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PREDICTION OF BED PRESSURE DROP AND TOP PACKED BED HEIGHT IN THREE PHASE SEM-FLUIDIZED BED OF REGULAR HOMOGENOUS TERNARY MICTURES

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ABSTRACT
Hydrodynamics of gas-liquid-solid semi-fluidized bed relating to packed bed formation and bed pressure drop with regular homogeneous ternary mixtures, have been studied in a 0.05m internal diameter Perspex column, with water and air (secondary) as fluidizing medium. Experimental parameters studied include superficial gas and liquid velocities, average particle size and static bed height and the bed expansion ratio. Empirical and semi-empirical models have been developed. The calculated values from predicted models have been compared with the experimental values and fairly good agreement has been obtained. The hydrodynamics study conducted and the correlations developed thereof can find potential applications in physical and chemical processing.

Keywords: Gas-Liquid–Solid semi-fluidization, regular homogeneous particles, ternary mixtures, hydrodynamics, dimensional and statistical analyses.

I. INTRODUCTION

Semi-fluidized bed concept was developed by Fan et al. in 1959 for better contacting of different phases in a single column. This bed has the advantages like minimization of back mixing, attrition and segregation of solid particles and erosion of confining vessel as are encountered in a fluidized bed and reduction of channeling and non-uniformity of temperature of a packed bed since a fluidized and a packed bed co-exist in a single column. Three-phase semi-fluidization is a gas-liquid-solid contacting technique that has great importance in case of solid-catalyzed gas-liquid reactions. Regular-shaped solid (porous/non porous) particles are generally being used in the industrial practice for various gas-liquid operations/reactions. In industrial practice 20 µm to 2.5 cm diameter spherical catalyst particles are generally used for fixed and fluidized bed reactors. Several investigators have been attempted to explain the behavior of semi-fluidized bed in gas-solid, liquid-solid or gas-liquid-solid systems with various types of particles and their mixtures. Most of the studies relate to single particle while a few studies on binary homogenous and heterogeneous irregular mixtures have been reported [1-6]. Samal et al. [7-8] have studied the hydrodynamics of liquid-solid semi-fluidized bed with irregular homogenous ternary mixture and three phase semi-fluidized bed with irregular binary mixture. Hydrodynamics of regular single particles of more than 2 mm diameter (glass beads) have been studied by Jena et al.[9].

Practically no work has been conducted on hydrodynamics of homogeneous ternary mixtures of regular particles in a gas-liquid-solid semi-fluidized bed. Thus, the hydrodynamics of regular homogenous ternary mixture particles have been studied in gas-liquid-solid semi-fluidized bed. The purposes of use of ternary mixture of glass bead are to investigate the effect of particle interaction on the hydrodynamic characteristics. The objective of the present work is to study the effect of mass velocities of gas and liquid (G_{sfg} & G_{sfl}), average particle diameter (d_{pav}) (mixture composition, wt. %), initial static bed height (H_s) and the bed expansion ratio (R) on the bed pressure drop and top packed bed formation. Simultaneously, correlations have been developed for the prediction of the responses in a liquid-solid semi-fluidized bed using dimensional and statistical analyses. The experimental data have been compared with the values obtained from the developed correlations in this study. The unique feature of the current study is the investigations carried out in 0.05m internal diameter cylindrical columns with ternary mixture of spherical glass beads of average particle size of 0.001854m (-8+10 BSS), 0.001504m (-10+12 BSS) and 0.001303m (-12+14 BSS), as in industrial practice 20 µm to 0.025 m diameter spherical catalyst particles are used for fixed and fluidized bed reactors.

Various applications in different fields have been reported in literature where semi-fluidization plays an important role. Dynamics of Fines Deposition in 2008 [10], Simultaneous Removal of Cyanide and copper Ions in 1999 [11], Formation of nitrogen oxides and deposits on the heating surfaces of boilers in 1995[12], Extractive fermentation of ethanol by immobilized yeast cells in 1991[13], Thin-layer drying of high-moisture faba beans in semi-fluidized bed [14] and the treatment of palm oil mill effluent [15] are some of them.

II. MATERIALS & METHODS

Schematic and pictorial representation of the experimental setup is shown in Fig. 1. The details of the set-up and the method of investigations are described in an earlier paper [8].

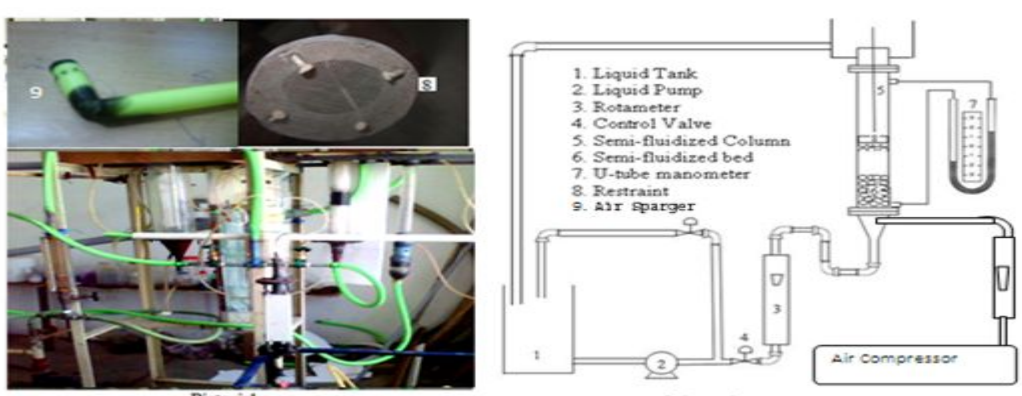

Fig. 1. Experimental Set-up

The scope of the experiment is presented in Table 1. The procedure was repeated varying the initial static bed height, average particle size, and bed expansion ratio for dimensionless responses like semi-fluidized bed pressure drop ($\Delta P_{sf}/\Delta P_{mf}$) and height of top packed bed (H_{pa}/H_s). The responses "$\Delta P_{sf}/\Delta P_{mf}$ and H_{pa}/H_s" respectively have been taken to be functions of sets of independent variables H_s/D_c, d_{pav}/D_c, G_{sfl}/G_{mfl}, G_{sfg}/G_{mfl}, R.

Table 1: Scope of the experiment

(A) Properties of bed material			(B) Ternary mixture properties	
	Particle size ($d_p \times 10^3$, m)	Mixture	Composition (wt. %)	Avg. particle Size ($d_{pav} \times 10^3$ m)
d_{p1}	1.854	Mixture 1	30 : 50 : 20	1.5438
d_{p2}	1.504	Mixture 2	40 : 40 : 20	1.5743
d_{p3}	1.303	Mixture 3	50 : 30 : 20	1.6060
		Mixture 4	60 : 20 : 20	1.6390
		Mixture 5	70 : 10 : 20	1.6735
(C) Materials				
Materials		Glass Beads		
ρ_s, kg/m^3		2600		
(D) Bed expansion ratio				
R 1.5	2.0	2.5	3.0	3.5

In this work mathematical and statistical model have been used for predicting the bed pressure drop and top packed bed formation. For statistical analysis, Central Composite Design (CCD) [16-18] has been used to develop correlations for four responses (dependent dimensionless variables). The complete experimental range and the levels of independent variables are given in Table 2.

Table 2: Level of independent variables

Variables	Symbol	- a	-1	0	+1	+a
Aspect Ratio (H_s/D_c)	X_1	0.65	1.2	1.6	2.0	2.55
Particle diameter (d_{pav}/D_c)	X_2	0.0306	0.0315	0.0321	0.0328	0.0337
Liquid mass velocity (G_{sfl}/G_{mf})	X_3	2.622	4.0	5.0	6.0	7.378
Gas mass velocity (G_{sfg}/G_{mf})	X_4	1.243	4.0	6.0	8.0	10.757
Bed expansion ratio (R)	X_5	1.31	2.0	2.5	3.0	3.69

The design of the experiment is given in Table 3 (dimensional analysis) and Table 4 (statistical analysis). For statistical analysis, 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.

Table 3:- Experimental design matrix and responses (Dimensional Analysis) for regular ternary mixture.

H_s/D_c	d_{pav}/D_c	G_{sfl}/G_{mfl}	G_{sfg}/G_{mfl}	R	Expt. $\Delta P_{sf}/\Delta P_{mfl}$	Cal. $\Delta P_{sf}/\Delta P_{mfl}$ (Eq. 1)	Expt. H_{pa}/H_s	Cal. H_{pa}/H_s (Eq. 2)
0.8	0.03212	5	6	2.5	25	24.31802	0.98	0.985504
1.2	0.03212	5	6	2.5	38	35.35578	0.82	0.814508
1.6	0.03212	5	6	2.5	50	46.10827	0.72	0.711499
2	0.03212	5	6	2.5	60	56.6535	0.63	0.640659
2.4	0.03212	5	6	2.5	70	67.03646	0.59	0.588046
1.6	0.030876	5	6	2.5	78	69.3566	0.98	1.024497
1.6	0.031486	5	6	2.5	62	56.65893	0.84	0.85524
1.6	0.03212	5	6	2.5	50	46.10827	0.72	0.711499
1.6	0.03278	5	6	2.5	40	37.366	0.58	0.589715
1.6	0.03347	5	6	2.5	30	30.12793	0.47	0.486564
1.6	0.03212	3	6	2.5	18	18.11505	0.32	0.348896
1.6	0.03212	4	6	2.5	30	30.65774	0.51	0.521177
1.6	0.03212	5	6	2.5	50	46.10827	0.72	0.711499
1.6	0.03212	6	6	2.5	70	64.35665	0.87	0.917555
1.6	0.03212	7	6	2.5	87	85.31637	0.95	1.137688
1.6	0.03212	5	2	2.5	13	13.59002	0.3	0.306589
1.6	0.03212	5	4	2.5	34	29.37415	0.5	0.521478
1.6	0.03212	5	6	2.5	50	46.10827	0.72	0.711499
1.6	0.03212	5	8	2.5	74	63.49078	0.9	0.886982
1.6	0.03212	5	10	2.5	83	81.37193	0.99	1.052391
1.6	0.03212	5	6	1.5	126	128.9582	0.99	1.057618
1.6	0.03212	5	6	2	76	72.25991	0.83	0.846012
1.6	0.03212	5	6	2.5	50	46.10827	0.72	0.711499
1.6	0.03212	5	6	3	32	31.9415	0.6	0.617632
1.6	0.03212	5	6	3.5	20	23.4188	0.52	0.547998

Table 4: Experimental design matrix and responses (Statistical Analysis) for regular ternary mixture.

Sl. No.	H_s/D_c	d_{pav}/D_c	G_{sf}/G_{mfl}	G_{sfg}/G_{mfl}	R	$\Delta P_{sf}/\Delta P_{mf}$	H_{pa}/H_s	Sl. No.	H_s/D_c	d_{pav}/D_c	G_{sf}/G_{mfl}	G_{sfg}/G_{mfl}	R	$\Delta P_{sf}/\Delta P_{mf}$	H_{pa}/H_s
1.	1.20	0.0315	4.000	4.000	2.00	28	0.63	26.	2.00	0.0315	4.000	8.000	3.00	44	0.61
2.	2.00	0.0315	4.000	4.000	2.00	46	0.49	27.	1.20	0.0328	4.000	8.000	3.00	18	0.54
3.	1.20	0.0328	4.000	4.000	2.00	20	0.43	28.	2.00	0.0328	4.000	8.000	3.00	30	0.42
4.	2.00	0.0328	4.000	4.000	2.00	30	0.34	29.	1.20	0.0315	6.000	8.000	3.00	58	0.99
5.	1.20	0.0315	6.000	4.000	2.00	60	0.99	30.	2.00	0.0315	6.000	8.000	3.00	92	0.99
6.	2.00	0.0315	6.000	4.000	2.00	98	0.87	31.	1.20	0.0328	6.000	8.000	3.00	38	0.94
7.	1.20	0.0328	6.000	4.000	2.00	40	0.76	32.	2.00	0.0328	6.000	8.000	3.00	62	0.74
8.	2.00	0.0328	6.000	4.000	2.00	64	0.60	33.	0.65	0.0321	5.000	6.000	2.50	20	0.99
9.	1.20	0.0315	4.000	8.000	2.00	62	0.99	34.	2.55	0.0321	5.000	6.000	2.50	70	0.57
10.	2.00	0.0315	4.000	8.000	2.00	100	0.84	35.	1.60	0.0306	5.000	6.000	2.50	76	0.99
11.	1.20	0.0328	4.000	8.000	2.00	42	0.73	36.	1.60	0.0337	5.000	6.000	2.50	28	0.46
12.	2.00	0.0328	4.000	8.000	2.00	66	0.58	37.	1.60	0.0321	2.622	6.000	2.50	14	0.29
13.	1.20	0.0315	6.000	8.000	2.00	132	0.99	38.	1.60	0.0321	7.378	6.000	2.50	94	0.99
14.	2.00	0.0315	6.000	8.000	2.00	210	0.99	39.	1.60	0.0321	5.000	1.243	2.50	8	0.21
15.	1.20	0.0328	6.000	8.000	2.00	86	0.99	40.	1.60	0.0321	5.000	10.757	2.50	88	0.99
16.	2.00	0.0328	6.000	8.000	2.00	138	0.99	41.	1.60	0.0321	5.000	6.000	1.31	168	0.99
17.	1.20	0.0315	4.000	4.000	3.00	12	0.46	42.	1.60	0.0321	5.000	6.000	3.69	20	0.52
18.	2.00	0.0315	4.000	4.000	3.00	20	0.36	43.	1.60	0.0321	5.000	6.000	2.50	46	0.70
19.	1.20	0.0328	4.000	4.000	3.00	8	0.31	44.	1.60	0.0321	5.000	6.000	2.50	46	0.70
20.	2.00	0.0328	4.000	4.000	3.00	14	0.25	45.	1.60	0.0321	5.000	6.000	2.50	44	0.69
21.	1.20	0.0315	6.000	4.000	3.00	26	0.80	46.	1.60	0.0321	5.000	6.000	2.50	46	0.70
22.	2.00	0.0315	6.000	4.000	3.00	42	0.63	47.	1.60	0.0321	5.000	6.000	2.50	48	0.71
23.	1.20	0.0328	6.000	4.000	3.00	18	0.55	48.	1.60	0.0321	5.000	6.000	2.50	46	0.70
24.	2.00	0.0328	6.000	4.000	3.00	28	0.44	49.	1.60	0.0321	5.000	6.000	2.50	46	0.70
25.	1.20	0.0315	4.000	8.000	3.00	28	0.78	50.	1.60	0.0321	5.000	6.000	2.50	46	0.70

III. RESULTS AND DISCUSSIONS

Hydrodynamic parameters for the gas-liquid-solid semi-fluidization using homogenous regular ternary mixtures viz. semi-fluidized bed pressure drop and height of top packed bed have been found to be dependent on material property (average particle size) and system parameters (initial static bed height, column diameter and bed expansion ratio). The detailed results and the correlations developed are presented below.

3.1 Development of correlations by Dimensional Analysis

For dimensionless bed pressure drop, the equation is

$$\Delta P_{sf}/\Delta P_{mfl} = 5\times10^{-16}(H_s/D_c)^{0.923}(d_{pav}/D_c)^{-10.336}(U_{sfl}/U_{mfl})^{1.8289}(U_{sfg}/U_{mfl})^{1.112}R^{-2.0134} \quad (1)$$

Fig. 2 shows the comparison between the experimental and calculated values of $\Delta P_{sf}/\Delta P_{mf}$ with a standard deviation of 3.13 and a coefficient of correlation of 0.9928 respectively.

For dimensionless top packed bed height, the equation is

$$H_{pa}/H_s=8\times10^{-16}\,(H_s/D_c)^{-0.47}(d_{pav}/D_c)^{-9.23}(U_{sfl}/U_{mfl})^{1.395}(U_{sfg}/U_{mfl})^{0.7663}R^{-0.776} \quad (2)$$

Fig. 3 shows the comparison between the experimental and calculated values of H_{pa}/H_s with a standard deviation of 0.0395 and a coefficient of correlation of 0.9847 respectively.

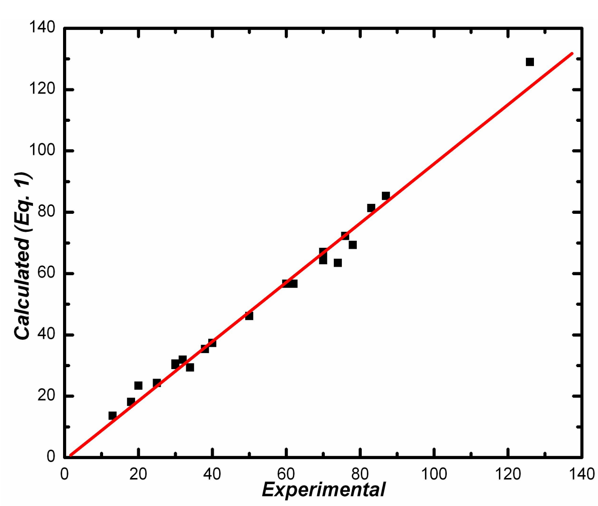

Fig. 2: Comparison of dimensionless bed pressure drop

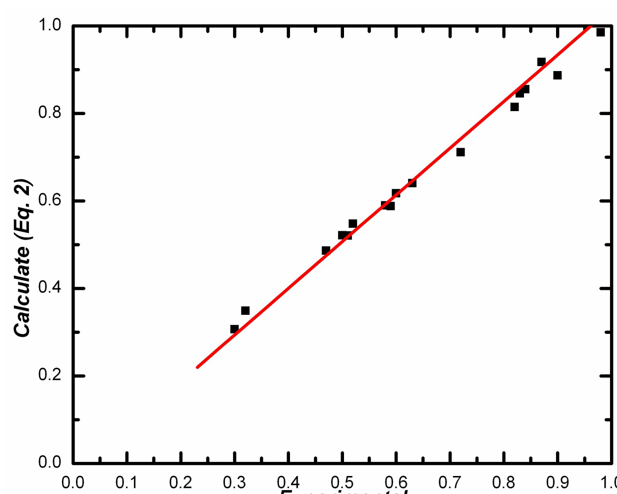

Fig. 3: Comparison of dimensionless top packed bed height

3.2 Development of correlations by statistical analysis approach

For dimensionless semi-fluidization pressure drop, the equation is

$$\Delta P_{sf}/\Delta P_{mf}=45.72+12.17\times X_1-10.85\times X_2+18.80\times X_3+19.45\times X_4-23.92\times X_5-2.63\times X_1\times X_2+4.50\times X_1\times X_3+4.62\times X_1\times X_4-4.88\times X_1\times X_5-4.12\times X_2\times X_3-4.25\times X_2\times X_4+4.5\times X_2\times X_5+7.13\times X_3\times X_4-7.63\times X_3\times X_5-7.75\times X_4\times X_5-0.43\times X_1^2+0.81\times X_2^2+1.16\times X_3^2+0.10\times X_4^2+8.23\times X_5^2 \quad (3)$$

For dimensionless top packed bed height, the equation is

$$H_{pa}/H_s=0.70-0.064\times X_1-0.094\times X_2+0.14\times X_3+0.14\times X_4-0.081\times X_5+2.088\times10^{-3}\times X_1\times X_2+6.353\times10^{-3}\times X_1\times X_3+5.474\times10^{-3}\times X_1\times X_4-3.644\times10^{-3}\times X_1\times X_5-9.616\times10^{-3}\times X_2\times X_3+9.531\times10^{-3}\times X_2\times X_4-2.005\times10^{-3}\times X_2\times X_5-7.239\times10^{-3}\times X_3\times X_4+6.873\times10^{-3}\times X_3\times X_5+6.439\times10^{-3}\times X_4\times X_5+0.013\times X_1^2+2.927\times10^{-3}\times X_2^2-0.012\times X_3^2-0.019\times X_4^2+8.652\times10^{-3}\times X_5^2 \quad (4)$$

Fig. 4 shows the comparison between the experimental and calculated values of $\Delta P_{sf}/\Delta P_{mfl}$ with a standard deviation of 8.25 and a coefficient of correlation of 0.9764 respectively. Fig. 5 shows the comparison between the experimental and calculated values of H_{pa}/H_s with a standard deviation of 0.064 and a coefficient of correlation of 0.9562 respectively.

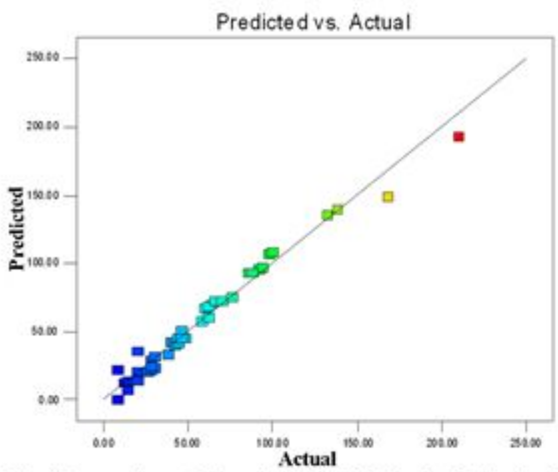

Fig. 4: Comparison of Experimental with Calculated (Eq. 3) values

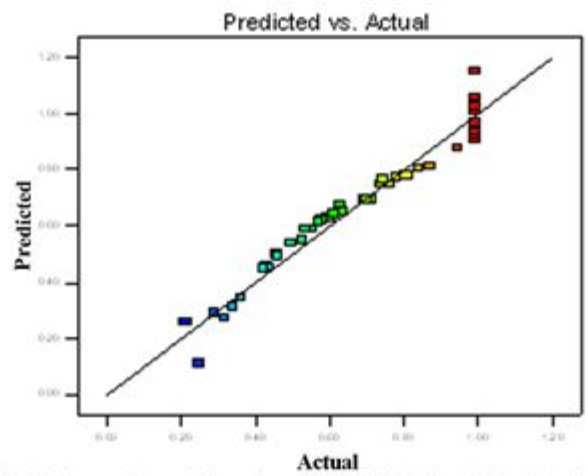

Fig. 5: Comparison of Experimental with Calculated (Eq. 4) values

IV. CONCLUSION

Investigations have been carried out to study the behavior of regular homogenous ternary mixtures with the superficial liquid and gas velocities in gas-liquid-solid semi-fluidized beds with particles of different size in 0.05 m column diameter. It may be concluded that the bed pressure drop and height of top packed bed are strong functions of initial static bed height, superficial liquid and gas velocities and the average size of particle. Correlations for the calculation of bed pressure drop and height of top packed bed have been proposed. The values calculated from the developed correlations have been compared with the experimental ones. The coefficients of correlations are found to be greater than 0.95 in both the approaches, 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 find potential applications in physical and chemical processing. In the present investigation, the wide range in experimental parameters involved especially with respect to mixture particle and bed expansion ratio, makes it amenable to logical scale-up while considering design of gas-liquid-solid semi-fluidization systems.

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Nomenclature

BSS	British Standard Sieve
D, d	Diameter, *m*
G	Mass velocity, $Kg.m^{-2}.s^{-1}$
H, h	Height, *m*
$K, k_{(i=1,2,...)}$	Constant
P	Pressure, $N.m^{-2}$
R	Bed expansion ratio
U	Velocity, $m.s^{-1}$
Greek letters	
Δ	Difference
Subscripts	
av	average
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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