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Hydrodynamic study of multi-phase semi-fluidization with binary mixtures of activated alumina beads

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Abstract: Semi-fluidization (sf) bed characteristics with activated alumina beads (AAB) are having importance when used as catalytic two and three phase processes and operations. The hydrodynamic studies have been made using binary mixtures of activated alumina beads (-3.5+4 and -4+5 BSS) as bed materials in 0.05 m internal diameter cylindrical columns with water as the fluidizing medium (two-phase semi-fluidization) and water in continuous phase with air in bubbling phase(three-phase semi-fluidization). Experimental parameters studied for the above cases include initial static bed height, average particle diameter, superficial liquid velocity, bed expansion ratio and in addition, superficial gas velocity (in case of three phase 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 results have also been compared with those available in the literature for single size AAB and regular binary homogenous mixtures.

Keywords: hydrodynamics, multi-phase semi-fluidization, binary mixtures, activated alumina beads, dimensional analysis, statistical analysis.

1. INTRODUCTION

Semi-fluidization process started in 1959 by L S Fan. This process which solves the major operational difficulties encountered in the fluidized and the packed bed like back mixing, attrition and segregation of solid particles and erosion of confining vessel and non-uniformity of temperature etc. Semi-fluidization is a combination of fluidization and packed bed operation simultaneously operating in a confined space. Different types of solids have been used for different process of semi-fluidization. Operations involving catalytic activities are main concern for semi-fluidization. Filtration, extraction, adsorption, catalytic reactions etc are the possible processes can be performed by using semi-fluidization technique. Multi-phase activities are also favorable in this technique.

Treatment of palm oil mill effluent[1], dynamics of fines deposition[2], simultaneous removal of cyanide and copper ions[3], formation of nitrogen oxides and deposits on the heating surfaces of boilers[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[7-19].

Activated alumina is used as catalyst and/or desiccant in chemical and biochemical operations. It is also used as an adsorbent for removal of oxygenates and mercaptans from the hydrocarbon feed streams, fluoride ions from water, etc[20-21]. 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 binary mixtures of spherical activated alumina beads. In view of its potential application in chemical and allied process industries, the hydrodynamic studies with binary mixtures of 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 results have also been compared with those available in the literature for single size AAB[18].

2. EXPERIMENTAL

Schematic representation of the experimental setup is shown[18] in Fig. 1.The scope of the experiment is presented[18] 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]. 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 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 ($m\times10^3$):	^{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		

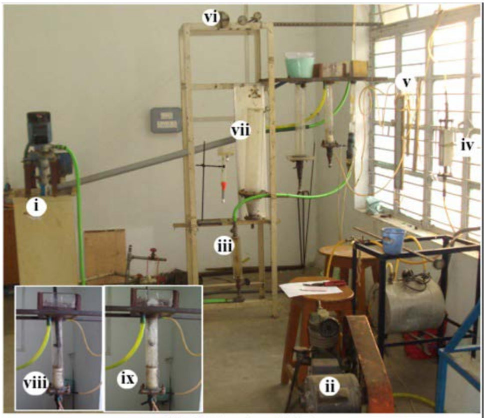

Fig. 1: Experimental Setup
(i) Liquid Pump (ii) Air Compresser (iii) Rotameter (water) (iv) Rotameter (air)
(v) U-Tube Manometer (vi) Top restraints (vii) Semi-Fluidized Columns
(viii) Liquid-Solid Semi-Fliuidized Bed (ix) Gas-Liquid-Solid Semi-Fluidized Bed

Table 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_{pav}/D_c	0.08136	0.08038	0.07943	0.0785	0.07758
Liquid mass velocity ratio	G_{sf}/G_{mf}	3.15	3.68	4.21	4.73	5.26
Bed expansion ratio	R	1.5	2.0	2.5	3.0	3.5

Statistical Analysis						
Variables	Symbols	- α	-1	0	+1	+α
Aspect ratio (H_s/D_c)	X_{1L}	0.8	1.2	1.6	2.0	2.4
Wall effect (d_{pav}/D_c)	X_{2L}	0.07758	0.0785	0.07943	0.08038	0.08136
Liquid mass velocity ratio (G_{sf}/G_{mf})	X_{3L}	3.15	3.68	4.21	4.73	5.26
Bed expansion ratio (R)	X_{4L}	1.5	2.0	2.5	3.0	3.5

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_{pav}/D_c	0.08136	0.08038	0.07943	0.0785	0.07758
Liquid mass velocity ratio	G_{sfl}/G_{mfl}	1.666	2.222	2.777	3.333	3.888
Gas mass velocity ratio	G_{sfg}/G_{mfg}	1.111	2.222	3.333	4.444	5.555
Bed expansion ratio	R	1.5	2.0	2.5	3.0	3.5

Statistical Analysis						
Variables	Symbols	- α	-1	0	+1	+α
Aspect ratio (H_s/D_c)	X_{1GL}	0.8	1.26	1.6	1.936	2.4
Wall effect (d_{pav}/D_c)	X_{2GL}	0.07758	0.0786	0.07947	0.08026	0.08136
Liquid mass velocity ratio (G_{sfl}/G_{mfl})	X_{3GL}	1.666	2.309	2.77	3.244	3.888
Gas mass velocity ratio (G_{sfg}/G_{mfg})	X_{4GL}	1.11	2.398	3.333	4.267	5.555
Bed expansion ratio (R)	X_{5GL}	1.5	2.079	2.5	2.92	3.5

3. RESULTS AND DISCUSSIONS

The effect of individual parameters on the bed responses are predicted by dimensional analysis and the effect of individual as well as combined effects are predicted by statistical analysis. The solid material (binary mixture of spherical AAB) has shown the similar trend on bed responses as single size AAB [18]. The developed equations by two approaches are;

3.1 Liquid-solid semi-fluidization

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

By dimensional analysis,

$$\Delta P_{sf}/\Delta P_{mf}=7.2\times10^{-15}(H_s/D_c)^{0.594}(d_{pav}/D_c)^{-12.96}(G_{sf}/G_{mf})^{1.944}R^{-2.043} \quad (1)$$

By statistical analysis,

$$\Delta P_{sf}/\Delta P_{mf}=4.28+0.71\times X_{1L}-0.73\times X_{2L}+1.14\times X_{3L}-2.13\times X_{4L}-0.11\times X_{1L}\times X_{2L}+0.18\times X_{1L}\times X_{3L}-0.29\times X_{1L}\times X_{4L}-0.18\times X_{2L}\times X_{3L}+0.3\times X_{2L}\times X_{4L}-0.47\times X_{3L}\times X_{4L}-0.057\times X_{1L}^{2}+0.033\times X_{2L}^{2}+0.039\times X_{3L}^{2}+0.7\times X_{4L}^{2} \quad (2)$$

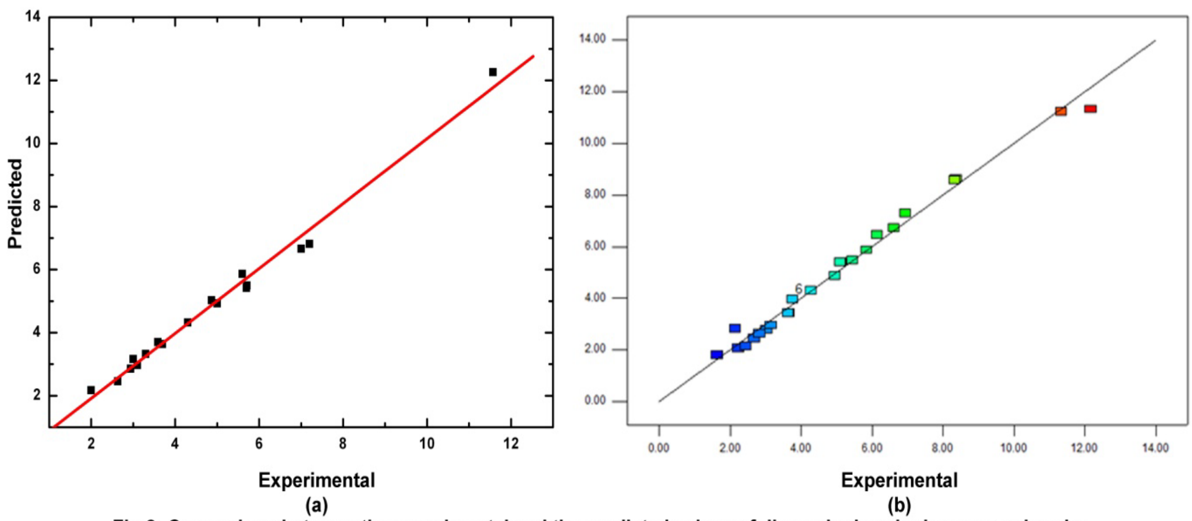

Fig.2: Comparison between the experimental and the predicted values of dimensionless bed pressure drop by (a) dimensional analysis and (b) statistical analysis

Fig. 2 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 0.2385, 0.9944 for Eq. (1) and 0.38, 0.9884 for Eq. (2) respectively.

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

By dimensional analysis,

$$H_{pa}/H_s=1.1\times10^{-9}(H_s/D_c)^{-0269}(d_{pav}/D_c)^{-6.5}(G_{sf}/G_{mf})^{3.697}R^{-2.412} \quad (3)$$

By statistical analysis,

$$H_{pa}/H_s=0.30-0.026\times X_{1L}-0.028\times X_{2L}+0.16\times X_{3L}-0.19\times X_{4L}+2.813\times10^{-3}\times X_{1L}\times X_{2L}-0.012\times X_{1L}\times X_{3L}+0.011\times X_{1L}\times X_{4L}-0.013\times X_{2L}\times X_{3L}+0.015\times X_{2L}\times X_{4L}-0.078\times X_{3L}\times X_{4L}+3.344\times10^{-3}\times X_{1L}^{2}-4.063\times10^{-4}\times X_{2L}^{2}+0.023\times X_{3L}^{2}+0.064\times X_{4L}^{2} \quad (4)$$

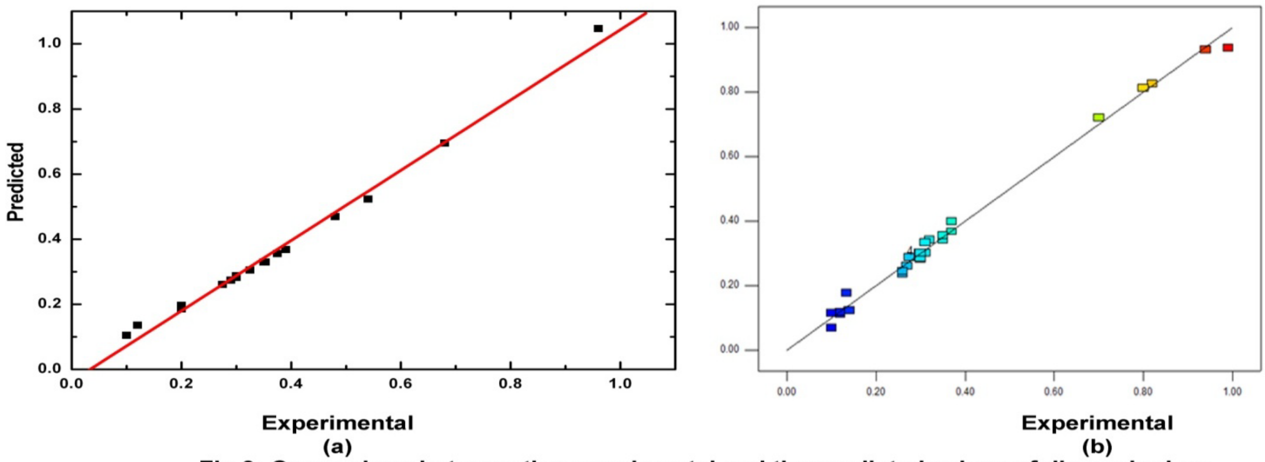

Fig.3: Comparison between the experimental and the predicted values of dimensionless top packed bed height by (a) dimensional analysis and (b) statistical analysis

Fig. 3 shows the comparison between the experimental and the predicted values (Eq. (3), (4)) of H_{pa}/H_s. The standard deviations and coefficients of correlation are 0.0201 and 0.9956, and 0.027 and 0.9938 for Eqns. (3) and (4) respectively.

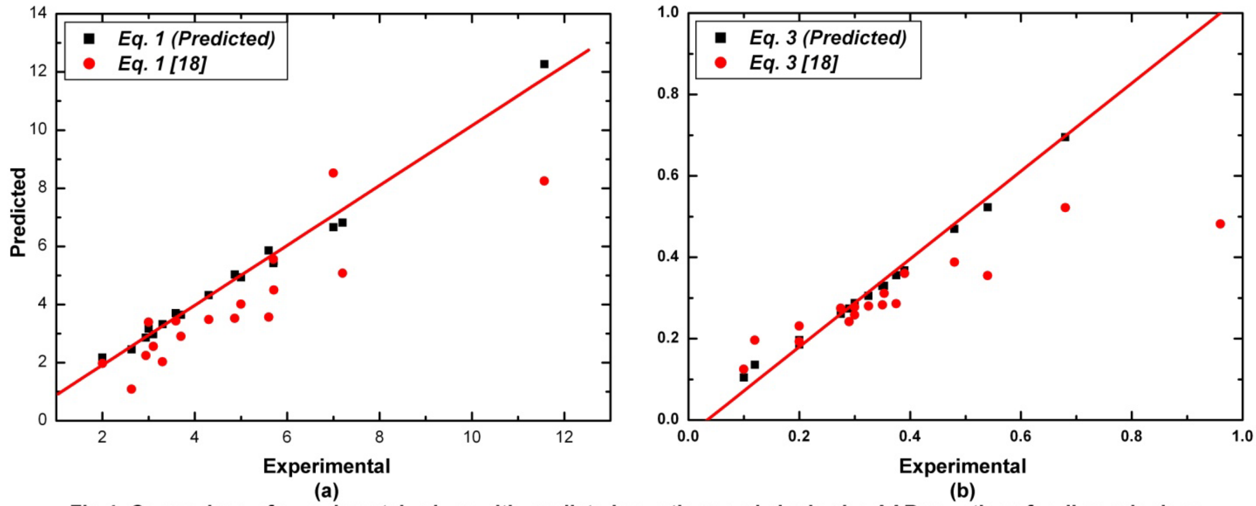

Fig.4: Comparison of experimental values with predicted equations and single size AAB equations for dimensionless (a) Bed pressure drop and (b) Height of top packed bed

The experimental data of binary mixture of AAB have been taken for comparison with the developed equations and existing single size AAB equations[18] in fig 4. It is clearly observe that developed equations are more suitable for predicting the two phase bed responses.

3.2. Gas-Liquid-solid semi-fluidization

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

By dimensional analysis,

$$\Delta P_{sf}/\Delta P_{mf}=8.2\times10^{-16}(H_s/D_c)^{0.562}(d_{pav}/D_c)^{-13.6}(G_{sfl}/G_{mf})^{1.963}(G_{sfg}/G_{mf})^{1.004}R^{-1.76} \quad (5)$$

By statistical analysis,

$\Delta P_{sf}/\Delta P_{mf}=4.79+0.62\times X_{1GL}-0.70\times X_{2GL}+1.67\times X_{3GL}+1.45\times X_{4GL}-1.64\times X_{5GL}-0.086\times X_{1GL}\times X_{2GL}+0.20\times X_{1GL}\times X_{3GL}+0.18\times X_{1GL}\times X_{4GL}-0.18\times X_{1GL}\times X_{5GL}-0.23\times X_{2GL}\times X_{3GL}-0.20\times X_{2GL}\times X_{4GL}+0.21\times X_{2GL}\times X_{5GL}+0.48\times$

$X_{3GL}\times X_{4GL}$-$0.49\times X_{3GL}\times X_{5GL}$-$0.43\times X_{4GL}\times X_{5GL}$-$0.037\times X_{1GL}^{2}+0.04\times X_{2GL}^{2}+0.12\times X_{3GL}^{2}$-$7.649\times 10^{-3}\times X_{4GL}^{2}+0.42\times X_{5GL}^{2}$ (6)

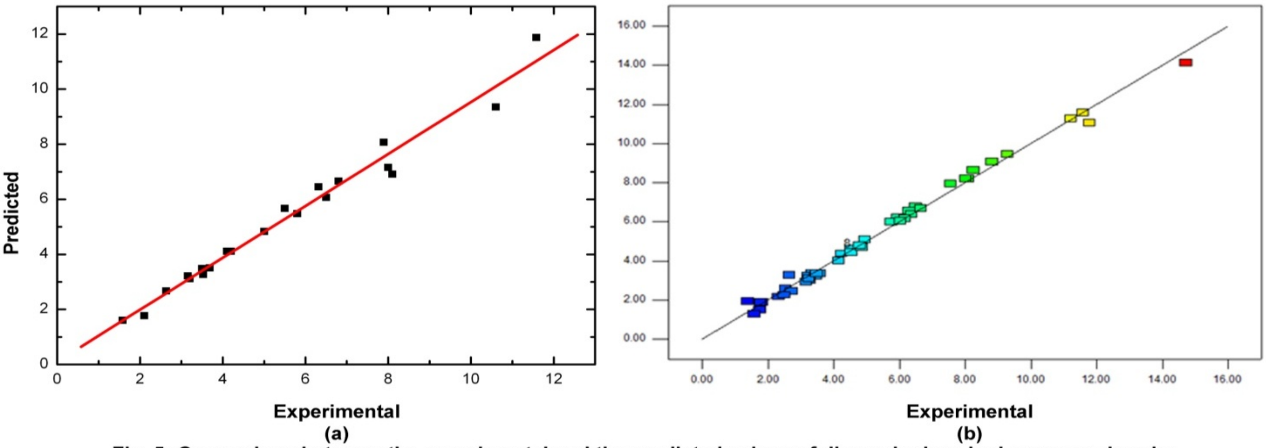

Fig. 5: Comparison between the experimental and the predicted values of dimensionless bed pressure drop by (a) dimensional analysis and (b) statistical analysis

Fig. 5 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 0.3622 and 0.9886and 0.32 and 0.9927for Eqns. (5) and (6) respectively.

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

By dimensional analysis,

$$H_{pa}/H_s=2.5\times 10^{-14}(H_s/D_c)^{0.756}(d_{pav}/D_c)^{-10.66}(G_{sfl}/G_{mf})^{3.441}(G_{sfg}/G_{mf})^{1.195}R^{-2.15} \quad (7)$$

By statistical analysis,

$$H_{pa}/H_s=0.37+0.053\times X_{1GL}-0.035\times X_{2GL}+0.21\times X_{3GL}+0.12\times X_{4GL}-0.14\times X_{5GL}-3.823\times 10^{-3}\times X_{1GL}\times X_{2GL}+0.015\times X_{1GL}\times X_{3GL}+5.11\times 10^{-4}\times X_{1GL}\times X_{4GL}-1.883\times 10^{-3}\times X_{1GL}\times X_{5GL}-0.01\times X_{2GL}\times X_{3GL}-7.979\times 10^{-4}\times X_{2GL}\times X_{4GL}+1.709\times 10^{-3}\times X_{2GL}\times X_{5GL}+0.045\times X_{3GL}\times X_{4GL}-0.05\times X_{3GL}\times X_{5GL}-0.018\times X_{4GL}\times X_{5GL}-3.367\times 10^{-3}\times X_{1GL}^{2}+5.899\times 10^{-4}\times X_{2GL}^{2}+0.026\times X_{3GL}^{2}+1.889\times 10^{-3}\times X_{4GL}^{2}+0.037\times X_{5GL}^{2} \quad (8)$$

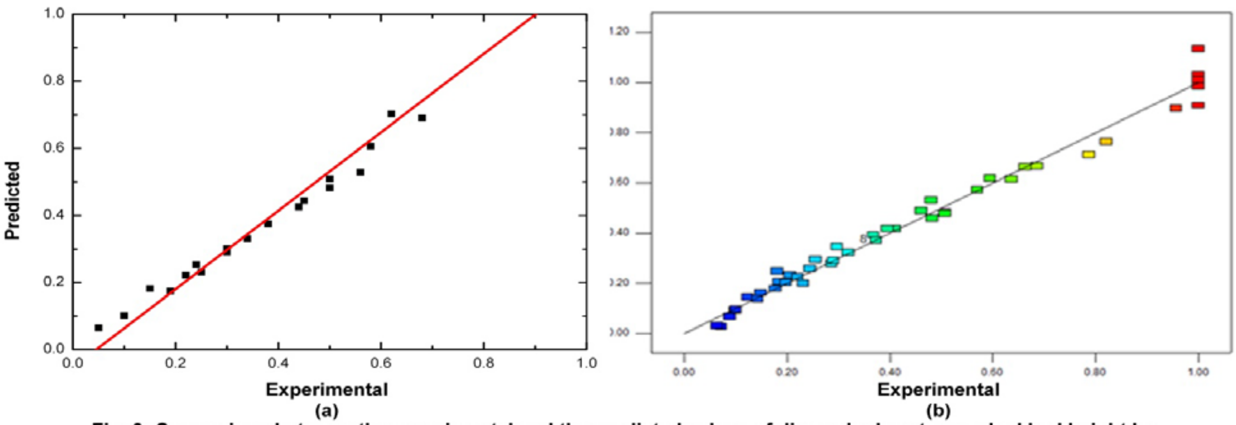

Fig. 6: Comparison between the experimental and the predicted values of dimensionless top packed bed height by (a) dimensional analysis and (b) statistical analysis

Fig. 6 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 0.0404 and 0.9895and 0.047 and 0.9834 for Eqns. (7) and (8) respectively.

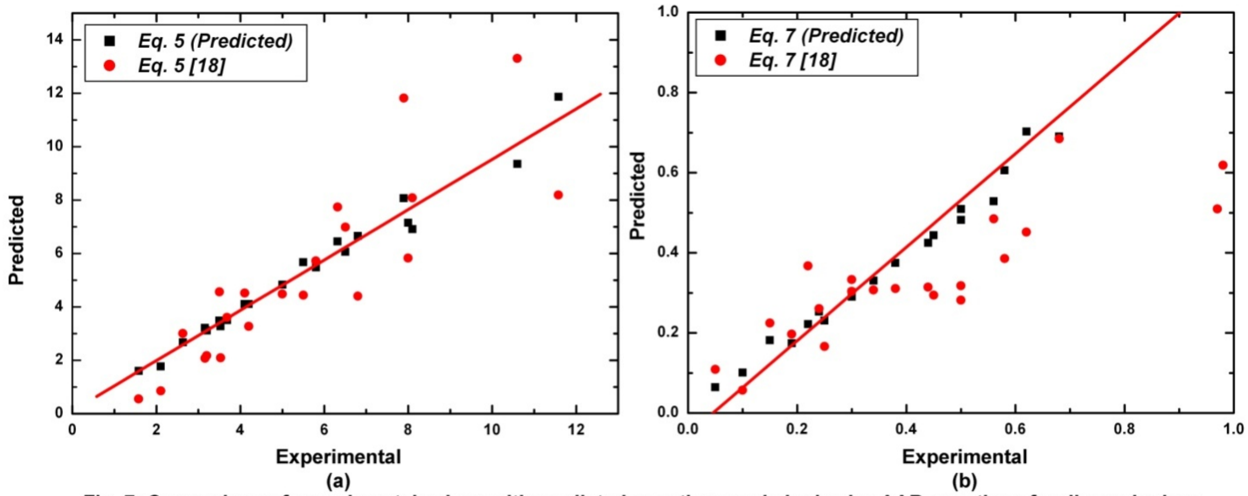

Fig. 7: Comparison of experimental values with predicted equations and single size AAB equations for dimensionless (a) Bed pressure drop and (b) Height of top packed bed

The experimental data of binary mixture of AAB have been taken for comparison with the developed equations and existing single size AAB equations[18] in fig 7. It is clearly observe that developed equations are more suitable for predicting the two phase bed responses.

4. CONCLUSION

Investigations have been carried out to study the behavior of binary mixtures 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. 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 different size of spherical activated alumina beads are used as catalyst and/or desiccant.

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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

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