Prediction of Bed Expansion in Unpromoted and Promoted Gas–Solid Fluidized Beds

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Correlations have been developed for the prediction of bed expansion ratio in the line of the Godard–Richardson equation (1969) for unpromoted as well as promoted beds. The correlation factor 'm' of the Godard–Richardson equation has been expressed as a function of promoter parameters for promoted beds in addition to bed parameters as in the case of unpromoted beds. Three correlations for 'm' have been proposed for unpromoted and promoted beds with rod and blade promoters. The comparison of the results reveals that the Godard–Richardson equation is more suitable for unpromoted beds in the original form. In the case of promoted beds, the prediction deviates from the corresponding experimental values due to poor representation of flow parameter. Hence, the flow parameter of the Godard–Richardson equation has also been modified for beds with rod and blade promoters. A comparison has been made between the predicted values of bed expansion using the modified Godard–Richardson equation and the predicted vlaues obtained by correlations developed by Kumar and Roy (2002a) and the corresponding experimental values.

Keywords blade promoter, expansion, gas–solid fluidization, Godard–Richardson equation, rod promoter, unpromoted

Introduction

A gas–solid fluidized bed is characterized by the formation of large-scale bubbles of varied sizes culminating in slugs. This results in nonuniform bed expansion and poor fluidization. Keeping in view these inherent drawbacks, a bed with a promoter (internal/baffle) can be employed in gas–solid fluidization to smoothen the bed expansion behavior and improve fluidization quality. A number of researchers have studied the effectiveness of promoters on various bed dynamics, such as bed expansion and fluctuation, minimum fluidization velocity, bubbling, and slugging in a gas-solid system. Most of the studies in the literature provide qualitative and visual observation on different fluidization aspects. Only a limited number of works present quantitative results. Krishnamurthy et al. (1981) studied slotted baffles and horizontal and vertical tube baffles in gas-solid beds for their effects on the

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quality of fluidization. Balakrishnan and Raja Rao (1975) used horizontal screen disk baffled fluidized beds on pressure drop and minimum fluidizing velocity. Williams (1972) concluded that baffles (promoters) within a fluidized bed lead to more frequent and smaller bubbles, of a more uniform size and distribution within the bed. Xavier et al. (1978) extended the above results to beds in which tube bundles occupy an appropriate fraction of the bed volume. Tubes or baffles (promoters) may either increase or decrease the bed expansion, depending on their effect on bubble size, coalescence pattern, and channeling. Singh (1997) and Singh and Roy (2000) studied the effect of bed and material properties on bed expansion and fluctuation ratios in the case of unpromoted columnar and non-columnar (semicylindrical, hexagonal and square) beds. Agarwal and Roy (1987) studied the bed fluctuation ratio in a gas-solid fluidized bed with a stirrer-type baffle (promoter). Kumar and Roy (2002b) investigated the effect of coaxial rod- and blade-type promoters on bed expansion ratio. They observed that coaxial rod- and blade-type promoters are quite effective in dampening bed fluctuation and thereby reducing the expanded bed height when compared with an unpromoted fluidized bed with identical system parameters. The ability of a pagoda-shaped internal to break up bubbles and enhance gas-solid contact has been demonstrated by Jin et al. (1980, 1982) using still and movie photographs. Dutta and Suciu (1992) studied the effectiveness of baffles/internals in breaking up bubbles. Kar and Roy (2000) reported the dynamics of a coaxial rod-promoted batch gas-solid fluidized bed.

The accurate prediction of bed expansion is of prime importance in the design of a fluidizer. The Godard–Richardson equation given below is considered to be one of the important empirical correlations for the prediction of bed expansion in unpromoted gas–solid fluidized beds:

$$\frac{h_F - h_o}{h_o} = R' = \frac{u - u_o}{m(0.35\sqrt{gD_c})} = \frac{1}{m} \times \frac{u - u_o}{(0.35\sqrt{gD_c})} \tag{1}$$

Since the introduction of a suitable promoter into a gas-solid system has been found to be advantageous in improving fluidization quality, the Godard-Richardson equation has been examined in the present case for promoted beds and suitably modified to calculate the expanded bed height. Experimentally, bed expansion has been found to be dependent on promoter parameter in the case of beds with a promoter in addition to other system variables considered for unpromoted beds. Sahoo and Roy (2005) presented the modified Godard-Richardson equation for a squared gas-solid promoted fluidized bed. In the present work, correlations for ‘m’ have been expressed in terms of system variables for unpromoted as well as promoted beds.

Experimental Setup and Data Collection

The experimental setup consists of an air compressor, constant pressure tank, rotameter, silica gel column, 50.8 mm i.d. Perspex column (fluidizer) with two pressure tappings, and a differential U-tube manometer containing carbon tetrachloride as the manometric liquid (see Figure 1). Compressed and dried air was used as the fluidizing medium. The calming section is followed by a GI plate one mm in thickness having 37 orifices placed in an equilateral triangular pattern at a pitch of 7.5 mm to act as an air distributor for the uniform entry of air to the fluidizer. A mild steel wire mesh is placed over the distributor to prevent the entry of materials

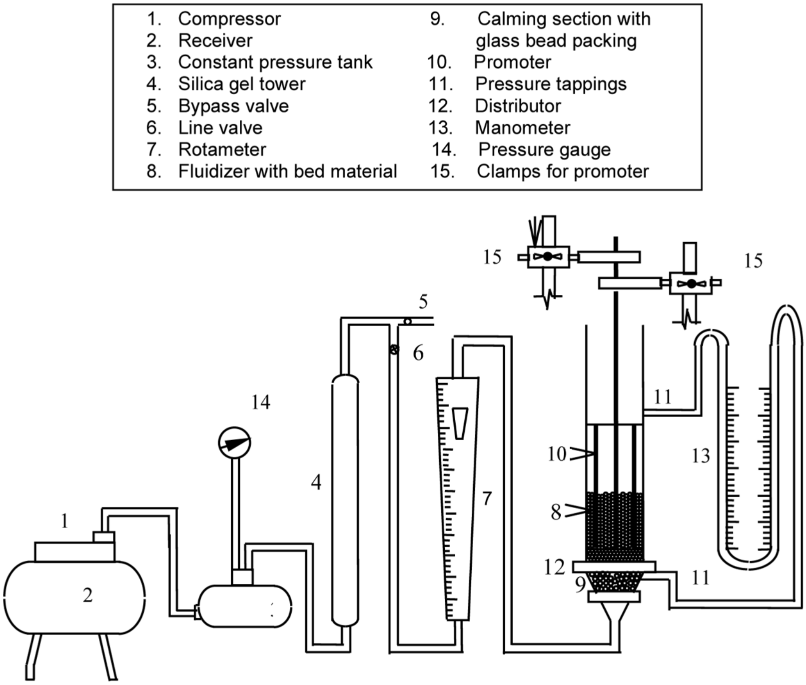

Figure 1. Experimental setup.

into the calming section. Two graduated graphs attached to the opposite faces of the fluidizer were used to measure the expanded bed heights.

The pressure drop and the bed expansion data for the bed were recorded as a function of the system variables, namely, flow rate, particle size and density, initial static bed height, and blockage volume of the rod promoter and one-blade promoter. The experimental plot of bed pressure drop versus incipient fluidizing velocity was used to obtain the value of minimum fluidization velocity in each case. The experimental data of bed expansion so collected were used to modify the expressions for the correlation factor ‘m’ of the Godard-Richardson equation (Godard & Richardson, 1969) in an unpromoted bed and ‘m’ and flow parameters for beds with rod- and blade-type promoters. The details of the rod and the blade promoters are presented in Figures 2 and 3 respectively. Each rod promoter has one central rod of 6.1 mm ϕ and varying numbers of radial rods of 4 mm ϕ. Figure 2 also details the number of radial rods in each promoter with their placement and configuration. The blades of the one-blade promoter were fixed to a 6.1 mm diameter central rod at equal spacing of 45.4 mm c/c and at an inclination of 10°, with the horizontal alternately in the opposite direction to minimize the accumulation of bed materials over the blades. The scope of the present investigation is given in Table 1.

Modification in Godard-Richardson Equation

The reciprocal of the correlation factor ‘m’ as it appears in the Godard-Richardson equation can be expressed as a function of the various dimensionless groups

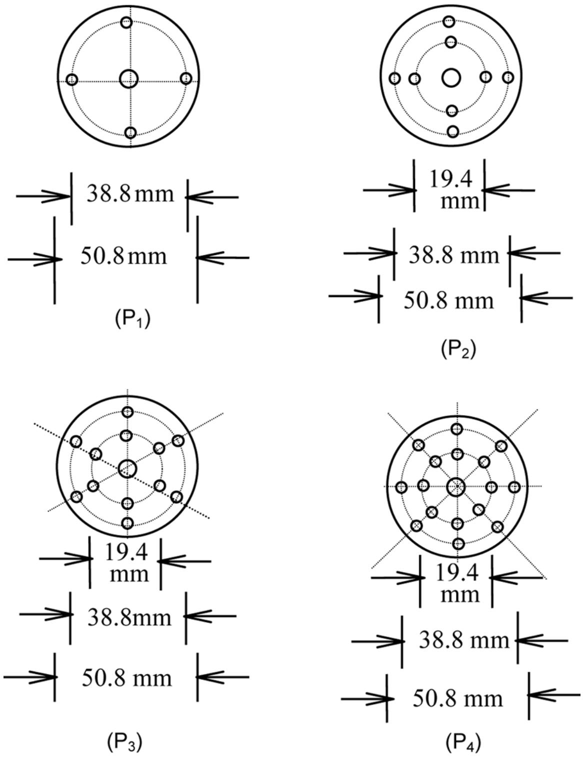

Figure 2. Configuration of rod promoters.

containing bed and promoter parameters and the properties of the fluidized particles and the medium as:

$$\frac{1}{\boldsymbol{m}} = \boldsymbol{f}\left(\frac{\rho_s}{\rho_f}, \frac{\boldsymbol{d}_p}{\boldsymbol{d}_o}, \frac{\boldsymbol{h}_s}{\boldsymbol{D}_c}, \frac{\boldsymbol{D}_e}{\boldsymbol{D}_c}\right) \tag{2}$$

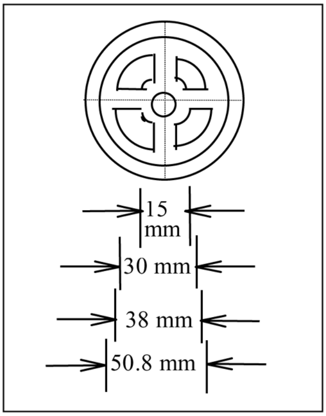

Figure 3. Configuration of blade promoter.

Table 1. Scope of the experiment

Materials	$D_p \times 10^3$, m	$\rho_s \times 10^{-3}$, kg/m^3		
	A. Properties of bed material			
Dolomite	1.125	2.817		
Dolomite	0.725	2.817		
Dolomite	0.463	2.817		
Dolomite	0.390	2.817		
Dolomite	0.328	2.817		
Alum	0.725	1.691		
Iron ore	0.725	3.895		
Manganese Ore	0.725	4.880		
	B. Bed parameter			
$h_S \times 10^2$, m	8	12	16	20
	C. Promoter details			
Promoter details	$D_k \times 10^3$, m	$t \times 10^3$, m	No. of 4 mm Φ longitudinal rods	
Rod: P_1	—	—	4	
P_2	—	—	8	
P_3	—	—	12	
P_4	—	—	16	
Blade: P_5	38.000	6.36	—	

or

$$\frac{1}{\boldsymbol{m}} = \boldsymbol{K}\left[\left(\frac{\rho_s}{\rho_f}\right)^a \times \left(\frac{\boldsymbol{d}_p}{\boldsymbol{d}_o}\right)^b \times \left(\frac{\boldsymbol{h}_s}{\boldsymbol{D}_c}\right)^c \times \left(\frac{\boldsymbol{D}_e}{\boldsymbol{D}_c}\right)^d\right] \tag{3}$$

The values of $\frac{1}{m}$ for the different beds with varying bed properties were obtained by the intercept of the log–log plot of R' versus $u - u_o/(0.35\sqrt{gD_c})$ for the respective beds. Analyzing the effect of the individual dimensionless parameter of Equation (3) for unpromoted and promoted beds, the final expressions for $\frac{1}{m}$ obtained are:

- For unpromoted bed:

$$\frac{1}{\boldsymbol{m}} = 0.074\left[\left(\frac{\rho_s}{\rho_f}\right)^{0.364}\left(\frac{\boldsymbol{d}_p}{\boldsymbol{d}_o}\right)^{0.118}\left(\frac{\boldsymbol{h}_s}{\boldsymbol{D}_c}\right)^{-0.402}\right] \tag{4}$$

- For bed with rod promoters:

$$\frac{1}{\boldsymbol{m}} = 0.1\left[\left(\frac{\rho_s}{\rho_f}\right)^{0.323}\left(\frac{\boldsymbol{d}_p}{\boldsymbol{d}_o}\right)^{0.110}\left(\frac{\boldsymbol{h}_s}{\boldsymbol{D}_c}\right)^{-0.441}\left(\frac{\boldsymbol{D}_e}{\boldsymbol{D}_c}\right)^{0.672}\right] \tag{5}$$

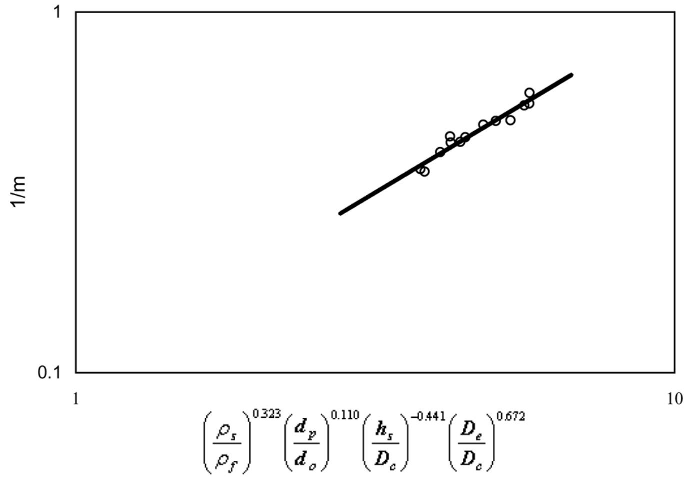

Figure 4. Variation of reciprocal of correlation factor (m) with system parameters for bed with rod promoter.

- For bed with blade-type promoter:

$$\frac{1}{m} = 0.115\left[\left(\frac{\rho_s}{\rho_f}\right)^{0.220}\left(\frac{d_p}{d_o}\right)^{0.139}\left(\frac{h_s}{D_c}\right)^{-0.421}\right] \quad (6)$$

A typical correlation plot for bed with rod promoter has been shown in Figure 4.

Substituting the expressions for $\frac{1}{m}$ in Equation (3), the modified forms of the Godard-Richardson equation for the different beds become:

- For unpromoted bed:

$$R' = 0.074\left[\left(\frac{\rho_s}{\rho_f}\right)^{0.364}\left(\frac{d_p}{d_o}\right)^{0.118}\left(\frac{h_s}{D_c}\right)^{-0.402}\right]\frac{u-u_o}{(0.35\sqrt{gD_c})} \quad (7)$$

- For bed with rod promoter:

$$R' = 0.1\left(\frac{\rho_s}{\rho_f}\right)^{0.323}\left(\frac{d_p}{d_o}\right)^{0.110}\left(\frac{h_s}{D_c}\right)^{-0.441}\left(\frac{D_e}{D_c}\right)^{0.672}\frac{u-u_o}{(0.35\sqrt{gD_c})} \quad (8)$$

- For bed with blade-type promoter:

$$R' = 0.115\left(\frac{\rho_s}{\rho_f}\right)^{0.220}\left(\frac{d_p}{d_o}\right)^{0.139}\left(\frac{h_s}{D_c}\right)^{-0.421}\frac{u-u_o}{(0.35\sqrt{gD_c})} \quad (9)$$

Figure 5 shows good agreement between the predicted values of bed expansion ratio using Equation (7) and the corresponding experimental values.

In the case of beds with rod and blade promoters Figures 6 and 7 indicate large deviations of predicted values using Equations (8) and (9) respectively from corresponding experimental values.

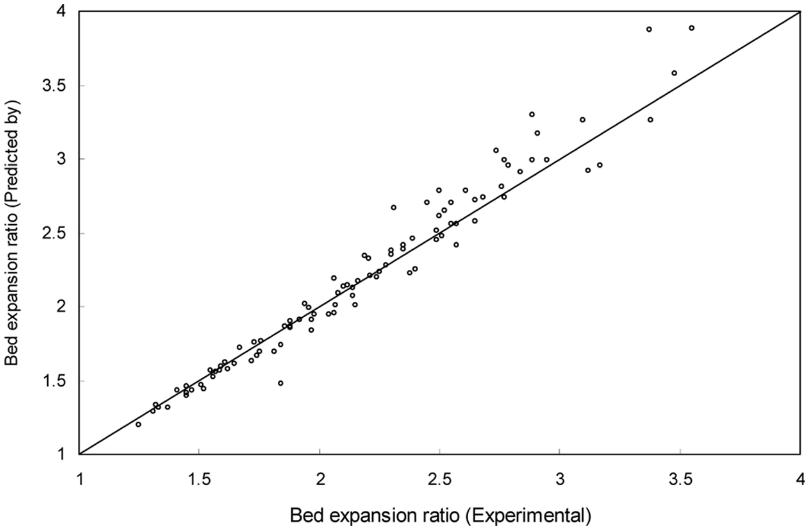

Figure 5. Comparison between experimental and predicted values of bed expansion ratio using modified Godard-Richardson equation (7) for unpromoted beds.

The mean and standard deviations (Table 2) indicate that the predictions obtained using Equations (8) and (9) are quite a bit larger than those obtained by other methods. It can also be observed (Figures 6 and 7) that the values of bed expansion ratio predicted by Equations (8) and (9) are less at lower flow rate $\boldsymbol{u} - \boldsymbol{u}_o/\left(0.35\sqrt{\boldsymbol{gD}_c}\right)$ and more at higher flow rate, than those of the corresponding experimental values. The deviation of the predicted values further increases with increase in flow parameter. This may be attributed to the improper representation

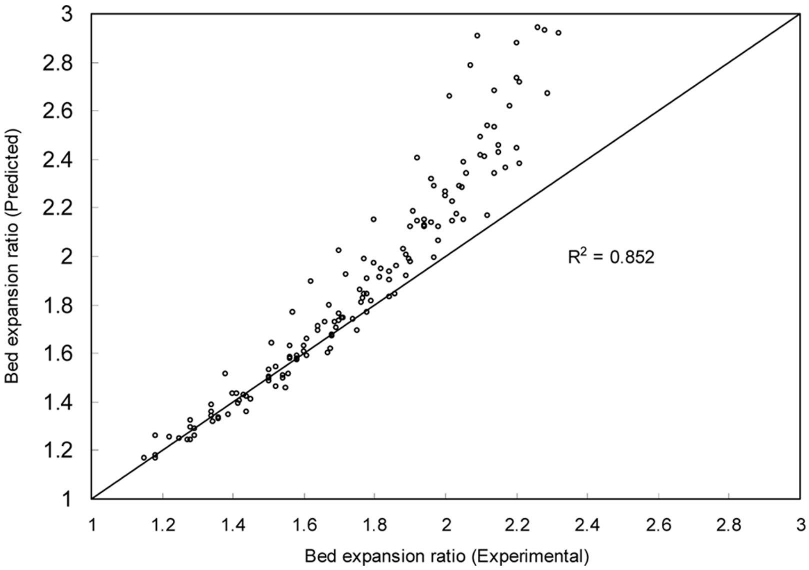

Figure 6. Comparison between experimental and predicted values of bed expansion ratio using Godard and Richardson equation (8) for bed with rod promoter.

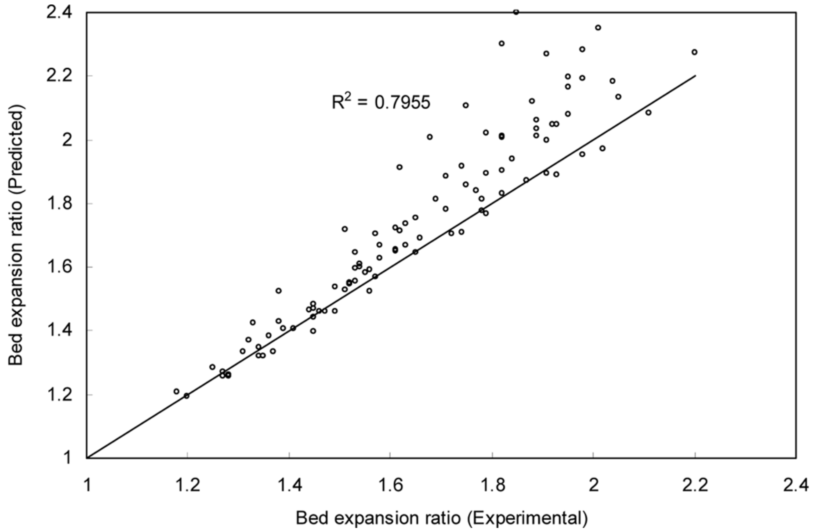

Figure 7. Comparison between experimental and predicted values of bed expansion ratio using Godard and Richardson equation (9) for bed with blade promoter.

of flow parameters for promoted beds. Hence, the flow parameters for the case of promoted beds are modified using Figure 8. The final expressions for the prediction of bed expansion ratio for promoted beds become:

- For bed with rod promoter:

$$\boldsymbol{R}' = 0.1\left(\frac{\rho_s}{\rho_f}\right)^{0.323}\left(\frac{\boldsymbol{d}_p}{\boldsymbol{d}_o}\right)^{0.110}\left(\frac{\boldsymbol{h}_s}{\boldsymbol{D}_c}\right)^{-0.441}\left(\frac{\boldsymbol{D}_e}{\boldsymbol{D}_c}\right)^{0.672}\left[\frac{\boldsymbol{u}-\boldsymbol{u}_o}{\left(0.35\sqrt{\boldsymbol{g}\boldsymbol{D}_c}\right)}\right]^{0.766} \quad (10)$$

- For bed with blade-type promoter:

$$\boldsymbol{R}' = 0.115\left(\frac{\rho_s}{\rho_f}\right)^{0.220}\left(\frac{\boldsymbol{d}_p}{\boldsymbol{d}_o}\right)^{0.139}\left(\frac{\boldsymbol{h}_s}{\boldsymbol{D}_c}\right)^{-0.421}\left[\frac{\boldsymbol{u}-\boldsymbol{u}_o}{\left(0.35\sqrt{\boldsymbol{g}\boldsymbol{D}_c}\right)}\right]^{0.724} \quad (11)$$

Table 2. Mean and standard deviations

Bed particulars	Unpromoted bed		Bed with rod promoter		Bed with blade-type promoter	
Statistical parameters	Kumar and Roy (2002a)	Equation (7)	Kumar and Roy (2002a)	Equation (10)	Kumar and Roy (2002a)	Equation (11)
Mean deviation	3.92	3.98	3.14	4.54	3.99	3.67
Standard deviation	4.82	5.52	3.44	5.07	4.82	4.56

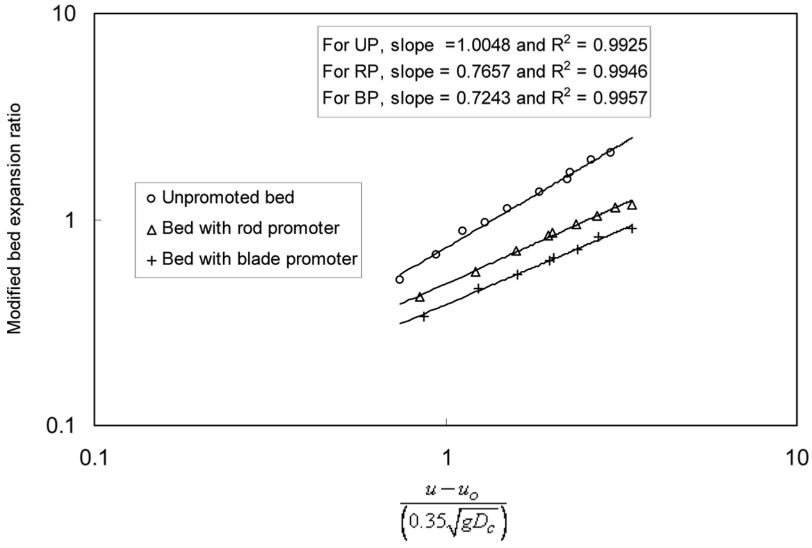

Figure 8. Variation of modified bed expansion ratio (R') with Godard and Richardson flow parameter for different beds.

Results and Discussion

The predicted values of bed expansion ratio using the modified form of the Godard-Richardson equations (7), (10), and (11) for the unpromoted bed and the beds with the rod- and the blade-type promoters respectively were compared with corresponding experimental values and those predicted by the equations given in Kumar and Roy (2002a). These comparisons are presented in Figures 9 to 11 for the unpromoted bed and the beds with the rod and the blade promoters respectively. From the comparison, it can be seen that the values of bed expansion ratio predicted using

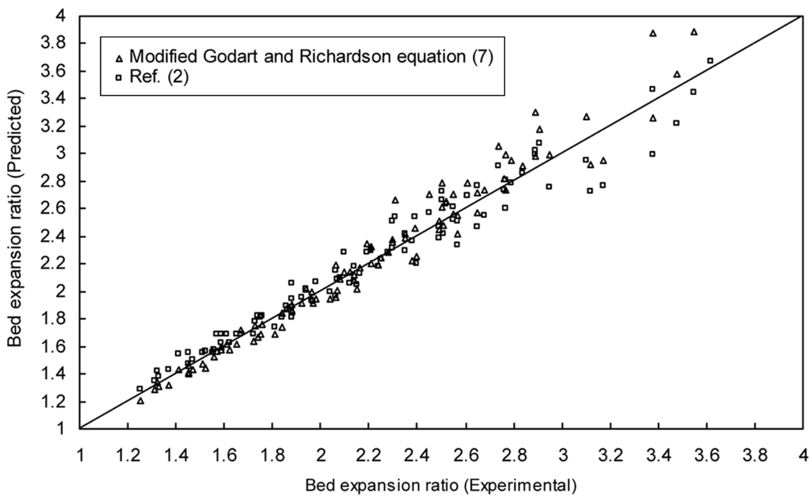

Figure 9. Comparison between experimental and predicted values of bed expansion ratio for unpromoted bed.

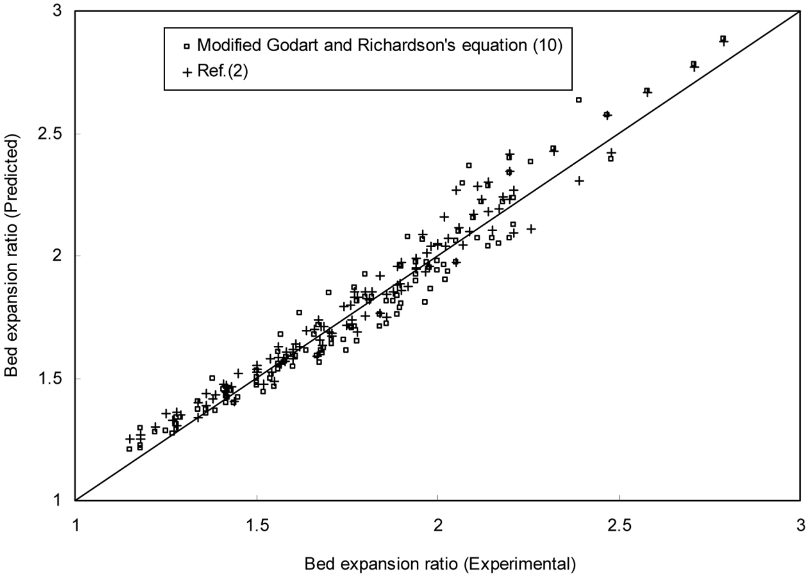

Figure 10. Comparison between experimental and predicted values of bed expansion ratio for bed with rod promoter.

the developed correlations (modified Godard-Richardson equations) for all the beds show fair agreement with the corresponding experimental values and those predicted by the correlations presented in Kumar and Roy (2002a). The effect of promoter over unpromoted bed is shown in Figure 8. The reduction in bed expansion ratio in beds with rod and blade promoters over the unpromoted bed can be attributed

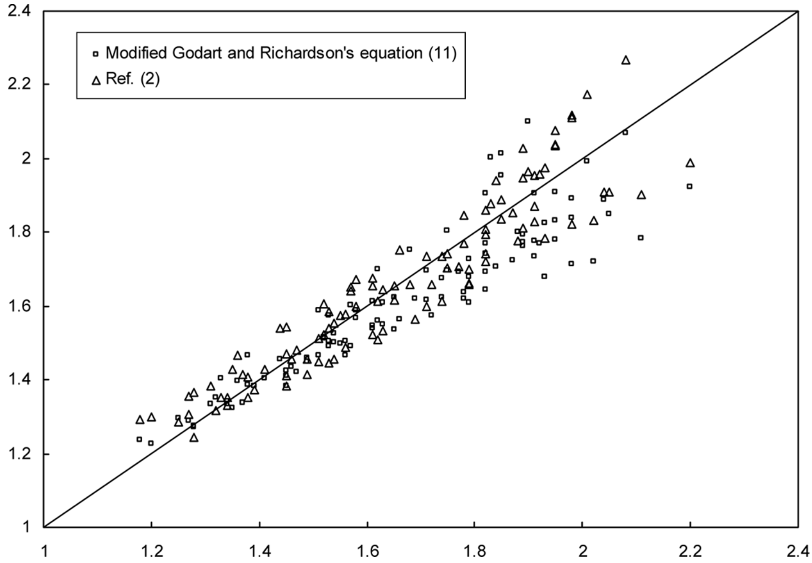

Figure 11. Comparison between experimental and predicted values of bed expansion ratio for bed with blade promoter.

to the effectiveness of the promoters in breaking up the bubbles and controlling their size and growth, leading to more frequent and smaller bubbles of uniform size distributed throughout the promoted beds. Further, the developed correlations for the bed with rod the promoter (Equation (10)) indicate that bed expansion decreases with decrease in equivalent diameter of the promoted bed (equivalent diameter of a promoted bed decreases with increase in blockage volume, which is due to increase in number of rods). The reduction in bed expansion ratio with increase in the number of rods in the case of the rod-promoted bed may be due to the increased effectiveness in breaking up bubbles and limiting their growth in the range of the present investigation. Figure 8 also indicates that the bed with blade promoter further reduces the expansion ratio under identical operating parameters. This can be attributed to the radial promoter elements, which facilitate smooth fluidization with negligible channeling and slugging compared to the unpromoted bed and the beds with rod-type promoter. With respect to the peripheral contact, the blade promoter exhibits larger contact with the fluidizing medium than that of the corresponding rod promoter of equal blockage. The larger peripheral contact further imposes resistance to the particle movements, thereby resulting in reduced bed expansion.

The mean and standard deviation of the predicted values from the corresponding experimental values and those obtained using the correlations given in Kumar and Roy (2002a) are presented in Table 2.

Conclusion

The modified form of Godard-Richardson equations (7), (10), and (11) can be used to satisfactorily calculate the expanded bed height in a gas-solid fluidization system for unpromoted and the promoted beds with rod- and blade-type promoters respectively. The bed expansion is dependent on the type of the promoters in addition to the other system parameters. A rod or a blade promoter in a gas-solid system reduces the bed expansion compared to conventional unpromoted beds. As the blockage volume of the rod promoter increases, the bed expansion has been found to decrease within the range of the present investigation. The blade promoter further improves the fluidization quality by breaking up the bubbles. This results in reduced bed expansion in bed with such a type of promoter over an unpromoted as well as a rod-promoted bed. For identical operating parameters, the bed expansion increases with increase in the flow parameter for both the unpromoted and the promoted beds. However, with constant flow parameter, the bed expansion ratio for a promoted bed is lower than that for the unpromoted ones.

Nomenclature

a, b, c, d	exponents
A_o	open area in promoted bed with rod promoter, L^2
D_c	column diameter, L
D_e	equivalent diameter of promoted bed, $4A_o/P$, L
d_o	orifice diameter, L
d_p	particle size, L
g	acceleration due to gravity, LT^{-2}
h_{av}, h_F	average bed height, $(h_{\max} + h_{\min})/2$, L
$h_{\max}$	maximum height of fluidized bed, L

$h_{\min}$	minimum height of fluidized bed, L
h_s, h_o	initial static bed height, L
K	constants
m	correlation factor in Equation (1)
P	total rod perimeter, L
R	bed expansion ratio, h_{av}/ h_s
R'	modified bed expansion ratio, $(R-1) = \frac{h_F - h_0}{h_0}$
u	superficial fluid velocity, LT^{-1}
u_o	superficial fluid velocity at minimum fluidization, LT^{-1}
ρ_f	density of fluid, ML^{-3}
ρ_s	density of solid, ML^{-3}

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