Design of a gas-solid semifluidizer

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Reprinted from Chemical Industry Developments incorporating CP&E, May 1973

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Abstract

A SEMIFLUIDIZED bed is a compromise between the packed and fluidized bed conditions, wherein certain drawbacks of both the operations are eliminated. Based on correlations developed by the authors for predicting the minimum and the maximum semi-fluidization velocities, the packed bed formation and the pressure drop across a semifluidized bed, a method is suggested for the design of a gas-solid semifluidizer.

SEMI-FLUIDIZATION is a recent development in the field of fluid-solid contact operations. This can be reviewed as the combination of a batch fluidized bed at the bottom and a fixed bed at the top. The process takes into consideration the merits of both fixed and fluidized beds. This technique can be successfully employed in industries such as catalytic reactors (mixed tubular reactors[1]), ion-exchange columns, heat exchangers, solvent extractors, driers, etc.

A glance into the literature reveals that scanty information is available in the field of semi-fluidization, liquid-solid as well as gas-solid systems. Some studies have been reported for the prediction of minimum and maximum semi-fluidization velocities[1,2,3,4,6,7] the packed bed formation[3,4,8,9] and the pressure drop across the bed[8]. Very little informations on heat and mass transfer in semifluidized bed is reported and there is considerable scope for work in these fields. The technique offers immense potential in processes involving heat and/or mass transfer, as well as in the field of reaction kinetics. The design approach for such units is lacking in literature and as such, a method, based on correlations developed by the authors for gas-solid systems, is reported in the present paper.

Maximum semi-fluidization velocity

The maximum semi-fluidization velocity has been defined as the velocity at which the entire solid particles are transferred to the top and give rise to a packed bed formation almost equal to initial static bed. This velocity also corresponds to the terminal free fall velocity of the particles. There are three methods for finding the maximum semi-fluidization velocity.

(i) Linear extrapolation of expanded bed voidage (ϵ_f) vs fluid mass velocity plot to the value of $\epsilon_f = 1.0$.

(ii) Extrapolation of h_{pa}/h_s vs fluid mass velocity plot to the value of $h_{pa}/h_s = 1.0$.

(iii) By calculation of terminal free fall velocity, either by the application of the laws of gravity settling in the appropriate ranges or by the method suggested by Pinchbeck and Popper[5].

For gas-solid system Fan et al. 4 compared maximum semi-fluidization velocity with the terminal free fall velocity of the particles. Comparison on a similar line has been made by Roy and Sarma[7] for liquid-solid system. An empirical equation for predicting the maximum semi-fluidization velocity for such system has also been developed as,

$$G_{msf} = 0.3\ (Ar)^{0.58}\ (\mu/d_p) \quad \ldots \quad (1)$$

Based on the above equation a nomograph was made for the rapid evaluation of G_{msf}[10]. Poddar and Dutt[8] have given the following equation for the prediction of the maximum semi-fluidization velocity in liquid-solid system.

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

$$\text{where } Re_{msf} = (d_p G_{msf})/\mu \quad \ldots \quad (3)$$

The present authors have deveioped- an equation applicable for gas-solid systems (spherical as well as non-spherical particles) as follows :

$$Re_{msf} = 1.15 \times 10^{-3}\ (Ar)^{0.676} \quad \ldots \quad (4)$$

Minimum semi-fluidization velocity

It is the minimum fluid velocity at which the first particle of the bed touches the top restraint of the semi-fluidizer. In an actual experiment, it is not exactly possible to visualise the situation. Hence the value of the minimum semi-fluidization velocity is to be obtained indirectly. The following two methods are normally used:

1. By plotting the fluid mass velocity against pressure drop on log paper, two distinct breaks are observed the first one corresponds to minimum fluidization velocity and the second for G_{osf}.

2. From the plot of h_f/h_s against fluid mass velocity, where the fluid velocity corresponding to $h_f/h_s = R$, represents the G_{osf}.

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The pioneer investigators Fan, Wang and Wen[3,4] studied the dynamical characteristics of semi-fluidized bed of single size particles for both liquid-solid and gas-solid systems. It was observed that G_{osf} is dependent on the physical properties of the system and the bed expansion ratio.

Poddar and Dutt[6] suggested the following equation for the prediction of G_{osf} in liquid-solid system.

$$18\ Re_{osf} + 2.7\ Re_{osf}^{1.687} = 0.966\phi_s^{0.88}\ G_a[1-(h_s/h)\ (1-\ \epsilon_{pa}]^{4.7} \qquad \ldots \quad (5)$$

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

$$(G_{osf}/G_{msf}) = 0.105\ (R) + [(\mathrm{Log}\ (Ar) + 2.465)/52] \qquad \ldots \quad (6)$$

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

Packed bed formation

In semi-fluidization, it is important to know the variation in the height of the packed bed with the change in the velocity of the fluid. Fan and co-workers[3,4] suggested the following relation (valid for gas-solid and liquid-solid systems) for the prediction of packed bed height,

$$f\left[\frac{h - h_s}{h - h_{pa}},\ \frac{G_{sf} - G_{mf}}{G_{msf} - G_{mf}}\right] = O \qquad (8)$$

Roy and Sarma[8] have offered a modified equation of the type,

$$\frac{h - h_s}{h - h_{pa}} = \left[\frac{G_{sf} - G_{osf}}{G_{msf} - G_{osf}}\right]^{0.2} \qquad \ldots \quad (9)$$

An altogether different type of correlation (obtained from material balance consideration) has been suggested by Fan and co-workers as,

$$h_{pa} = (h_f\text{-}h).\ [(1\text{-}\epsilon_f)/\ (\epsilon_f\text{-}\epsilon_{pa})] \qquad \ldots \quad (10)$$

Based on the data for gas-soild system the following equation has been developed" by the present authors relating h_{pa}/h_s with G_{sf}/G_{msf},

$$\frac{G_{sf}}{G_{msf}} = 1.52\times10^{3}\ \left(\frac{D_c}{d_p}\right)^{0.40} \left(\frac{\partial_s}{\partial_f}\right)^{-1.24} \left(\frac{h_s}{D_c}\right)^{-1.58} (R)^{0.94} \left(\frac{h_{pa}}{h_s}\right)^{0.56} \qquad \ldots \quad (11)$$

Pressure drop

The pressure drop in a semifluidized bed should be ideally equal to the algebraic sum of the pressure drops across the fluidized section and the packed section, as both are aligned in series in the direction of flow. Fan and Co-workers[4] measured the total pressure drop occurring during semi-fluidization and compared these measured values with those calculated from theoretical equations. They have used Ergun's equation for calculation of the pressure drop for the packed section. The equation for total pressure drop was given as :

$$\begin{aligned}\triangle P_t &= (\triangle P/L)_{pa}.h_{pa} + (\triangle P/L)_f\ (h - h_{pa})\\ &= [150(1\text{-}\epsilon_{pa}/\epsilon_{pa}^{3})\ (\mu u/d_p^{2}) + 1.75\ (1\epsilon_{pa}/\epsilon_{pa}^{3})\ (Gu/d_p)]\\ &\quad [(h_f - h)\ (1\text{-}\epsilon_f/\epsilon_f\text{-}\epsilon_{pa})]\ ^{1/g_c}\\ &\quad + [h_f\text{-}(1\text{-}\epsilon_{pa})\ (h_f\text{-}h)]/\ [(\epsilon_f\text{-}\epsilon_{pa})]\ [1\text{-}\epsilon_f)\ (\partial_f\text{-}\partial_s)]\end{aligned} \qquad 12$$

The authors concluded that equation (12) gives lower values compared to the experimental ones.

The present authors have developed correlations for predicting the pressure drop in a gas-solid semi-fluidized bed. The pressure drop for packed section has been calculated using Ergun's equation and for the fluidized section, Leva's equation has been used. The sum total of the calculated pressure drop, $(\triangle P_t)_{calculated}$ was correlated[14] with $(\triangle P_t)_{actual}$ as follows:

$$\frac{(\triangle P_t)_{actual}}{(\triangle P_t)_{calculated}} = 1.96 \times 10^{-1}$$

$$[(D_c/d_p)^{-0.24}\ (\partial_s/\partial_f)^{0.55}\ (h_s/D_c)^{-0.94}\ R^{0.72}\ (h_{pa}/h_s)^{0.29}] \quad \ldots\ 13$$

The use of the above equations for the design of a gas-solid semi-fluidizer may be illustrated with the help of the following example.

Illustration

It is desired to semifluidize a bed of dry silica gel using air at 70°F such that 1/3rd of the total material (by weight) goes to the packed section, while the balance remains in the fluidized state. The bed contains 1 kg of silica gel and the internal diameter of the semi-fluidizer is 7.5 cms. The top restraint is placed at a height equal to twice the initial static bed height. Calculate, (a) the ranges for the semi-fluidization operation, (b) the heights of the packed and the fluidized sections, (c) the semi-fluidization velocity and (d) the power necessary for the above case.

The following data are given:

For air

Density	0.0012 gms/cc.
Viscosity	0.00018 poise

For dry silica gel shape-irregular

Density	2.65 gms/cc.
Particle size	0.0442 cm.
Porosity ϵ_{pa}	0.451
Sphericity, ϕ_s	0.798
Surface area, S_o	170.5 cm^2/sec.

The bed expansion data for silica gel-air system are as follows:

G, Kg/hr.m^2	780	1433	1790	2315	2590	2960	3490	4100	4590	5095	5550	6350	6815
ϵ_f	0.506	0.560	0.636	0.697	0.720	0.745	0.768	0.784	0.799	0.812	0.824	0.839	0.849
$\frac{h_f}{h_s}$	1.112	1.245	1.510	1.810	1.962	2.150	2.360	2.545	2.740	2.925	3.110	3.400	3.620

Solution

Part (a)

It is well-known that the semi-fluidization operation may range between the minimum and the maximum semi-fluidization velocities.

Maximum **semi-fluidization velocity**:

For the given conditions the Archimedes number becomes,

$$Ar = \frac{(0.0442)^3 \times 981 \times 2.65 \times (2.65 - 0.0012)}{(0.00018)^2} = 1.84\times10^7$$

From equation (4),

$$Re'_{msf} = 1.15\times10^{-3}\ (1.84\times10^7)^{0.676} = 93.5$$

$$\text{i.e.,}\ \frac{6\ G_{msf}}{\mu_f\ \phi_s\ S_o} = 93.5$$

$$\text{So, } G_{msf} = \frac{93.5\times0.00018\times0.798\times170.5}{6}\ \frac{gm}{cm^2.\ sec.}$$

$$= 13{,}720\ Kg/hr.m^2$$

Minimum semi-fluidization velocity

The minimum semi-fluidization velocity can be calculated from equation (7). In the present case,

$$\frac{D_o}{d_p} = \frac{7.5}{0.0442} = 169.8$$

$$\frac{\partial_s}{\partial_f} = \frac{2.65}{0.0012} = 2{,}208;\quad R = 2.0$$

$$\therefore \frac{G_{osf}}{G_{msf}} = 48.0\ (169.8)^{0.38}\ (2{,}208)^{-1.05}\ (2)^{0.64} = 0.162$$

$$\text{or, } G_{osf} = 0.162\ G_{msf} = 0.162\times13{,}720 = 2{,}225\ Kg/hr.m^2$$

So, semi-fluidization occurs between fluid mass velocities of 2,225 to 13,720 Kg/hr.m^2

Part (b)

The initial static bed height may be calculated as follows:

$$\text{Weight of material} = 1.0\ Kg$$

$$\text{Solid volume} = \frac{1.0 \times 1000}{2.65} = 378\ c.c.$$

$$\epsilon_{pa} = 0.451$$

$$\text{Again, solid volume} = A \times h_s\ (1 - \epsilon_{pa})$$

$$\text{Area of cross-section, } A = \pi/4\ (7.5)^2 = 44.2\ cm^2$$

$$\therefore h_s = 378/44.2\times(1\text{-}0.451) = 15.6\ cms.$$

Since R = 2.0 × the height of semifluidized bed,

$$h = 15.6 \times 2 = 31.2\ cms.$$

The height of packed section in the semifluidized bed,

$$h_{pa} = 1/3h_s = 1/3 \times 15.6 = 5.2\ cms.$$

$$\text{Height of fluidized section,}\quad h_f = 31.2 - 5.2 = 26.0\ cms.$$

Part (c)

The semi-fluidization velocity for the conditions stated is calculated by using equation (11).

In this case,

$$\frac{h_s}{D_o} = \frac{15.6}{7.5} = 2.08;\ \frac{h_{pa}}{h_s} = 0.33$$

$$\frac{G_{sf}}{G_{msf}} = 1.52\times10^3\ (169.8)^{0.40}\ (2{,}208)^{-1.24}$$

$$(2.08)^{-1.58}\ (2.0)^{0.94}\ (0.33)^{0.56}\ ] = 0.276$$

$$\text{i.e., } G_{sf} = 0.276\ G_{msf} = 0.276\times13{,}720$$

$$= 3{,}790\ Kg/hr.\ m^2$$

Part (d)

The bed expansion ratio, h_f/h_s and expanded bed porosity e_f have been plotted as functions of fluid mass velocity in Figs. 1 and 2 respectively. For finding the pressure drop across the semifluidized bed equations (12) and (13) may be used.

In the present case,

G_{sf} = 3,790 Kg/hr.m^2; U = 3790/1.2 = 3160 m/hr.

The value of h_f/h_s corresponding to G_{af} = 3,790 Kg/hr.m^2 is obtained from Fig. 1 and equals to 2.45 So. h_1 = 15.6 X 2.45 = 38.2 cms.

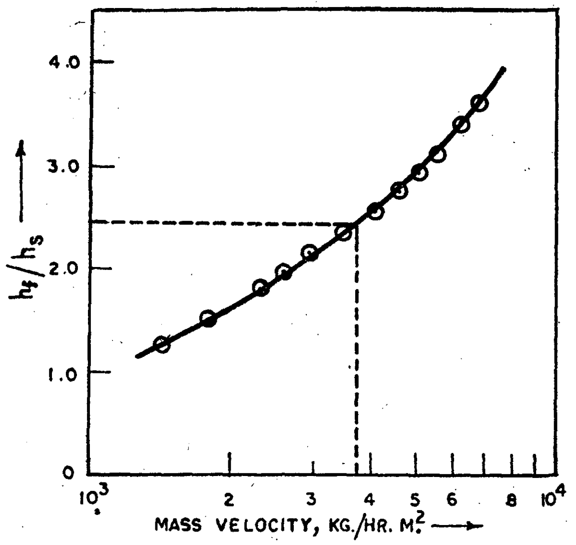

Fig. 1
Variation of bed expansion ratio with fluid mass velocity.

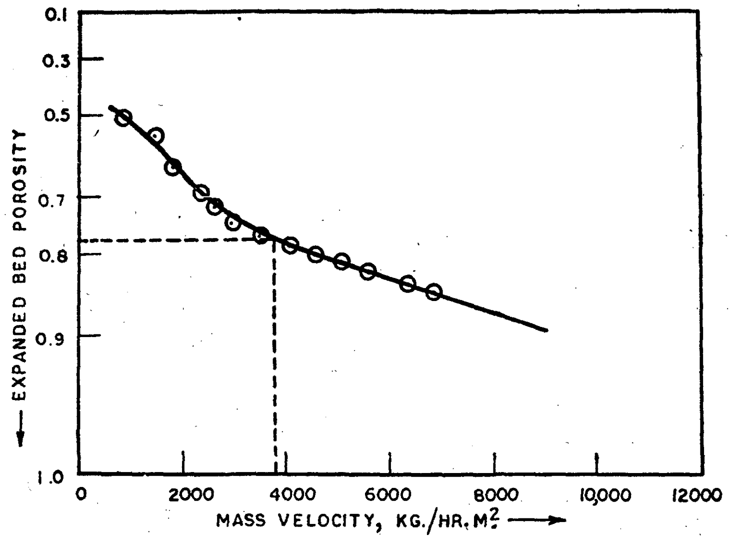

Fig. 2
Variation of expanded bed porosity with fluid mass velosity.

From Fig. 2, $\epsilon_f = 0.780$
Substituting the values in equation (12)

$$(\triangle P_t)_{\text{calculated}} = \left[150\,\frac{(-0.451)^2}{(0.451)^3} \times \frac{(0.0648)\ (3{,}160)}{(0.000442)^2}\right] + \left[1.75\,\frac{(1\text{-}0.451)}{(0.451)^3} \times \frac{(3{,}790)\ (3{,}160)}{0.000442}\right]$$

$$\left[\frac{1}{100}\,(38.2\text{-}31.2)\,\frac{(1\text{-}0.780)}{(0.780\text{-}0.451)}\right]\left[\frac{1}{1.272\times 10^8} + \frac{1}{100}\right]\left[38.2 - \frac{(1\text{-}0.451)\ 38.2\text{-}31.2)}{0.780\text{-}0.451}\right]\left[(1\text{-}0.780)\ (2.650\text{-}1.2)\right]$$

$= 293.0 + 145.0 = 447.0$ Kg/m².
$(\triangle P_t)_{\text{actual}}$ is obtained from equation (13),

$$\text{i.e., } \frac{(\triangle P_t)_{\text{actual}}}{(\triangle P_t)_{\text{calculated}}} =$$

$$1.95\times 10^{-1}\left[(169.8)^{-0.24}(2{,}208)^{0.55}(2.08)^{-0\cdot 94}(2.0)^{0.72}(0.33)_0^{\cdot 23}\right]$$
$$= 2.37$$

i.e., $(\triangle P_t)_{\text{actual}} = 2.37\times 447 = 1{,}060$ Kg/m².
Flow rate $= A.\ U = \pi/4\ (7.5/100)^2 \times 3{,}160$
$= 13.96$ m³/hr.
∴ Power reqd $= 1{,}060 \times 13.96 \times 3{,}653 \times 10^{-6}$
$= 0.054$ h.p.

Nomenclature

A	cross-sectional area of column, L^2
Ar	Archimedes Number dimensionless, $d_p^3\, g_c\, \partial_s\, (\partial_s\text{-}\partial_f)/\mu^2$
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 semi-fluidization, onset of semi-fluidization and semi-fluidization conditions respectively.
Ga	Gaileleo Number, $d_p^3\, g_c\, \partial_t\, (\partial_s\text{-}\partial_f)/\mu^2$
g_c	gravitational constant. $L\theta^{-2}$
h	bed height, L; 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, FL^{-2}
$\triangle P/L$	pressure drop per unit length, FL^{-3}; subscripts f and pa refer to fluidized section and packed section of the semifluidiser respectively.
R	bed expansion ratio in case of semi-fluidization, h/h_s

Re	Reynold's Number d_p G/μ; subscripts msf and osf refer to maximum semi-fluidization and onset of semi-fluidization conditons respectively.
Re'_{msf}	modified Reynold's number; 6 $G_{msf}/\mu\phi_s$ So
So	interfacial area of packed solid, L^2/L^3
u	superficial velocity of the fluid $L\theta^{-1}$

Greek letters

ϵ_f	porosity of fluidized section or fully fluidized bed.
ϵ_{pa}	porosity of the packed section
μ	viscosity of fluid, ML^{-1} 0^{-1}
∂_f	density of the fluid, ML^{-3}
∂_s	density of the solid, ML^{-3}
ϕ_s	shape factor

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