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Research Article

Hydrodynamic study of multi-phase semi-fluidization with activated alumina beads of 2-6 mm size

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Abstract: For application of semi-fluidized bed of activated alumina beads in different processes and operations, the hydrodynamic studies have been made using five different sizes of activated alumina beads (2-6 mm diameter) as bed materials in 0.05 m internal diameter cylindrical columns with water as the fluidizing medium in case of two-phase semi-fluidization (sf) and water (in continuous phase) with air (in bubbling phase) in case of three-phase semi-fluidization. Spherical sizes (-2.5+3.5, -3.5+4, -4+5, -5+6 and -6+8 British Standard Sieve BSS) have been used as the solid-phase. Experimental parameters studied for the above cases include superficial liquid velocity, particle diameter, initial static bed height, bed expansion ratio and in addition, superficial gas velocity (in case of gas-liquid-solid sf). Empirical and semi-empirical models have been developed with the help of dimensional and statistical analyses. The calculated values from the predicted models have been compared with the experimental ones and fairly good agreement has been obtained. The present hydrodynamics study along with the developed correlations can find potential application in physical and chemical processing where activated alumina is used as catalyst and/or desiccant.
Keywords: multi-phase semi-fluidization, activated alumina beads, hydrodynamics, dimensional analysis, statistical analysis.

INTRODUCTION

In 1959 pioneer researcher L S Fan and his team have started this concept which solves the major operational difficulties encountered in the fluidized and the packed bed. Semi-fluidized bed is a combination of fluidized and packed beds coexisting in a single column. Dynamics of fines deposition [1], simultaneous removal of cyanide and copper ions [2], formation of nitrogen oxides and deposits on the heating surfaces of boilers [3], treatment of palm oil mill effluent [4], drying of faba bean [5] and extractive fermentation of ethanol by immobilized yeast cells [6] are some of the applications of semi-fluidized bed which encourage the researchers for investigating more and more in the area of semi-fluidization. Good amounts of work have been reported on the hydrodynamics of two and three phase semi-fluidization with various types of bed materials [7-17].

Most of the fluids, including the liquids, can be dried by activated alumina. Liquids are generally dried in the up-flow mode to maximize distribution over the alumina bed. Activated alumina is used as catalyst and/or desiccant in most of cases. It is also used as an adsorbent for removal of oxygenates and mercaptans from the hydrocarbon feed streams, fluoride ions from water, etc [18-19]. It has superior mechanical strength and resistance to attrition than molecular sieves and silica gel, which are important considerations for its use in moving bed applications.

Practically no work has been reported on the hydrodynamics of two and three phase semi-fluidized beds using spherical activated alumina beads. In view of its potential application in chemical and allied process industries, the hydrodynamic studies with activated alumina beads have been made in liquid-solid and gas-liquid-solid semi-fluidized beds. The objective of the present work is to study the effect of superficial liquid mass velocity (G_{sfl}), particle diameter (d_p), initial static bed height (H_s), bed expansion ratio (R) and superficial gas mass velocity (G_{sfg}) (only in gas-liquid-solid sf) on the bed pressure drop and height of top packed bed formation, the two important parameters in the design of a semi-fluidized bed. Simultaneously, correlations have been developed for the prediction of the responses in a liquid-solid/gas-liquid-solid semi-fluidized bed using dimensional and statistical analyses. The experimental data have been compared with the values obtained from the developed correlations of the present study. The unique feature of the current study is the investigations carried out with spherical activated alumina beads of particle size ranging from 2 to 6mm.

MATERIALS AND METHODS

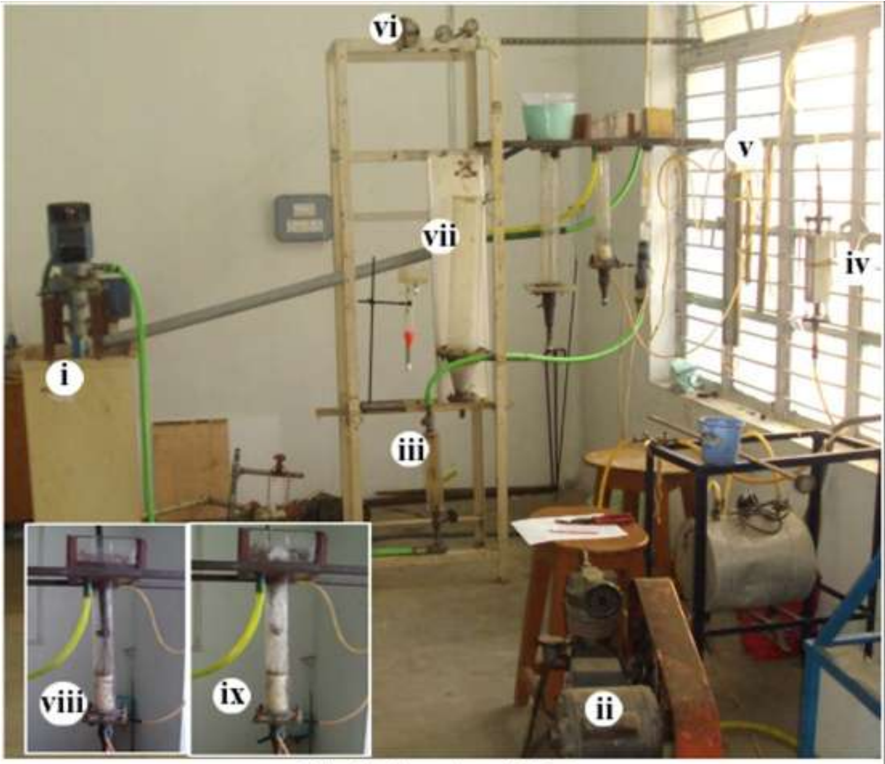

Fig. 1: Experimental Setup

(i) Liquid Pump (ii) Air Compresser (iii) Rotameter (water) (iv) Rotameter (air)
(v) U-Tube Manometer (vi) Top restraints (vii) Semi-Fluidized Columns
(viii) Liquid-Solid Semi-Fliuidized Bed (ix) Gas-Liquid-Solid Semi-Fluidized Bed

Table 1: Scope of the Experiment

System:	(i)	Liquid-solid
	(ii)	Gas-liquid-solid
Column diameter, m:		0.05
Bed materials:		Activated alumina beads
Properties of bed materials;		
(i)	Shape:	Spheres / Balls
(ii)	Sizes ($m \times 10^3$):	^{i}5.867, ^{ii}4.333, ^{iii}3.833, ^{iv}3.085, ^{v}2.425
(iii)	BSS	^{i}-2.5+3.5, ^{ii}-3.5+4, ^{iii}-4+5, ^{iv}-5+6, ^{v}-6+8
(iv)	Bulk density (Kg/m^3):	740-890

Schematic representation of the experimental setup is shown in Fig. 1. The scope of the experiment is presented in Table 1.

Accurately weighed amount of activated alumina beads was fed to the column, fluidized and de-fluidized slowly and adjusted for a specific reproducible initial static bed height.

For liquid-solid and gas-liquid-solid semi-fluidization, the experimental procedures have been detailed elsewhere [12, 17].

Table 2: Level of independent variables (Liquid-solid semi-fluidization)

Dimensional Analysis						
Variables	Symbols	Study values				
Aspect ratio	H_s/D_c	0.8,	1.2,	1.6,	2.0,	2.4
Wall effect	d_p/D_c	0.1173,	0.0866,	0.0766,	0.0617,	0.0485
Liquid mass velocity ratio	G_{lf}/G_{mf}	4.242,	4.848,	5.454,	6.060,	6.666
Bed expansion ratio	R	1.5,	2.0,	2.5,	3.0,	3.5

Statistical Analysis						
Variables	Symbols	$-\alpha$	-1	0	+1	$+\alpha$
Aspect ratio (H_s/D_c)	X_{1L}	0.8	1.2	1.6	2.0	2.4
Wall effect (d_p/D_c)	X_{2L}	0.049	0.062	0.074	0.09	0.1
Liquid mass velocity ratio (G_{lf}/G_{mf})	X_{3L}	4.242	4.848	5.454	6.06	6.666
Bed expansion ratio (R)	X_{4L}	1.5	2.0	2.5	3.0	3.5

In this work, mathematical and statistical models have been used to predict the dimensionless responses like semi-fluidized bed pressure drop ($\Delta P_{sf}/\Delta P_{mf}$) and the height of top packed bed (H_{pa}/H_s). The levels of independent variables are given in Table 2 (liquid-solid sf) and Table 3 (gas-liquid-solid sf). A statistical software package Design-Expert-8.0.7.1, Stat-Ease, Inc., Minneapolis, USA, has been used for regression analysis of the semi-fluidized bed responses for the statistical analysis.

Table 3: Level of independent variables (Gas-liquid-solid semi-fluidization)

Dimensional Analysis						
Variables	Symbols	Study values				
Aspect ratio	H_s/D_c	0.8,	1.2,	1.6,	2.0,	2.4
Wall effect	d_p/D_c	0.1173,	0.0866,	0.0766,	0.0617,	0.0485
Liquid mass velocity ratio	G_{slf}/G_{mf}	2.424,	3.03,	3.636,	4.242,	4.848
Gas mass velocity ratio	G_{sfg}/G_{mf}	2.424,	3.03,	3.636,	4.242,	4.848
Bed expansion ratio	R	1.5,	2.0,	2.5,	3.0,	3.5

Statistical Analysis						
Variables	Symbols	$-\alpha$	-1	0	+1	$+\alpha$
Aspect ratio (H_s/D_c)	X_{1GL}	0.8	1.26	1.6	1.94	2.4
Wall effect (d_p/D_c)	X_{2GL}	0.04	0.06	0.07	0.09	0.1
Liquid mass velocity ratio (G_{slf}/G_{mf})	X_{3GL}	2.42	3.13	3.64	4.15	4.85
Gas mass velocity ratio (G_{sfg}/G_{mf})	X_{4GL}	2.42	3.13	3.64	4.15	4.85
Bed expansion ratio (R)	X_{5GL}	1.5	2.08	2.5	2.92	3.5

RESULTS AND DISCUSSIONS

While in dimensional analysis, the effect of individual parameter is reflected on the bed responses, statistical analysis predicts the effect of individual as well as combined effects. The value of bed pressure drop helps to determine the capacity of pump and/or compressor for a specific operation. On the other hand, the height of top packed bed formation decides the process efficiency through an optimal distribution of the bed materials between the two sections of the semi-fluidized bed viz. the packed and the fluidized ones.

Liquid-solid semi-fluidization

Hydrodynamic parameters for the liquid-solid semi-fluidization using activated alumina beads viz. the bed pressure drop and the height of top packed bed formation have been found to be depend on superficial liquid velocity, particle size and system parameters viz. the initial static bed height and the bed expansion ratio. The detailed results and the correlations developed are presented below.

Semi-fluidized bed Pressure drop (ΔP_{sf})

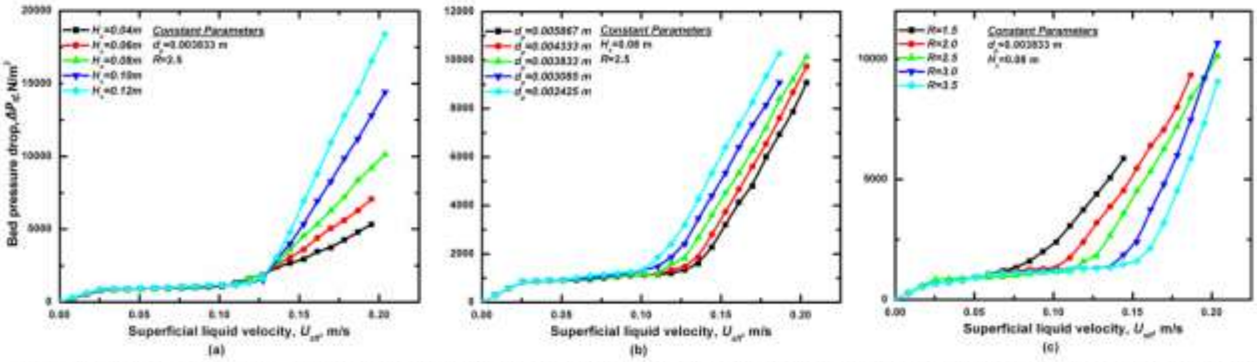

Fig. 2: Variation of bed pressure drop with respect to superficial liquid velocity for different values of (a) initial static bed height, (b) particle size and (c) bed expansion ratio

Fig. 2 shows the variation of bed pressure drop with superficial liquid velocity for different values of initial static bed height, particle diameter and bed expansion ratio. The behavior of semi-fluidized bed is almost identical to all the parameters as has been already discussed in an earlier paper [12].

The developed equations for bed pressure drop in dimensionless form by the above two analyses are as below;

By dimensional analysis,

$$\Delta P_{sf}/\Delta P_{mf}=2.5\times10^{-3}(H_s/D_c)^{0.632}(d_p/D_c)^{-1.07}(G_{sf}/G_{mf})^{4.021}R^{-1.69} \qquad (1)$$

By statistical analysis,

$$\Delta P_{sf}/\Delta P_{mf}=10.60+1.94\times X_{1L}-2.26\times X_{2L}+5.25\times X_{3L}-4.42\times X_{4L}-0.37\times X_{1L}\times X_{2L}+0.86\times X_{1L}\times X_{3L}-0.66\times X_{1L}\times X_{4L}-0.97\times X_{2L}\times X_{3L}+0.77\times X_{2L}\times X_{4L}-1.78\times X_{3L}\times X_{4L}-0.11\times X_{1L}^2+0.36\times X_{2L}^2+0.77\times X_{3L}^2+1.22\times X_{4L}^2 \qquad (2)$$

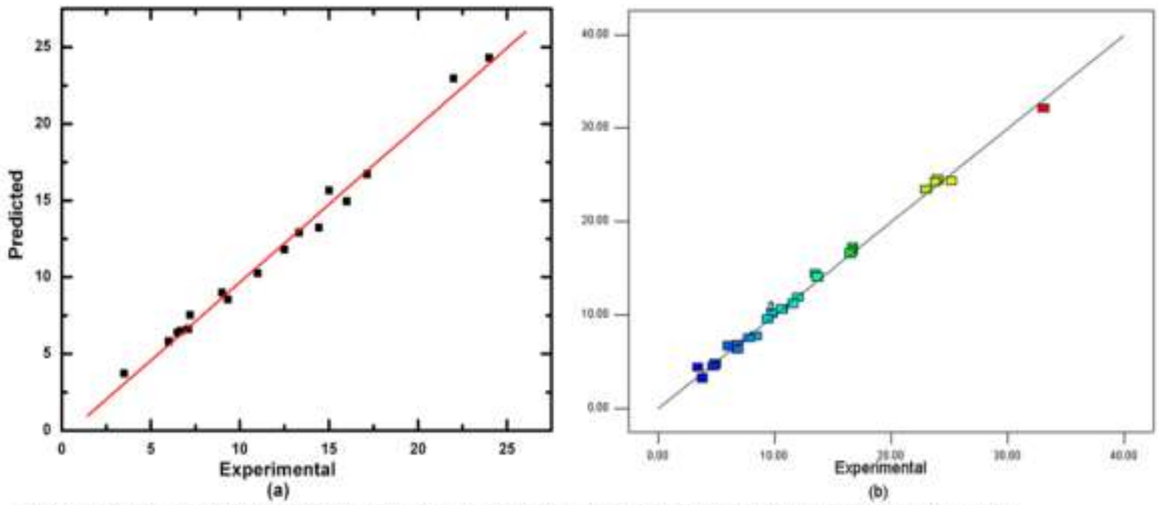

Fig. 3: Comparison between the experimental and the predicted values of dimensionless bed pressure drop by (a) dimensional analysis and (b) statistical analysis

Fig. 3 shows the comparison between the experimental and the predicted values (Eq. (1) and (2)) of $\Delta P_{sf}/\Delta P_{mf}$. The standard deviations and coefficients of correlation are 0.5855, 0.9945 for Eq. (1) and 0.68, 0.9954 for Eq. (2) respectively.

Height of the top packed bed formation (H_{pa})

Fig. 4 shows the variation of the height of top packed bed formation with superficial liquid velocity for different values of initial static bed height, particle diameter and bed expansion ratio. The behavior of semi-fluidized bed is similar to all the parameters as has been already discussed in earlier paper [12].

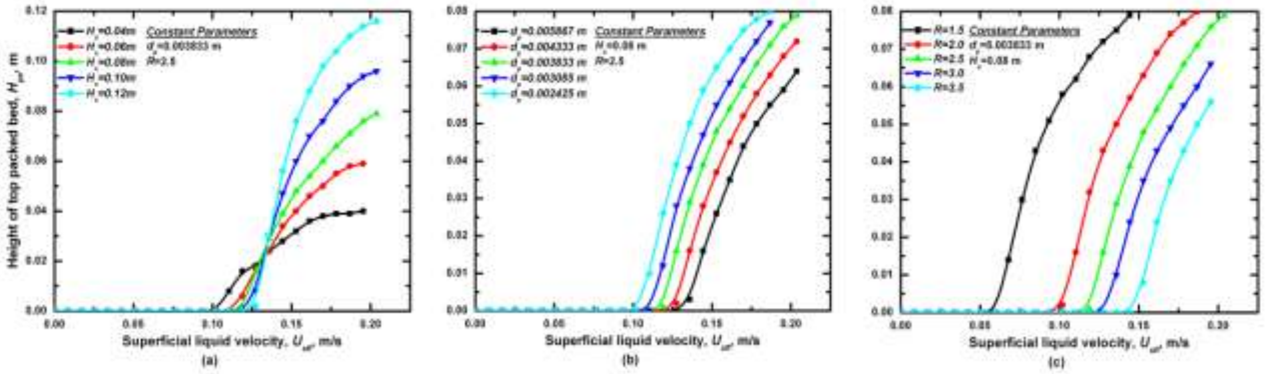

Fig. 4: Variation of height of top packed formation with respect to superficial liquid velocity for different values of (a) initial static bed height, (b) particle size and (c) bed expansion ratio

The developed equations for the top packed bed height formation in dimensionless form by dimensional and statistical analyses method are as under,

By dimensional analysis,

$$H_{pa}/H_s=2.05\times10^{-3}\,(H_s/D_c)^{-0.363}\,(d_p/D_c)^{-0.808}(G_{sf}/G_{mf})^{2.792}R^{-1.06} \quad \text{------(3)}$$

By statistical analysis,

$$H_{pa}/H_s=0.61-0.055\times X_{1L}-0.075\times X_{2L}+0.18\times X_{3L}-0.12\times X_{4L}-4.375\times10^{-3}\times X_{1L}\times X_{2L}-3.125\times10^{-3}\times X_{1L}\times X_{3L}-1.875\times10^{-3}\times X_{1L}\times X_{4L}-1.875\times10^{-3}\times X_{2L}\times X_{3L}-5.625\times10^{-3}\times X_{2L}\times X_{4L}-0.014\times X_{3L}\times X_{4L}+0.010\times X_{1L}^2+0.012\times X_{2L}^2+7.813\times10^{-3}\times X_{3L}^2+0.024\times X_{4L}^2 \quad \text{-----(Quadratic) ------(4a)}$$

$$H_{pa}/H_s=0.65-0.055\times X_{1L}-0.075\times X_{2L}+0.18\times X_{3L}-0.12\times X_{4L} \quad \text{...... (Linear) ------(4b)}$$

Fig. 5 shows the comparison between the experimental and the predicted values (Eq. (3), (4a) and (4b)) of H_{pa}/H_s. The standard deviations and coefficients of correlation are 0.029 and 0.9892, 0.043and 0.9801 and 0.045 and 0.9631 for Eqns. (3), (4a) and (4b) respectively.

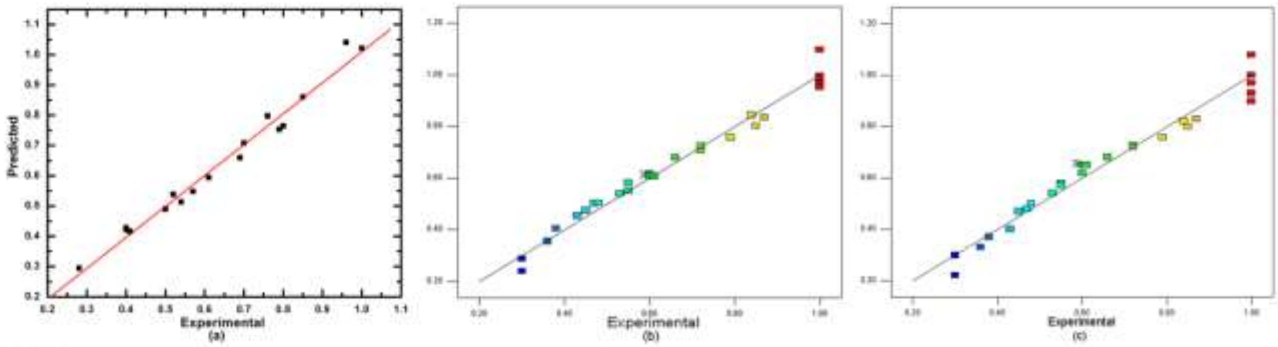

Fig. 5: Comparison between the experimental and the predicted values of dimensionless height of top packed bed formation by (a) dimensional analysis, (b) statistical analysis (Quadratic) and (c) statistical analysis (Linear)

Gas-Liquid-solid semi-fluidization

The hydrodynamic study of gas-liquid-solid semi-fluidization with activated alumina beads shows the similar trend as liquid-solid semi-fluidization when experimental investigations are conducted with identical system and operating parameters. Superficial mass velocity of gas has a prominent role next to that of the superficial liquid mass velocity.

Semi-fluidized bed Pressure drop (ΔP_{sf})

Fig. 6 shows the variation of bed pressure drop with superficial liquid mass velocity for different values of initial static bed height, particle diameter, bed expansion ratio and superficial gas mass velocity. The behavior of semi-fluidized bed is similar to all the parameters as has been already discussed in an earlier paper [17].

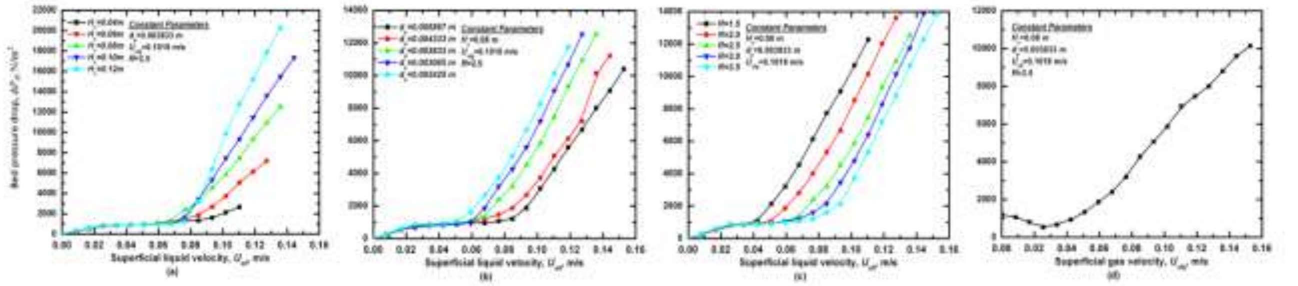

Fig. 6: Variation of bed pressure drop with respect to [superficial liquid velocity for different values of (a) initial static bed height, (b) particle size, (c) bed expansion ratio], (d) superficial gas velocity

The developed equations for bed pressure drop in dimensionless form by above two analyses are,

By dimensional analysis,

$$\Delta P_{sf}/\Delta P_{mf}=0.195\times(H_s/D_c)^{1.096}(d_p/D_c)^{0.745}(G_{sfl}/G_{mf})^{3.234}(G_{sfg}/G_{mf})^{1.899}R^{-1.182} \quad (5)$$

By statistical analysis,

$$\Delta P_{sf}/\Delta P_{mf}=12.00+3.02\times X_{1GL}+1.65\times X_{2GL}+5.77\times X_{3GL}+3.45\times X_{4GL}-2.75\times X_{5GL}+0.39\times X_{1GL}\times X_{2GL}+1.33\times X_{1GL}\times X_{3GL}+0.82\times X_{1GL}\times X_{4GL}-0.62\times X_{1GL}\times X_{5GL}+0.73\times X_{2GL}\times X_{3GL}+0.45\times X_{2GL}\times X_{4GL}-0.34\times X_{2GL}\times X_{5GL}+1.52\times X_{3GL}\times X_{4GL}-1.15\times X_{3GL}\times X_{5GL}-0.70\times X_{4GL}\times X_{5GL}+0.026\times X_{1GL}^2-0.037\times X_{2GL}^2+0.85\times X_{3GL}^2+0.20\times X_{4GL}^2+0.53\times X_{5GL}^2 \quad (6)$$

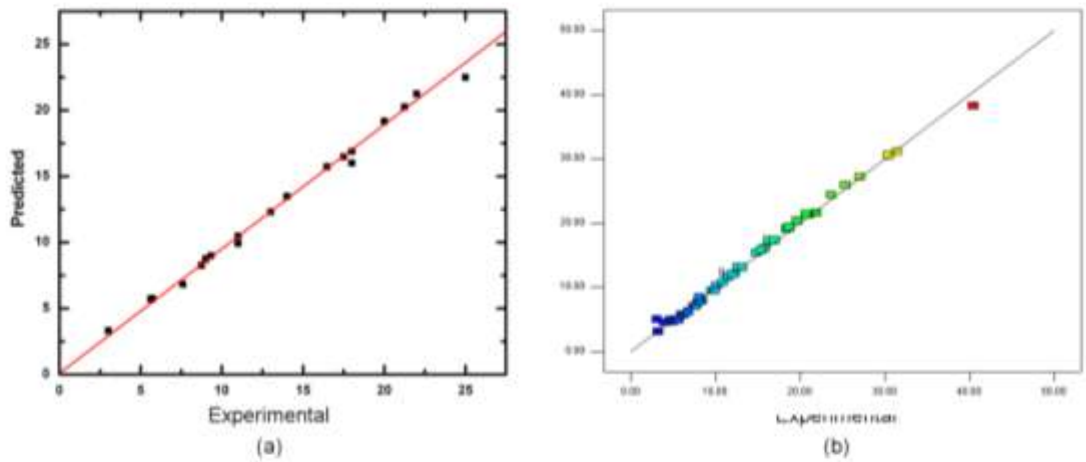

Fig. 7: Comparison between the experimental and the predicted values of dimensionless bed pressure drop by (a) dimensional analysis and (b) statistical analysis

Fig. 7 shows the comparison between the experimental and the predicted values (Eq. (5) and (6)) of $\Delta P_{sf}/\Delta P_{mf}$. The standard deviations and coefficients of correlation are 0.5855 and 0.9945 and 0.76 and 0.9947 for Eqns. (5) and (6) respectively.

Height of the top packed bed formation (H_{pa})

Fig. 8 shows the variation of the top packed bed formation with superficial liquid velocity for different values of initial static bed height, particle diameter and bed expansion ratio. Also in this figure, the variation of the height of top packed bed formation with superficial gas mass velocity has been presented. The behavior of a semi-fluidized bed is almost similar with respect to the above parameters as has already been discussed in earlier paper [12].

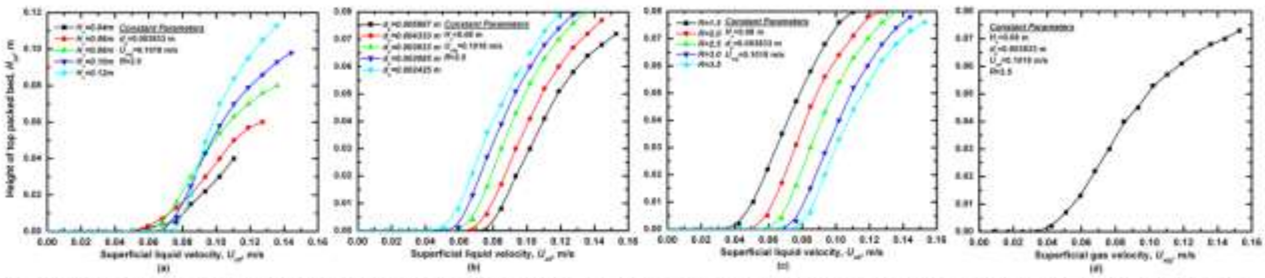

Fig. 8: Variation of height of top packed bed formation for different parameter with respect to [superficial liquid velocity (a) initial static bed height, (b) particle size, (c) bed expansion ratio], (d) superficial gas velocity

The developed equations for the formation of top packed bed height in dimensionless form by dimensional and statistical analyses method are:

By dimensional analysis,

$$H_{pa}/H_s=0.0014\times(H_s/D_c)^{-0.242}(d_p/D_c)^{-0.967}(G_{sfl}/G_{mf})^{2.047}(G_{sfg}/G_{mf})^{1.547}R^{-0.967} \quad \text{------}(7)$$

By statistical analysis,

$$H_{pa}/H_s=0.66-0.038\times X_{1GL}-0.12\times X_{2GL}+0.20\times X_{3GL}+0.15\times X_{4GL}-0.12\times X_{5GL}+6.054\times10^{-3}\times X_{1GL}\times X_{2GL}-0.010\times X_{1GL}\times X_{3GL}-8.006\times10^{-3}\times X_{1GL}\times X_{4GL}+6.064\times10^{-3}\times X_{1GL}\times X_{5GL}-0.033\times X_{2GL}\times X_{3GL}-0.025\times X_{2GL}\times X_{4GL}+0.019\times X_{2GL}\times X_{5GL}+0.044\times X_{3GL}\times X_{4GL}-0.033\times X_{3GL}\times X_{5GL}-0.025\times X_{4GL}\times X_{5GL}+4.706\times10^{-3}\times X_{1GL}^2+0.020\times X_{2GL}^2+0.013\times X_{3GL}^2+5.024\times10^{-3}\times X_{4GL}^2+0.021\times X_{5GL}^2 \quad \text{------}(8)$$

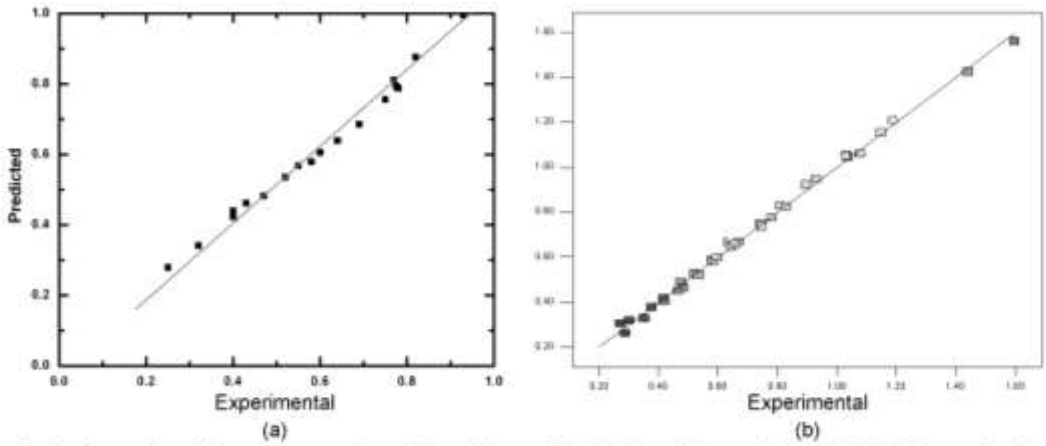

Fig. 9: Comparison between the experimental and the predicted values of dimensionless height of top packed bed formation by (a) dimensional analysis and (b) statistical analysis

Fig. 9 shows the comparison between the experimental and the predicted values of H_{pa}/H_s obtained by Eq. (7) and (8). The standard deviations and coefficients of correlation are 0.032 and 0.9899 and 0.018 and 0.9977 for Eqns. (7) and (8) respectively.

CONCLUSION

Investigations have been carried out to study the behavior of spherical activated alumina beads in liquid-solid as well as gas-liquid-solid semi-fluidized beds with a view to quantifying the important hydrodynamic parameters viz. the bed pressure drop and the top packed bed formation through developed correlations for both non-aerobic (two-phase) and aerobic (three-phase) bed conditions. The values calculated from the developed correlations have been compared with the experimental ones with fairly good agreement, thus emphasizing the validity of the developed correlations over the range of the operating parameters investigated.

The present hydrodynamics study along with the developed correlations can be of significant use in the design of semi-fluidized bed systems for physical and chemical processing, where activated alumina is used as catalyst and/or desiccant.

Acknowledgement

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Nomenclature

BSS British Standard Sieve
D, d Diameter, *m*
G Mass velocity, $Kg/m^2\ s$
H Height, *m*
P Pressure, N/m^2
R Bed expansion ratio, (ratio of the height of the top restraint to initial static bed height)
U Velocity, *m/s*

Greek letters

Δ Difference

Subscripts

c column
f fluid
g gas
l liquid
mf minimum fluidization
p particle
pa top packed bed
s static
sf semi-fluidization

REFERENCES

1. Dehkissia S, Baçaoui A, Iliuta I, Larachi F; Dynamics of Fines Deposition in an Alternating Semi-fluidized Bed, A. I.Ch. E. Journal, 2008;54: 2120-2131.
2. Kim SJ, Hwang KR, Cho SY, Moon H; Simultaneous Removal of Cyanide and copper Ions in a Semi-Fluidized Ion Exchanger Bed. Korean Journal of Chemical Engineering, 1999; 16: 664-669.
3. Is'emin RL, Zaitseva NA, Osipov AD, Akol'zin AP; Formation of nitrogen oxides and deposits on the heating surfaces of boilers with semi-fluidized bed furnaces fired with low grade coal. Promyshlennaya Energetika, 1995; 2: 37-38.
4. *Alade AO, Jameel AT, Muyibi SA, Karim MIA, Alam Z;* Application of semi- fluidized bed bioreactor as novel bioreactor system for the treatment of palm oil mill effluent (POME). African Journal of Biotechnology. 2013; 10(81):18642-18648.
5. Chayjan RA, Shadidi B; Modeling high-moisture faba bean drying in fixed and semi-fluidized bed conditions. Journal of Food Processing and Preservation, 2014; 38(1):200-211.
6. Dias SMM; Extractive fermentation of ethanol by immobilized yeast cells. NTIS. Report, Dept. Engg., Tech. Univ. Lisbon, Lisbon, 199; 218.
7. Murthy JSN, Roy GK; Semi-fluidization: a Review, Indian Chemical Engineer, 1986; Vol. XXIX, No.2: 9-22.
8. Kurian J, RajaRao M; Hydrodynamics of semi-fluidized bed, Indian Journal of Technology, 1970; 8: 275-284.
9. Dash J, Roy GK; Liquid-Solid Semi-fluidization of Homogeneous Mixture—I, Prediction of Onset Semi-fluidization Velocity'. Indian Chemical Journal, February, 1977; p 1.
10. Roy GK, Sarma KJR; Relation between maximum semi-fluidization and minimum fluidization velocity in liquid-solid systems JI. of the Inst, of Engrs., (India), 1974; 54: 34
11. Mydlarz Jerzy; Prediction of the packed bed height in liquid-solid semi-fluidization of homogeneous mixtures. The Chemical Engineering Journal, 1987; 34: 155 – 158
12. Samal DK**,** Mohanty YK, Roy GK; Hydrodynamics of liquid-solid semi-fluidized bed with irregular homogenous ternary mixture. Powder Technology, 2013; 235: 921-930
13. Jena HM**,** Roy GK, Meikap BC; Hydrodynamics of regular particles in a liquid-solid semi-fluidized bed. Powder Technology, 2009; 196: 246-256
14. Biswal KC, Sahoo SN, Verma P, Murthy JSN, Roy GK; Dynamics of Gas-Solid Semi-Fluidization of Binary Homogeneous and Heterogeneous Mixtures. Chemical Engineering Journal, 1990;70 : 61-64.
15. Chern SH, Muroyama K, Fan LS; Hydrodynamics of constrained inverse fludization and semi-fluidization in a gas-liquid-solid system. Chem. Eng. Sci., 1983; 38 : 1167.
16. Chern SH, Fan LS, Muroyama K; Hydrodynamic of concurrent gas-*liquid-solid* semi-fluidization with a Liquid as the continuous Phase. *A. I. Ch. E.* Journal, *1984;* 30(2): 288-294.
17. Samal DK**,** Mohanty YK, Roy GK; Prediction of bed pressure drop and top packed bed formation in gas-liquid-solid semi-fluidized bed with irregular homogenous binary mixtures. Korean J. of Chemical Engineering, 2013; 30(6): 1326-1334.
18. Buekens A, Zyaykina NN; Adsorbents and Adsorption Processes for Pollution Control, Pollution Control Technologies- Vol. II, 2003.
19. Ghorai S, Pant KK; Investigations on the column performance of fluoride adsorption by activated alumina in a fixed-bed. Chemical Engineering Journal, 2004; 98:165-173.