV. EXPERIMENTAL RESULT

IV.I Model development and validation

The statistical software package “Design Expert” has been used for regression analysis of experimental data and to draw response surface plot. Analysis of variance(ANOVA) has been used to estimate the statistical parameters. The complete experimental range and level of variables are given in the Table 1 and Table 2 shows the design of experiments together with the experimental results. On the basis of experimental data the models were developed by employing response surface methodology based central composit design[18,19,20, 21, 22 and 23] As suggested by the software, the quadratic model has been selected which was not aliased. The final empirical model in terms of

Response	Variables	Sumbol	-α	-1	0	+1	+α
Pressure drop	Particle size, mm	A	0.55	0.89	1.23	1.56	1.9
	Static bed height, cm	B	3	4.75	6.5	8.25	10
	Column diameter ×0.393, cm	C	3	3.5	4	4.5	5
	Superficial gas velocity, m/s	D	0.07	0.6	1.13	1.66	2.19
4	1.5625	8.25	8.89	0.6	0.9899	0.8414	0.7424
5	0.8875	4.75	11.43	0.6	0.6698	0.5693	0.5023
6	1.5625	4.75	11.43	0.6	1.1345	0.9643	0.8509
7	0.8875	8.25	11.43	0.6	0.7249	0.6161	0.5436
8	1.5625	8.25	11.43	0.6	1.0577	0.8991	0.7933
9	0.8875	4.75	8.89	1.66	1.0102	0.8587	0.7577
10	1.5625	4.75	8.89	1.66	1.0010	0.8509	0.7508
11	0.8875	8.25	8.89	1.66	0.7602	0.6462	0.5701
12	1.5625	8.25	8.89	1.66	0.9582	0.8145	0.7187
13	0.8875	4.75	11.43	1.66	0.7598	0.6458	0.5699
14	1.5625	4.75	11.43	1.66	1.0779	0.9162	0.8084
15	0.8875	8.25	11.43	1.66	0.7414	0.6302	0.5560
16	1.5625	8.25	11.43	1.66	1.0283	0.8740	0.7712
17	0.55	6.5	10.16	1.13	0.6589	0.5601	0.4942
18	1.9	6.5	10.16	1.13	1.0254	0.8716	0.7691
19	1.225	3	10.16	1.13	0.9453	0.8035	0.7089
20	1.225	10	10.16	1.13	0.8385	0.7127	0.6289
21	1.225	6.5	7.62	1.13	1.0120	0.8602	0.7590
22	1.225	6.5	12.7	1.13	0.9895	0.8411	0.7421
23	1.225	6.5	10.16	0.07	0.9753	0.8290	0.7315
24	1.225	6.5	10.16	2.19	1.0001	0.8501	0.7501
25	1.225	6.5	10.16	1.13	1.0001	0.8501	0.7501
26	1.225	6.5	10.16	1.13	1.0001	0.8501	0.7501
27	1.225	6.5	10.16	1.13	1.0001	0.8501	0.7501
28	1.225	6.5	10.16	1.13	1.0001	0.8501	0.7501
29	1.225	6.5	10.16	1.13	1.0001	0.8501	0.7501
30	1.225	6.5	10.16	1.13	1.0001	0.8501	0.7501

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coded factor for mixing index for lower, middle and upper bed of the multistage fluidized bed is shown in Eq. (4) (5) and (6) respectively

$$R1=1.00+0.12A-0.028B-0.00608C+0.00975D-0.00842AB+0.036AC-0.040AD+0.017BC-0.017BD-0.00896CD-0.044A^2-0.031B^2-0.0004C^2-0.00725D^2 \quad (4)$$

$$R2=0.85+0.11A-0.024B-0.005172C+0.008294D-0.007123AB+0.030AC-0.034AD+0.014BC-0.014BD-0.00762CD+0.037A^2-0.027B^2-0.0003408C^2-0.006184D^2 \quad (5)$$

$$R3=0.75+0.093A-0.021B-0.004563C+0.007318D-0.00632AB+0.027AC-0.030AD+0.013BC-0.013BD-0.00672CD-0.033A^2-0.023B^2-0.0003C^2-0.00545D^2 \quad (6)$$

The model F values of of each model 12.54 implies that the models are significant. Further Values of “Prob > F” less than 0.0500 indicate that the model terms are significant. In this case, A, B,, AC, AD A² and B² are significant model terms. Adequacy Precision measures the signal to noise ratio and it compares the range of the predicted values at the design points to the average prediction error. A ratio greater than 4 is desirable. The ratio of 13.831 in our study, indicates an adequate signal. Hence this model can be used to navigate the design space.

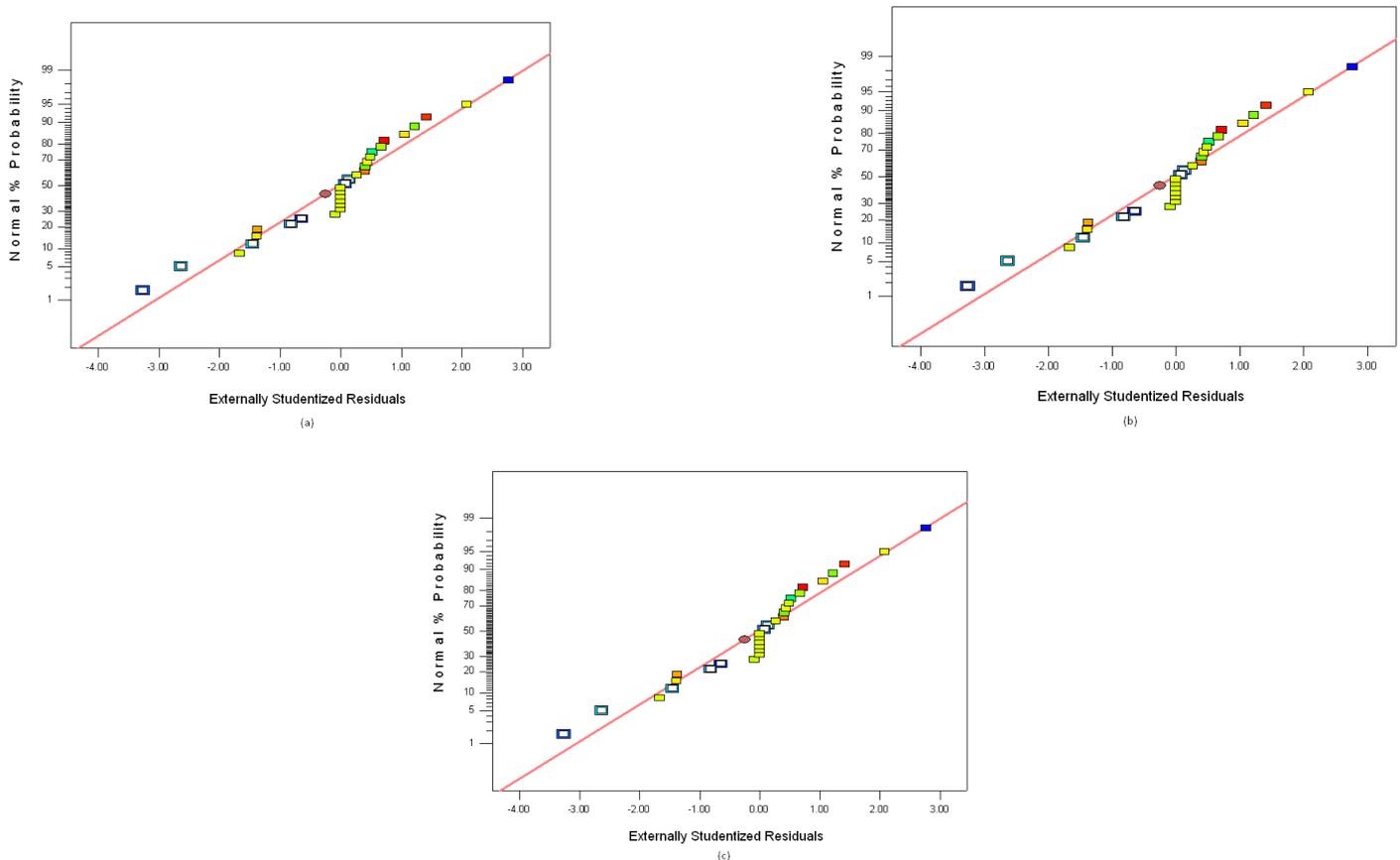


Fig.2 Studentized residue and normal percentage probability for mixing index of (a)lower bed (b) middle bed (c) upper bed

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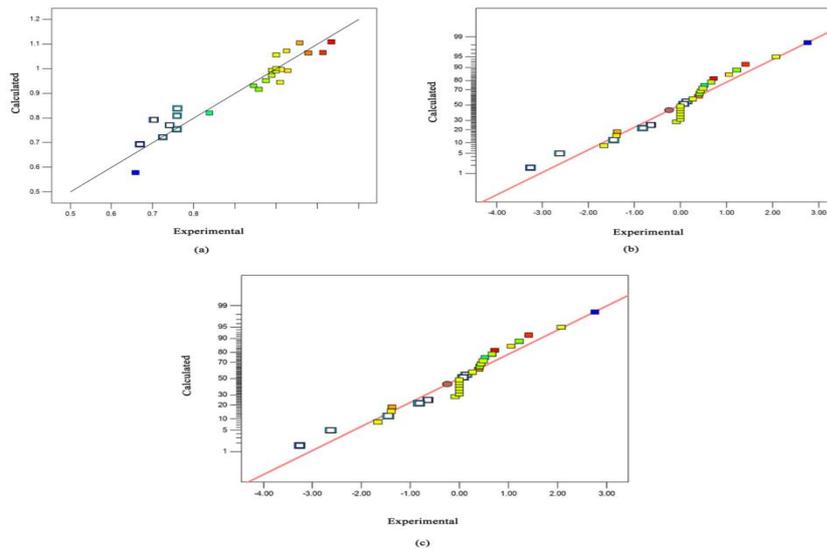


Fig.3. Comparison of experimental value of mixing index with predicted value for (a) lower bed (b) middle bed (c) upper bed

One of the most important parts of the data analysis is to check the adequacy of the developed model. This is done by examining the residual plots which have been shown in the Figs. 2 and 3. It is observed from the Fig. 2 that there was neither response transformation nor any apparent problem with normality. Fig. 2 shows the internally studentised residual vs predicted mixing index which represents a random scatter plot indicating that the variance of residual observation is constant for all values of the response. This is also an indication that there was no need for transformation of response variables. However, this plot would exhibit a funnel shaped pattern if the variance of the response depended on the mean level of response. The actual and the predicted mixing index have been shown in Fig. 3 and it is observed that the values of R^2 and R^2_{adj} have been found to be 92% and 84%.for all the three models. The fair correlation coefficient 84% might be due to the insignificant terms in Tables 3,4 and 5 as well as the non-linear influence of the investigated variables on the response.

Table3
ANOVA for lower bed mixing index

Source	Sum of Squares	Degrees of freedom	Mean Square	F Value	p-value Prob > F	Remark
Model	0.5167	14	0.0369	12.5410	0.0000	significant
A	0.3664	1	0.3664	124.5016	0.0000	significant
B	0.0184	1	0.0184	6.2426	0.0246	significant
C	0.0009	1	0.0009	0.3019	0.5908	
D	0.0023	1	0.0023	0.7764	0.3921	
AB	0.0011	1	0.0011	0.3861	0.5437	
AC	0.0205	1	0.0205	6.9669	0.0186	significant
AD	0.0260	1	0.0260	8.8313	0.0095	significant
BC	0.0046	1	0.0046	1.5611	0.2307	
BD	0.0046	1	0.0046	1.5617	0.2306	
CD	0.0013	1	0.0013	0.4373	0.5184	
A ²	0.0523	1	0.0523	17.7649	0.0008	significant
B ²	0.0268	1	0.0268	9.0908	0.0087	significant
C ²	0.0004	1	0.0004	0.1498	0.7042	
D ²	0.0015	1	0.0015	0.4933	0.4932	
Residual	0.0441	15	0.0029			
Lack of Fit	0.0441	10	0.0044			
Pure Error	0.0000	5	0			
Cor Total	0.5609	29				93%
R²						84%
R²_{adj}						84%

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Table4

ANOVA for middle bed mixing index

Source	Sum of Squares	Degrees of freedom	Mean Square	F Value	p-value Prob > F	
Model	0.3733	14	0.0267	12.5410	<0.0001	significant
A	0.2647	1	0.2647	124.5016	<0.0001	significant
B	0.0133	1	0.0133	6.2426	0.0246	significant
C	0.0006	1	0.0006	0.3019	0.5908	
D	0.0017	1	0.0017	0.7764	0.3921	
AB	0.0008	1	0.0008	0.3861	0.5437	
AC	0.0148	1	0.0148	6.9669	0.0186	significant
AD	0.0188	1	0.0188	8.8313	0.0095	significant
BC	0.0033	1	0.0033	1.5611	0.2307	
BD	0.0033	1	0.0033	1.5617	0.2306	
CD	0.0009	1	0.0009	0.4373	0.5184	
A ²	0.0378	1	0.0378	17.7649	0.0008	significant
B ²	0.0193	1	0.0193	9.0908	0.0087	significant
C ²	0.0003	1	0.0003	0.1498	0.7042	
D ²	0.0010	1	0.0010	0.4933	0.4932	
Residual	0.0319	15	0.0021			
Lack of Fit	0.0319	10	0.0032			
Pure Error	0.0000	5	0			
Cor Total	0.4052	29				93%
R ²						84%
R ² _{adj}						

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Table 5

ANOVA for upper bed mixing index

Source	Sum of Squares	Degrees of freedom	Mean Square	F Value	p-value Prob > F	
Model	0.2906	14	0.0208	12.5410	<0.0001	significant
A	0.2061	1	0.2061	124.5016	<0.0001	significant
B	0.0103	1	0.0103	6.2426	0.0246	significant
C	0.0005	1	0.0005	0.3019	0.5908	
D	0.0013	1	0.0013	0.7764	0.3921	
AB	0.0006	1	0.0006	0.3861	0.5437	
AC	0.0115	1	0.0115	6.9669	0.0186	significant
AD	0.0146	1	0.0146	8.8313	0.0095	significant
BC	0.0026	1	0.0026	1.5611	0.2307	
BD	0.0026	1	0.0026	1.5617	0.2306	
CD	0.0007	1	0.0007	0.4373	0.5184	
A ²	0.0294	1	0.0294	17.7649	0.0008	significant
B ²	0.0150	1	0.0150	9.0908	0.0087	significant
C ²	0.0002	1	0.0002	0.1498	0.7042	
D ²	0.0008	1	0.0008	0.4933	0.4932	
Residual	0.0248	15	0.0017			
Lack of Fit	0.0248	10	0.0025			
Pure Error	0.0000	5	0			
Cor Total	0.3155	29				93%
R ²						84%
R ² _{adj}						

IV.II Combined effect of operating variables on mixing index

The mixing index in gas solid fluidization plays an important role in the design of multistage fluidized bed column. Response surface methodology(RSM) based central composit design have been employed to study both the individual and combined effect of operating variables viz. static bed height, column diameter, particle size and superficial gas velocity on mixing index of three stage fluidized bed column. Fig. 4(a)-(e) shows effect of two variables on mixing index at a fixed value of other two variables for lower bed. Effect of particle size and static bed height, particle size and column diameter, and particle size and superficial gas velocity on mixing index is shown in Fig.4(a),(b) and (c) respectively. It is observed that with an increase of particle size, static bed height, column diameter and superficial gas velocity the mixing index increases. However the combined effect of particle and static bed height on mixing index is just the reverse of the individual effect. This may be due to the fact that increase in particle size and static bed height increases the weight of the bed for which the pressure drag increases[24]. As pressure drag increases part of the kinetic energy is lost as a result of which the bubble in the bed collapse instead of rising up. Fig. 4(c) shows that the mixing index decreases when particle size and superficial gas velocity increases simultaneously keeping static bed height and column diameter at a constant value. Here though the superficial gas velocity increases the increase in particle size dominant over gas velocity.

Combined effect of static bed height and column diameter, static bed height and gas velocity, and column diameter and gas velocity is shown in Fig4.(d), (e) and (f) respectively. It is observed that mixing index has an direct function of combined effect of static bed height and column diameter where as it has an inverse function of combined effect of static bed height and gas velocity as well as column diameter and gas velocity. Similarly the combined effect of operating variables on Mixing index of middle and upper bed has been shown in Fig5(a) –(f) and 6(a)-(f)

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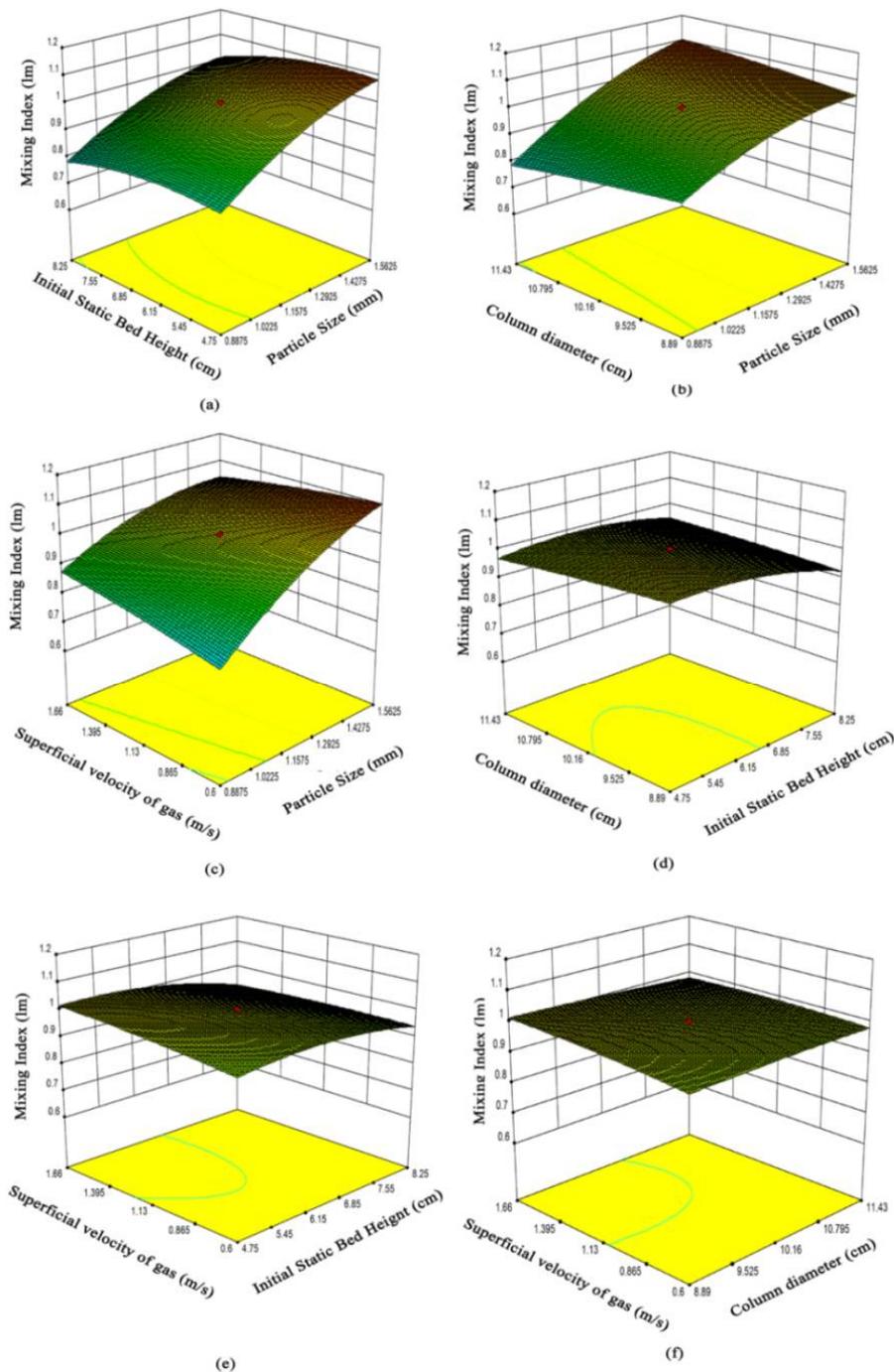


Fig.4. Combined effect of (a) particle size and static bed height (b) particle size and column diameter (c) particle size and superficial gas velocity (d) column diameter and static bed height (e)static bed height and superficial gas velocity (f)Superficial gas velocity and column diameter on lower bed mixing index

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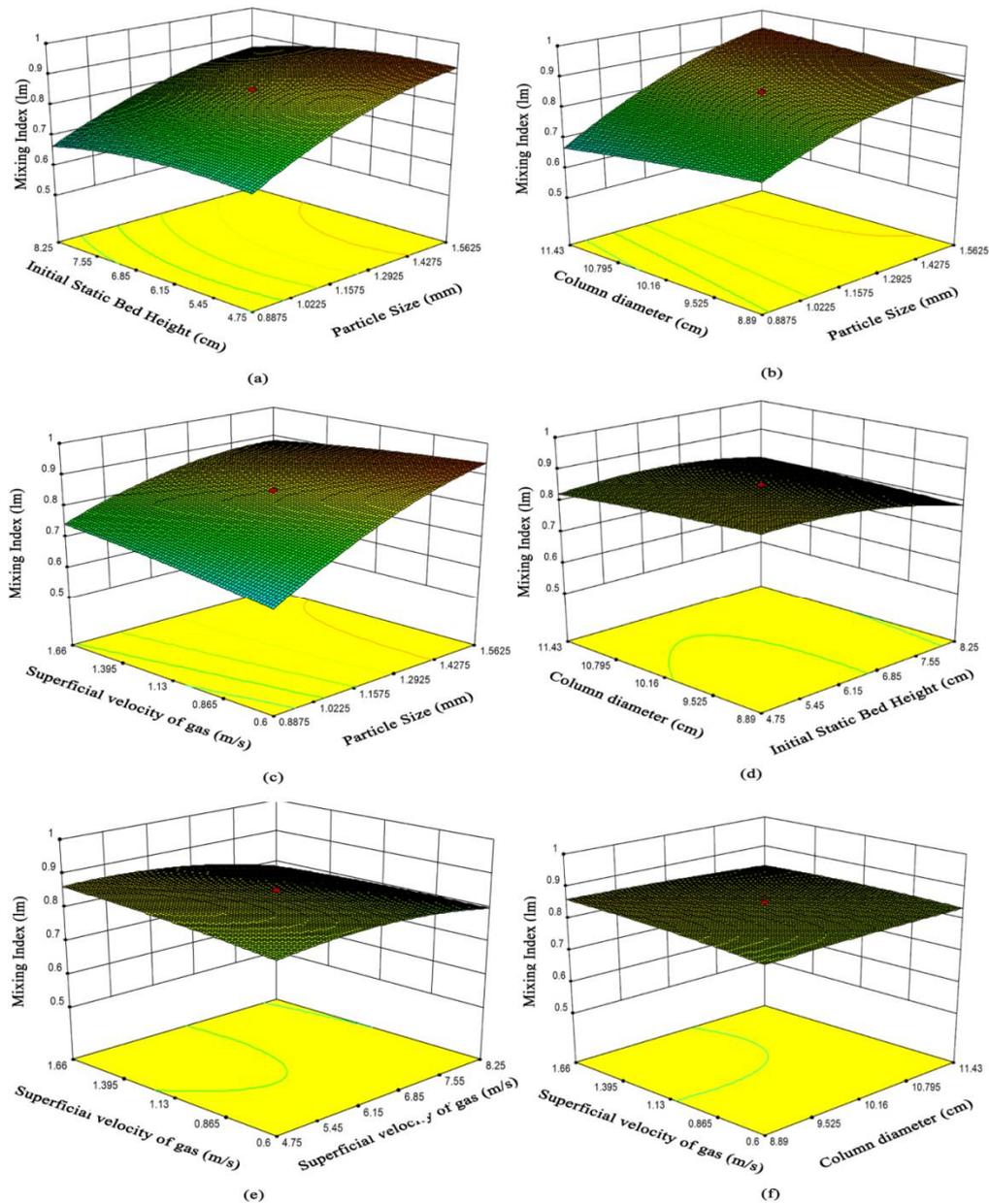


Fig.5. Combined effect of (a) particle size and static bed height (b) particle size and column diameter (c) particle size and superficial gas velocity (d) column diameter and static bed height (e)static bed height and superficial gas velocity (f)Superficial gas velocity and column diameter on middle bed mixing index

A careful observation of Table 2 reveals that Mixing index of lower bed is very close to 1 (jetsam and float sam concentration of 0.5, i.e $I_M=1$). This indicates that there is perfect mixing in lower bed as compared to middle and upper bed where the values of mixing index is not close to 1. This implies that flow pattern of solids changes from being well

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mixed in lower bed to a plug flow in the upper bed , with intermediate flow pattern in the middle bed. Therefore it may concluded that in industrial fluidized column where two different mode of operations i.e mixing and segregation is required in that case the multistage fluidized bed column can be a best option .This is due to the fact that the moment where the lower bed serves the purpose of mixing while the middle and upper bed bed serves the purpose of segregation.

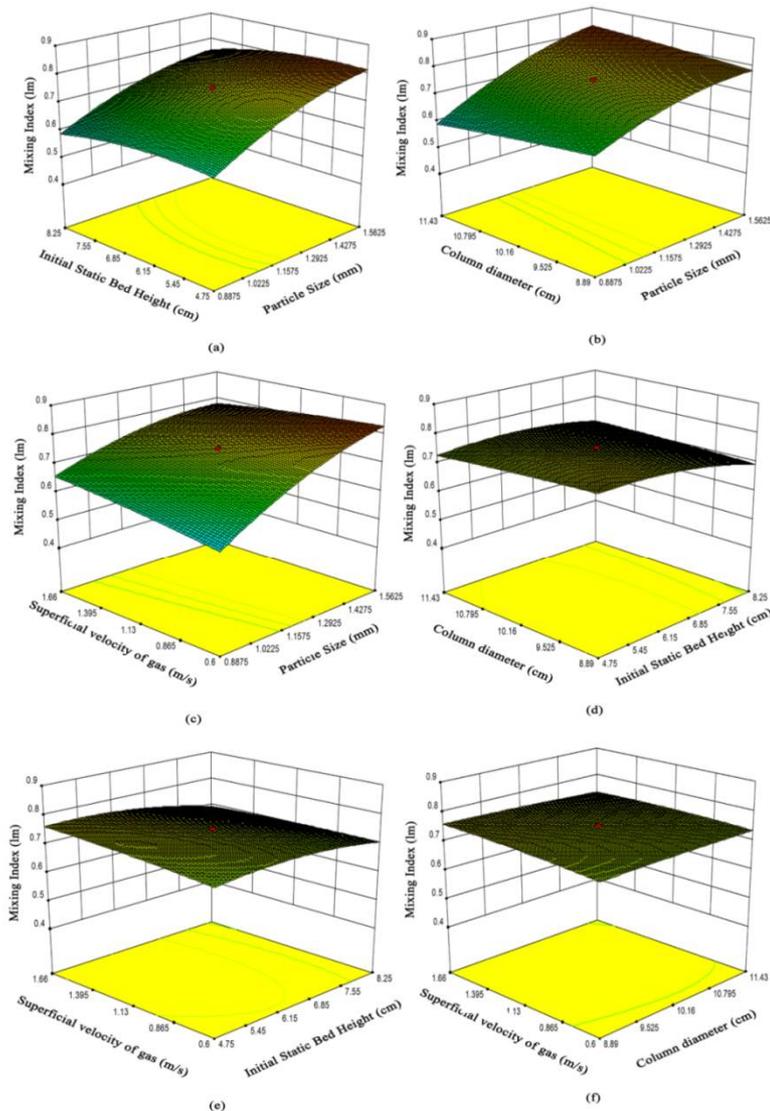


Fig.6. Combined effect of (a) particle size and static bed height (b) particle size and column diameter (c) particle size and superficial gas velocity (d) column diameter and static bed height (e)static bed height and superficial gas velocity (f)Superficial gas velocity and column diameter on upper bed mixing index

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V. CONCLUSION

In this paper, we examine the hydrodynamic characteristics relating mixing index in a multistage fluidized bed. The parameters affecting the mixing index were found to be static bed height, particle size, column diameter and superficial gas velocity. It was observed that the flow pattern changes from being well mixed in lower bed to plug flow in upper bed. Further it is observed that both mixing and segregation can take place simultaneously in a multistage fluidized bed with mixing in the lower bed and segregation in the subsequent bed. The correlation developed for mixing index in this study can effectively be used within the design space with very good correlation coefficient. The result of this study can be effectively used in design and develop a fluidized bed agglomerating combustor or gasifier where both mixing and segregation takes place simultaneously.

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