Semifluidization — a review

G. K. ROY & K. J. R. SARMA,
Regional Engineering College Rourkela-8.

Scope of semifluidization

SEMIFLUIDIZATION is a new and unique type of fluid-solid contacting technique which has been reported recently. In most of the chemical plants we come across situations where a solid phase has to be kept in contact with a fluid phase — for example diffusional operations like drying, adsorption, reaction kinetics, solid catalysed reactions, heat transfer, etc. In all these cases fluid solid contacting is very essential and developments to increase the efficiency of contact are always welcome. Fixed bed or packed bed, batch and continuous fluidization and semifluidization all are two phase phenomena. In case of batch fluidization if the free expansion of the bed is restricted by the introduction of porous disc or sieve and the fluid velocity is increased the particles are fluidized and the expansion starts with further increase in velocity of fluid—the particles will be carried and the formation of a fixed bed results at the top. So by the introduction of restraint some of the particles are distributed to bottom section which is in the form of a packed bed. This is known as semifluidization which can be considered as a new type of solid-fluid contacting method which combines the features of both fixed and fluidized beds.

This type of technique overcomes the disadvantages of fluidized bed namely back mixing of solids, attrition of solids and problems involving erosion of surfaces. This also overcomes certain draw backs of packed bed, viz., non-uniformity in temperature in the bed, channel flow and seggregation of solids.

Application of semifluidization in the field of reaction kinetics has already been initiated. This technique is advantageous for fast exothermic reactions such as vapour phase oxidation and chlorination of hydrocarbons, etc. Use of this technique in studies in 'mass transfer have shown that the magnitudes of mass transfer coefficients can be controlled approximately linearly and within the limits of a completely fixed bed and fully fluidized bed by means of bed expansion alone.

Semifluidization is a compromise between the two and the particles can be distributed into the two sections as desired by chosing the parameters like position of restraint, fluid velocity, etc.

Present state of development

The literature available so far on semifluidization can be classified under the following heads: (i) Studies oriented towards prediction of the onset and maximum semifluidization velocities; (ii) Studies oriented towards the prediction of packed bed height; (iii) Studies on total pressure drop; and (iv) Studies on mass transfer, reaction kinetics and other related fields.

Minimum (onset) and maximum semifluidization velocities

Minimum (onset) semifluidization velocity (G_{osl})

This depends upon (i) characteristics of particles (ii) fluidizing medium and also upon the quantity of particles in relation to column size (i.e.) h_s/h ratio. When the restraint is very near the initial packed height $h_s/h = 1$, the onset of fluidization velocity itself, is the semifluidization velocity. When the restraint is far above the initial packed bed h_s/h approaches zero, semifluidization cannot be achieved unless the velocity of the fluid approaches that of the terminal velocity of the particles.

Mdocimum semifluidization velocity (G_{msf}): While the minimum semifluidization velocity depends upon static bed height relative to the overall height of the bed, the maximum semifluidization velocity corresponds to the terminal free fall velocity of the particles. Above this velocity all the particles will be in the packed section and the entire bed will be fixed one.

There are three methods of estimating the maximum semifluidization velocity: (i) linear extrapolation of ϵ_f vs. G curves to value of $\epsilon_f = 1.0.$; (ii) Extrapolation of h_{pa}/h_s vs. G curves to values of $h_{pa}/h_s = 1.$, and (iii) by calculation of terminal free fall velocity by one of the three methods, namely, (i) Application of laws of gravity settling in the appropriate ranges, (ii) Method of Pinchbeck and Popper using equation

$$Re_T = -.6 + \sqrt{36 + 2/3\ g(\rho_s - \rho_f)\ \rho_f D_p^3/\mu^2} \quad (1)$$

and (ii) Plots of $C_d.\ Re^2$ vs. Re.

$$Cd.Re^2 = \left\{[4g\ \rho_f\ D_p^3(\rho_s - \rho_f)]/\ (3\mu^2_f),\right\}, \quad [Re\ D_p\mu t\ \rho_f]/\mu_f \quad \ldots \quad (2)$$

The first method is based on the fact that if the bed expansion is not restricted, at velocities above the maximum semifluidization the particles will be simply carried out of the column — approaching condition of $\epsilon_f = 1$. The second method is based on the fact that if all the particles in the fluidized bed are to be transferred to the packed bed the velocity must be maximum semifluidization velocity beyond which there is no semifluidization. The third method is based on the assumption that the particles can be carried over only when the fluid velocities are higher than the free fall velocity of the particles. If the values of G_t evaluated by these three methods are compared, one will observe that there is a difference.

The values obtained by the second method are always greater than method one. The reasons may be due to the following facts: (i) the particles are not of uniform size always, and (ii) porosity of the packed bed above is assumed to be the same as that of the least dense static bed which was there prior to fluidization. The values of the first method are less due to the fact that porosity of the bed is not uniform. The values calculated by the laws of settling are much lower because the equations for gravity settling are derived for single particles. There is definite influence of the other particles also of the column and supporting screen.

Fan, Yang and Wen, Poddar and Dutta, Roy and. Sarma are the main workers who have reported correlations for prediction of the onset and 'maximum semifluidization velocities.

Fan and Co-workers' correlation for predicting the packed bed formation can also be used to predict the maximum semifluidization velocity. The relationship is as follows.

$$f\left(\frac{h - h_s}{h - h_{pa}}, \frac{G - G_{mf}}{G_t - G_{mf}}\right) = O \qquad \ldots (3)$$

(i.e.) when $\frac{h - h_s}{h - h_{pa}}$ is plotted vs. $\frac{G - G_{mf}}{G_t - G_{mf}}$ on log graph a straight line relation is obtained. In this G_t values are to be determined from extrapolation of h_{pa}/h_s to 1. G_{mf} to be calculated by Leva's equation.

$$G_{mf} = \frac{688\ d_p^{1.82}\ [\rho_f\ (\rho_s - \rho_f)^{0.84}]}{\mu^{0.88}} \qquad \ldots (4)$$

Poddar and Dutt presented equations of the following type for the prediction of minimum and maximum semifluidization velocities, from the physical properties of the solids and flow characteristics. The equations are: For minimum,

$$18\ Re_{osf} + 2.7\ Re_{osf}^{1.687} = 0.966 \times \phi_s^{0.88}\ Ga\ [1 - \frac{h_o}{h}\ (1 - \epsilon_{pa})]^{4.7} \qquad \ldots (5)$$

where, $Re_{osf} = \frac{dp\ G_{ms}}{\mu}$

For maximum,

$$18Re_{msf} + 2.7\ Re_{msf}^{1.687} = Ga \qquad \ldots (6)$$

The basis was shown to be the relation between the expanded voidage function proposed by Wen and Yu.

Roy and Sarma have presented equations for the prediction of minimum and maximum semifluidization velocities as follows:

Minimum (onset of) semifluidized velocity.

$$\frac{G_{osf}}{G_{msf}} = 0.105\ (R) + \frac{\log.Ar + 2.465}{52} \qquad \ldots (7)$$

and maximum semifluidization velocity

$$G_{mf} = 0.3\ (Ar)^{0.58}\ \left(\frac{\mu}{d_p}\right) \qquad \ldots (8)$$

The method proposed by Fan et al, involves the evaluation of onset of fluidization felocity for which a number of methods are available in literature, Poddar's equations for predicting G_{osf} and G_{msf} values involve either a trial and error or a graphical solution. The method suggested by the authors involves a knowledge of only the physical properties of the system and this is more convenient for use.

Packed bed height in semifluidization

Fan and Coworkers proposed an equation (3) for the prediction of packed bed height from the valuation of maximum semifluidization velocity and minimum fluidization velocity.

Poddar and Dutt presented equation for the prediction of packed bed formation in semifluidized bed from the properties of the system and fluid velocity. The equation is,

$$h_{pa} = \frac{h_o}{} \frac{(1 - \epsilon_{pa})}{\epsilon_f - \epsilon_{pa}} - \frac{h_f\ (1 - \epsilon_f)}{\epsilon_f - \epsilon_{pa}} \qquad \ldots (9)$$

Where, ϵ_f can be related to

$$\epsilon_f = \left[\frac{18Re + 2.7\ Re^{1.687}}{Ga}\right]^{.2125} \qquad \ldots (10)$$

The only assumption in the derivation of equation (9) is that the porosity of packed bed formed just below the preventing screen is assumed to be the same as that of the original bed.

Total pressure drop

Measurments of total pressure drop occurring in semifluidization have been reported only by Fan et al., and these measured values have been compared with those calculated in the following way.

The total pressure drop should be the algebraic sum of the pressure drops across the fluidised section and the packed bed.

$$\Delta P_t = \left(\frac{\Delta P}{L}\right)_f (h - h_{pa}) + \left(\frac{\Delta P}{L}\right)_{pa} (H_{pa}) \quad (11)$$

In the case of fluidized bed pressure drop is equation to the effective weight.

$$\left(\frac{\Delta P}{L}\right)_f = (h - h_{pa}) = \frac{(1 - X)W}{A} \quad \frac{\rho_s - \rho_f}{\rho_a} \quad (12)$$

Using Ergun's equation for pressure drop for flow of fluids through packed beds and utilizing the above equation, the pressure drop expression for semifluidized bed has been derived, which is given by the expression-

$$\Delta Pt = \left\{\left[h_f - \frac{(1 - \epsilon_{pa})\ (h_f - h)}{\epsilon_f - \epsilon_{pa}}\right](1 - \epsilon_f)\ (\rho_s - \rho_f)\right\}$$
$$+ \left[150\ \frac{(1 - \epsilon_{pa})^2}{\epsilon_{pa}{}^3} \cdot \frac{\mu u}{d_p{}^2} + 1.75\ \frac{(1 - \epsilon_{pa})}{\epsilon_{pa}{}^3} \cdot \frac{Gu}{d_p}\right]$$
$$+ \left[(h_f - h)\ \frac{(1 - \epsilon_f)}{(\epsilon_f - \epsilon_{pa})}\right]\frac{1}{g_o} \quad \ldots (13)$$

It was observed that the experimental values are much higher when compared with the values calculated by the above method. This reason can be due to the uncertainty in evaluation of packed bed porosities. Any equation available for the prediction of packed bed porosity is very sensitive to changes in **e_{pa} values.**

Mass transfer and reaction kinetics and other related aspects

As has been pointed earlier, the beginning in semifluidization was made in 1959 with mass transfer studies by Fan et al. Later Baburao and Doraiswamy have taken this work with a view to develop a semifluidized M.T. reactor. Incidentally they conducted experiments on semifluidization (gas-solid system). They introduced a new dimensionless group called the semifluidization group,

$$s_f = \frac{W_s - W_p}{(h - h_o)^3 \rho_s} \quad \ldots (14)$$

and with the help of Archimedes group for semifluidization

$$Ar = \frac{d_p{}^3\ g_o\ p_s\ (p_s - p_f)}{\mu^2} \quad \ldots (15)$$

the ratio of semifluidization velocity to terminal velocity was expressed as

$$\frac{G_s}{G_t} = K\ (A_r)^a (S_f)^b$$
$$= K\ (A_r)^{-0-15}\ (S_f)^{-0,136} \quad \ldots (16)$$

where, $K = 17.3/(D)^{-0,372}$ (D in feet) ... (17)

Sunkoori and Kaparthi have studied the dynamics of semifluidization in solid liquid systems. It was observed by them that the ratio of free surface fluid bed height to fluid bed height in semifluidization can be related as:

$$(h_f/h) \quad d_p{}^2 = A.e^{0.1G} \quad \ldots (18)$$

Where, A is a function of (h_t/h_o) which can be expressed in the form $A = 0.007\,(h_f/h_o)^{2,5}$ ... (19)

A phase diagram showing the regions of restricted packed bed fluidized bed and semifluidized bed was also presented by them by plotting the variation of bed height with fluid mass velocities. The data obtained under conditions of restricted packed bed, fluidized bed and semifluidized bed were found to fit well plotted in terms of modified friction factor (f_m) vs. N.Rep as suggested by Leva et al. Studies on wall to fluid heat transfer have also been made by these authors (Kaparthi and Rao). Air solid systems were studied and the data has been co-related in the form of Nusselt group, particle Reynolds number and porosity ratio.

Scope **for further studies**

So far the studies that have been made are only confined to the prediction of the minimum and maximum semifluidization velocities the formation of the packed bed below the restraining screen. While the total pressure drop in semifluidization has been expressed as a summation of the pressure drop in packed bed and fluidized bed only, correlations are yet to be developed for the prediction of total pressure **drop** in terms of the properties of the systems and **flow** characteristics. There is plenty of scope for further studies in this aspect as well as in heat and mass transfer. The application of the semifluidization technique to the field of reaction kinetics has already been initiated. Further investigations on these lines will be of immense help in reactor design.

Notation :

A = Cross section of column, L^2

A_r = Archimedes number, dimensionless group

C_d = Drag coefficient

d_p = Particle diameter, L

D = Dia. of reactor, L

f = Function

g_o = Gravitational constant, L θ^{-2}

G = Mass velocity of fluid, $M.\theta^{-1}\ L^{-2}$

G_{mf} = Onset velocity of fluidization, $M.\theta^{-1}L^{-2}$

G_{osf} = Onset velocity of semifluidization, $M.\theta^{-1}L^{-2}$

G_{msf} = Maximum semifluidization velocity $M.\theta^{-1}\ L^{-2}$

G_{osf} = Semifluidized velocity $M.\theta^{-1}\ L^{-2}$

G_s = Free fall terminal velocity (maximum semifluidization velocity calculated, $M.\theta^{-1}\ L^{-2}$

h = Overall height of column (or semifluidized bed) L

h_f = Height of fully fluidized bed, L

h_s = Height of initial static bed, at least dense condition, L.

h_{pa} = Height of packed section in semifluidized bed, L.

K = Constant of dimensionless equation (12)

MT = Mixed tubular reactor system

ΔP_t = Overall pressure drop through the semifluidized bed, FL^{-2}

ΔP_f = Pressure drop through fluidized section, F L^{-2}

ΔP_{pa} = Pressure drop through packed section, F L^{-2}

$\left(\frac{\Delta P}{L}\right)_f$ = Pressure gradient across fluidized bed, FL^{-3}

$\left(\frac{\Delta P}{L}\right)_{pa}$ = Pressure gradient across packed bed, FL^{-3}

R = Bed expansion ratio dimensionless

Re = Reynolds number dimensionless

Re_T = Terminal Reynolds number, dimensionless

Re_{msf} = Reynolds number at max. semifluidization, dimensionless

S_f = Semifluidization group dimensionless

u = Velocity of fluid, L θ^{-1}

u_t = Terminal velocity of solid in the fluid, L θ^{-1}

W = Total weight of particles in column, M

W_p = Packed bed weight KM

W_s = Initial weight of the static bed, M.

X = Weight fraction of particle in packed section

Greek Letters

Δ = Finite change of variable

ϵ_f = Porosity of fluidized section or porosity of fully fluidized bed

ϵ_{pa} = Porosity of packed section

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

ρ_f = Density of fluid, ML^{-3}

ρ_s = Density of solid particle, ML^{-3}

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