Journal of Bioprocessing & Biotechniques

Samal et al., J Bioproces Biotechniq 2014, 4:2
DOI: 10.4172/2155-9821.1000151

Research Article Open Access

Hydrodynamics of Liquid-Solid Semi-fluidized Bed with Regular Homogenous Ternary Mixture

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Abstract

Hydrodynamics studies in Semi-fluidized bed relating to bed pressure drop, height of top packed bed, minimum and maximum semi-fluidization velocities with regular (spherical glass beads) homogeneous ternary mixtures, have been made in 0.01, 0.025, 0.037, 0.05, and 0.065 m internal diameter Perspex columns, with water as the fluidizing medium. Ternary mixtures of glass beads of different sizes (-8+10, -10+12 and -12+14 BSS) have been used as the semi-fluidized solids. Experimental studies relate to establish the effect of system parameters viz. column diameter, average particle size of semi-fluidized solid and initial static bed height and operating parameters viz. superficial liquid velocity and bed expansion ratio on the above mentioned system variables. Empirical and semi-empirical models have been developed using dimensional as well as statistical analyses. The calculated values from the predicted models have been compared with their experimental counterparts and fairly good agreement has been obtained. The results have also been compared with those available in the literature for irregular homogenous ternary mixtures.

Keywords: Semi-fluidization; Liquid-solid system; Homogeneous ternary mixtures; Regular particles; Hydrodynamics; Mathematical modeling

Nomenclature

BSS	British Standard Sieve
D, d	Diameter, *m*
G	Mass velocity, kg/m^2s
H, h	Height, *m*
P	Pressure, N/m^2
R	Bed expansion ratio
U	Velocity, *m/s*
Greek letters	
μ	Viscosity, *kg/m.s*
Δ	Difference
Subscripts	
av	average
c	column
f	fluid
l	liquid
mf	minimum fluidization
msf	maximum semi-fluidization
osf	onset of semi-fluidization
p	particle
pa	top packed bed
s	static/superficial
sf	semi-fluidization
w	water

Introduction

Semi-fluidization is a novel technique of fluid-solid contacting which is a stage between fluidization and pneumatic conveyance. Semi-fluidization begins when the expanded bed of fluidization is restricted at certain height by means of a restraint which only allows the fluid to pass. A semi-fluidized bed is thus obtained by increasing the fluid velocity beyond minimum fluidization velocity and thereafter arresting the movement of the solid particles with a restraint fixed at a suitable height towards the top of the conduit. This results in the formation of packed bed below the top restraint. The velocity at which the first particle of solid touches the top restraint is called minimum semi-fluidization velocity (U_{osf}). Similarly when all the bed materials form a packed bed below the top restraint, the corresponding fluid velocity is called the maximum semi-fluidization velocity (U_{msf}) [1]. The pioneering work as regards the concept and application of a semi-fluidized bed started by Fan et al. [2]. Hydrodynamic study on single size particle in solid-liquid system was highlighted by Fan and Wen [3]. Investigations relating to various aspects of semi-fluidized bed behavior involving different systems are available in literature. Considerable work on hydrodynamic studies in semi-fluidized bed has been reported by Roy et al. [4-6] and Ho et al. [7]. Murthy and Roy reviewed the various studies on semi-fluidization [8]. Of late, hydrodynamic investigations relating to mixtures (binary/ternary) of homogenous or heterogeneous nature has become essential in view of their potential applications in slurry and gas-solid reactions. A few articles on hydrodynamic characteristics of liquid-solid binary homogenous and heterogeneous mixtures in semi-fluidization have been reported [1,5,9,10]. The use of mixtures have the

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Received January 05, 2014; **Accepted** February 03, 2014; **Published** February 11, 2014

Citation: Samal DK, Mohanty YK, Roy GK (2014) Hydrodynamics of Liquid-Solid Semi-fluidized Bed with Regular Homogenous Ternary Mixture. J Bioprocess Biotech 4: 151 doi: 10.4172/2155-9821.1000151

advantages in semi-fluidization as with less pressure drop both fluidized and the packed bed condition can be achieved compared to a particle [1]. The maiden investigations relating to hydrodynamics of liquid-solid semi-fluidized bed with irregular homogenous ternary mixtures have been reported by present author [1]. The correlations developed from dimensional analysis approach are as under:

For the bed pressure drop,

$$\Delta P_{sf}/\Delta P_{mf}=2\times10^{-7}(\rho_{sav}/\rho_f)^{1.675}(D_c/d_{pav})^{3.338}(G_{sf/}G_{mf})^{3.094}(H_s/D_c)\text{-}^{0.424}R\text{-}^{0.938} \quad (1)$$

For the top packed bed formation,

$$H_{pa}/H_s=1\times10^{-5}(\rho_{sav}/\rho_f)^{3.155}(D_c/d_{pav})_{1.510}(G_{sf}/G_{mf})^{2.426}(H_s/D_c)^{-0.52}4R^{-1.676} \quad (2)$$

For minimum semi-fluidization velocity,

$$U_{osf}/U_{mf}=296.5(\rho_{sav}/\rho_f)^{-0.451}(D_c/d_{pav})^{-1.343}(H_s/D_c)^{0.228}R^{0.755} \quad (3)$$

For maximum semi-fluidization velocity,

$$U_{msf}/U_{mf}=0.001(\rho_{sav}/\rho_f)^{-0.680}(D_c/d_{pav})^{2.430}(H_s/D_c)^{0.613}R^{0.633} \quad (4)$$

Investigation relating to liquid-solid semi-fluidization regular homogenous ternary mixtures is almost absent. The objective of the present work is to study the hydrodynamics of liquid-solid semi-fluidization viz. the bed pressure drop, height of the top packed bed, minimum and maximum semi-fluidization velocities using homogenous ternary mixture of spherical glass beads. In addition the current study includes investigations carried out in five different column diameters with five different ternary mixtures of spherical glass beads of diameter 0.001854, 0.001504,0.001303 m. The experimental data have been correlated with the system parameters by two different approaches viz. the dimensional analysis and the statistical analyses.

Material and Methods

Schematic representation of the experimental setup is shown in Figure 1. The details of the experimental set up and its components are given elsewhere [1]. The scope of the experiment is presented in

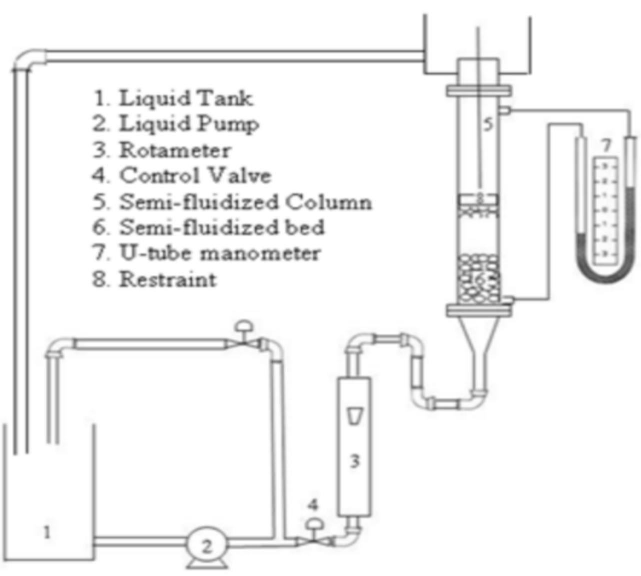

Figure 1: Experimental Set up.

a) System	Liquid-Solid
b) Liquid	Water
c) Solid	Regular
i. Material	Glass beads (Spherical)
ii. Density (ρ_{sav}), Kg/m³	2470
iii. Size (d_p), m	d_{p1}=0.001854, d_{p2}=0.001504, d_{p3}=0.001303
iv. Composition (wt. %)	[i]20:30:50, [ii]20:40:40, [iii]20:50:30, [iv]20:60:20, [v]20:90:10
d) Average particle diametr (d_{pav} × 10^3), m	[i]1.457, [ii]1.482, [iii]1.509, [iv]1.536, [v]1.565
e) Initial Static Bed Height (H_s), m	0.033, 0.06, 0.08, 0.10, 0.128
f) Bed Expansion Ratio, (R)	1.3, 2.0, 2.5, 3.0, 3.7
g) Column Diameter (Dc), m	0.01, 0.025, 0.037, 0.05, 0.065

Table 1: Scope of the experiment.

Variables	Symbol	-α	-1	0	+1	+α
H_s/D_c	X_1	0.917	1.673	2.222	2.771	3.527
D_c/H_s	X_2	0.125	0.324	0.469	0.613	0.813
d_{pav}/D_c	X_3	0.0405	0.0413	0.0420	0.0426	0.0435
G_{sf}/G_{mf}	X_4	405	5.08	5.5	5.92	6.5
R	X_5	1.3	2.0	2.5	3.0	3.7

Table 2: Level of independent variables.

Table 1. Accurately weighed amount of material was fed into the column, fluidized and de-fluidized slowly and adjusted for a specific reproducible initial static bed height. Liquid was then pumped to the fluidizer through a rotameter and the temperature was maintained at 25 ± 5°C. At least two minutes were allowed to attain a steady state and then the readings of the manometers and the top packed bed height for each liquid flow rate were noted. The procedure was repeated for different values of initial static bed height, column diameter, the average particle size and the bed expansion ratio. In this work dimensional and statistical analyses approach have been used for predicting dimensionless responses like semi-fluidized bed pressure drop ($\Delta P_{sf}/\Delta P_{mf}$), height of top packed bed (H_{pa}/H_s), and minimum and maximum semi-fluidization velocities (U_{osf}/U_{mf} *and* U_{msf}/U_{mf}) as functions of the dimensionless parameters viz. H_s/D_c, D_c/H_s, d_{pav}/D_c, G_{sf}/G_{mf}, and R. For statistical analysis, Central Composite Design (CCD) [11-13] has been used to develop correlations for responses for the four dependent variables in dimensionless form. The complete experimental range and the levels of the independent variables are given in Table 2. The design of the experiment is given in Table 3 (dimensional analysis) and Tables 4a and 4b (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.

Results and Discussions

The minimum and maximum semi-fluidization velocities are determined by the extrapolation of H_{pa}/H_{sto} 1 on H_{pa}/H_{svs} U_{sf} plot which also used in present investigation. During the present investigation it has been found that maximum contribution for the semi-fluidized bed pressure drop is due to the top packed bed. Also it has been observed that due to the presence of fines in mixture though bulk density of bed increases, but the fines move faster to form top packed bed. The experimental investigations has established that the semi- fluidized bed responses viz. ΔP_{sf}, H_{pa}, U_{osf}, and U_{msf} not only depend on fluid velocity and the material properties, but also on other system parameters like initial static bed height, column diameter and bed expansion ratio. The detailed results on individual parameters and the correlations developed are presented below.

Sl.No	H_s/D_c	D_c/H_s	d_{pav}/D_c	G_{sf}/G_{mf}	R	ΔP_{sf} / ΔP_{mf}		H_{pa} / H_s				U_{mf} / U_{mc}			U_{mg} / U_{mf}		
						Cal. (eq. 4)	Expt.	Cal. (eq. 5)	Cal. (eq. 1a)	Cal. (eq. 1b)	Expt.	Cal. (eq. 6)	Cal. (eq. 2)	Expt.	Cal. (eq. 7)	Cal. (eq. 3)	Expt.
1	0.916	0.45	0.0419	5.5	2.5	18.828	18	0.731	3.643	0.699	0.75	3.081	3.381	3	6.502	8.130	6.6
2	1.666	0.45	0.0419	5.5	2.5	17.874	17.5	0.674	2.653	0.652	0.69	3.213	3.381	3.125	7.074	10.08	7
3	2.222	0.45	0.0419	5.5	2.5	17.432	16.8	0.648	2.217	0.628	0.67	3.278	3.381	3.2	7.367	11.18	7.3
4	2.777	0.45	0.0419	5.5	2.5	17.097	16	0.629	1.966	0.612	0.65	3.330	3.381	3.25	7.602	12.11	7.63
5	3.527	0.45	0.0419	5.5	2.5	16.745	25	0.609	1.744	0.596	0.61	3.386	3.381	3.3	7.863	13.20	8
6	2.222	0.125	0.0419	5.5	2.5	29.233	17.5	1.179	24.620	0.895	1	1.939	3.381	2.222	4.669	11.18	5.1
7	2.222	0.3125	0.0419	5.5	2.5	20.196	15	0.769	3.394	0.669	0.72	2.823	3.381	3	6.470	11.18	6.6
8	2.222	0.625	0.0419	5.5	2.5	15.297	13.5	0.556	0.508	0.506	0.55	3.751	3.381	4	8.281	11.18	9
9	2.222	0.8125	0.0419	5.5	2.5	13.733	11.5	0.492	0.315	0.471	0.45	4.177	3.381	4.3	9.092	11.18	9.8
10	2.222	0.45	0.040	5.5	2.5	19.166	18.5	764	2.438	0.639	0.75	3.223	3.425	3.157	6.120	11.31	6.315
11	2.222	0.45	0.041	5.5	2.5	18.307	17	0.706	2.353	0.635	0.7	3.250	3.403	3.173	6.694	11.24	6.938
12	2.222	0.45	0.042	5.5	2.5	16.613	15.8	0.596	1.994	0.617	0.6	3.307	3.358	3.25	8.094	11.11	8.1
13	2.222	0.45	0.043	5.5	2.5	15.787	15	0.546	1.795	0.607	0.55	3.337	3.335	3.3	8.943	11.04	9
14	2.222	0.45	0.0419	5.5	2.5	9.557	9	0.485			0.45						
15	2.222	0.45	0.0419	5.5	2.5	13.103	13	0.565			0.55						
16	2.222	0.45	0.0419	5.5	2.5	22.622	21	0.735			0.71						
17	2.222	0.45	0.0419	5.5	2.5	28.750	26.5	0.826			0.8						
18	2.222	0.45	0.0419	5.5	2.5	26.648	23	0.975	349.05	1.505	1	1.663	1.852	1.55	4.892	7.12	4.6
19	2.222	0.45	0.0419	5.5	2.5	20.148	18.5	0.745	9.586	0.814	0.75	2.600	2.753	2.6	6.406	9.58	6.1
20	2.222	0.45	0.0419	5.5	2.5	15.487	13.7	0.579	0.660	0.507	0.6	3.961	3.998	3.8	8.258	12.68	8
21	2.222	0.45	0.0419	5.5	2.5	13.516	11.5	0.508	0.129	0.383	0.48	4.925	4.849	4.8	9.416	14.65	9

Table 3: Experimental design matrix and responses (Dimensional analysis).

Sl.No	H_s/D_c	D_c/H_s	d_{pav}/D_c	G_{sf}/G_{mf}	R	ΔP_{sf} / ΔP_{mf}	H_{pa} / H_s
1	1.673	0.3242	0.04133	5.08	2	19.32	0.86
2	2.77	0.3242	0.04133	5.08	2	18.5	0.8
3	1.673	0.6132	0.04133	5.08	2	15	0.64
4	2.77	0.6132	0.04133	5.08	2	14.3	0.6
5	1.673	0.3242	0.04260	5.08	2	17.8	0.75
6	2.77	0.3242	0.04260	5.08	2	17	0.7
7	1.673	0.6132	0.04260	5.08	2	13.76	0.55
8	2.77	0.6132	0.04260	5.08	2	13.2	0.5
9	1.673	0.3242	0.04133	5.92	2	30.6	1
10	2.77	0.3242	0.04133	5.92	2	29.2	1
11	1.673	0.6132	0.04133	5.92	2	23.6	0.8
12	2.77	0.6132	0.04133	5.92	2	22.6	0.74
13	1.673	0.3242	0.04260	5.92	2	28.2	0.93
14	2.77	0.3242	0.04260	5.92	2	27	0.87
15	1.673	0.6132	0.04260	5.92	2	21.8	0.7
16	2.77	0.6132	0.04260	5.92	2	21	0.65
17	1.673	0.3242	0.04133	5.08	3	15	0.66
18	2.77	0.3242	0.04133	5.08	3	14.2	0.62
19	1.673	0.6132	0.04133	5.08	3	11.45	0.5
20	2.77	0.6132	0.04133	5.08	3	11	0.46
21	1.673	0.3242	0.04260	5.08	3	13.6	0.58
22	2.77	0.3242	0.04260	5.08	3	13	0.54
23	1.673	0.6132	0.04260	5.08	3	10.5	0.43
24	2.77	0.6132	0.04260	5.08	3	10.1	0.4
25	1.673	0.3242	0.04133	5.92	3	23.4	0.83
26	2.77	0.3242	0.04133	5.92	3	22.42	0.77
27	1.673	0.6132	0.04133	5.92	3	18.1	0.61
28	2.77	0.6132	0.04133	5.92	3	17.3	0.58
29	1.673	0.3242	0.04260	5.92	3	21.6	0.72
30	2.77	0.3242	0.04260	5.92	3	20.6	0.67
31	1.673	0.6132	0.04260	5.92	3	16.7	0.54
32	2.77	0.6132	0.04260	5.92	3	16	0.5
33	0.916	0.4687	0.04197	5.5	2.5	18.45	0.71
34	3.527	0.4687	0.04197	5.5	2.5	16.4	0.6
35	2.221	0.125	0.04197	5.5	2.5	29.1	1
36	2.221	0.8125	0.04197	5.5	2.5	13.7	0.49
37	2.221	0.4687	0.04047	5.5	2.5	18.8	0.75
38	2.221	0.4687	0.04347	5.5	2.5	15.5	0.53
39	2.221	0.4687	0.04197	4.5	2.5	9.4	0.47
40	2.221	0.4687	0.04197	6.5	2.5	28.2	0.8
41	2.221	0.4687	0.04197	5.5	1.3	26.1	0.95
42	2.221	0.4687	0.04197	5.5	3.7	13.2	0.5
43	2.221	0.4687	0..197	5.5	2.5	17	0.63
44	2.221	0.4687	0.04197	5.5	2.5	17.1	0.63
45	2.221	0.4687	0.04197	5.5	2.5	17.1	0.61
46	2.221	0.4687	0.04197	5.5	2.5	17	0.62
47	2.221	0.4687	0.04197	5.5	2.5	16.96	0.62
48	2.221	0.4687	0.04197	5.5	2.5	17	0.63
49	2.221	0.4687	0.04197	5.5	2.5	17	0.63

Table 4a: Experimental design matrix and responses for $\Delta P_{sf}/\Delta P_{mf}$ and H_{pa}/H_s (Statistical analysis).

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

Figure 2 shows the variation of semi-fluidized bed pressure drop with respect to the superficial liquid velocity for different values of initial static bed height for average particle diameter of 0.001509 m at constant bed expansion ratio (R=2) in the 0.05 m internal diameter column. From Figure 2, it has been observed that with increase in initial static bed height, the bed pressure drop increases. This is due to the increase in the bed weight and therefore an increase in the top packed bed formation with all the other variables remaining constant. Effect of fines in the mixture is shown in Figure 3 shows the variation of semi-fluidized bed pressure drop with superficial liquid velocity for different average particle diameter with constant bed expansion ratio (R=2), initial static bed height (H_s=0.08m) in 0.05 m internal diameter column. Increase of fines results in a relatively fast formation of top packed bed leading to higher values of semi-fluidized bed pressure drop, which is evident from Figure 3. Figure 4 shows the variation of pressure drop

Sl.No	H_s/D_c	D_c/H_s	d_{pav}/D_c	G_{sf}/G_{mf}	R	ΔP_{sf} / ΔP_{mf}	H_{pa} / H_s
1	1.5695	0.297	0.04125	1.9	2	4.7	1.5695
2	2.8745	0.297	0.04125	1.9	2.1	5.1	2.8745
3	1.5695	0.641	0.04125	1.9	2.76	6.16	1.5695
4	2.8745	0.641	0.04125	1.9	2.88	6.7	2.8745
5	1.5695	0.297	0.04275	1.9	2	5.66	1.5695
6	2.8745	0.297	0.04275	1.9	2.15	6.2	2.8745
7	1.5695	0.641	0.04275	1.9	2.8	7.44	1.5695
8	2.8745	0.641	0.04275	1.9	2.94	8.1	2.8745
9	1.5695	0.297	0.04125	3.1	3.35	6.4	1.5695
10	2.8745	0.297	0.04125	3.1	3.5	7	2.8745
11	1.5695	0.641	0.04125	3.1	4.6	8.4	1.5695
12	2.8745	0.641	0.04125	3.1	4.8	9.11	2.8745
13	1.5695	0.297	0.04275	3.1	3.4	7.7	1.5695
14	2.8745	0.297	0.04275	3.1	3.55	8.4	2.8745
15	1.5695	0.641	0.04275	3.1	4.67	10.11	1.5695
16	2.8745	0.641	0.04275	3.1	4.9	11	2.8745
17	0.917	0.469	0.042	2.5	3.14	6.7	0.917
18	3.527	0.469	0.042	2.5	3.45	8	3.527
19	2.222	0.125	0.042	2.5	1.95	4.72	2.222
20	2.222	0.813	0.042	2.5	4.2	9.2	2.222
21	2.222	0.469	0.0405	2.5	3.28	6.24	2.222
22	2.222	0.469	0.0435	2.5	3.4	9.1	2.222
23	2.222	0.469	0.042	1.3	1.7	5	2.222
24	2.222	0.469	0.042	3.7	5	9.66	2.222
25	2.222	0.469	0.042	2.5	3.33	7.56	2.222
26	2.222	0.469	0.042	2.5	3.34	7.55	2.222
27	2.222	0.469	0.042	2.5	3.31	7.56	2.222
28	2.222	0.469	0.042	2.5	3.34	7.54	2.222
29	2.222	0.469	0.042	2.5	3.32	7.56	2.222
30	2.222	0.469	0.042	2.5	3.34	7.56	2.222

Table 4b: Experimental design matrix and responses for U_{osf}/U_{mf} and U_{msf}/U_{mf} (Statistical analysis).

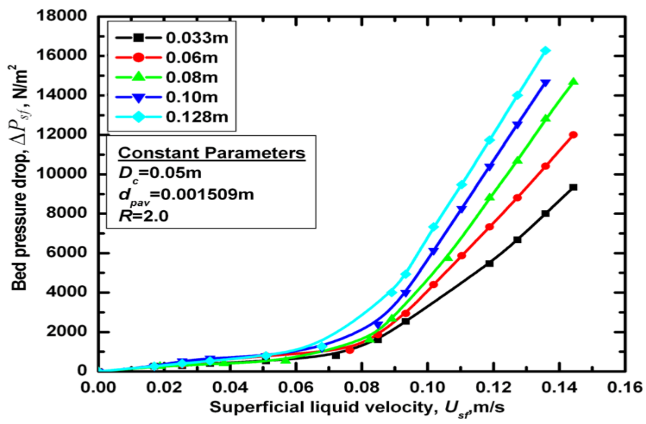

Figure 2: Variation of bed pressure drop with respect to superficial liquid velocity for different initial static bed height.

with superficial liquid velocity for different bed expansion ratio for an initial static bed height of 0.08 m, with a mixture of average particle diameter of 0.001457 m in 0.05 m internal diameter column. From Figure 4, it is clearly observed that with increase in bed expansion ratio the pressure drop decreases. This is due to the fact that, relatively less amount of particles reach the top restraint to form the top packed bed, which has also been observed in other systems. Figure 5 shows the variation of bed pressure drop with superficial liquid flow rate for different column diameters for average particle diameter of 0.01509 m with 0.08 m initial static bed height and a bed expansion ratio of 2.5. The superficial liquid velocity decreases as the column diameter increases for a constant liquid flow rate. Decrease in velocity results in

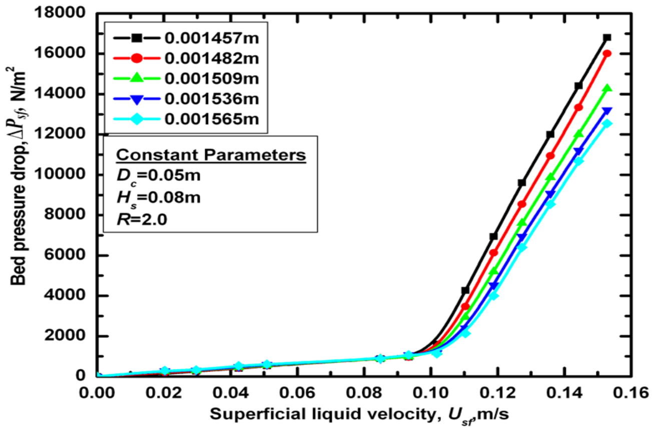

Figure 3: Variation of bed pressure drop with respect to superficial liquid velocity for different average particle diameter.

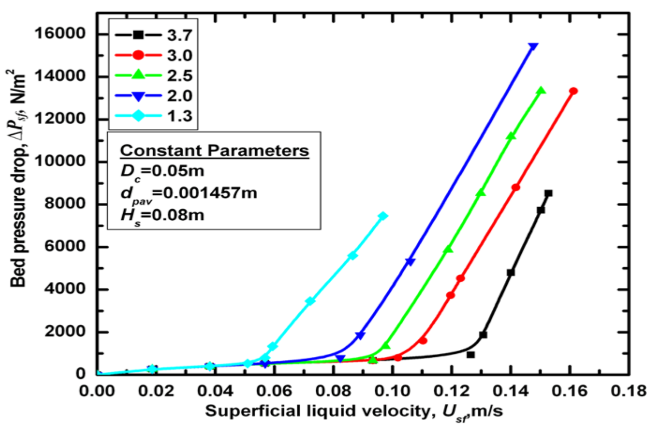

Figure 4: Variation of bed pressure drop with respect to superficial liquid velocity for different bed expansion ratio.

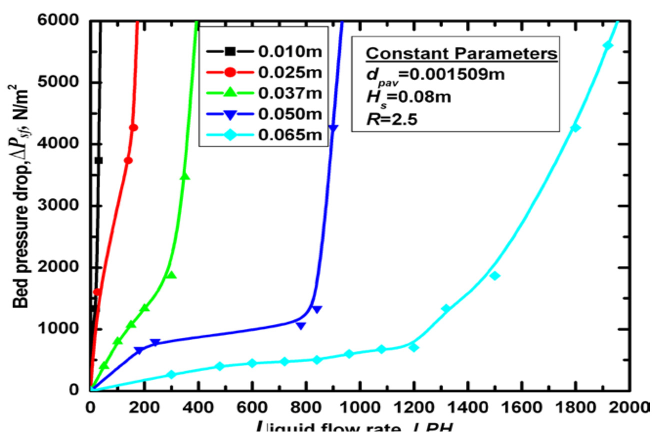

Figure 5: Variation of bed pressure drop with respect to liquid flow rate for different column diameters.

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lesser transport of bed solids to the top with slower formation of top packed bed and thereby lower values of bed pressure drop.

Formation of Top packed bed (H_{pa})

Formation of the top packed bed in a semi-fluidized bed is controlled not only by the superficial liquid velocity but also by other variables like bed expansion ratio, initial static bed height, column diameter and average particle diameter. Figure 6 shows the variation of the height of top packed bed in semi-fluidized bed with respect to the superficial liquid velocity for different values of initial static bed height for average particle diameter of 0.001509 m at constant bed expansion ratio (*R*=2) in 0.05 m internal diameter column. From Figure 6, it has been observed that with increase in initial static bed height, the height of top packed bed increases. This is because of the increase in fines in the increased bed which help rapid formation of the top packed bed when the other variables remaining constant. Figure 7 shows the variation of height of top packed bed in semi-fluidized bed with superficial liquid velocity for different average particle size at constant bed expansion ratio (*R*=2) in 0.05 m internal diameter column. Increase of fines result in a relatively fast formation of top packed bed, which is evident from Figure 7. Figure 8 depicts the variation of height of top packed bed with superficial liquid velocity for different bed expansion ratio for an initial static bed height of 0.08 m, with a mixture of average particle diameter of 0.001457 m in 0.05 m internal diameter column. From Figure 8, it is clearly observed that with increase in bed expansion ratio the height of top packed bed decreases. This is due to the fact that the buoyancy force is insufficient to lift the particles when the restraint is placed a higher distance in the column with superficial liquid velocity remaining unchanged. The effect of column diameter is shown in Figure 9 where the variation of dimensionless height of top packed bed with superficial liquid flow rate for different diameter columns for an average particle diameter of 0.01509 m, 0.08 m initial static bed height and a bed expansion ratio of 2.5. Increase in column diameter decreases the superficial liquid velocity and thereby relatively fewer amounts of solids are transported to the top.

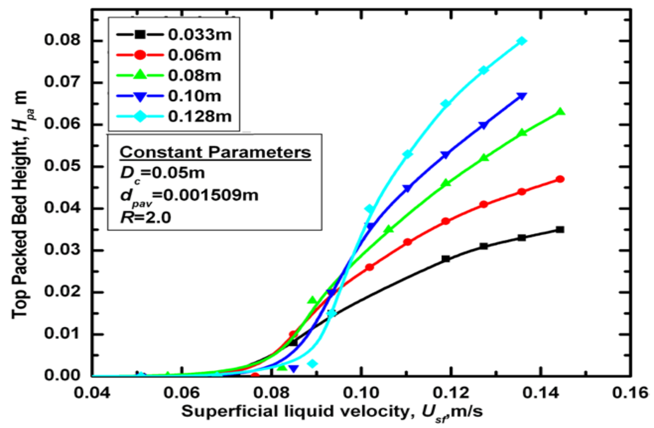

Figure 6: Variation of height of top packed bed with respect to superficial liquid velocity for different initial static bed height.

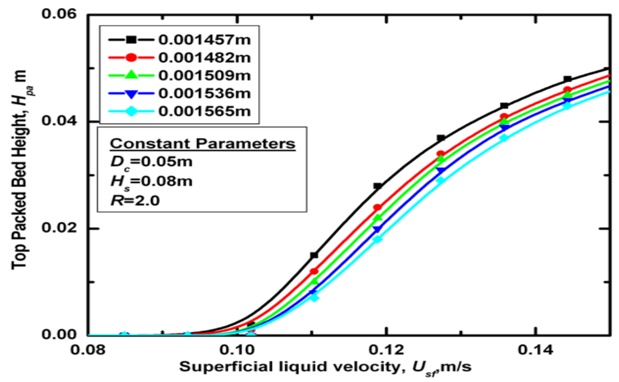

Figure 7: Variation of height of top packed bed with respect to superficial liquid velocity for different average particle diameter.

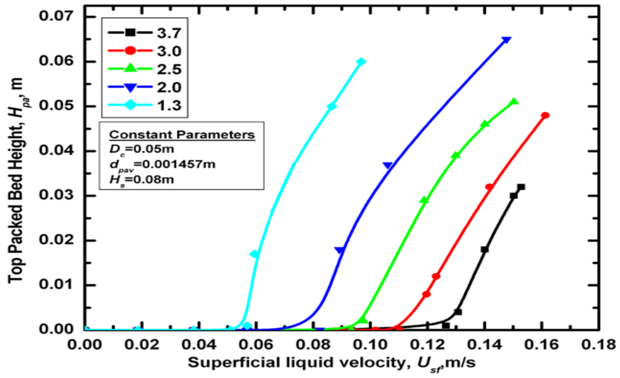

Figure 8: Variation of height of top packed bed with respect to superficial liquid velocity for different bed expansion ratio.

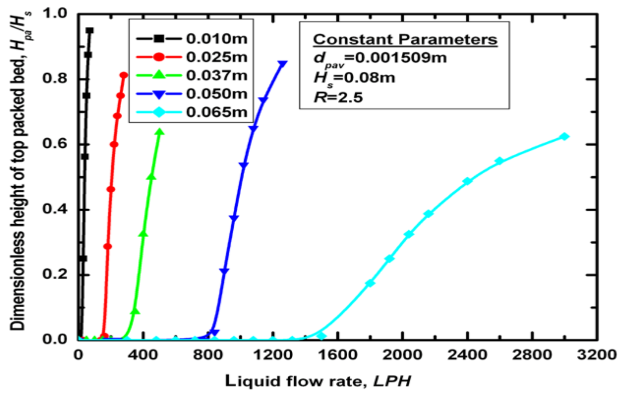

Figure 9: Variation of dimensionless height of top packed bed with respect to liquid flow rate for different column diameters.

Development of correlations by dimensional analysis

The dimensionless semi-fluidized bed pressure drop and top packed bed height are found to be dependent on five different variables viz. H_s, D_c, d_{pav}, G_{sf} and R while dimensionless minimum and maximum semi-fluidization velocities are functions of H_s, D_c, d_{pav}, G_{sf} and R. The values of the parameters and responses for the developing correlations are given in Table 3 and the developed correlations are represented as Eqs. (5) - (8).

For dimensionless semi-fluidized bed pressure drop,

$$\Delta P_{sf}/\Delta P_{mf}=2.73\times10^{-5}(H_s/D_c)^{-0.087}(D_c/H_s)^{-0.404}(d_{pav}/D_c)^{-2.712}(G_{sf}/G_{mf})^{2.995}R^{-0.649} \quad (5)$$

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For dimensionless top packed bed height,

$$H_{pa}/H_s=2.6\times10^{-8}(H_s/D_c)^{-0.135}(D_c/H_s)^{-0.467}(d_{pav}/D_c)^{-4.688}(G_{sf}/G_{mf})^{1.447}R^{-0.623} \quad (6)$$

For dimensionless minimum semi-fluidization velocity,

$$U_{osf}/U_{mf}=7.74(H_s/D_c)^{0.070}(D_c/H_s)^{0.410}(d_{pav}/D_c)^{0.485}R^{1.038} \quad (7)$$

For dimensionless maximum semi-fluidization velocity,

$$U_{msf}/U_{mf}=1\times10^{8}(H_s/D_c)^{0.141}(D_c/H_s)^{0.356}(d_{pav}/D_c)^{5.304}R^{0.626} \quad (8)$$

Figure 10 shows the comparison between the experimental and calculated values (Eq. (1) and Eq.(5)) of $\Delta P_{sf}/\Delta P_{mf}$. The standard deviations and coefficients of correlation are 0.39 and 0.662 for Eq. (1) and 0.94 and 0.982 for Eq. (5) respectively. Figure 11 shows the comparison between the experimental and calculated values (Eq. (2) and Eq. (6)) of H_{pa}/H_s. The standard deviations and coefficients of correlation are 0.06 and 0.703 for Eq. (2), 0.043 and 0.967 for Eq.(6) respectively. Figure 12 shows the comparison between the experimental and calculated values (Eq.(3) and Eq. (7)) of U_{osf}/U_{mf}, which shows standard deviations and coefficients of correlation of0.64 and 0.792 for Eq.(3) and 0.13 and 0.984 for Eq. (7) respectively. Figure 13 shows the comparison between the experimental and calculated values (Eq. (4) and Eq. (8)) of U_{msf}/U_{mf}, which shows standard deviations and coefficients of correlation of 0.60 and 0.460 for Eq. (4) and0.32 and 0.973 for Eq. (8) respectively.

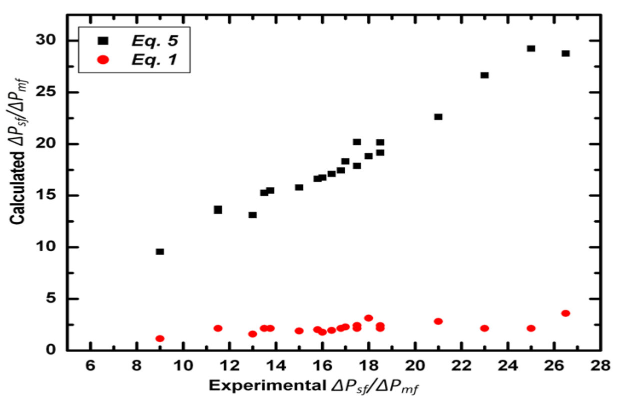

Figure 10: Comparison between the experimental and calculated (Eq. (1) and (5)) values of dimensionless semi-fluidized bed pressure drop.

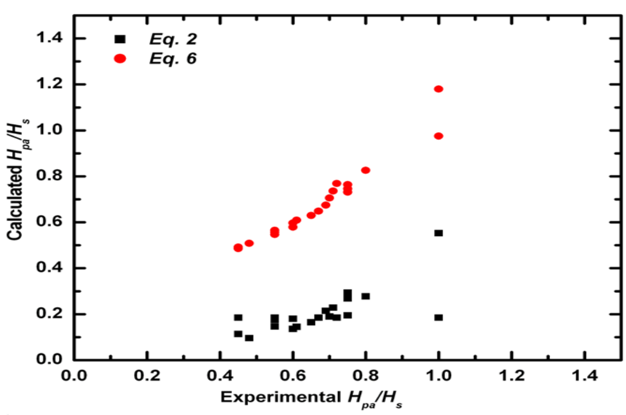

Figure 11: Comparison between the experimental and calculated (Eqs. (2) and (6)) values of dimensionless height of top packed bed.

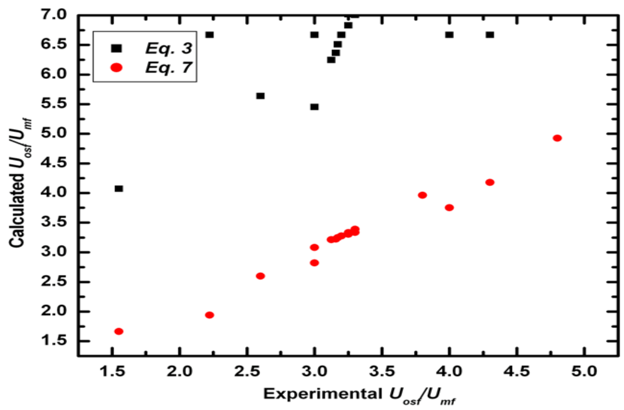

Figure 12: Comparison between the experimental and calculated (Eqs. (3) and (7)) values of dimensionless minimum semi-fluidization.

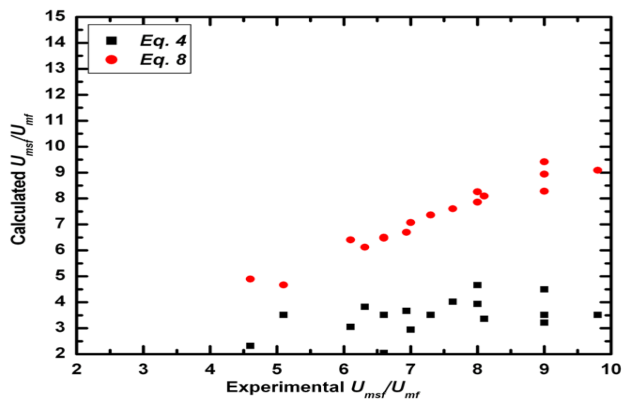

Figure 13: Comparison between the experimental and calculated (Eqs. (4) and (8)) values of dimensionless maximum semi-fluidization velocity.

Development of correlations by Statistical analysis

The method of experimentation is based on statistical design of experiments (Factorial Design Analysis) in order to bring out the interaction effects of variables, which would not otherwise be found by conventional experimentation and to explicitly find out the effect of each of the variables quantitatively on the response. In addition, the number of experiments required is far less compared to the conventional experiments [1].The equations developed by the statistical analysis approach are:

For dimensionless semi-fluidized bed pressure drop:

$$\Delta P_{sf}/\Delta P_{mf}=16.99-0.41\times X_1-2.58\times X_2-0.74\times X_3+4.09\times X_4-2.51\times X_5+0.068\times X_1\times X_2+0.028\times X_1\times X_3-0.086\times X_1\times X_4+0.048\times X_1\times X_5+0.11\times X_2\times X_3-0.53\times X_2\times X_4+0.301.50\times X_2\times X_5-0.14\times X_3\times X_4+0.081\times X_3\times X_5-0.56\times X_4\times X_5+0.034\times X_1^2+0.74\times X_2^2-0.014\times X_3^2+0.28\times X_4^2+0.43\times X_5^2 \quad (9)$$

In Figure 14, the experimental values of $\Delta P_{sf}/\Delta P_{mf}$ have been compared with the calculated values obtained from Eq. (9). The values of standard deviation and correlation coefficient are 0.55 and 0.993.

For dimensionless top packed bed height:

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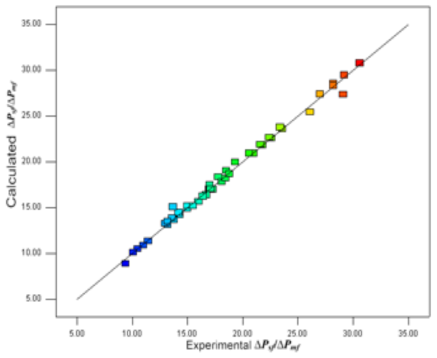

Figure 14: Comparison between the experimental and calculated (Eq. (9)) values of dimensionless semi-fluidized bed pressure drop.

$$H_{pa}/H_s=0.62-0.022\times X_1-0.100\times X_2-0.045\times X_3+0.072\times X_4-0.087\times X_5+6.25\times10^{-4}\times X_1\times X_2-1.250\times10^{-3}\times X_1\times X_3+0.000\times X_1\times X_4+1.250\times10^{-3}\times X_1\times X_5+3.75\times10^{-3}\times X_2\times X_3-7.500\times10^{-3}\times X_2\times X_4+0.011\times X_2\times X_5-1.875\times10^{-3}\times X_3\times X_4+4.375\times10^{-3}\times X_3\times X_5-8.125\times10^{-3}\times X_4\times X_5+5.510\times10^{-3}\times X_1^2+0.021\times X_2^2+3.413\times10^{-3}\times X_3^2+1.974\times10^{-3}\times X_4^2+0.018\times X_5^2 \quad (10)$$

In Figure 15, the experimental values of H_{pa}/H_s have been compared with the calculated values obtained from Eq. (10). The values of standard deviation and correlation coefficient are 0.013and 0.995.

For dimensionless minimum semi-fluidization velocity:

$$U_{osf}/U_{mf}=3.33+0.077\times X_1+0.53\times X_2+0.027\times X_3+0.82\times X_5+8.75\times10^{-3}\times X_1\times X_2+6.25\times10^{-3}\times X_1\times X_3+0.014\times X_1\times X_5+7.50\times10^{-3}\times X_2\times X_3+0.13\times X_2\times X_5+7.5\times10^{-3}\times X_3\times X_5-7.083\times10^{-3}\times X_1^2-0.062\times X_2^2+4.167\times10^{-3}\times X_3^2+6.667\times10^{-3}\times X_5^2 \quad (11)$$

In Figure 16, the experimental values of Uosf/Umf have been compared with the calculated values obtained from Eq. (11). The values of standard deviation and correlation coefficient are 0.023and 0.999.

For dimensionless maximum semi-fluidization velocity:

$$U_{msf}/U_{mf}=7.55+0.32\times X_1+1.03\times X_2+0.7\times X_3+1.14\times X_5+0.035\times X_1\times X_2+0.034\times X_1\times X_3+0.047\times X_1\times X_5+0.095\times X_2\times X_3+0.15\times X_2\times X_5+0.097\times X_3\times X_5-0.041\times X_1^2-0.14\times X_2^2+0.039\times X_3^2-0.046\times X_5^2 \quad (12)$$

In Figure 17, the experimental values of U_{msf}/U_{mf} have been compared with the calculated values obtained from Eq. (12). The values of standard deviation and correlation coefficient are 0.091and 0.998.

The coefficient of correlations for statistical analysis is more than that of dimensional analysis.

Conclusion

Hydrodynamic parameters for the liquid-solid semi-fluidization using homogenous regular ternary mixture viz. the minimum and maximum semi-fluidization velocities, semi-fluidized bed pressure drop, height of top packed bed have the importance for knowing the limits of operational parameters when the semi-fluidized beds are in use. In the current study, investigations have been carried out to study the behavior of homogenous ternary mixtures of regular glass beads with the superficial liquid velocity in a liquid-solid semi-fluidized bed. To get the advantages of a semi-fluidized bed, the fines in the mixture have a great role as those help the fast formation of top packed bed, which is desirable. For small and large scale operations, conduits of different sizes are required. The effects of column diameter and the fines have been studied along with other process variables. Correlations for the calculation of semi-fluidized bed pressure drop, height of top packed bed, minimum and maximum semi-fluidization velocities have been proposed. The values calculated from the developed correlations have been compared with the experimental ones. The values of coefficients of correlation are found to be greater than0.96, thus emphasizing the validity of the developed correlations over the range of the operating parameters investigated. The statistical analysis approach can suitably be used for the development of model equations as it expresses the individual, interaction and cubic effects. Apart from this

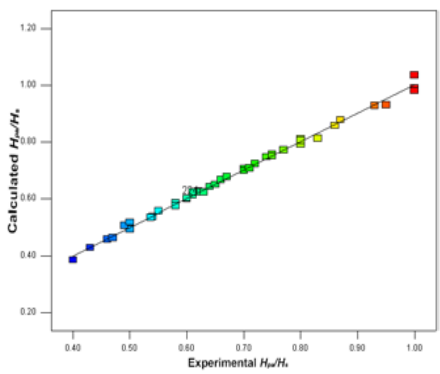

Figure 15: Comparison between the experimental and calculated (Eq. (10)) values of dimensionless height of top packed bed.

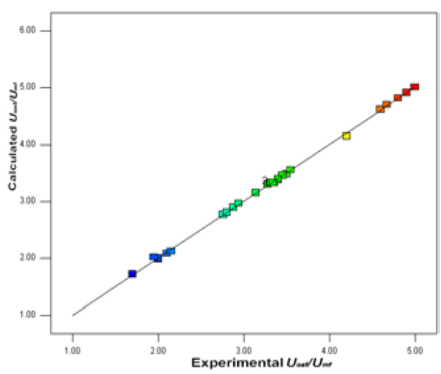

Figure 16: Comparison between the experimental and calculated (Eq. (11)) values of dimensionless minimum semi-fluidization velocity.

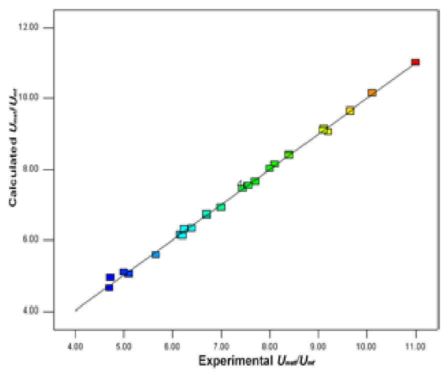

Figure 17: Comparison between the experimental and calculated (Eq. (12)) values of dimensionless maximum semi-fluidization velocity.

the requirement of number of experimental data is less as compared to the conventional method.

The hydrodynamics study conducted and the correlations developed thereof can find potential applications in physical and chemical processing. In the present investigation, the wide range in experimental parameters involved especially with respect to the mixture compositions and the column diameter makes it amenable to logical scale-up while considering design of liquid-solid semi-fluidization systems, involving ternary mixtures of homogenous particles.

Acknowledgement

The authors gratefully acknowledge the support and encouragement received from GIET, Gunupur, Odisha, India-765022.

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