Published in China Particuology
Volume 5, Issue 4, August 2007, Pages 261-266
http://dx.doi.org/10.1016/j.cpart.2007.05.004

Bed Dynamics of Gas-Solid Fluidized Bed with Rod Promoter

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Abstract

The dynamic characteristics of a gas-solid fluidized bed with different rod promoters have been investigated in terms of bed expansion and fluctuation, minimum fluidization velocity and distributor-to-bed pressure drop ratio at minimum fluidization velocity. Experimentation based on statistical design has been carried out and model equations using factorial design of experiments have been developed for the above mentioned quantities for a promoted gas-solid fluidized bed. The model equations have been tested with additional experimental data. The system variables include four types of rod promoters of varying blockage volume, bed particles of four sizes and four initial static bed heights. A comparison between the predicted values of the output variables using the proposed model equation with their corresponding experimental ones shows fairly good agreement.

Keywords: dynamic characteristics, statistical design, gas-solid fluidization, rod promoter

1. Introduction

A gas-solid fluidized bed is characterized by the formation of bubbles and their ultimate growth to form slugs. The collapsing of bubbles causes erratic bed expansion with intense bed fluctuation. This results in poor bed performance with increased height of the fluidizer and makes the operation uneconomical. Williams (1972), Krishnamurthy et al. (1981), Dutta and Suciu (1992), Duursma et al. (1994), Kar and Roy (2000), Kumar and Roy (2002a, b, and c), Kumar (2003), and Sahoo and Roy (2005) have stressed upon the use of promoters in a gas-solid fluidized bed to improve its fluidization quality in terms of delaying bubble formation, breaking up bubbles to smaller sizes and minimizing slug formation and thereby reducing bed expansion and fluctuation.

In addition, Balakrishnan and Raja Rao (1975) and Kumar and Roy (2002d) observed higher minimum fluidization velocity in promoted beds compared to the unpromoted ones. To minimize channeling in the bed and for active and stable operation of all the orifices in the grid, researchers have recommended a wide range of the distributor-to-bed pressure drop ratio at the onset of fluidization. For a porous distributor plate and at the condition near minimum fluidization, Hiby (1964) indicated that the pressure drop through the distributor should be at least 30% of that through the bed to provide uniform fluidization. Siegel (1976) suggested that for a wide range of Galelio number ($1\text{-}10^4$), the minimum ratio of the distributor to bed resistance required for stability is between 0.14 and 0.22. Saxena et al. (1979) obtained this value to be 0.21. The experimental investigation of Whitehead and Dent (1967) and theoretical analysis of Siegel (1976) reported a pressure drop ratio as low as 0.05 and as high as 1.0. Sathiyamoorthy and Rao (1981) obtained the distributor to bed pressure drop ratio as 0.24 and 0.12 for coarse and the fine particles respectively. Qureshi and Creasy (1979) reported that a number of investigators obtained pressure drop ratios between 0.11 and 1.0 using multiorifice distributor plates.

In the present work, the experimental data obtained on the basis of statistical design have been used to develop model equations for the prediction of bed expansion and fluctuation and the pressure drop ratio.

2. Experimental

A schematic diagram of the experimental setup and the details of the rod promoters are presented in Figs. 1 and 2 respectively**.** A galvanized iron plate of 1 mm thickness having 37 orifices with 2.5 mm diameter placed on an equilateral triangular pattern at a pitch of 7.5 mm was used as an air distributor to facilitate uniform air entry to the fluidizer. A mild steel wire mesh was placed over the distributor to prevent the entry of materials into the calming section. A known amount of bed material (dolomite, specific gravity = 2.82) was charged to the column from the top. The reproducible static bed height was obtained after fluidizing the bed gradually and then allowing it to settle slowly at least three times. The distributor and the total (bed + distributor) pressure drop and the fluctuation for the top of the expanded bed (maximum and minimum levels) have been recorded with varying air flow rate, particle size, initial static bed height and the blockage volume of the rod promoter. The scope of the factors taken for the experimental study is presented in Table 1.

The experiments carried out are on the basis of advance planning according to method of Factorial Design Analysis. Such statistical design of experiments (Davies, 1978; Dieter, 1987) stands for planning in advance, and enables to study the interacting effects of variables with minimum experimental runs.

2.1 Design of experiment

The independent variables affecting the bed outputs, viz. bed expansion and fluctuation ratio, minimum fluidization velocity and distributor to bed pressure drop ratio at the onset of fluidization are: (i) flow parameter, $\left(G_{\mathrm{f}} - G_{\mathrm{mf}}\right)$, (ii) particle size, d_{p} (iii) initial static bed height, h_{s} and (iv) equivalent diameter of the promoted bed, D_{e}. The total number of experiments required at two levels for four variables are 2^4 =16 for the above mentioned outputs. To test the developed model equations, some more experimentation has to be carried out with the values of variables in between the low and the high levels.

2.2 Development of model equation

The model equation can be presented in the following general form:

$$\text{Output } (R,\ r,\ G_{\mathrm{mf}}\ \mathit{and}\ \frac{\Delta p_{\mathrm{d}}}{\Delta p_{\mathrm{b}}}) = b_0 + b_1 x_1 + b_2 x_2 + \cdots + b_{12} x_1 x_2 + b_{13} x_1 x_3 + \cdots$$
$$+ b_{123} x_1 x_2 x_3 + \cdots + b_{1234} x_1 x_2 x_3 x_4\ . \qquad (1)$$

The values of the above coefficients (Table 2) have been calculated by using the experimental data of different outputs collected for the runs planned according to the Yate's standard order and treatment combinations of the design of experiments. Thus,

$$b_i = \sum \alpha_i Y_i / N\,, \tag{2}$$

where, b_i is the coefficient, Y_i is the response, α_i is the level of the variables and N is the total number of treatments. The values of the coefficient indicate the effect of the variables and the sign of the coefficient gives the direction of the effect of the variables. Thus, a positive value of the coefficient indicates an increase and negative value indicates a decrease in the value of response with increase in the value of the variables. Ranking the values of the coefficients of the variables for their effects (based on their contribution to output values), the effect of all the four variables and some of the first order interactions have been found to be significant. The effects of the other first order, second and third order interactions between the respective variables have been found to be inappreciable and negligible.

Thus, considering the significance of the main variables and their interactions and neglecting other insignificant interactions between variables, the final model equation (1) for different response becomes:

$$R = 1.795 + 0.389x_1 + 0.141x_2 - 0.144x_3 + 0.112x_4 + 0.069x_1x_2 - 0.070x_1x_3 \tag{3}$$

$$r = 1.618 + 0.285x_1 + 0.094x_2 - 0.106x_3 + 0.102x_4 + 0.043x_1x_2 - 0.049x_1x_3\,, \tag{4}$$

$$G_{\mathrm{mf}} = 1824.75 + 1242.75x_2 - 55.25x_4 - 37.25x_2x_4\,, \tag{5}$$

$$\left(\frac{\Delta p_{\mathrm{d}}}{\Delta p_{\mathrm{b}}}\right)_{G_{\mathrm{mf}}} = 0.0788 + 0.0412x_2 - 0.0388x_3 - 0.0102x_4 - 0.0203x_2x_3\,. \tag{6}$$

The level of the system variables can be obtained as under:

Level of $x_1 = \left(\dfrac{X_1 - 2215}{1525}\right)$,

Level of $x_2 = \left(\dfrac{X_2 - 0.000727}{0.00039}\right)$, Level of $x_3 = \left(\dfrac{X_3 - 0.14}{0.06} \right)$,

Level of $x_4 = \left(\dfrac{X_4 - 0.0265}{0.0076} \right)$.

3. Results and discussion

Positive values of the coefficients of the parameters x_1, x_2, and x_4 for the case output variables as R and r, and x_2 for G_{mf} and $\left(\dfrac{\Delta p_{\mathrm{d}}}{\Delta p_{\mathrm{b}}} \right)_{G_{\mathrm{mf}}}$ indicate increase in the respective output values with increase in excess mass velocity, particle size, and equivalent diameter of the promoted bed. In other words, bed expansion and fluctuation ratios reduce with increase in blockage volume of the rod promoter, i.e. with increase in number of rods in the fluidized bed. Negative value of the coefficient of x_3 for the output variables R and r, and $\left(\dfrac{\Delta p_{\mathrm{d}}}{\Delta p_{\mathrm{b}}} \right)_{G_{\mathrm{mf}}}$ shows reduction in bed expansion and fluctuation ratio and distributor-to-bed pressure drop ratio at the onset of fluidization with increase in initial static bed height. Also, negative value of the coefficient of x_4 for $\left(\dfrac{\Delta p_{\mathrm{d}}}{\Delta p_{\mathrm{b}}} \right)_{G_{\mathrm{mf}}}$ infers decrease in pressure drop ratio with increase in equivalent diameter of the promoted bed. Similarly positive values of the coefficient of the parameters of first and higher order interactions between variables show increasing trend and negative values show decreasing trend of the respective output variables with the corresponding system variables. Figs. 3, 4, 5 and 6 (response plots) show the variation of different outputs viz. bed expansion and fluctuation ratios, minimum fluidization velocity and distributor-to-bed pressure drop ratio (at the onset of fluidization) with different system variables respectively and justify the above observations.

Reduction in bed expansion and fluctuation ratios can be attributed to the effectiveness of the promoter in breaking up of the bubbles. Further, the predicted values of bed expansion and fluctuation ratio, minimum fluidization velocity and distributor-to-bed pressure drop ratio using the developed model equations have been compared with the corresponding experimental ones (Figs. 7, 8, 9 and 10) for the data different from the minimum and the maximum levels used in the development of the model equations. Also, the predictions made from the model equations for bed expansion and fluctuation ratios have been compared with those obtained by Kumar and Roy (2002b, c). The mean and the standard deviations for the predicted values of the different output variables from the corresponding experimental ones are presented in Table 3.

Conclusion

The use of a rod type promoter in gas-solid fluidized bed has been found effective to be in reducing bed expansion and fluctuation ratio (Figs. 3 and 4). The effectiveness of the promoter further increases with increase in the number of rods, i.e. with decrease in the equivalent diameter of the promoted bed. This helps in reducing the overall size of a fluidizer and the operation becomes more economical. Further, the use of a rod promoter in a gas-solid fluidized bed has been observed to enhance the minimum fluidization velocity (Fig. 5), which agrees with the findings of Balakrishnan and Raja Rao (1975). The minimum fluidization velocity increases with the increase in the number of radial rods in the bed. With respect to the distributor-to-bed pressure drop ratio (at minimum fluidization velocity), the use of a rod promoter has been found to increase the ratio with the increase of the number of rods (i.e. decrease of the equivalent diameter) as represented in Fig. 6(b).

Also, the number of experimental runs required to develop a model equation using the Statistical Design approach is considerably less in comparison to the conventional approaches. In addition to bringing out the effect of the variables explicitly and quantitatively, this method also brings out the interactions between the variables, thereby giving a more accurate prediction. The comparison plots and the mean and standard deviations of the calculated values of the respective output using the developed equation, indicate a good agreement with the corresponding experimental ones.

Nomenclature

A_o	open area of the promoted bed, m
D_e	equivalent diameter of promoted bed, $4A_o / P$, m
d_p	particle size, m
G_f	fluidization mass velocity, $kg/m^2 \cdot h$
G_{mf}	minimum fluidization mass velocity, $kg/m^2 \cdot h$
h_{av}	average bed height, $(h_{max} + h_{min})/2$, m
h_{max}	maximum height of fluidized bed, m

$h_{\min}$	minimum height of fluidized bed, m
h_s	initial static bed height, m
P	total perimeter, m
R	bed expansion ratio, h_{av} / h_s
r	bed fluctuation ratio, $h_{\max} / h_{\min}$
$X_1 - X_4$	decoded (original) values of variables
$x_1 - x_4$	coded (leveled) values of variables
Δp_b	bed pressure drop, Pa
Δp_d	distributor pressure drop, pa

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Table 1 Scope of the factors (factorial design analysis)

Variables (general) symbol	Factorial design symbol	Minimum level		Maximum level		Magnitude of variables
		coded	decoded	coded	decoded	
$\left(G_{\mathrm{f}}-G_{\mathrm{mf}}\right)$	x_1	-1	600	+1	3650	600–3650
$d_{\mathrm{p}}\times10^{-3}$, m	x_2	-1	0.328	+1	1.125	0.328, 0.390, 0.463, 0.725, 1.125
$h_{\mathrm{s}}\times10^{-2}$, m	x_3	-1	8	+1	20	8, 12, 16, 20
$D_{\mathrm{e}}\times10^{-2}$, m	x_4	-1	1.89	+1	3.40	1.89, 2.24, 2.72, 3.40

[The values do not match.], corrected

Table 2 Values of coefficients of Eq. (1)

Output variable (→) Co-efficient (↓)	R	r	G_{mf}	$\frac{\Delta p_d}{\Delta p_b}$
b_0	1.795	1.618	1824.75	0.079
b_1	0.389	0.285	–	–
b_2	0.141	0.094	1242.75	0.041
b_3	-0.144	-0.106	–	-0.039
b_4	0.112	0.102	-55.25	-0.010
b_{12}	0.069	0.043	–	–
b_{13}	-0.070	-0.049	–	–
b_{23}	-0.025	-0.016	–	-0.020
b_{123}	-0.012	-0.007	–	–
b_{14}	0.055	0.047	–	–
b_{24}	0.019	0.015	-37.25	-0.005
b_{34}	-0.020	-0.017	–	0.005
b_{124}	0.010	0.007	–	–
b_{134}	-0.010	-0.008	–	–
b_{234}	-0.003	-0.003	–	0.003
b_{1234}	-0.002	-0.001	–	–

Table 3 Mean and standard deviations

Output parameters	Mean Deviation		Standard Deviation	
	Eq. (2)	Kumar and Roy, 2002b,c	Eq. (3)	Kumar and Roy, 2002b,c
Bed expansion ratio	5.14 (Eq.2)	5.50	6.28	6.42
Bed fluctuation ratio	3.57	4.12	4.00	5.31
Minimum fluidization mass velocity	4.22		4.96	
Distributor-to-bed pressure drop ratio at the onset of fluidization	12.39		13.57	

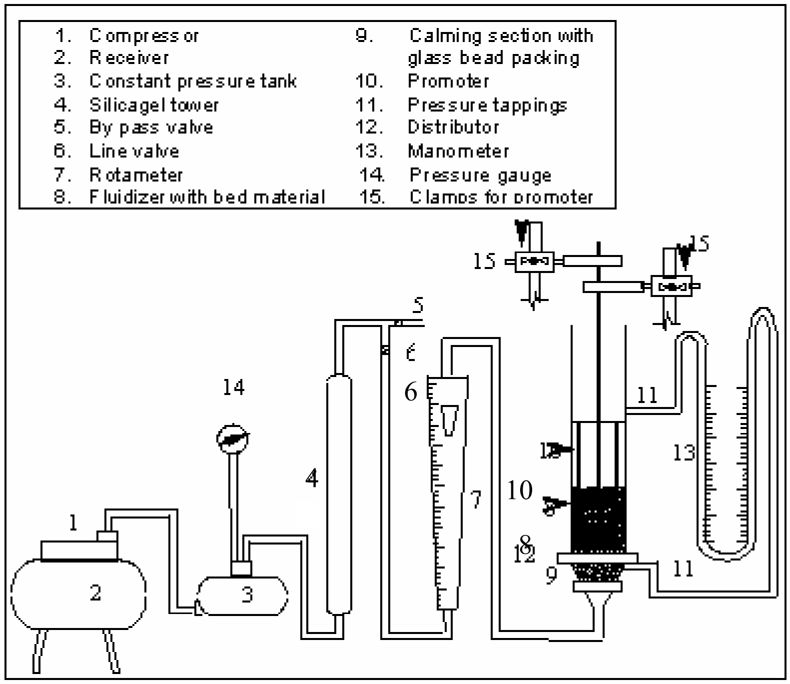

Fig. 1 Experimental setup.

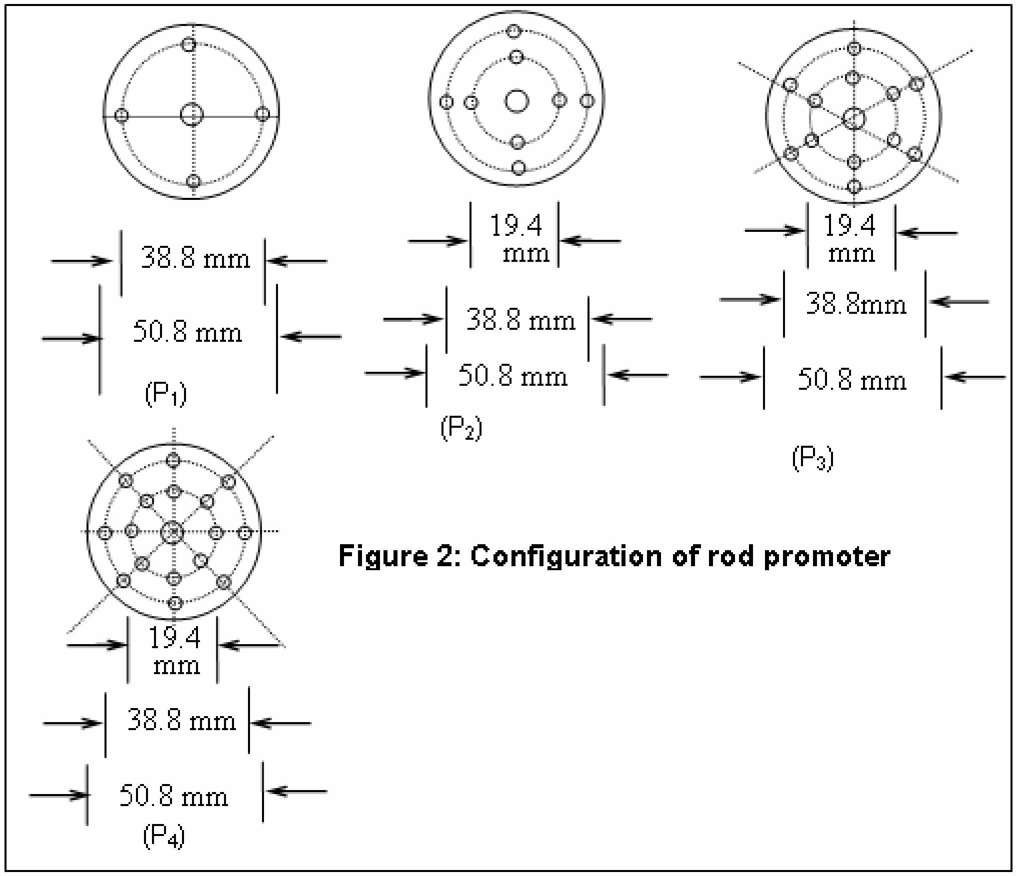

Fig. 2 Configuration of rod promoter.

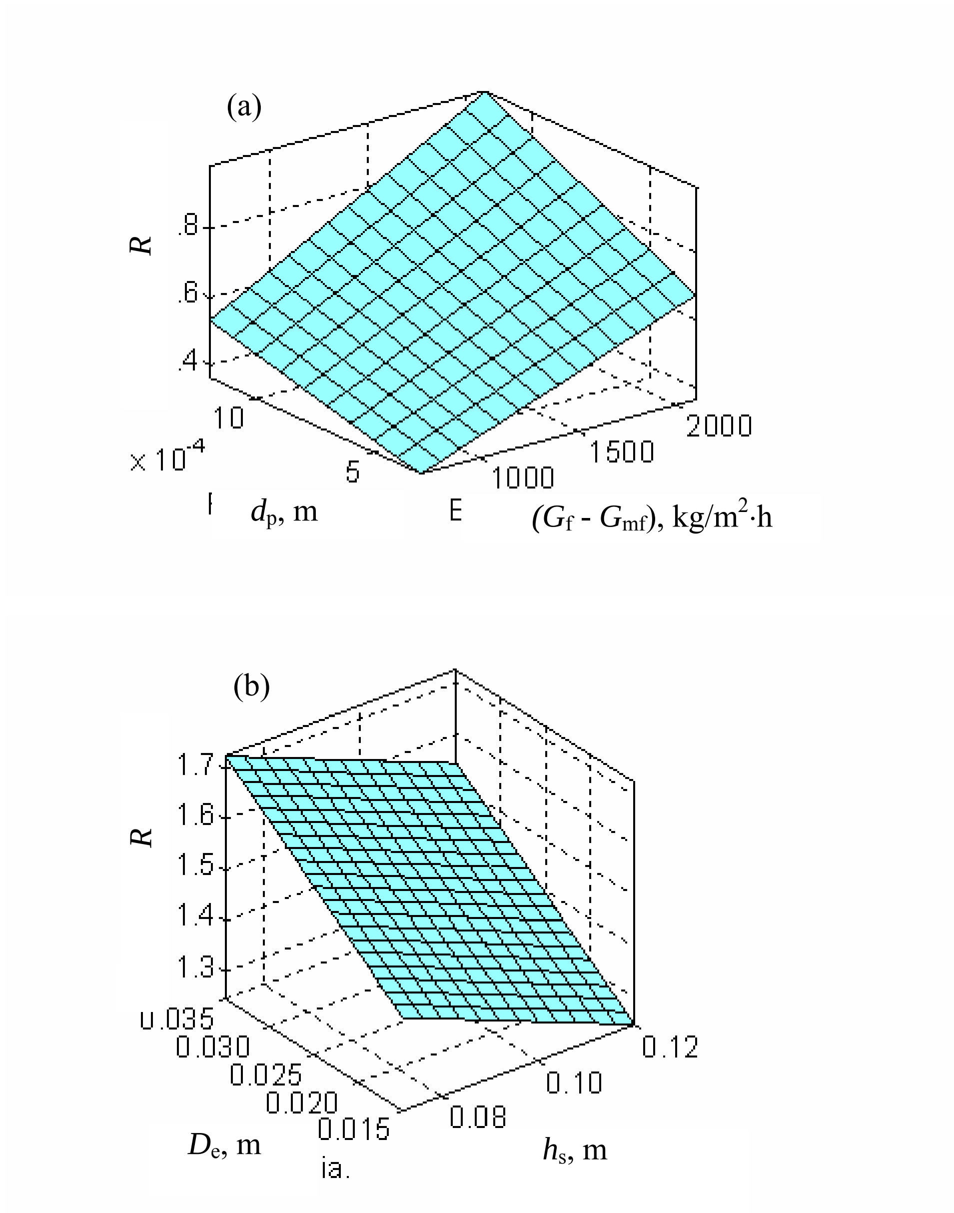

Fig. 3 Variation (response surface) of bed expansion ratio (a) with excess mass velocity and particle size at initial static height=0.12 m and equivalent bed diameter=0.0272 m; (b) with initial static height and equivalent bed diameter at particle size=0.000725 m and excess mass velocity=1000 kg/m^2·h.

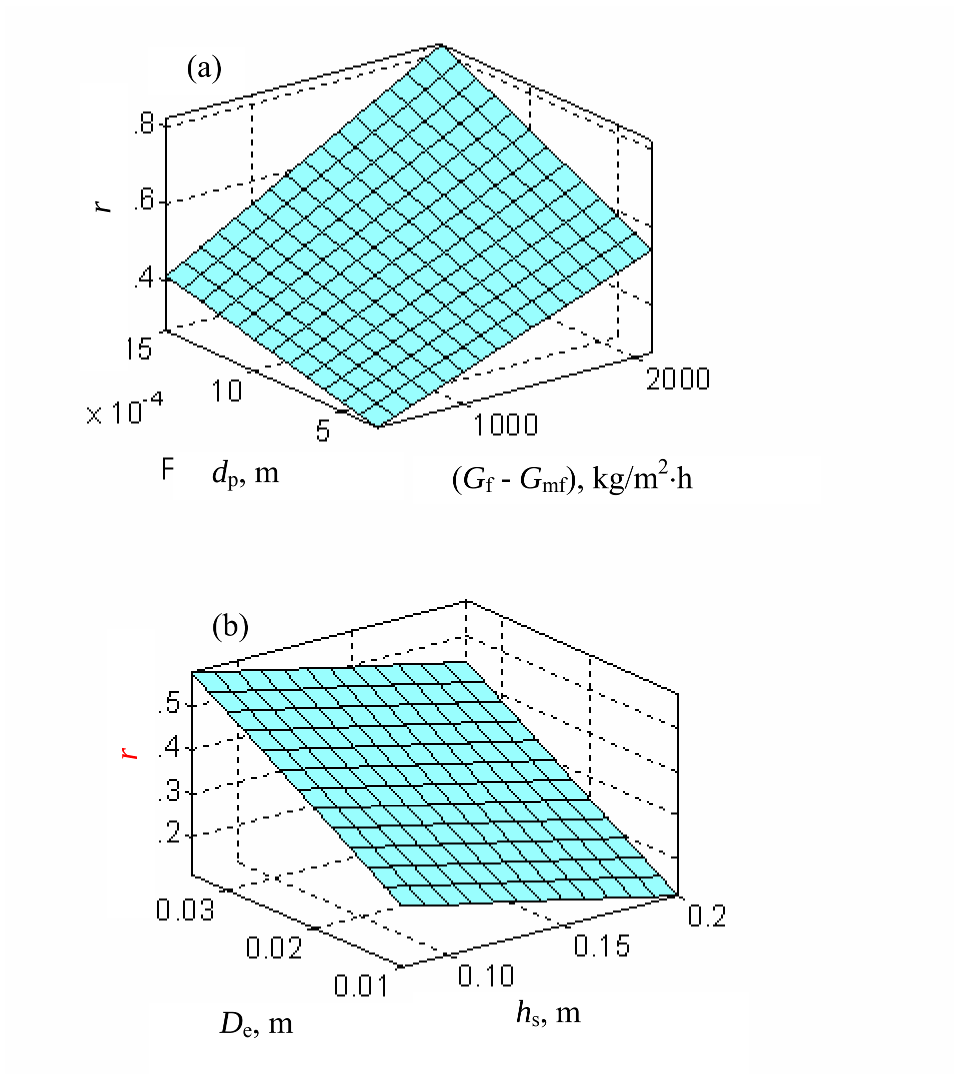

Fig. 4 Variation (response surface) of bed fluctuation ratio (a) with excess mass velocity and particle size at initial static height=0.12 m and equivalent bed diameter=0.0272 m; (b) with initial static height and equivalent bed diameter at size=0.000725 m and excess mass velocity=1000 kg/m^2·h.

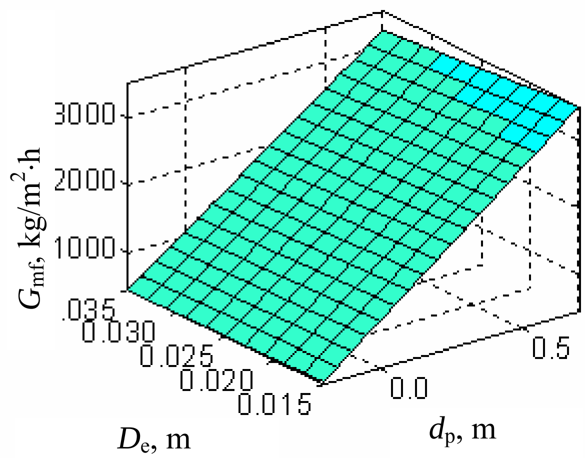

Fig. 5 Variation (response surface) of minimum fluidization mass velocity with particle size and equivalent bed diameter.

[Please check G_{mf} vs. D_e function in Fig. 5 and Eq.4]

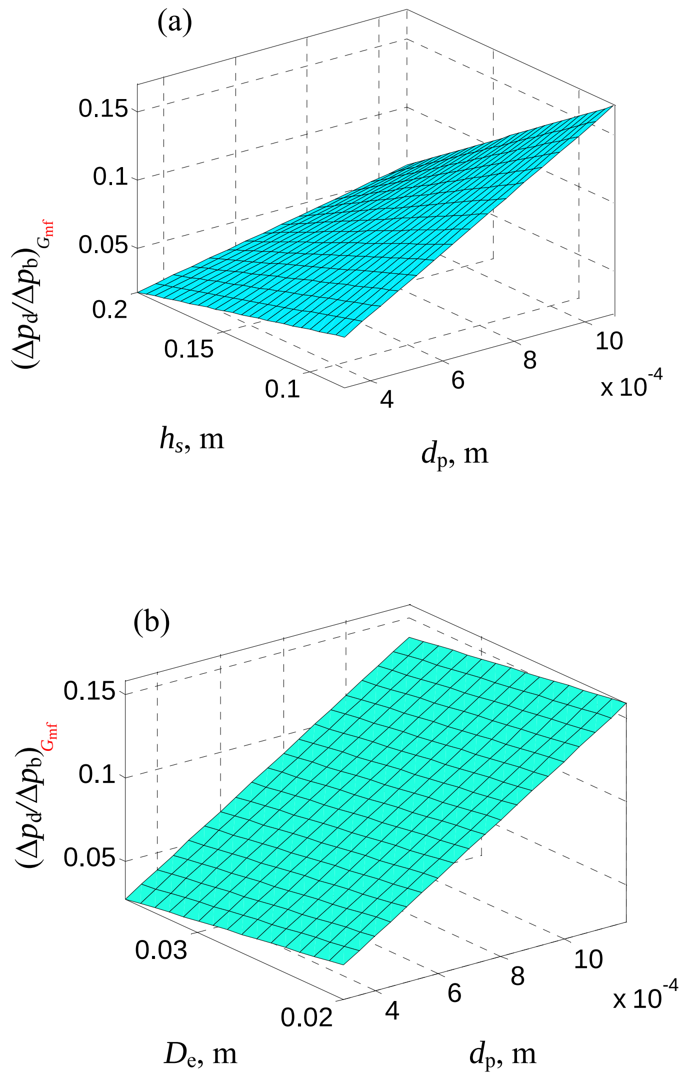

Fig. 6 Variation (response surface) of pressure drop ratio at the onset of fluidization with particle size and at initial static bed height=0.12 m. (a) bed-to-distributor; (b) distributor-to-bed.

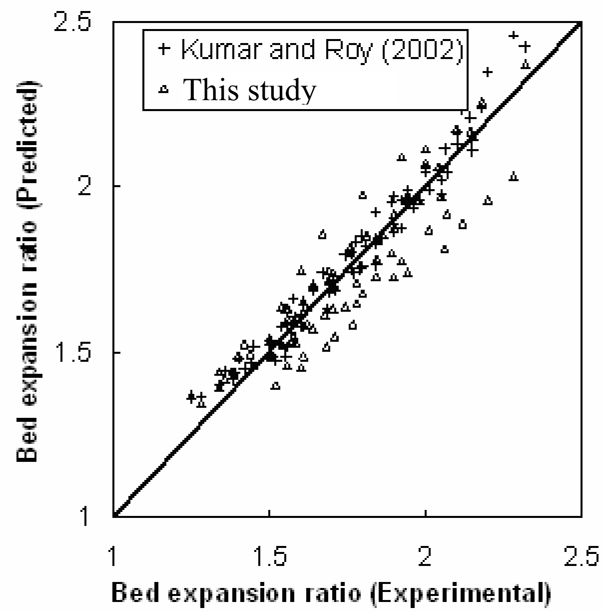

Fig. 7 Comparison between experimental and predicted values of bed expansion ratio using Eq. (2).

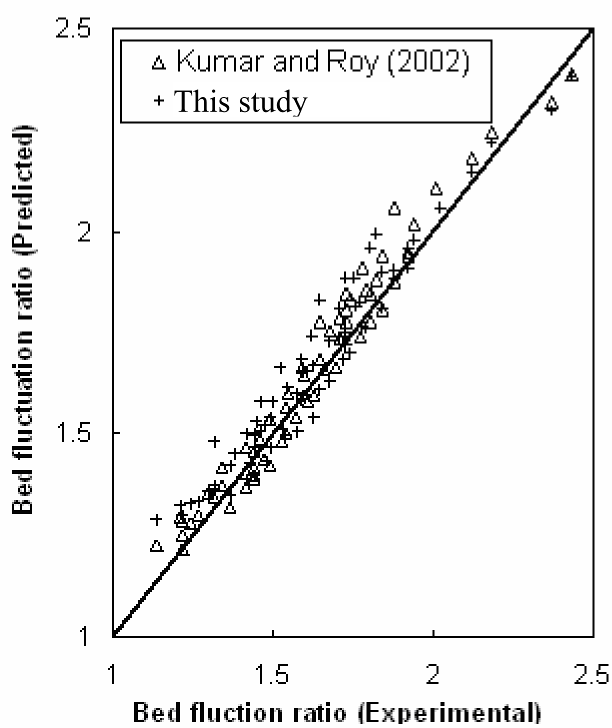

Fig. 8 Comparison between experimental and predicted values of bed fluctuateon ratio using Eq. (3).

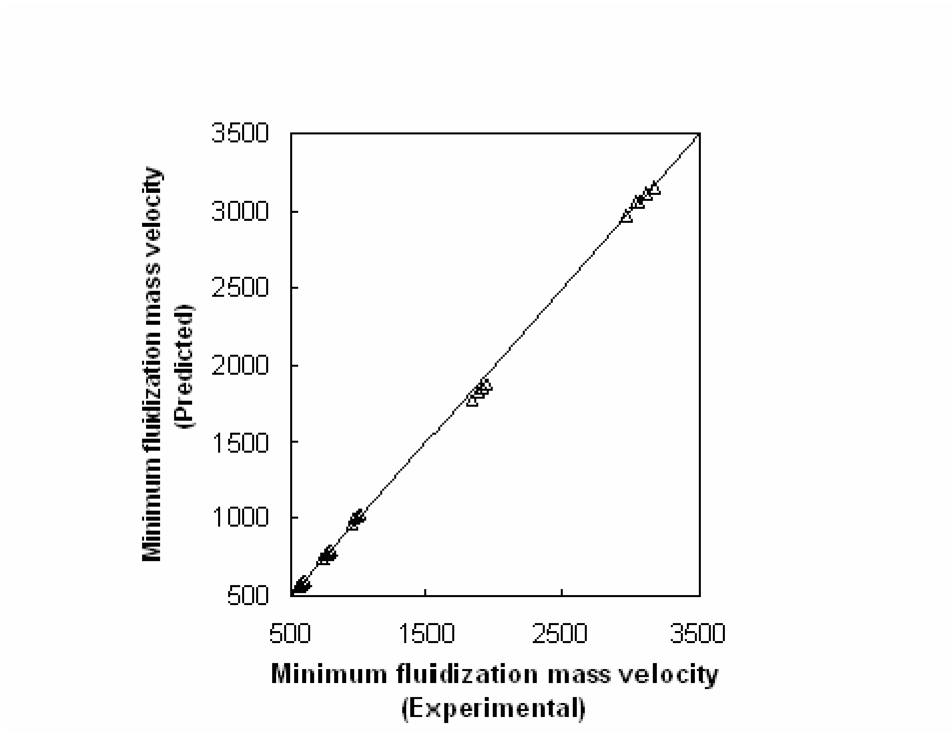

Fig. 9 Comparison between experimental and predicted values of bed expansion ratio using Eq. (4).

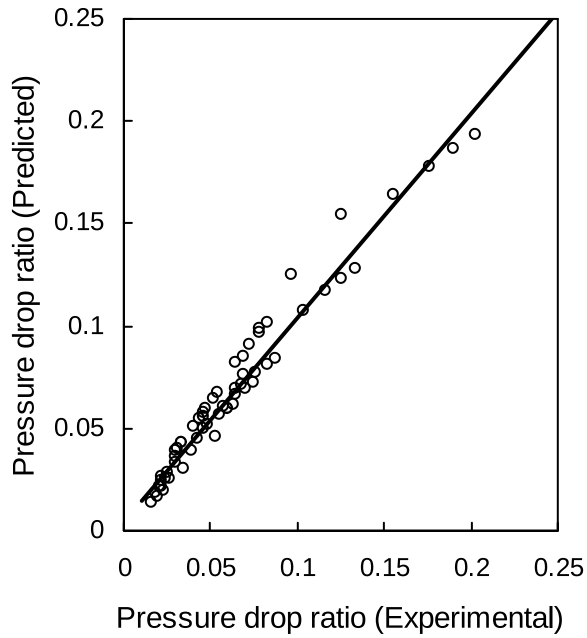

Figure 10: Comparison between experimental and predicted values of distributor-to-bed pressure drop ratio at the onset of minimum fluidization using equation (5)