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Semifluidization Characteristics of Some Gas-Solid Systems

Data on semifluidization characteristics of a few gas-solid systems are reported and the effects of different parameters discussed. Correlations for predicting the minimum and maximum semifluidization velocities, the packed bed formation and the bed pressure drop have been developed and presented.

SEMIFLUIDIZATION is a recent development in the field of fluid-solid contact operations. Like the packed and the fluidized beds, this is also a two-phase phenomenon. A semifluidized bed can be viewed as the combination of a batch fluidized bed at the bottom and a fixed bed at the top. Such a bed can be obtained by providing sufficient space for the free expansion of the static bed, and then arresting the escape of the particles out of the system by means of a top restraint. A bed of this nature overcomes the disadvantages of fluidized bed, namely, back-mixing of solids, attrition of particles and problems involving erosion of surfaces, as well as that of the packed bed such as non-uniformity in bed temperature, channel flow and segregation of solids. Consequently, the technique is being successfully employed in industries such as catalytic reactors (mixed tubular reactorsl), ion-exchange columns, heat exchangers, solvent extractors, driers etc.

A review of the literature indicates that very little information is available in the field of semi-fluidization. Comparatively more studies have been made on momentum transfer, the aspects of heat and mass transfer remaining almost untouched.

The pioneer investigators in the field of semi-fluidization are Fan and co-workers[2,3,4] who studied the mechanical and dynamical characteristics of semifluidized bed of single and mixed particles both in liquid-solid and gas-solid systems. Some more studies dealing with various aspects of liquid-solid semifluidization have been reported in literature[5,6,7,8]. It is observed that the data on gas-solid semifluidization are rather meagre[9,10,11,12] Considerable work has still to be carried out to develop correlations for direct prediction of minimum and maximum semifluidization velocities, packed bed formation and pressure drop across the bed, which should take into account the effect of different operating variables in liquid-solid as well as gas-solid systems.

Experimental Set-up and Procedure :

The experimental set-up used in the present study is shown in Fig. 1.

The semifluidizer is made of perspex column of i.d. 4.5 cm and of 57 cm in length. The bottom grid is of a 150 mesh stainless steel screen. A movable restraint made of porous brass plate and a brass screen of 80 mesh both soldered to a brass cone, are rigidly fixed to a 3/16 in. diameter mild steel rod extending to the top of the semifluidizer. Two pressure taps are provided for the orificemeter to record the flow rate of air through the column. The bed pressure drop is noted with two pressure taps, one below the bottom grid and the other at the top of the column. Two sets of manometers are provided, one set for the orifice-meter and the other for measuring the bed pressure drop. One manometer in each set is used for the lower range of flow and the other for the higher range.

While taking a run, a definite amount of material is charged into the column and the bed height is noted. The movable restraint is adjusted for a mixed bed expansion ratio. With increase in air flow rate, pressure drops across the bed and the orificemeter are recorded. The top bed formations are also noted after the onset of semifluidization. The static and expanded bed porosities are determined in separate experiments with weighed amount of samples.

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The materials investigated are quite varied in nature, both spherical and non-spherical materials

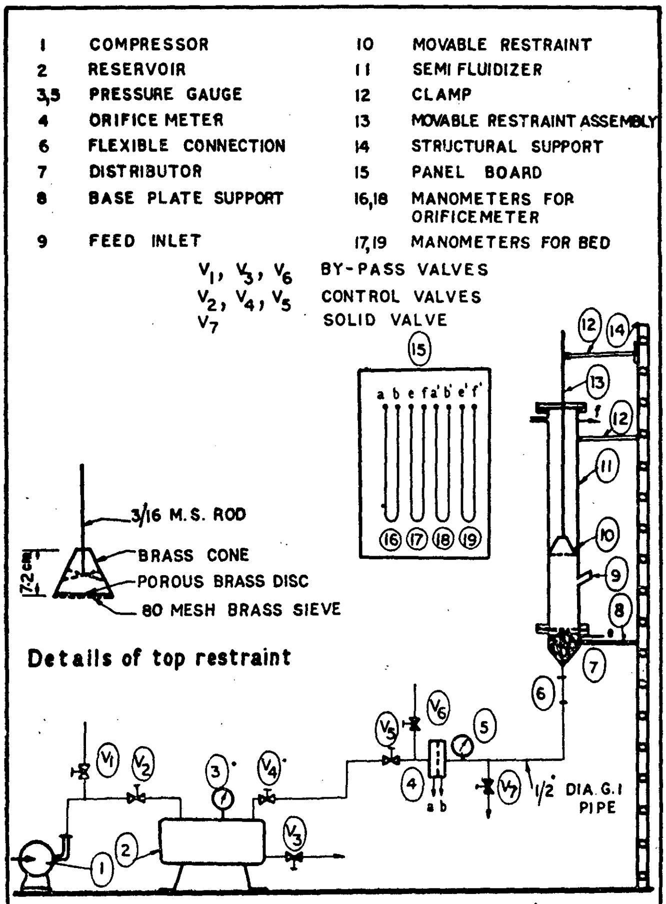

FIG. 1. EXPERIMENTAL SET-UP

being used. Table salt of various size ranges, ammonium sulphate, sand, magnesite, mustard seed and sago have been used. Other important parameters include the initial height of the packed bed, bed expansion ratio and flow rate. The lowest and highest densities of the solids used are 1.12 and 2.80 gm/cm^3 respectively. Four size ranges 20/30, 30/40, 40/52 and 52/60 B.S.S. of materials have been studied. The initial packed bed height varied from 9 to 12 cm. Four bed expansion ratios equal to 2.0, 2.5, 3.0 and 3.5 have been employed. The air pressure was slightly above atmospheric and temperature about 25°C. The humidity of the air used varied between 25% and 30%.

Results and Discussions

Maximum semifluidization velocity (G_{msf}) : The maximum semifluidization velocity has been defined in literature as the final velocity at which the entire solid particles are transferred to the top and give rise to a packed bed formation almost equal to the initial static bed. There are various methods for its prediction. In the present case the values of the maximum semifluidization velocities have been found by using the following methods :

(i) Extrapolation of h_{pa}/h_s versus G plot to a value of $h_{pa}/h_s=1.0$

(ii) Extrapolation of E_f value equal to unity from the plot E_f of versus G.

The values of the maximum velocity obtained by the above two methods are given in Table 1. It can be

TABLE 1

COMPARISON OF MAXIMUM SEMIFLUIDIZATION VELOCITIES (EXPERIMENTAL)

Sl. No.	System	d_p mx10^4	Sphericity	G_{msf}, Kg./hr. m^2 from h_{pa}/h_s vs. G plot for $h_{pa}/h_s=1$	from ϵ_f vs. G plot for $\epsilon_f=1$
	Non-spherical				
1.	Table salt-air	7.51	0.331	14,000	15,000
2.	Table salt-air	4.42	0.452	10,500	12,000
3.	Table salt-air	3.38	0.587	7,500	9,700
4.	Table salt-air	2.74	0.654	5,500	9,200
5.	Ammonium sulphate-air	4.42	0.832	9,000	14,000
6.	Sand-air	4.42	0.798	14,000	15,500
7.	Magnesite-air	4.42	0.770	15,000	16,000
	Spherical				
8.	Mustard seed-air	11.05	1.000	12,400	14,200
9.	Sago-air	11.05	1.000	14,000	15,500

seen that, comparatively higher values of the maximum semifluidization velocity are obtained by extrapolation of E_f versus G plots. The reason is that the correct evaluation of the expanded bed voidage is difficult (owing to slugging, etc.) and as a result, the observed values are always lower than the actual ones. This implies that fluid velocity lesser than the predicted value can be used for the complete transfer of the material to the top.

It is observed that the initial static bed height and the position of movable restraint have no appreciable effect on the maximum semifluidization velocity. The size and density of the material have been found to bear exponential relationship with G_{msf}. These effects have been taken into account by using a dimensionless group, the Archimedes number (Ar) in the correlation,

$$Re_{msf} = 1.15 \times 10^{-3} (Ar)^{0.676} \quad (1)$$

It should be noted that a similar correlation for liquid-solid system had earlier been suggested by the present authors and a nomograph was made[8] for the rapid evaluation of G_{msf}. Similar physical property group was used by Poddar and Butt[5] in their correlation for the liquid-solid system, namely.

$$18\, Re_{msf} + 2.7\, (Re_{msf})^{1.687} = Ga \quad (2)$$

Minimum semifluidization velocity : It is the fluid velocity at which the first particle of the bed touches the top restraint of the semifluidizer[2]. In an actual experiment, it is not exactly possible to visualize this situation. Hence the value of the minimum semifluidization velocity is to be obtained indirectly, When the pressure drop across a bed is plotted against fluid mass velocity on a log-log paper, two distinct breaks are observed in the curve. These two points corresponding to the change of slopes indicate the onset of fluidization (G_{mf}) and the onset of semifluidization (G_{osf}) velocities in order of occurrence.

An alternative method of obtaining the minimum semifluidization velocity is to use the expanded bed data. In the h_f/h_s versus G plots, the fluid velocity corresponding to h_f/h_s=R, represents the minimum semifluidization velocity.

Both the above methods have been used for the prediction of minimum semifluidization velocity in the present case. The values of G_{osf} obtained by the first method are given in Table 2 and for the second in Table 3. It can be seen that comparatively higher values of G_{osf} are obtained in the latter case.

TABLE 2-A

EXPERIMENTAL MINIMUM SEMIFLUIDIZATION VELOCITIES

Sl. No.	System	Red height h_s, cm.	Minimum semifluidization velocity at various bed expansion ratio (R), kg/hr.m² R=2.0	R=2.5	R=3.0	R=3.5
	Effect of particle size					
1.	Table Salt-air (20/30 B.S.S.)	9.0	2,200	2,600	2,900	3,300
		10.0	2,200	2,700	3,000	3,300
		11.0	2,200	2,700	2,800	3,200
		12.0	2,200	2,600	2,800	3,200
2.	Table Salt-air (30/40 B.S.S.)	9.0	1,900	2,000	2,300	2,600
		10.0	1,900	2,000	2,350	2,600
		11.0	1,800	2,000	2,250	2,600
		12.0	1,800	2,000	2,200	2,600
3.	Table Salt-air (40/52 B.S.S.)	9.0	1,550	1,700	2,100	2,300
		10.0	1,450	1,700	2,000	2,200
		11.0	1,450	1,650	2,000	2,200
		12.0	1,400	1,650	2,000	2,200
4.	Table Salt-air (52/60 B.S.S.)	9.0	1,250	1,600	1,850	2,000
		10.0	1,250	1,550	1,850	1,900
		11.0	1,250	1,500	1,850	2,000
		12.0	1,250	1,550	1,850	1,900
	Effect of density of materials					
5.	Ammonium sulphate-air (30/40 B.S.S.)	9.0	1,800	2,100	2,500	2,800
		10.0	1,800	2,100	2,600	2,800
		11.0	1,700	2,000	2,500	2,900
		12.0	1,700	2,000	2,600	2,900
6.	Sand-air (30/40 B.S.S.)	9.0	1,900	2,100	2,500	2,700
		10.0	1,850	2,100	2,450	2,800
		11.0	1,850	2,000	2,500	2,700
		12.0	1,800	2,000	2,450	2,800
7.	Magnesite-air (30/40 B.S.S.)	9.0	1,900	2,100	2,500	2,900
		10.0	1,850	2,000	2,500	2,900
		11.0	1,850	2,200	2,500	2,900
		12.0	1,900	2,100	2,500	2,900
	Effect of sphericity of particles					
8.	Mustard seed-air (14/20 B.S.S.)	9.0	2,500	2,700	3,200	4,000
		10.0	2,400	2,800	3,400	4,000
		11.0	2,400	2,700	3,500	4,000
		12.0	2,500	3,000	3,500	4,000
9.	Sago-air (14/20 B.S.S.)	10.00	2,500	2,900	3,500	4,100

TABLE 2-B

AVERAGE VALUE OF MINIMUM SEMIFLUIDIZATION VELOC TY (EXPERIMENTAL)

Sl. No.	System	Average value of minimum semifluidization velocity at various bed expansion ratios, R, kg/hr.m² R=2 0	R=2.5	R=3.0	R=3.5
	Non-spherical				
1.	Table Salt-air (20/30 B.S.S.)	2,200	2,650	2,900	3,250
2.	Table Salt-air (30/40 B.S.S.)	1,850	2,000	2,275	2,600
3.	Table Salt-air (40/52 B.S.S.)	1,462	1,675	2,025	2,225
4.	Table Salt-air (52/60 B.S.S.)	1,250	1,550	1,850	1,950
5.	Ammonium Sulphate-air (30/40 B.S.S.)	1,750	2,050	2,550	2,850
6.	Sand-air (30/40 B.S.S.)	1,850	2,050	2,450	2,750
7.	Magnesite-air (30/40 B.S.S.)	1,875	2,100	2,500	2,900
	Spherical				
8.	Mustard seed-air (14/20 B.S.S.)	2,450	2,800	3,400	4,000
9.	Sago-air (14/20 B.S.S.)	2,500	2,900	3,500	4,100

TABLE 3
EXPERIMENTAL MINIMUM SEMIFLUIDIZATION VELOCITIES (FROM EXPANDED BED DATA)

Sl. No.	System	d_p m × 10^4	Minimum semifluidization velocities at various bed expansion ratios, R, kg/hr.m^2			
			R=2.0	R=2.5	R=3.0	R=3.5
Non-spherical						
1.	Table Salt air	7.51	3,700	4,600	5,600	6,400
2.	,, ,,	4.42	2,600	3,200	3,800	4,400
3.	,,	3,38	2,150	2,750	3,400	4,000
4.	,,	2.74	1,800	2,350	3,000	3,700
5.	Ammonium Sulphate-air	4.42	2,300	3,050	3,900	4,700
6.	Sand-air	4.42	2,750	3,900	5,200	6,450
7.	Magnesite-air	4.42	3,100	3,800	4,700	5,600
Spherical						
8.	Mustard seed-air	11.05	3,600	4,700	5,500	6,400
9.	Sago-air	11.05	3,800	4,700	5,700	6,750

In gas-soild semifluidization, the properties of the fluid and the solid as well as the geometry of the system will determine the velocity at which the onset of semifluidization occurs. Among the variables, the important ones are h_s, D_c, d_p, P_s, P_f and R. It has been observed in course of investigation that the static bed height has no appreciable effect on the onset of semifluidization velocity (Table 2-A). As a result, an average value of the minimum semifluidization velocity at a particular bed expansion ratio can be used irrespective of the static bed height (Table 2-B). Also the column diameter has not been altered in the present study. Therefore, the effects of h_s and D_c are not relevant. The effect of particle size on the minimum semifluidization velocity is quite pronounced and it is found that the coarser is the particle, the higher will be the velocity. Similarly, in studying the effect of density it is found that the higher is the density of the material, the higher will be the onset of semifluidization velocity. The effect of bed expansion ratio on the minimum semifluidization velocity is quite prominent. An increase in the bed expansion ratio will increase the onset velocity of semifluidization. Poddar and Dutt[5] suggested the following equation for the pediction of G_{0sf} in liquid-solid system.

$$18\,Re_{osf} + 2.7\,Re_{osf}^{1.687} = 0.966\varphi_s^{0.88}\,Ga\left[1 - \frac{h_s}{h}\left(1 - \epsilon_{pa}\right)\right]^{4.7} \quad (3)$$

For liquid--solid system Roy and Sarma[7] suggested an equation relating G_{osf} with G_{msf} as

$$G_{osf}/G_{msf} = 0.105\,(R) + \frac{\log(Ar) + 2.465}{52} \quad (4)$$

Considering the parameters of importance, the following equation has been developed by the present authors[12] for predicting G_{osf} for gas-solid systems :

$$G_{osf}/G_{msf} = 48.0\,(D_c/d_p)^{0.38}\,(\rho_f/\rho_s)^{1.05}\,R^{0.64} \quad (5)$$

Packed bed formation : It is important to know the variation in the height of packed bed with change in the velocity of the fluid, the two limits of the velocity being the onset of semifluidization velocity and the maximum semifluidization velocity.

Fan and co-workers proposed an expression (valid for both gas-solid and liqid-solid systems) for the prediction of packed bed height. The equation suggested is,

$$f\,[(h-h_s)/(h-h_{pa}),\ (G_{sf}-G_{mf})/(G_{msf}-G_{mf})] = 0 \quad (6)$$

Roy and Sarma[7] modified equation(6) by introducing the onset of semifluidization velocity (G_{osf}) term in place of the minimum fluidization velocity (G_{mf}). Thus,

$$(h-h_s)/(h-h_{pa}) = [(G_{sf}-G_{osf})/(G_{msf}-G_{osf})]^{0.2} \quad (7)$$

Besides equation(6), Fan and co-workers suggested an altogether different type of correlation from material balance considerations. Thus.

Thus, $$h_{pa} = (h_f-h)\frac{(1-\epsilon_f)}{(\epsilon_f-\epsilon_{pa})} \quad (8)$$

The experimental and calculated values of packed bed formation were comparable upto a value of Ef=0.8.

The present authors have developed the following relationships for the prediction of packed bed formation in gas-solid semifluidization[1]!.

For spherical particles,

$$\frac{h_{pa}}{h_s} = 1.25\text{x}10^{-5}(G_{sf}/G_{msf})^{3.13}\left(\frac{D_c}{d_p}\right)^{-0.72}\left(\frac{\rho_s}{\rho_f}\right)^{2.19}\left(\frac{h_s}{D_c}\right)^{2.79}(R)^{-1.66} \quad (9)$$

For non-spherical particles,

$$\frac{h_{pa}}{h_s} = 1.07\times10^{-5}\left(\frac{G_{sf}}{G_{msf}}\right)^{3.22}\left(\frac{D_c}{d_p}\right)^{-0.71}\left(\frac{\rho_s}{\rho_f}\right)^{2.18}\left(\frac{h_s}{D_c}\right)^{2.78}(R)^{-1.66} \quad (10)$$

Pressure drop across the bed : The pressure drop in a semifluidized bed should be ideally = the algebraic sum of the pressure drop across the fluidized section and the packed section, as both are aligned in series in the direction of the flow. For the systems investigated, the experimental pressure drops have been compared with those calculated by using equations suggested in literature. In finding the pressure drop in the fluidized section, Leva's equation has been used. The pressure drop for the packed section has been calculated by using three equations, namely, (1) Kozeny-Carman, (2) Leva, and (3) Ergun's equation. Judging from all considerations Ergun's equation has been found to be the most suitable relationship. It is observed that the sum total of the pressure drops calculated as above deviate considerably from the experimental pressure drops across the bed. Also, it is seen that the magnitude of this deviation depends on the system and the conditions of the experiment. Accordingly, the ratio of the pressure drops, $(\triangle P_t)$ actual/$(\triangle P_t)$ calculated has been correlated[10] with the system variable in the following manner :

For non-spherical particles,

$$\frac{(\triangle P_t)\ \text{actual}}{(\triangle P_t)\ \text{calculated}} = 1.95\times 10^{-1}\left(\frac{D_c}{d_p}\right)^{-0.24}\left(\frac{\rho_s}{\rho_f}\right)^{0.55}\left(\frac{h_s}{D_c}\right)^{-0.94}(R)^{0.72}\left(\frac{h_{pa}}{h_s}\right)^{0.29} \quad (11)$$

For spherical particles,

$$\frac{(\triangle P_t)\ \text{actual}}{(\triangle P_t)\ \text{calculated}} = 7.3\times 10^{-3}\left(\frac{D_c}{d_p}\right)^{-0.53}\left(\frac{\rho_s}{\rho_f}\right)^{1.18}\left(\frac{h_s}{D_c}\right)^{-2.05}(R)^{1.56}\left(\frac{h_{pa}}{h_s}\right)^{0.64} \quad (12)$$

For a given set of experimental conditions $(\triangle P_t)$ calculated can be known beforehand and using equations(11) or (12) the actual pressure drop can be calculated.

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NOMENCLATURE

Ar Archimedes number, $d_p^3 g_c \rho_s(\rho_s-\rho_f)/\mu^2$

d_p particle diameter, L.

D_c diameter of semifluidizer, L.

G mass velocity of fluid, $ML^{-2}\theta^{-1}$; subscripts 'mf', 'msf', 'osf' and 'sf' refer to minimum fluidization, maximum semifluidization, onset of semifluidization and semifluidization conditions respectively.

G_a Galileo number, $d_p^3 g_c \rho_f(\rho_s-\rho_f)/\mu^2$

g_c gravitational constant, $L\theta^{-2}$

h bed height (or height of semifluidizer); subscripts 'f', 'pa' and 's' refer to the heights of fully fluidized bed, packed bed in semi-fluidization and initial static bed respectively.

$\triangle P_t$ overall pressure drop through the semifluidized bed, $ML^{-1}\theta^{-2}$

R bed expansion ratio, h/h_s

Re Reynolds number, $d_p G/\mu$; subscripts 'osf' and 'msf' refer to onset of semifluidization and maximum semifluidization conditions respectively.

GREEK LETTERS

ϵ porosity; subscripts 'f' for fluidized and 'pa' for packed beds respectively.

ρ density, ML^{-3}; subscripts 'f' for fluid and 's' for solid respectively

μ viscosity of fluid, $ML^{-1}\theta^{-1}$

$\varnothing_s$ particle shape factor.

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