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Review Article

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Solid-liquid semifluidization

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ABSTRACT

Mixing is an important unit operation encountered in chemical and allied industries. Mixing can be achieved by many ways. One such way is fluidized bed. The efficiency of conventional fluidized bed is enhanced by semi-fluidized bed reactor. Semi-fluidization is a novel solid-fluid contact technique conceived in the late eighties. Many investigations have been made into the various aspects of the phenomenon which have been reported in the literature. Semi-fluidization 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 transfer and industrial applications) for a better understanding of the phenomenon and to provide more rational approaches to the design of semi-fluidization systems.

Keywords: Semi-fluidization, Pressure drop, Minimum and Maximum semi-fluidization velocity

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INTRODUCTION

A Semi-fluidized bed can be viewed as the combination of a batch fluidized bed at the bottom and a fixed bed at the top within a single vessel. The possible alteration of the internal structure allows the device to be utilized for a wide range of physical, chemical and biochemical applications. Very few information is available on semi-fluidization in the liquid-solid two phase systems, which can best be used as immobilized cell bioreactor. A Semi-fluidization bed has the advantages of both the packed and the fluidized beds. It 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. The development and advantages of the semi-fluidized bed relating to studies on hydrodynamics, mass transfer, reaction kinetics and filtration . Fixed bed or packed bed, batch and continuous fluidization and semi-fluidization 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. A restraint provide 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. This is known as semi-fluidization which can be considered as a new type of solid-fluid contacting method which combines the features of both fixed and fluidized beds .

Semi-fluidization 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 segregation of solids. The present article is designed to review the available literature on semi-fluidization under the following headings: momentum transfer, miscellaneous industrial applications.

1.1 Momentum Transfer:
This part deals with the determination of (a) pressure drop (b) minimum semi-fluidization velocity (c) maximum semi-fluidization velocity (d) height of top packed bed formation.

1.1.1 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,

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

Through an overall mass balance Fan and co-workers [9,10] presented 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

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

While there is essentially only one generalised equation[9,15] for the prediction of the pressure drop across a fluidized bed,

$$\left(\frac{\Delta P}{L}\right)_t = (\rho_s - \rho_t)\,(1-\epsilon_t) \tag{2}$$

there are various correlations available for the determination of the pressure drop across a packed bed. These include the Kozeny-Carman equation[15] Leva's equation,[45] and Ergun's equation[85] The equation for pressure drop across a semifluidized bed using Ergun's equation is given by

$$(\Delta P)_T = \frac{1}{g_c}\left[150\,\frac{(1-\epsilon_{pa})^2}{\epsilon_{pa}^3}\,\frac{\mu_f V_0}{d_p^2} + 1.75\,\frac{(1-\epsilon_{pa})}{\epsilon_{pa}^3}\,\frac{G_{V0}}{d_p}\right]\left[\left(h_f - h_s\right)\frac{1-\epsilon_f}{\epsilon_f-\epsilon_{pa}}\right] + \left[h_f - \frac{(1-\epsilon_{pa})(h_f-h)}{\epsilon_f-\epsilon_{pa}}\right]\left(1-\epsilon_f\right)\left(\rho_s-\rho_f\right) \tag{3}$$

Fan and Wen[11] 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 experi-mental 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[45] proposed equation the following to take into account this additional pressure drop. They observed that the pressure drop was greater than that given by equation (4).

$$\Delta P_a = 2.10\ X\ 10^{-3} G_{af}^{1.56} d_p^{-0.94} h_{pa}^{0.59} \tag{4}$$

To overcome wide discrepancies between the experimental and the calculated values, Roy and Sen Gupta[40] and Roy and Sarma[31] have suggested a correc-tion factor, G, in terms of system parameters. The correction factor is defined as

$$C = \frac{\Delta(P_T)_{exp}}{\Delta(P_T)_{cal}} \tag{5}$$

The calculated values of ΔP_T were obtained using equation (4). The proposed correlation for the correction factor is given below

$$C = 1{\cdot}67\left(\frac{D_c}{d_p}\right)^{-0.59}\left(\frac{\rho_s}{\rho_t}\right)^{0.67}\left(\frac{h_s}{D_c}\right)^{-0.43}\left(\frac{h_{pa}}{h_s}\right)^{0.03}(R)^{0.03} \tag{6}$$

Another dimensionless correlation for pressure drop in liquid-solid have also suggested by

Roy and Sarma[35,36] is given below

$$\frac{\Delta P_r}{\Delta P_{osf}} = 19{\cdot}5 \left(\frac{D_c}{d_p}\right)^{-0.17} \left(\frac{\rho_s}{\rho_f}\right)^{0.48} (R)^{0.28} \left(\frac{h_{pa}}{h_s}\right)^{0.89} \quad (7)$$

For regular mixtrures, Roy and Sarma[14] proposed correlation for the pressure drop across the bed is given below

$$\Delta P_{sf} = \Delta P_f + \Delta P_{pa} + \Delta P_r \quad (8)$$

$$\Delta P_{sf} = \frac{M_b g}{A_c} + 150\frac{(1-\varepsilon_{pa})^2}{(\varepsilon_{pa})^3}\frac{\mu_l U_l h_{pa}}{(\varphi_s d_p)^2} + 1.75\frac{1-\varepsilon_{pa}}{(\varepsilon_{pa})^3}\frac{\rho_l U_l^2 h_{pa}}{\varphi_s d_p} \quad (9)$$

The maiden investigations relating to hydrodynamics of liquid-solid semi-fluidized bed with irregular homogeneous ternary mixtures have been reported by (Samal, Mohanty and Roy)[43]. The correalation developed from dimensional analysis approach is as

$$\Delta P_{sf}/\Delta P_{mf} = 2\times10^{-7}(\rho_{sav}/\rho_f)^{1.675}(D_c/d_{pav})^{3.338}(G_{sf}/G_{mf})^{3.094}(H_s/D_c)^{-0.424}R^{-0.938} \quad (10)$$

1.1.2 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.

For water –solids (Roy and Sarma,1971)[28]

$$\frac{G_{osf}}{G_{msf}} = 0{\cdot}015\,(R) + (\log Ar + 2{\cdot}456)/52$$

$$\frac{G_{osf}}{G_{msf}} = 0.105R + 0.0577 \log d_p + 0.0192 \log [\rho_s\ (\rho_s - \rho_f)] + 0.2018$$

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

For water –solids (Roy and Sarma,1972)[29]

$$\frac{G_{osf}}{G_{msf}} = 0{\cdot}30 \left(\frac{D_c}{d_p}\right)^{-0.21} \left(\frac{\rho_s}{\rho_f}\right)^{0.41} (R)^{0.66}$$

For water – non spherical and non spherical particles (Roy and Sarma,1972)

$$\frac{G_{osf}}{G_{msf}} = 1{\cdot}625 \left(\frac{D_c}{d_p}\right)^{0.266} \left(\frac{\rho_s}{\rho_f}\right)^{-0.228} (R)^{0.585}$$

$$\frac{G_{osf}}{G_{mf}} = 1{\cdot}875 \left(\frac{D_c}{d_p}\right)^{0.266} \left(\frac{\rho_s}{\rho_f}\right)^{-0.228} (R)^{0.585}$$

For liquid –solids (Roy,1975)[21]

$$\frac{G_{osf}}{G_{msf}} = 0{\cdot}475 \left(\frac{D_c}{d_p}\right)^{-0.20} \left(\frac{\rho_s}{\rho_f}\right)^{0.17} (R)^{0.38}$$

For irregular particles, Roy and Sarma[34] have given the following correlation for the prediction of semi-fluidization velocity of irregular particles in liquid solid systems from a knowledge of the properties of the system and the solid and fluid properties. The proposed correlation is

$$\frac{G_s}{G_{msf}} = 0{\cdot}945 \left(\frac{D_c}{d_p}\right)^{-0{\cdot}15} \left(\frac{\rho_s}{\rho_f}\right)^{-0.11} (R)^{0{\cdot}57} \left(\frac{h_s}{D_c}\right)^{0.10} \left(\frac{h_{pa}}{h_s}\right)^{0.66} \tag{11}$$

Roy and Sharatchandra[25] 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

$$(\rho_{sav}) = \Sigma\, W / \Sigma \frac{W}{\rho_s} \tag{12}$$

in the equation for minimum semifluidization proposed by Roy[21]

$$\frac{G_{osf}}{G_{msf}} = 0\ 473 \left(\frac{D_c}{d_p}\right)^{0.20} \left(\frac{\rho_s}{\rho_f}\right)^{0.17} (R)^{0.38} \tag{13}$$

The values of G_{msf} were calculated from equation (12) replacing the particle density term with the average particle density is defined in the equation (10) and compared with the experimental values.

$$G_{msf} = \frac{1{\cdot}85\times10^4\, d_p^{0.65}\,[\rho_f\,(\rho_s-\rho_f)]^{0.55}}{\mu_f^{0.1}} \tag{14}$$

For homogeneous mixture, Roy and Dash[24] developed a correlation by substituting average particle size $(d_p)_{av}$ instead of d_p in the above equations, where $(d_p)_{av}$ is given by

$$\frac{1}{(d_p)_{av}} = \Sigma \frac{x}{d_p} \tag{15}$$

For regular particles, Roy and Sarma[14] presented a dimensional correlation for the minimum semi-fluidization velocity where it is correlated with initial static bed height, bed expansion ratio, particle size and liquid viscosity. The developed correlation is

$$U_{osf} = 0.14 R^{0.9} d_p^{0.5} \mu_l^{-0.25} \tag{16}$$

$$U_{msf} = 0.5 h_s^{0.35} R^{0.67} d_p^{0.62} \mu_l^{-0.47} \tag{17}$$

The dimensionless minimum semi-fluidization velocity (U_{osf}/U_{mf}) can be represented as

$$\frac{U_{osf}}{U_{mf}} = f(h_s, D_c, d_p, \rho_s, \rho_L, \mu_l, R) \tag{18}$$

$$\frac{U_{osf}}{U_{mf}} = f\left[\frac{h_s}{D_c}, \frac{d_p}{D_c}, \frac{\rho_s}{\rho_L}, \frac{\mu_l}{\mu_w}, R\right] \tag{19}$$

Since the column diameter and the density of solid are constant, the variation in the liquid density is negligible and the effect of static bed height is not relevant, with the help of the remaining experimental parameters, the equations developed are;

$$\frac{U_{osf}}{U_{mf}} = 0.388 d_p^{-0.37} \mu_l^{0.1} R^{0.92} \tag{20}$$

$$\frac{U_{osf}}{U_{mf}} = 0.45\left(\frac{d_p}{D_c}\right)^{-0.37}\left(\frac{\mu_l}{\mu_w}\right)^{1.14}(R)^{0.92} \tag{21}$$

The values of the dimensionless minimum semi-fluidization velocity predicted from above equations are in very close agreement with the experimental values with a standard deviation of 2.59%.

A new correlation has been proposed for the prediction of U_{osf}/U_{msf} is given below

$$\frac{U_{osf}}{U_{msf}} = 0.254\left(\frac{h_s}{D_c}\right)^{-0.3}\left(\frac{d_p}{D_c}\right)^{-0.05}\left(\frac{\mu_l}{\mu_w}\right)^{0.16}(R)^{0.3} \tag{22}$$

The maiden investigations relating to hydrodynamics of liquid-solid semi-fluidized bed with irregular homogeneous ternary mixtures have been reported by (Samal, Mohanty and Roy)[43]. The correalation for minimum semi-fluidization velocity developed from dimensional analysis approach is given as

$$U_{osf}/U_{mf} = 296.5(\rho_{sav}/\rho_f)^{-0.451}(D_c/d_{pav})^{-1.343}(H_s/D_c)^{0.228}R^{0.755} \tag{23}$$

1.1.3 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 [35] for the determination of G_{msf} experimentally. (a) from the plot of G Vs porosity of the fluidized bed (b) from the plot of h_{pa}/h_s Vs G graphs are also available for its rapid prediction for liquid-solid and gas-solid systems respectively. The correlations have been developed for its prediction from the minimum fluidization velocity[33,26] are presented below

For liquid –solids (Roy,1975)[21]

$$G_{msf} = \frac{1{\cdot}85 \times 10^{4}\,(d_p)^{0.65}\,[\rho_f\,(\rho_s - \rho_f)]^{0.55}}{\mu_f\,0{\cdot}1}$$

For liquid-solid (Roy and Sarma)[28]

$$G_{msf} = 0{\cdot}3\ (Ar)^{0.56}\ (\mu_f/d_p)$$
$$G_{msf}/G_{mf} = 5{\cdot}71\ (D_c/d_p)^{0.42}\ (\rho_s/\rho_f)^{0.67}$$

For liquid-solids (Poddar and Dutta, 1969)[18]

$$18\ Re_{msf} + 2{\cdot}7\ Re_{msf}^{1.687} = Ga$$

For regular particles, a new correlation has been developed by Roy and Jena[14] from the experimental values of U_{msf}/U_{mf} with a correlation factor of 0.973

$$\frac{U_{msf}}{U_{mf}} = 1.565\left(\frac{h_s}{D_c}\right)^{0.36}\left(\frac{d_p}{D_c}\right)^{-0.33}\left(\frac{\mu_l}{\mu_w}\right)^{-0.08}(R)^{0.69} \qquad (24)$$

The maiden investigations relating to hydrodynamics of liquid-solid semi-fluidized bed with irregular homogeneous ternary mixtures have been reported by (Samal, Mohanty and Roy)[43]. The correalation for maximum semi-fluidization velocity developed from dimensional analysis approach is given as

$$U_{msf}/U_{mf} = 0.001(\rho_{sav}/\rho_f)^{-0.680}(D_c/d_{pav})^{2.430}(H_s/D_c)^{0.613}R^{0.633} \qquad (25)$$

1.1.4 Height of Packed Bed

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

The methods available for the prediction of the height of the packed section in semifluidization are (a) the method of Fan, et al[9] based on a material balance approach. Fan and Wen[11] and Wen, et al[11] have also suggested a dimensionless correlation for the prediction of the packed-bed height (b) experimental determination with the parameters such as the position of screen and the fluid mass velocity (c) Poddar and Dutt[19] 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 proper-ties 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[28] in the derivation of Fan and Wen* and Wen, et a*l*[11] . Correlations proposed for the prediction of packed bed height are presented below,
For solid-liquid (Fan and Wen ,1961)[45]

$$h_{pa} = (h_f - h_{sf})\frac{(1 - \epsilon_f)}{(\epsilon_f - \epsilon_{pa})}$$

For solids-liquids (Poddar and Dutta, 1970)[19]

$$h_{pa} = \frac{h_{sf}(1-\epsilon_{pa})}{(\epsilon_f-\epsilon_{pa})} - \frac{h_s(1-\epsilon_{pa})}{(\epsilon_f-\epsilon_{pa})}$$

$$\epsilon_f = \frac{(18\,\mathrm{Re} + 2{\cdot}7\,\mathrm{Re}^{1.687})^{0.2125}}{\mathrm{Ga}}$$

For solid –liquid (Roy and Sarma, 1971)[28]

$$\frac{(h_{sf}-h_s)}{(h_{sf}-h_{pa})} = \left(\frac{G_{sf}-G_{osf}}{G_{msf}-G_{osf}}\right)^{0.20}$$

For liquid- non-spherical and spherical solids (Roy and Sarma,1973)[30]

$$\frac{h_{pa}}{h_s} = 1{\cdot}09\ (G_{sf}/G_{msf})^{1.51}\ (D_c/d_p)^{0.23}(\rho_s/\rho_f)^{0.17}\ (R)^{-0.86}\ (h_s/D_c)^{-0.15}$$

$$h_{pa}/h_s = 2{\cdot}21\ (G_{sf}/G_{msf})^{2.08}\ (D_c/d_p)^{0.23}\ (\rho_s/\rho_f)^{0.17}(R)^{-0.88}\ (h_s/D_c)^{-0.15}$$

For regular particles, Roy and Jena[14] has been made an attempt to propose a correlate the experimental data for the larger size regular particles and obtained the following relationships for the entire range of experimentation

$$\frac{h-h_s}{h-h_{pa}} = 1.104\left(\frac{U_s-U_{mf}}{U_t-U_{mf}}\right)^{0.48} \qquad (26)$$

The correlations developed were given below

$$\frac{h_{pa}}{h_s} = 0.05\left(\frac{U_s}{U_{osf}}\right)^{6.6}\left(\frac{h_s}{D_c}\right)^{-0.08}\left(\frac{d_p}{D_c}\right)^{-0.21}\left(\frac{\mu_l}{\mu_w}\right)^{0.09}(R)^{-0.42}$$

for $h_{pa}/h_s < 0.42$.

$$\frac{h_{pa}}{h_s} = 0.325\left(\frac{U_s}{U_{osf}}\right)^{0.97}\left(\frac{h_s}{D_c}\right)^{-0.05}\left(\frac{d_p}{D_c}\right)^{-0.13}\left(\frac{\mu_l}{\mu_w}\right)^{0.05}(R)^{-0.26}$$

for $h_{pa}/h_s > 0.42$.

For liquid-solid semi-fluidized bed with irregular homogeneous ternary mixtures[43], correalation for height of packed bed has been developed from dimensional analysis approach reported by (Samal, Mohanty and Roy) and it is given as

$$H_{pa}/H_s = 1\times10^{-5}(\rho_{sav}/\rho_f)^{3.155}(D_c/d_{pav})_{1.510}(G_{sf}/G_{mf})^{2.426}(H_s/D_c)^{-0.524}R^{-1.676} \qquad (27)$$

Poddar and Dutt[19] have reported data on semifluidization in liquid-solid systems. They employed the correlation of Wen and Yu[11] for the voidage function and the relationship between f and the voidage fucntion to obtain the condition for minimum . semifluidization. Roy and Sarma[28] obtained the experi-mental data for a few water-solid systems, and developed the following correlation for the prediction of minimum semifluidization velocity

1.1.5 State of semi-fluidization

when the bed is in a semifluidized condition ,Empirical equations based on the dimensional analysis approach have been proposed to relate the various parameters. Thus, based on the dimensional analysis of the continuity and momentum equations for particle fluidization proposed by Fan and Wen[11] have obtained the follow-ing relationship for a semifluidized bed

$$f\left[\frac{(h-h_s)}{(h-h_{pa})},\ \frac{G-G_{mf}}{G_t-G_{mf}}\right]=0 \tag{28}$$

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

$$\frac{G-G_{mf}}{G_t-G_{mf}}=0.61\left[\frac{h-h_{pa}}{h-h_s}\right]^{-1.2} \tag{29}$$

On the other hand, Roy and Sarma[30] introduced the minimum semifluidization velocity in place of fluidi-zation velocity in equation (29) and developed the following expression

$$\frac{h-h_s}{h-h_{pa}}=\left[\frac{G-G_{osf}}{G_t-G_{osf}}\right]^{0.2} \tag{30}$$

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

$$f\left[\frac{G}{G_t},\frac{h_{pa}}{h_s},\frac{D_c}{d_p},\frac{\rho_s}{\rho_f},R,\frac{h_s}{D_c}\right]=0 \tag{31}$$

All these correlations for the state of semi-fluidization are given below

For liquid – spherical solids (Roy and Sarma, 1973)[30]

$$\frac{G_{sf}}{G_{msf}}=0{\cdot}684\left(\frac{D_c}{d_p}\right)^{-0.11}\left(\frac{h_s}{D_c}\right)^{-0.07}\left(\frac{\rho_s}{\rho_f}\right)^{-0.08}\left(\frac{h_{pa}}{h_s}\right)^{1.00}(R)^{0.42}$$

For liquid-solids (Roy, 1975)[21]

$$\frac{G_{sf}}{G_{msf}}=0{\cdot}925\left(\frac{D_c}{d_p}\right)^{-0.15}\left(\frac{\rho_s}{\rho_f}\right)^{-0.12}\left(\frac{h_{pa}}{h_s}\right)^{0.32}(R)^{0.43}$$

For liquid-irregular particles (Roy and Biswal, 1977)[22]

$$\frac{G_{sf}}{G_{msf}}=0{\cdot}925\left(\frac{D_c}{d_p}\right)^{-0.15}\left(\frac{\rho_s}{\rho_f}\right)^{-0.13}(R)^{0.43}\left(\frac{h_{pa}}{h_s}\right)^{0.32}$$

2. MISCELLANEOUS INDUSTRIAL APPLICATIONS

The application of semifluidized beds has been broadly described by Fan and Hsu[7] and Baburao, *et al[2]*

Semifluidized beds find wide application as reactors (for exothermic and bioreactions) in filtration operations for the removal of suspended particles from gases or liquids and ion exchange. A brief description of the utility of semifluidized beds in each of the above operations is given below.

2.1 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 semi-fluidized 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.

Hsu and Fan[12] 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.

2.2 Ion Exchange

semifluidized beds found wide applications with ion-exchange resins[7]. 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[16,6]. 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.

2.3 Bio-Rectors

The unique advantage of a semifluidized bed as a bioreactor has been presented by Fan and Hsu[7,8]. 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 waste-water treatment achieved removal of more than 70 TSS, 50 BOD and 60 TOC with a residence time of less than 5 hours[8].

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 un-stable 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.

The comparative study of immobilized cell bioreactors with semi-fluidized bed reactors for the treatment of waste water was briefly explained by Roy, Meikap[13]. The relative advantages of various modern bioreactors workingon immobilization technique have been projected. A comparative picture with respect tovarious modern bioreactors has been presented and the uniqueness of the fluidized and semi-fluidized bed bioreactors in the treatment of wastewater has been emphasized.

Performance Characteristics of Semifluidized bed biofilm reactors with liquid phase oxygen utilization(LPO) was analysed by Narayanan[17]. The study also confirms the applicability of LPO (Liquid Phase Oxygen) utilization forthe operation of aerobic biofilm reactors. Due to LPO utilization, the operation of the bioreactor reduces to that of a two phase system (conventional aerobic reactors being three phase systems) and it also significantly lowers the overall operating cost of the bioreactor.

The application of semifluidized bed bioreactor for the treatment of palm oil mill effluent (POME) has been mentioned in detail by Abass O. Alade, Ahmad T. Jameel[1] .other conventional methods have been reported to be less effective for the treatment of increasing volume of POME. Therefore The use of semifluidized bed bioreactor containing immobilized cells for the biodegradation of various high strength organic wastewater have been reported as highly efficient treatment method.

The uniqueness of the fluidized and semi-fluidized bed bioreactors in the treatment of phenolic wastewater has been emphasized by Roy and Jena. semi-fluidized bed bioreactor is a novel and efficient one, which can be adopted for the treatment of industrial wastewater containing phenolic compounds and other pollutants even at lower concentration.

2.4 Chemical Reactors

Cholette, Blanche and Cloutier[4,5] have shown that a combination of mixed and tubular reactors is often theoretically more efficient than either of these reactors operated independently. For endothermic re-actions, 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.

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. 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.

CONCLUSION

The review of the literature reveals that the information on semifluidization is highly incomplete.Prediction of pressure drop is still not very accurate. Much additional work is required for the accurate determination of packed and fluidized bed heights.The literature on the determination of the heights-of packed, fluidized and lean beds in semifluidization' is very limited. 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 highly significant. Hence, there is additional need for investigations on bed semifluidized systems on a broader spectrum to judge their suitability to different process applications that have become common for other fluid-solid systems such as packed and fluidized beds. Any developments made in semi-fluidized bed reactors to enhance mixing are always welcome.

NOMENCLATURE

a	specific surface area of the particle
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
$\triangle P_T$	total pressure drop across a semifluidized bed
R	bed expansion ratio. $=h_{sf}/h_{pa}$.
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

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 $= \frac{d_p^3 g_c \rho_s(\rho_s - \rho_f)}{\mu_f^2}$
Ga Galileo number $= \frac{d_p^3 \rho_f(\rho_s - \rho_f)g}{\mu_f^2}$
j_D mass transfer factor
j_H heat transfer factor
Nu_p particle Nusselt number, $= \frac{H\, d_p}{k_f}$
N_{sh} Sherwood number, $k_L h/D$
N_{Re} or Re_p particle Reynolds number, $\frac{d_p G}{\mu_f}$
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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