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Semifluidization: a Review

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Semifluidization is a novel solid-fluid contact technique conceived in the late fifties. Over the last two-and-a-half decades considerable investigation has been made into the various aspects of the phenomenon which have been reported in the literature. In view of its unique usefulness, semifluidization will become increasingly important, specifically in the design of several physical and chemical systems. This review presents a concise picture of the various aspects of semi-fluidization (momentum, heat and mass transfer, design of reactors and industrial applications) for a better understanding of the phenomenon and to provide more rational approaches to the design of semifluidization systems.

THE phenomenon of semifluidization, a unique and novel technique of fluid-solid contact proposed by Fan, *et al.*[1] in the late fifties, can be viewed as a combination of a batch fluidized bed at the bottom and a fixed bed at the top. This is obtained by providing enough space available for free expansion of the bed, and increasing the flow rate of fluid through the bed of particles sufficiently high to buoy the solid particles. A restraint provided at the top of the bed prevents the escape of the particles from the system and helps to form a packed-bed section just below the restraint. A semifluidized bed overcomes certain inherent disadvantages of fluidized and fixed beds. Semifluidized beds find wide applications as exothermic chemical reactors,[2] ion-exchangers,[3] filters,[3,4] and for the removal of fine particles suspended in gases or liquids and bioreactors.[3,5]

The present article is designed to review the available literature on semifluidization under the following headings: (a) momentum transfer, (b) heat and mass transfer, (c) application to the design of reactors, and (d) miscellaneous industrial applications.

Momentum Transfer

This part deals with the determination of (a) pressure drop, (b) minimum semifluidization velocity (onset of semifluidization velocity), (c) maximum semifluidization velocity (d) height of the packed bed and lean bed, and (e) residence-time distribution.

Pressure Drop

In semifluidization the total pressure drop is ideally the algebraic sum of the pressure drop across the fluidized and the packed sections. Hence,

$$\Delta P_T = \left(\frac{\Delta P}{L}\right)_f (h - h_{pa}) + \left(\frac{\Delta P}{L}\right)_{pa} h_{pa} \qquad (1)$$

Through an overall mass balance Fan and co-workers[1,6] established that the following relationship exists between the magnitude of the space occupied by the packed bed and that by the fluidized bed in a semifluidized bed

$$h_{pa} = (h_f - h)\,\frac{1 - \epsilon_f}{\epsilon_f - \epsilon_{pa}} \qquad (2)$$

While there is essentially only one generalised equation[1,7] for the prediction of the pressure drop across a fluidized bed,

$$\left(\frac{\Delta P}{L}\right)_f = (\rho_s - \rho_f)\,(1 - \epsilon_f) \qquad (3)$$

there are various correlations for the determination of the pressure drop across a packed bed. These include the Kozeny-Carman equation,[7] Leva's equation,[8] and Ergun's equation.[8] The equation for pressure drop across a semifluidized bed using Ergun's equation is given by

$$(\Delta P)_T=\frac{1}{g_c}\left[150\frac{(1-\epsilon_{pa})^2}{\epsilon^3_{pa}}\frac{\mu_f v_o}{d_p^2}+1\cdot75\frac{(1-\epsilon_{pa})}{\epsilon^3_{pa}}\frac{Gv_o}{d_p}\right]$$

$$\left[(h_f-h_s)\frac{1-\epsilon_f}{\epsilon_f-\epsilon_{pa}}\right]+\left[h_f-\frac{(1-\epsilon_{pa})\ (h_f-h)}{\epsilon_f-\epsilon_{pa}}\right]$$

$$(1-\epsilon_f)\ (\rho_s-\rho_f) \qquad (4)$$

Fan and Wen[9] measured the pressure drop in fixed and fluidized beds separately and obtained the total pressure drop using equation (1). This was compared with that calculated using equation (4). The experimental values were nearer to those calculated using equation (1) whereas equation (4) gave lower values. For small and irregular-shaped particles, Kurian and Raja Rao[10] observed that the pressure drop was greater than that given by equation (4), and the following equation was proposed to take into account this additional pressure drop

$$\Delta P_a=2\cdot10\times10^{-3}\quad G_{sf}^{1.56}\ d_p^{-0.94}\ h_{pa}^{0.59} \qquad (5)$$

To overcome wide discrepancies between the experimental and the calculated values, Roy and Sen Gupta[11] and Roy and Sarma[12] have suggested a correction factor, G, in terms of system parameters. The correction factor is defined as

$$C=\frac{\Delta(P_T)_{exp}}{(\Delta P_T)_{cal}} \qquad (6)$$

The calculated values of (ΔP_T) were obtained using equation (4). The proposed correlations for the correction factor are presented in *Table I.*

Roy and Sarma[13,14] have also suggested another dimensionless correlation for pressure drop in liquid-solid and gas-solid systems *(Table II).*

TABLE I

CORRELATIONS FOR THE CORRECTION FACTOR

Sl. No.	**Correlation**	**System**
1. (*a*)	$C=7\cdot3\times10^{-3}\left(\frac{D_c}{d_p}\right)^{-0.53}\left(\frac{\rho_s}{\rho_f}\right)^{1.18}\left(\frac{h_s}{D_c}\right)^{-2.05}(R)^{1.56}\left(\frac{h_{pa}}{h_s}\right)^{0.64}$	Gas-spherical solids[11] (Roy and Sen Gupta, 1973)
(*b*)	$C=1\cdot95\times10^{-1}\left(\frac{D_c}{d_p}\right)^{-0.59}\left(\frac{\rho_s}{\rho_f}\right)^{0.55}\left(\frac{h_s}{D_c}\right)^{-0.94}\left(\frac{h_{pa}}{h_s}\right)^{0.29}(R)^{0.72}$	Gas-non spherical solids[11] (Roy and Sen Gupta, 1973)
2.	$C=1\cdot67\left(\frac{D_c}{d_p}\right)^{-0.59}\left(\frac{\rho_s}{\rho_f}\right)^{0.67}\left(\frac{h_s}{D_c}\right)^{-0.43}\left(\frac{h_{pa}}{h_s}\right)^{0.08}(R)^{0.08}$	Liquid-solid[12] (Roy and Sarma, 1974)

TABLE II

CORRELATIONS FOR $\Delta P_T/\Delta P_{osf}$

Sl. No.	**Correlation**	**System**
1.	$\frac{\Delta P_T}{\Delta P_{osf}}=0\cdot22\left(\frac{D_c}{d_p}\right)^{-0.21}\left(\frac{\rho_s}{\rho_f}\right)^{0.43}(R)^{1.71}\left(\frac{h_{pa}}{h_s}\right)^{1.24}$	Gas-solids[13] (Roy and Sarma, 1977)
2.	$\frac{\Delta P_T}{\Delta P_{osf}}=19\cdot5\left(\frac{D_c}{d_p}\right)^{-0.17}\left(\frac{\rho_s}{\rho_f}\right)^{0.48}(R)^{0.28}\left(\frac{h_{pa}}{h_s}\right)^{0.89}$	Liquid-solids[14] (Roy and Sarma, 1978)

Saha and Dutt[15] have put forward a generalized correlation for the prediction of pressure drop in a solid-liquid semifluidized bed. The correlation includes two friction-factor terms, one for the fluidized section and the other for the packed section of the bed. The correlation obtained for the prediction of pressure drop in a semifluidized bed is

$$\Delta P_T=\left(\frac{130}{Ref}+1{\cdot}25\right)\left(\frac{\rho_s}{\rho_f}\right)^{0.24}R^{-0.15}\frac{G_{sf}V_o(1-\epsilon_f)(h_s-h_{pa})}{\epsilon_f^3\,g_c\,d_p}+\left(\frac{150}{Re_{pa}}+1{\cdot}75\right)R^{0.14}\,\phi_s{}^{-1.8}\left[1+{\cdot}02F'\frac{h_{pa}G_{sf}V_o\,(1-\epsilon_{pa})}{g_c\,d_p\,\epsilon_{pa}^3}\right] \quad (7)$$

where F' is the fraction of solids transferred to the packed bed section.

Minimum Semifluidization Velocity, G_{osf}

The minimum semifluidization velocity, or onset velocity of semifluidization, is defined as the fluid velocity at which the top of the fluidized bed just touches the top restraint of the semifluidizer. A number of correlations have been proposed to predict this velocity which are summarized below.

Poddar and Dutt[15] have reported data on semifluidization in liquid-solid systems. They employed the correlation of Wen and Yu[17] for the voidage function and the relationship between f and the voidage fucntion (Wilhelm and Kwauk,[18] Lewis, *et. al.*[19] Richardson and Zaki[20]) to obtain the condition for minimum semifluidization. Roy and Sarma[21] obtained the experimental data for a few water-solid systems, and developed the following correlation for the prediction of minimum semifluidization velocity

$$G_{osf}=0{\cdot}2042\ G_a^{0.675}\,[1-(1/R)\ (1-\epsilon_{pa})]^{2.87}\left(\frac{\mu_f}{d_p}\right) \quad (8)$$

Empirical correlations are also available in the form of equation (9)[21–26] and presented in *Table III*

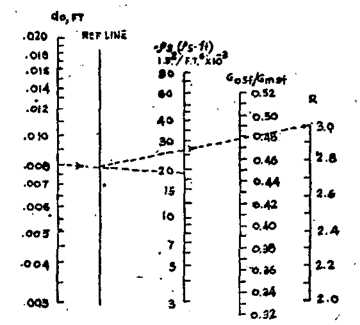
$$f\left[\frac{G_{osf}}{G_{omf}}\text{ or }\frac{G_{osf}}{G_{msf}},\ \frac{D_e}{dp},\ \frac{\rho_s}{\rho_f},\ R\right]=O \quad (9)$$

A few monographs[27,28] are also available for the rapid estimation of minimum semifluidization velocity *(Figures 1 and 2).*

TABLE III

CORRELATIONS FOR PREDICTION OF MINIMUM SEMIFLUIDIZATION VELOCITY

Sl. No.	Correlation	System
1.	$\frac{G_{osf}}{G_{msf}}=0{\cdot}015\,(R)+(\log Ar+2{\cdot}456)/52$	Water-solids[21] (Roy and Sarma, 1971)
2.	$\frac{G_{osf}}{G_{msf}}=0{\cdot}30\left(\frac{D_c}{d_p}\right)^{-0.21}\left(\frac{\rho_s}{\rho_f}\right)^{0.41}(R)^{0.66}$	Water-solids[31] (Roy and Sarma, 1972)
3. (*a*)	$\frac{G_{osf}}{G_{msf}}=1{\cdot}625\left(\frac{D_c}{d_p}\right)^{0.266}\left(\frac{\rho_s}{\rho_f}\right)^{-0.228}(R)^{0.585}$	Liquid-non-spherical particles[25] (Roy and Sarma, 1972)
(*b*)	$\frac{G_{osf}}{G_{mf}}=1{\cdot}875\left(\frac{D_c}{d_p}\right)^{0.266}\left(\frac{\rho_s}{\rho_f}\right)^{-0.228}(R)^{0.585}$	Liquid-spherical solids[25] (Roy and Sarma, 1972)
4. (*a*)	$\frac{G_{osf}}{G_{mf}}=2{\cdot}66\times10^2\left(\frac{D_c}{d_p}\right)^{0.62}\left(\frac{\rho_s}{\rho_f}\right)^{-1.00}(R)^{0.50}$	Gas-non-spherical particles[24] (Roy and Sen Gupta, 1972)
(*b*)	$\frac{G_{osf}}{G_{mf}}=3{\cdot}4\times10^3\left(\frac{D_c}{d_p}\right)^{1.11}\left(\frac{\rho_s}{\rho_f}\right)^{-1.78}(R)^{0.89}$	Gas-spherical particles[24] (Roy and Sen Gupta, 1972)
5. (*a*)	$\frac{G_{osf}}{G_{msf}}=0{\cdot}475\left(\frac{D_c}{d_p}\right)^{-0.20}\left(\frac{\rho_s}{\rho_f}\right)^{0.17}(R)^{0.38}$	Liquid-solids[23] (Roy, 1975)
(*b*)	$\frac{G_{osf}}{G_{msf}}=0{\cdot}071\left(D_c\right)^{-0.20}\left(\frac{\rho_s}{\rho_f}\right)^{0.17}(R)^{0.38}$	Gas-solids[23] (Roy, 1975)
6.	$\frac{G_{osf}}{G_{msf}}=48{\cdot}0\left(\frac{D_c}{d_p}\right)^{0.38}\left(\frac{\rho_s}{\rho_f}\right)^{-1.05}(R)^{0.64}$	Gas-solids[26] (Roy and Sen Gupta, 1975)



(a) VALUES OF d_p , $\rho_s(\rho_s-\rho_f)$ AND R ARE NOTED

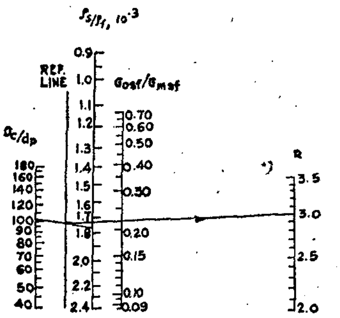
(b) VALUES OF d_p AND $\rho_s(\rho_s-\rho_f)$ ARE JOINED TO CUT THE REFERENCE LINE

(c) THE POINT OF INTERSECTION ON THE REFERENCE LINE AND R ARE CONNECTED CUTTING THE LINE OF G_{osf}/G_{msf}

(d) THE VALUE OF G_{osf}/G_{msf} IS NOTED FROM THE POINT OF INTERSECTION

(e) THE VALUE OF G_{osf} IS CALCULATED KNOWING THE VALUE OF G_{msf} FROM FIGURE 7

Fig. 1 Prediction of minimum semifluidization velocity for liquid-solid systems



(a) D_c/d_p , ρ_s/ρ_f AND R ARE FOUND

(b) D_c/d_p AND ρ_s/ρ_f VALUES ARE JOINED BY A STRAIGHT LINE TO CUT THE REFERENCE LINE

(c) THE POINT OF INTERSECTION ON THE REFERENCE LINE AND R ARE JOINED TO CUT THE LINE OF G_{osf}/G_{msf}

(d) THE VALUE G_{osf} IS CALCULATED AFTER KNOWING THE VALUE OF G_{msf} FROM FIGURE 5.

Fig. 2 Prediction of minimum semifluidization velocity for air-solid systems

Roy and Sharatchandra[29] obtained the data on liquid-solid semifluidization characteristics for systems of a heterogeneous mixture, viz. dolomite-chromite, dolomite-baryte, dolomite-iron ore, iron ore-chromite and iron ore-baryte. They have substituted an average density (ρ_{sav}) for the term particle density by

$$(\rho_{sav}) = \Sigma W / \Sigma \frac{W}{\rho_s} \tag{10}$$

in the equation for minimum semifluidization proposed by Roy[23]

$$\frac{G_{osf}}{G_{msf}} = 0{\cdot}473 \left(\frac{D_c}{d_p}\right)^{0.20} \left(\frac{\rho_s}{\rho_f}\right)^{0.17} (R)^{0.38} \tag{11}$$

The values of G_{msf} were calculated from equation (12) replacing the particle density term with the average particle density as defined in equation(lO), and compared with the experimental values

$$G_{msf} = \frac{1{\cdot}85\times10^4\, d_p^{0.65}\, [\rho_f\,(\rho_s-\rho_f)]^{0.55}}{\mu_f^{0.1}} \tag{12}$$

For homogeneous mixtures, Roy and Dash[30] developed a correlation relating the ratio of maximum semifluidization velocity to minimum semifluidization velocity with the system parameters, substituting average particle size $(d_p)_{av}$ instead of d_p in equations (11) and (12), where $(d_p)_{av}$ was given by

$$\frac{1}{(d_p)_{av}} = \Sigma \frac{x}{d_p} \tag{13}$$

X being the mass fraction of the components of the mixtures.

Maximum Semifluidization Velocity, G_{msf}

This is defined as the fluid velocity at which all solid particles are supported by the fluid in the packed portion of the bed. There are three methods[10] for the determination of G_{msf} experimentally *(Figures 3* and *4* refer to two of them).

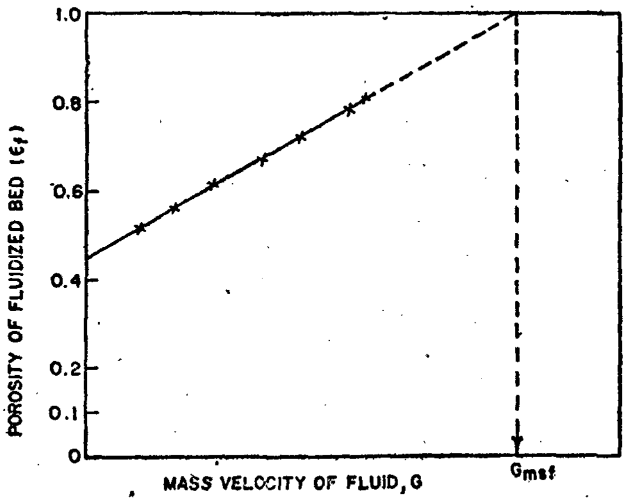


Fig. 3 Determination of G_{msf} from ϵ_f vs. G plot

A number of correlations are also proposed in the literature[16,21,28,30,31] for the prediction of maximum semifluidization velocity from system properties. Nomographs are also available for its rapid prediction as shown in *Figures* 5 and *6* for liquid-solid and gas-solid systems respectively.[27,30] Equations have also been developed for its prediction from the minimum fluidization velocity[32,33]. These correlations are presented in *Table IV.*

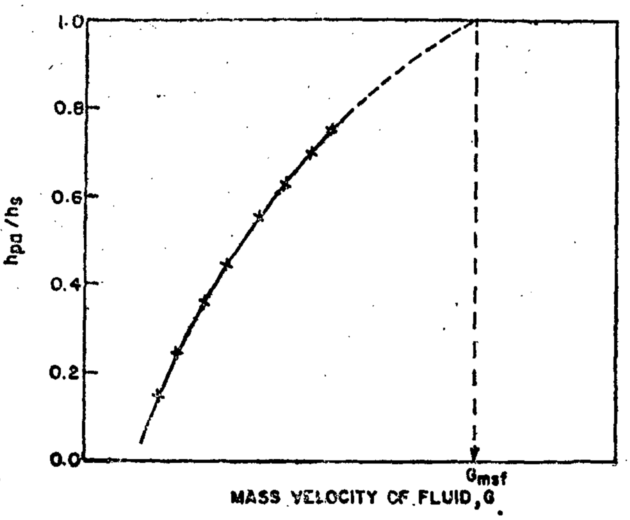
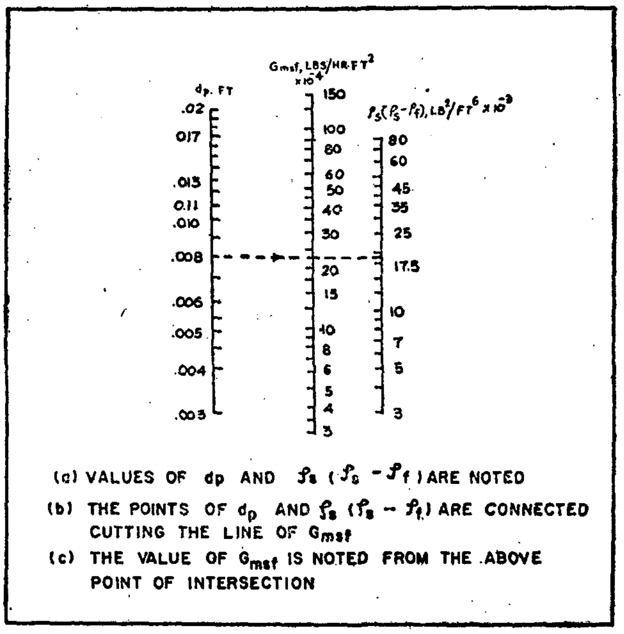


Fig. 4 Determination of G_{msf} *from* h_{ps}/h_s *vs.* G *plot*

Roy and Dash[34] developed a correlation for maximum semifluidization velocity in homogeneous mixtures. A similar correlation for heterogeneous mixtures has also been proposed by Roy and Sharat Chandra.[35]



(a) VALUES OF dp AND ρ_s ($\rho_s - \rho_f$) ARE NOTED

(b) THE POINTS OF d_p AND ρ_s ($\rho_s - \rho_f$) ARE CONNECTED CUTTING THE LINE OF G_{msf}

(c) THE VALUE OF G_{msf} IS NOTED FROM THE ABOVE POINT OF INTERSECTION

Fig. 5 Prediction of maximum semifluidization velocity for liquid-solid systems

TABLE IV

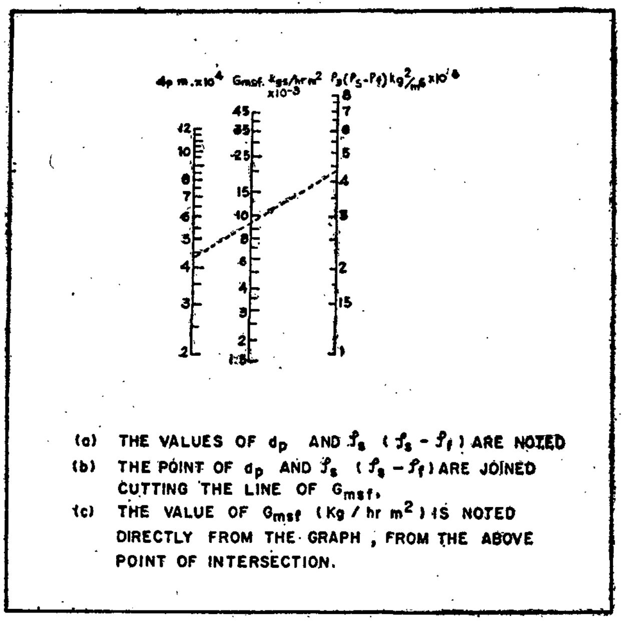
CORRELATIONS FOR PREDICTION OF MAXIMUM SEMIFLUIDIZATION VELOCITY

Sl. No.	Correlation	System
1.	$18\,Re_{msf}+2{\cdot}7\,Re_{msf}^{1.687} = Ga$	Liquid-solids (Poddar and Dutta, 1969)[16]
2.	$G_{msf} = 0{\cdot}3\,(Ar)^{0.56}\,(\mu_f/d_p)$	Liquid-solids (Roy and Sarma, 1971)[21]
3.	$G_{msf}/G_{mf} = 5{\cdot}71\,(D_c/d_p)^{0.42}\,(\rho_s/\rho_f)^{0.67}$	Liquid-solids (Roy and Sarma, 1974)[32]
4. (*a*)	$Re_{msf} = 1{\cdot}15\times10^{-3}\,(G_a)^{0.676}$	Gas-solids (Roy and Sen Gupta, 1975)[26]
(*b*)	$Re_{msf} = 1{\cdot}15\times10^{-3}\,(Ar)^{0.676}$	Gas-solids (Roy and Sen Gupta, 1975)[49]
5. (*a*)	$G_{msf} = \dfrac{1{\cdot}85\times10^{4}\,(d_p)^{0.68}\,[\rho_f\,(\rho_s-\rho_f)]^{0.55}}{\mu_f\,0{\cdot}1}$	Liquid-solids (Roy, 1975)[23]
(*b*)	$G_{msf} = \dfrac{1{\cdot}37\times10^{4}\,(d_p)^{0.65}\,[\rho_f\,(\rho_s-\rho_f)]^{0.55}}{\mu_f\,0{\cdot}10}$	Gas-solids (Roy, 1975)[23]
6.	$G_{msf}/G_{mf} = 130\,(D_c/d_p)^{0.6}\,(\rho_s/\rho_f)^{-0.72}$	Gas-solids (Roy and Saratchandra, 1976)[33]

Note: Equation (5): d_p *in metres;* ρ_s *and* ρ_f *in kg/m*^{3}*;* μ_f *in kg/m.hr;* G_{msf} *in kg/m*^{2}*.hr.*

Height of Packed Bed

For purposes of design it is imperative to know the variation in the height of the packed bed-formed below the restraint-with the change in fluid mass velocity, the limits for the same being values corresponding to the onset and the maximum semifluidization conditions.



(a) THE VALUES OF d_p AND ρ_s $(\rho_s - \rho_f)$ ARE NOTED

(b) THE POINT OF d_p AND ρ_s $(\rho_s - \rho_f)$ ARE JOINED CUTTING THE LINE OF G_{msf}.

(c) THE VALUE OF G_{msf} (Kg / hr m²) IS NOTED DIRECTLY FROM THE GRAPH, FROM THE ABOVE POINT OF INTERSECTION.

Fig. 6 Prediction of maximum semifluidization velocity for air-solid systems

The methods available for the prediction of the height of the packed section in semifluidization are: (a) experimental determination with the parameters such as the position of screen and the fluid mass velocity, and (b) the method of Fan, *et al.*[1] based on a material balance approach. Fan and Wen[9] and Wen, *et* al.[36] have also suggested a dimensionless correlation for the prediction of the packed-bed height. Poddar and Dutt[37] have given a mathematical explanation for the packed bed formation under semifluidized condition, and have proposed a correlation for the estimation of the same for a solid-liquid system, based on the properties of solid and liquid and the flow conditions.

Since the formation of the packed bed begins at the onset of semifluidization and ends with the maximum semifluidization velocity, the introduction of the onset velocity of semifluidization, G_{osf}, instead of minimum fluidization velocity was considered to be more relevant by Roy and Sarma[21] in the derivation of Fan and Wen* and Wen, *et* a/.[36] .

All the correlations proposed for predicting the height of the packed-bed are presented in *Table V.*

TABLE V

CORRELATIONS FOR PREDICTION OF PACKED BED HEIGHT

Sl. No.	Correlation	System
1.	$h_{pa} = \frac{h_{sf}(1-\epsilon_{pa})}{(\epsilon_f-\epsilon_{pa})} - \frac{h_s(1-\epsilon_{pa})}{(\epsilon_f-\epsilon_{pa})}$ $\epsilon_f = \frac{(18\,Re + 2{\cdot}7\,Re^{1.687})^{0.2125}}{Ga}$	Liquid-solids[37] (Poddar and Dutta, 1970)
2.	$h_{pa} = (h_f - h_{sf})\frac{(1-\epsilon_f)}{(\epsilon_f - \epsilon_{pa})}$	Liquid-solids[10,36] (Fan and Wen, 1961; Wen, *et al.*, 1963)
3.	$\frac{(h_{sf}-h_s)}{(h_{sf}-h_{pa})} = \left(\frac{G_{sf}-G_{osf}}{G_{msf}-G_{osf}}\right)^{0.20}$	Liquid-solids[21] (Roy and Sarma, 1971)
4. (*a*)	$\frac{h_{pa}}{h_s} = 1{\cdot}09\,(G_{sf}/G_{msf})^{1.51}\,(D_c/d_p)^{0.23}(\rho_s/\rho_f)^{0.17}\,(R)^{-0.86}\,(h_s/D_c)^{-0.15}$	Liquid-non-spherical solids[45] (Roy and Sarma, 1973)
(*b*)	$h_{pa}/h_s = 2{\cdot}21\,(G_{sf}/G_{msf})^{2.08}\,(D_c/d_p)^{0.23}\,(\rho_s/\rho_f)^{0.17}(R)^{-0.88}\,(h_s/D_c)^{-0.15}$	Liquid-spherical solids[45] (Roy and Sarma, 1973)
5. (*a*)	$h_{pa}/h_s = 1{\cdot}07\times10^{-5}\,(G_{sf}/G_{msf})^{3.22}\,(D_c/d_p)^{-0.17}(\rho_s/\rho_f)^{2.18}\,(h_s/D_c)^{2.78}\,(R)^{-1.66}$	Gas-non-spherical solids[48] (Roy and Sen Gupta, 1974)
(*b*)	$h_{pa}/h_s = 1{\cdot}25\times10^{-5}\,(G_{sf}/G_{msf})^{3.13}(D_c/d_p)^{-0.72}\,(\rho_s/\rho_f)^{2.19}\,(h_s/D_c)^{2.19}\,(R)^{-1.66}$	Gas-spherical solids[48] (Roy and Sen Gupta, 1974)

Lean Bed Zone

It has been observed by Wen, *et al.*[36] and Rao and Ramalingam that there exists a zone more or less devoid of solids in between the fluidized and packed-bed sections of a fluid-solid semifluidized bed and that this was more prominent in the case of gas-solid systems. Murthy, *et al.*[40] obtained data on the heights of the lean-bed zone in semifluidized beds for air-solid systems. Based on the lines of statistical design and dimensional analysis, an equation was presented for the prediction of the height of the lean-bed zone in terms of solid, fluid and bed properties as given below

$$\begin{aligned}Y = {} & 138.7+2.5\ X_1^2+5.1\ X_2^2+20.6x_3^2+6.0\ X_4^2+2.5 \\ & X_5^2-16.1\ X_1+26.3\ X_4+19.5\ X_5+10.3\ X_4X_5 \\ & +X_3(16.8\,X_1-17.4\,X_4-16.9\,X_5-10.2\,X_2) \quad (14)\end{aligned}$$

The equation has been found to hold good within ± 15 per cent.

Total Bed Height

Sunkoori, *et al.* [41] have ovserved an exponential relationship between the ratio of free surface fluid-bed height to fluid-bed height in semifluidization; and the ratio of total semifluidization height to static-bed height is given by the following equations

$$\left(\frac{h_{ff}}{h_f}\right) = A\,e^{0.1G} \qquad (15)$$

$$A = 0.007\left(\frac{h_{sf}}{h_s}\right)^{2.5} \qquad (16)$$

These authors have expressed the variation of the bed height with mass velocity in a phase diagram for the water-quartz system as shown in *Figure 7.*

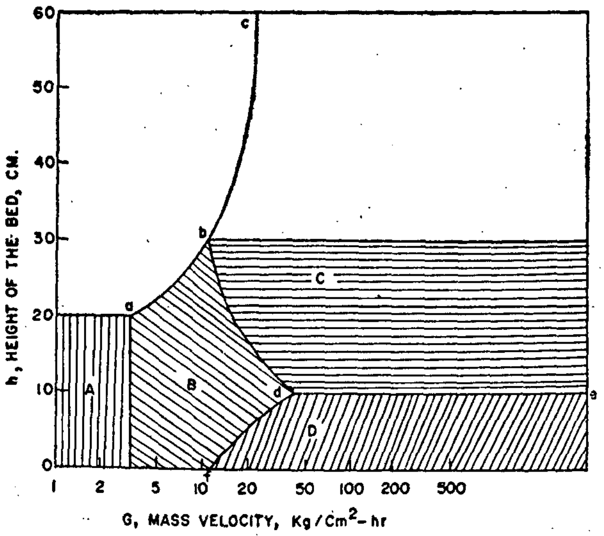


Fig. 7 Phase diagram : variation of bed height with mass velocity (h_s=20 cm)

Residence Time Distribution (RTD)

This is an essential aspect of the design and proper working of semifluidized bed reactors. The only reported study on this aspect is by Saxena and Pandey.[42] They have measured RTD in semifluidized beds for glass beads and crushed calcite with water as the fluidizing medium. The effect of different variables has been studied and interpreted in the light of work done for fixed and fluidized systems.

It has been found that particle size has no effect on RTD for a fluidized bed but has an effect on a fixed bed. In the case of a semifluidized bed, the effect of particle diameter on residence time depends upon the extent to which the fixed-bed portion is formed. There was an increase in residence time with decrease in column diameter which has been attributed to the greater wall effect. The relationship between particle Reynolds number and residence time was given by the equation

$$\bar{t}_{sf}=13.78\times10^3\ (N_{Re})^{-0.76}\left(\frac{d_p}{D_c}\right)^{0.72} \qquad (17)$$

with the maximum deviation of ±20 per cent.

By considering the semifluidized bed as a combination of fluidized and packed beds, they proposed another correlation relating t_{Sf} to t_{fo} (mean residence time of free fluidized bed, i.e. without top restraint under similar conditions)

$$\frac{\bar{t}_{sf}}{(\bar{t}_{fo})_{\ calc}}=8.3\times10^{-1}\left[\frac{(1-\epsilon_e)}{(1-\epsilon_{fo\ cal})}\times\frac{\epsilon_p}{\epsilon_{fo\ cal}}\right]^{0.42} \qquad (18)$$

Pandey and Saxena[43] studied the axial dispersion in lquid semifluidized beds in glass columns of varying diameters with glass beads of different sizes as the bed material and. water as the fluidizing medium. The effect of different variables has been investigated and the following correlation has been developed for the determination of the axial dispersion coefficient in a semifluidized bed

$$\left(\frac{D}{V_oL}\right)_{sf} = 1.3\times10^{-4}\,(N_{Rem})\ \frac{1.85}{SF}(dp/D_c)^{-0.80} \qquad (19)$$

State of Semifluidization

Empirical equations based on the dimensional analysis approach have been proposed to relate the various parameters when the bed is in a semifluidized condition. Thus, based on the dimensional analysis of the continuity and momentum equations for particle fluidization proposed by Beranek[38] and Beranek and Klumper,[43] Fan and Wen[9] have obtained the following relationship for a semifluidized bed

$$f\left[\frac{(h-h_s)}{(h-h_{pa})},\ \frac{G-G_{mf}}{G_t-G_{mf}}\right]=0 \tag{20}$$

A two-parameter fit by Kurian and Rajarao[10] yielded an explicit form of the relationship as

$$\frac{G-G_{mf}}{G_t-G_{mf}}=0.61\left[\frac{h-h_{pa}}{h-h_s}\right]^{-1.2} \tag{21}$$

On the other hand, Roy and Sarma[45] introduced the minimum semifluidization velocity in place of fluidization velocity in equation (21) and developed the following expression

$$\frac{h-h_s}{h-h_{pa}}=\left[\frac{G-G_{osf}}{G_t-G_{osf}}\right]^{0.2} \tag{22}$$

Other investigators 23.28.45-48 empirically correlated the state of semifluidization in various forms of the function

$$f\left[\frac{G}{G_t},\frac{h_{pa}}{h_s},\frac{D_c}{d_p},\frac{\rho_s}{\rho_f},R,\frac{h_s}{D_c}\right]=0 \tag{23}$$

All these correlations are given in *Table VI*

TABLE VI

EQUATIONS WHICH DESCRIBE STATE OF SEMIFLUIDIZTAION

Sl. No.	Equation	Systems
1.	$\frac{G_{sf}}{G_t}=\frac{4{\cdot}62}{D_c^{-0.372}}(Ga)^{-0.15}(Sf)^{-0.186}$	Gas-solids[47] (Baburao and Doraiswamy, 1967)
2.	(*a*) $\frac{G_{sf}}{G_{msf}}=0{\cdot}684\left(\frac{D_c}{d_p}\right)^{-0.11}\left(\frac{h_s}{D_c}\right)^{-0.07}\left(\frac{\rho_s}{\rho_f}\right)^{-0.08}\left(\frac{h_{pa}}{h_s}\right)^{1.00}(R)^{0.42}$	Liquid-spherical solids[45] (Roy and Sarma, 1973)
	(*b*) $\frac{G_{sf}}{G_{msf}}=0{\cdot}945\left(\frac{D_c}{d_p}\right)^{-0.15}\left(\frac{h_s}{D_c}\right)^{-0.10}\left(\frac{\rho_s}{\rho_f}\right)^{-0.11}\left(\frac{h_{pa}}{h_s}\right)^{0.66}(R)^{0.57}$	Liquid-non-spherical solids[45] (Roy and Sarma, 1973)
3.	(*a*) $\frac{G_{sf}}{G_{msf}}=37{\cdot}07\left(\frac{D_c}{d_p}\right)^{0.23}\left(\frac{h_s}{D_p}\right)^{-0.89}\left(\frac{\rho_s}{\rho_f}\right)^{-0.71}\left(\frac{h_{pa}}{h_s}\right)^{0.32}(R)^{0.53}$	Gas-spherical solids[26] (Roy and Sen Gupta,1975)
	(*b*) $\frac{G_{sf}}{G_{msf}}=35{\cdot}16\left(\frac{D_c}{d_p}\right)^{0.22}\left(\frac{h_s}{D_c}\right)^{-0.86}\left(\frac{\rho_s}{\rho_f}\right)^{-0.68}\left(\frac{h_{pa}}{h_s}\right)^{0.31}(R)^{0.51}$	Gas-non-spherical solids[26] (Roy and Sen Gupta, 1975)
4.	(*a*) $\frac{G_{sf}}{G_{msf}}=4{\cdot}8\left(\frac{D_c}{d_p}\right)^{-0.18}\left(\frac{\rho_s}{\rho_f}\right)^{-0.32}\left(\frac{h_{pa}}{h_s}\right)^{0.59}(R)^{0.81}$	Gas-solids[23] (Roy, 1975)
	(*b*) $\frac{G_{sf}}{G_{msf}}=0{\cdot}925\left(\frac{D_c}{d_p}\right)^{-0.15}\left(\frac{\rho_s}{\rho_f}\right)^{-0.12}\left(\frac{h_{ps}}{h_s}\right)^{0.32}(R)^{0.43}$	Liquid-solids[23] (Roy, 1975)
5.	$\frac{G_{sf}}{G_{msf}}=0{\cdot}925\left(\frac{D_c}{d_p}\right)^{-0.15}\left(\frac{\rho_s}{\rho_f}\right)^{-0.12}(R)^{0.43}\left(\frac{h_{pa}}{h_s}\right)^{0.32}$	Liquid-solids[46] (Irregular particles) (Roy and Biswal, 1977)

The hydrodynamic behaviour of semifluidization has been investigated by S.H. Chem, *et al.*[49] Various parameters under extensive analysis include pressure drop, gas hold-up, onset liquid velocity for semifluidization and the height of the packed bed and the fluidized bed sections. The pressure drop of the semifluidized bed obtained experimentally was found to compare favourably with that predicted by the model equations.

Heat and Mass Transfer Operations

A brief review dealing with heat and mass transfer studies was made by Murthy, *et al.*[50] A summary of the investigations conducted so far on heat and mass transfer in semifluidized beds is given below.

Heat Transfer

There are three important aspects that may be investigated in connection with semifluidized bed heat transfer: (i) fluid-to-particle heat transfer; *(ii)* wall-to-fluid heat transfer; and *(iii)* particle-to-fluid heat transfer. The published literature refers to wall-to-fluid heat transfer.

Purnachandra Rao and Kaparthi[39] reported the studies on the wall-heat transfer coefficients of semifluidized beds in a 25 mm copper column, employing different sizes of glass beads, quartz and aluminium particles fluidized with air. The overall heat transfer coefficient of the bed was predicted using Leva and Grummers[51] equation for packed bed, the equation of Urie[52] for the fluidized bed and the Sieder Tate[53] equation for the empty-section heat transfer coefficient from a knowledge of the heights of the various sections of a semifluidized bed. The equation was given as

$$H_{sf} = \frac{H_{pa}\,h_{pa} + H_f\,h_f + H_e\,h_e}{h_{pa} + h_f + h_e} = \Sigma\,\frac{hH}{h} \qquad (24)$$

Based on experimental observations, the authors concluded that the wall-to-bed heat transfer coefficients decreased with porosity and particle density and increase with particle diameter.

Verma, *et al.*[54] studied the heat transfer characteristic of semifluidized beds using liquid-solid systems and reported similar observations as those by Rao and Kaparthi[39] for gas-solid systems.

Murthy, *et al.*[55] obtained data for heat transfer coefficients for air-solid systems. With the help of dimensional analysis and based on statistical experimental design, an equation was formulated to predict the Nusselt number in terms of different system variables.

Empirical equations reported in the literature for the prediction of heat transfer coefficient in semifluidized beds are given in *Table VII*

TABLE VII

EQUATIONS FOR PREDICTION OF HEAT TRANSFER COEFFICIENTS

Sl. No.	Equation	System
1.	$Nu_p = 0{\cdot}014\,(Re_p)^{1{\cdot}1}\left(\frac{1-\epsilon}{\epsilon}\right)^{0{\cdot}4}$	Gas-solids[39] (Purnachandra Rao and Ramalingam, 1969)
2. (*a*)	$Nu_p = 0{\cdot}0285\,(Re_p)^{1{\cdot}21}(Pr)^{0{\cdot}33}\,(R)^{-1{\cdot}1}\left(\frac{d_p}{D_c}\right)^{-0{\cdot}58}$	Water-glass beads[54] (Verma, *et al.* 1972)
(*b*)	$Nu_p = 0{\cdot}0032\,(Re_p)^{1{\cdot}21}\,(Pr)^{0{\cdot}33}\,(R)^{-1{\cdot}1}\left(\frac{d_p}{D_c}\right)^{-0{\cdot}58}$	Water-aluminium particles[54] (Verma, *et al.* 1972)
3.	$Z = 0{\cdot}975 - 0{\cdot}067\,Y_1 - 0{\cdot}052\,Y_2 + 0{\cdot}093\,Y_3 - 0{\cdot}043\,Y_4 + 0{\cdot}07\,Y_1\,Y_4$	Air-solids[55] (Murthy, *et al.* 1983)

Mass Transfer

Fan, *et al.*[1] initiated the studies in the field of mass transfer with a benzoic acid-water system, and correlated the mass transfer data in terms of the j_d factor and the modified Reynolds number. Fan, *et al** also suggested the correlations in terms of the Sherwood and Reynolds numbers for a packed bed and fluidized bed and for a combination of the fluidized and packed beds.

Rai, *et al.*[56] under took the work to study the effect of variables, viz. the properties of the solid particles (density, shape and size) and the fluid (density and viscosity) and operating conditions (fluid velocity and diffusivity). Benzoic acid, cinnamic acid and 2-naphthol were used as the solid particles with water as the fluidizing medium. Govindarajan and Sen Gupta[57] obtained mass transfer data for the benzoic acid-water system for various particle sizes and initial static bed heights. The correlations proposed by the various investigators relating to mass transfer studies are presented in *Table VIII.*

Design of Semifluidized Beds

The application of a semifluidized bed reactor was illustrated by Baburao[58] in a study involving the Oxidation of benzene. The optimal conversion condition was obtained by modelling the semifluidized bed reactor as a CSTR and a tubular reactor in series. After the relative sizes of the fluidized and the packed sections were determined, the equation for the state of semifluidization described earlier 48 was used to determine the operating parameters. Experimental conversion values of the semifluidized bed, the mixed and the tubular reactors were compared and an improved performance was obtained in the case of the semifluidized one.

Murthy, *et al.*[59] suggested a detailed procedure for the design of a semifluidized bed reactor. They proposed a modified form of the reactor suggested by Baburao, *et al.*[2] Equations proposed for the study of momentum transfer operations and the optimal criteria suggested by Baburao[58] were made use of in the suggested design procedure. Upadhrashta, *et al.*[60] have presented the salient design features of a semifluidized bed reactor for the vapour-phase oxidation of napthalene to phthalic anhydride (an exothermic reaction). They have ovserved that the lowest catalyst-to-reactant-flow rate ratio is achieved for such a reactor.

TABLE VIII

CORRELATIONS FOR MASS TRANSFER IN SEMIFLUIDIZED BEDS

Sl. No.	Correlation	System
1.	$J_D = 1{\cdot}865\,(Re_m)^{-0{\cdot}48};\ Re_m = Re_p/(1-\epsilon);\ 5 < Re_m < 30$	Water-benzoic acid[1] (Fan, *et al.*, 1959)
2.	$N_{sh} = 2{\cdot}0 + 0{\cdot}312\,(Re_p)^{0{\cdot}608}\,(N_{sc})^{0{\cdot}333}$	Water-solids[6] (Fan, *et al.*, 1960)
3. (*a*)	$N_{sh} = 0{\cdot}0637\left(\frac{\rho_s-\rho_f}{\rho_f}\right)\left(\frac{d_p}{D_c}\right)^{0.63}(N_{Rep})^{0{\cdot}729}\,(N_{sc})^{0{\cdot}333}$	Water-solids[56] (Rai, *et al.*, 1970)
(*b*)	$N_{sh} = 0{\cdot}226\left(\frac{\rho_s-\rho_f}{\rho_f}\right)\left(\frac{d_p}{D_c}\right)^{-0.588}(N_{Rep})^{0{\cdot}729}\,(N_{sc})^{0{\cdot}5}$	Water-benzoic acid[56] (Rai, *et al.*, 1970)
4. (*a*)	$J_D = 2{\cdot}745\,(N_{Rep})^{-0{\cdot}484}$	Water-benzoic acid[56] (Rai, *et al.*, 1970)
(*b*)	$J_D = 2{\cdot}35\,(N_{Rep})^{-0{\cdot}484}$	Water-cinnamic acid[56] (Rai, *et al.*, 1970)
(*c*)	$J_D = 1{\cdot}865\,(N_{Rep})^{-0{\cdot}484}$	Water-2-naphthol[56] (Rai, *et al.*, 1970)
5.	$k_La = 2{\cdot}512\times10^{-5}\left(\frac{d_p\,G_{sf}}{\mu_f}\right)^{0.51}(R)^{-1{\cdot}03}$	Water-benzoic acid[57] (Govindarajan, 1976)

Note: k_L *in cm/sec*

The design of a semifluidizer for a liquid-solid system was given by Roy[61] and for a gas-solid system by Roy and Sen Gupta.[62] The method of calculating the various quantities including (a) the range of semifluidization operation, *(b)* the height of the packed and fluidized sections, (c) semifluidization velocity, and *(d)* the power requirement, were described for given operating conditions in the case of a dolomite-water system.

Miscellaneous Industrial Applications

The application of semifluidized beds has been broadly stressed by Fan and Hsu[3] and Baburao, *et al.*[2] Semifluidized beds find wide application as reactors (for exothermic and bioreactions) in ion exchange and in filtration operations for the removal of suspended particles from gases or liquids. A brief description of the utility of semifluidized beds in each of the above operations is given below.

Ion Exchange

Mobay Chemical Company, Asahi Chemical Company of Japan, Bayer A G (Germany) and its U.S. counterpart, Lewatit Company, are advocating the use of semifluidized beds with ion-exchange resins.[3] This action arises from the discovery that a fluidized bed followed by a fixed bed increases the efficiency of resin utilization by improving liquid-resin contact. The fixed bed acts as a polishing section, handles the ion leakage from the fluidized bed and prevents elutriation of resin particles.[63]-[65] In addition to a higher resin utilization efficiency, a semifluidized bed also minimizes the volume of regenerant and wash water needed, reduces pressure drop and operates more consistently then the conventional fixed bed process.

Filtration

For filtration purposes the fixed bed section functions as a deep bed filter, and turbulence generated in the fluidized section scours the deposited solids, delaying the build-up of pressure drop. When the fixed portion of a filtration bed is used in conjunction with a fluidized portion of the bed, as is possible in a semifluidized bed, unique advantages are obtained. During the filtration cycle most of the filtered particles are retained in the fluidized bed portion. As the cake of the filtered particles collects at the bottom of the fixed-bed portion, the filtered particles then circulate with the fluidized media in the bed. This action eliminates the blinding of the filter bed and thus prolongs the filtration cycle. Moreover, the pressure drop across the fixed bed can be maintained uniformly.

This method of filtration has application in the removal of insoluble ash and mineral matter from coal oil obtained from the hydrogenation and dissolution of coal; and in the removal of fine particles in a hot flue gas from power plants or from the product gases of coal-conversion reactors.

Hsu and Fan[4] carried out an experimental study of filtration of a slurry composed of 50-mesh coal particles dispersed in water. The filtering medium consisted of —20 *to* +50-mesh silica sand. Filter performance was determined with 25, 50, 75 and 100 per cent of the filtering medium initially in the packed section of the semifluidized bed. Filtration with 100 per cent of the bed particles corresponds to the conventional up-flow deep bed filtration. Samples of the filtrate were collected intermittently from a sample point located between the upper porous plate and the outlet. These samples were then filtered to determine the solid content.

The results of the study showed that the performance of the semifluidized bed filter was far superior to that of the deep bed filter. It was also established that filtration runs lasting as long as 6 times that of the deep bed filter could be attained without apparent deterioration in the quality of the filtrate.

Bio-Rectors

The unique advantage of a semifluidized bed as a bioreactor has been mentioned in detail by Fan and Hsu.[3,5] Studies have shown that when micro-organisms are attached to inert supports their effectiveness is immensely improved in the degradation of hazardous organic contaminants and nitrogen compounds, in the reduction of total organic carbon (TOC), BOD and total suspended solids (TSS), and in the conversion of volatile solids to methane gas. A packed-bed operation using immobilized micro-organisms in anaerobic wastewater treatment achieved removal of more than 70 TSS, 50 BOD and 60 TOC with a residence time of less than 5 hours.[5]

In fluidized bed operations the use of immobilized micro-organisms can achieve near complete removal of organic toxicants, nitrogen and BOD with a residence time of a few minutes compared to 1 to 3 hours for conventional processes.

The use of a semifluidized bed would eliminate the disadvantages of a fluidized bed, for example elutriation of the particles coated with micro-organisms, and unstable bed expansion. The semifluidized bed would also reduce or eliminate plugging of the bed by solids (waste or microbial cells) experienced in fixed-bed operations.

Initially, the semifluidized bed may be seeded by introducing micro-organisms and nutrients to the bed under flow rates slightly higher than the minimum fluidization velocity. The micro-organisms will first grow in suspended phase and then attach themselves to the available surface area, i.e., the column wall and the fluidizing particles. The particles may consist of sand, coal or packings with large surface area. Once the particles are covered with microbes the semifluidized bed reactor is in operation.

The fluidized bed portion of the bed will carry the main load of digestion with the packed bed acting as a polishing section. The fluid reaching the latter section will be lean in nutrients (or waste constituents) and thus will not contribute excessively to an increase in cell masses that can clog the bed. To control the microbial population the entire bed should periodically be fluidized. A saving of about 95 per cent in space can be realized by installing a semifluidized bed bioreactor instead of a conventional suspended-growth waste-treatment unit.

Chemical Reactors

Cholette, Blanche and Cloutier[66,67] have shown that a combination of mixed and tubular reactors is often theoretically more efficient than either of these reactors operated independently. For endothermic reactions, a tubular reactor is always superior, while for exothermic reactions a CSTR is superior to. a tubular reactor up to a certain conversion after which a tubular reactor is more efficient.

In carrying out an exothermal reaction under adiabatic conditions in a tubular reactor two opposite influences may be noted: (i) an increase in reaction rate due to an adiabatic rise in temperature, and (ii) a decrease in reaction rate due to a decrease in reactants' concentration. In the earlier action of the reactor the influence of the temperature is normally more marked leading to an increase in reaction rate. After a certain stage the effect of concentration exerts a greater influence leading to a decrease in reaction rate. That portion of the reaction which occurs in the increasing-rate zone can be advantageously carried out in a fully mixed reactor. The subsequent part, occuring in the decreasing rate zone, should be carried out in a tubular reactor.

It is clear from the above argument that for an exothermal adiabatic reaction the first reactor should be a CSTR which will give an outlet conversion corresponding to the maximum reaction rate. The products can then be led into a tubular reactor for achieving the final degree of conversion required.

The theoretical advantage of the mixed reactor-tubular reactor (MT) combination has been practically realized in a simple reactor system utilizing the principle of semifluidization.[2] For this purpose, a bundle of rigid plastic tubes were fixed to a perforated plate. This bundle was inserted into a fluidized bed reactor. It was possible *to* form fixed beds in the tubes while at the same time retaining a portion of the solids in a fluidized state at the bottom of the reactor. The proportion of solids in the tubular fixed and fluidized beds was varied both by varying the velocity of the fluid and the portion of the tubular bundle. Thus, this type of reactor can be operated as an MT combination, the lower fluidized bed providing the mixed reactor and the top packed portion as the tubular reactor. The fraction of the bed that should act as a CSTR can be calculated from the equation developed by Aris.[68] With this conversion as the starting point the length of the tubular reactor for attaining a given conversion can be calculated With the help of available methods.

The reactor of the above type has specific advantages for fast exothermic reactions such as the vapour-phase oxidation and chlorination of hydrocarbons.

Scope for Future Work

The review of the literature reveals that the information on semifluidization is highly incomplete especially with respect to heat and mass transfer studies. In addition, information relating to the design of semifluidized systems is too meagre.

Available work in the field of heat transfer is too limited to assess the effect of the system variables, viz. fluid and solid properties and the operating conditions. Hence, systematic and thorough investigations are warranted in this field to study the effect of the above variables on heat transfer rate.

Further, for the prediction of heat transfer rates in a semifluidized bed the formulation of equations based on a theoretical standpoint will be more dependable and of wider applicability then the empirical relations developed so far.

Mass transfer in a semifluidized bed is considered *to* be a gray area, most of which still remains unexplored. Available information is highly empirical in nature and of limited use. Hence it is desirable to make a detailed study of the effect of all the variables on mass transfer rate in a semifluidized bed, and *to* propose correlations based on a theoretical background which will be of a general nature and valid beyond experimental conditions.

Prediction of pressure drop is still not very accurate due to non-availability of a suitable method for the correct determination of porosity in the packed section of the semifluidized bed. Hence;, independant determination of this important parameter is required,.

The literature on the determination of the heights-of packed, fluidized and lean beds in semifluidization' is very limited. Much additional work is warranted for the accurate determination of these heights.

The design of semifluidized beds for various applications is a field virtually untouched. Hence,.

there is wide scope to deal with the design aspects of a number of important systems of both a chemical and physical nature where the semifluidized bed can find a potential use in view of its proven advantages over the conventional fixed and fluidized beds.

Dynamic and microscopic studies, e.g. analysis of pressure fluctuations and particle motion, need to be intensified.

Conclusion

In recent years, the application of semifluidization., to different, physical and chemical processes is gaining momentum. Recent developments of semifluidized; bed ion-exchangers, adsorbers, filters and reactors on a laboratory scale are significant in this respect. There has been a conceptual development of a semifluidized bed reactor in the form of the MT-reactor on a laboratory scale, which is advocated as being more efficient than either the fixed or the fluidized bed (for fast exothermic reactions). However, attempts to scale up and analyze its performance are few. Hence, there is need for investigations on bed semifluidized systems on a broader spectrum to judge their suitability to different process applications along the lines that have become common for other fluid-solid systems such as packed and fluidized beds.

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NOMENCLATURE

a	specific surface area of the particles
C	pressure drop correction factor
C_{pf}	specific heat of fluid
C_{ps}	specific heat of solid
D	diffusivity
D_c	diameter of column
d_p	diameter of particle
f	friction factor
g_c	gravitational constant
G	mass velocity of fluid
G_{mf}	minimum fluidization mass velocity
G_{osf}	onset mass velocity of semifluidization
G_{sf}	semifluidization mass velocity
G_t	free-settling mass velocity of the solid
h	height of semifluidized bed
h_e	height of empty section
h_f	height of fluidized bed
h_{ff}	free fluidized bed height
h_{lbz}	height of lean bed zone
h_{pa}	height of packed bed
h_s	static bed height
h_{sf}	height of semifluidized bed
H_e	heat transfer coefficient of solids free section
H_f	heat transfer coefficient of fluidized section
H_{pa}	heat transfer coefficient of packed bed section
H_{sf}	heat transfer coefficient of semifluidized bed section
k_f	thermal conductivity of the fluid
k_L	mass transfer coefficient
$\triangle P_T$	total pressure drop across a semifluidized bed
R	bed expansion ratio. $=h_{sf}/h_{pa}$.
t_{fo}	mean residence time for free fluidized bed
t_{sf}	mean residence time for semifluidized bed
V_o	linear velocity of fluid
W_p	weight of solid in packed section in semifluidization
W_s	weight of solid in initial static bed
W	weight of the solid mixture
X	mass fraction of the material
x_1	D_c/d_p
x_2	ρ_s/ρ_f
x_3	G_{sf}/G_{msf}
x_4	R
x_5	h_s/d_p
X_1	$(x_1—77.16)/(25.72)$
X_2	$(x_2—77.16)/(25.72)$
X_3	$(x_3—0.6)/(0.15)$
X_4	$(x_4—3.5)/(0.5)$
X_5	$(x_5—144.05)/(20.55)$
Y	h_{lbz}/d_p
y_1	G_{sf}/G_{msf}
y_2	ρ_s/ρ_f
y_3	C_{ps}/C_{pf}
y_4	R
Y_1	$(y_1—0.575)/(0.175)$
Y_2	$(y_2—2.725\times10^3)/(0.275\times10^3)$
Y_3	$(y_3—0.87)/(0.207)$
Y_4	$(y_4—3.25)/(0.75)$
Z	$h d_p/k_f$

Greek letters

ρ_s	density of solid material
ρ_f	density of fluid
β	constant
ϵ	porosity of initial static bed
ϵ_{pa}	porosity of the packed bed section of semifluidized bed
ϵ_f	porosity of the fluidized bed section of semifluidized bed
μ_f	viscosity of fluid
ϕ_s	shape factor

Subscripts

a	additional
av	average
f	fluidized bed
fo	free fluidized bed

msf	maximum semifluidization condition
osf	onset of semifluidization
pa	packed bed condition
sf	semifluidization condition

Dimensionless groups/numbers

Ar	Archimedis number $= \dfrac{d_p^3 g_c \rho_s(\rho_s-\rho_f)}{\mu_f^2}$
Ga	Galileo number $= \dfrac{d_p^3 \rho_f(\rho_s-\rho_f)g}{\mu_f^2}$
j_D	mass transfer factor
j_H	heat transfer factor
Nu_p	particle Nusselt number, $= \dfrac{H\,d_p}{k_f}$
N_{sh}	Sherwood number, $k_L h/D$
N_{Re} or Re_p	particle Reynolds number, $\dfrac{d_p G}{\mu_f}$
N_{sc}	Schimdt number, $\mu_f/\rho_f D$
Re_{mf}	$D_p\, G/\mu_f(1-\epsilon_f)$
Sf	Semifluidization number, $=(w_s-w_o)/(h-h_s)\,\rho_s$

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