Heat & Mass Transfer Studies in Semifluidized Beds—A Review

—*J. S. N. Murthy, G. K. Roy, & K. J. R. Sarma**

THE technique of semifluidization is one of the major achievements in the past decade. This is also a two phase phenomena like the packed and fluidized bed operation. A semi-fluidized bed is a compromise between the packed and fluidized bed conditions and can be achieved in a conventional fluidizer by incorporating suitable modifications in the column construction.

The studies relating to semifluidization may broadly be classified as (1) Momentum Transfer Studies, (2) Heat Transfer Studies and (3) Mass Transfer Studies.

Literature reveals that comparatively much, work has been reported in the field of momentum transfer, whereas information available on heat and mass transfer aspects is very scanty. The present paper summarizes the earlier work and discusses some salient aspects of heat and mass transfer in semifluidized beds.

HEAT TRANSFER

There are three important aspects that may be investigated in connection with semifluidized bed heat transfer. (1) Fluid-to-particle heat transfer. (2) Particle-to-fluid heat transfer and (3) Wall-to-fluid heat transfer. The published literature refers to the second aspect (i.e.) the aspect of wall-to-fluid heat transfer only and that is discussed here.

Rao and Kaparthi (1) were the first to report their studies on wall heat transfer coefficients of semifluidized beds in 1" copper column employing different sizes of quartz particles, glass beads and aluminium particles fluidized with air. The variation of wall heat transfer coefficient with mass velocity for the entire region of packed, fluidized and semifluidized beds was studied. The investigators reported the presence of empty section between fluidized and packed section. The overall heat transfer coefficient of the bed was predicted using Leva and Grummer (10) equation for packed bed, equation of Urie (11) for the fluidized bed and Sieder-Tate (12) equation for empty section heat transfer coefficients, and from a knowledge of heights of various sections of the semifluidized bed. The proposed equation is given as

$$h_{SF} = \frac{L_{pa}\, h_{pa} + L_f\, h_f + L_e\, h_e}{L_{pa} + L_f + L_e} = \varepsilon\, hL/\varepsilon L.$$

Based on the experimental observations the authors concluded that the wall-to-bed heat transfer coefficients decrease with bed porosity and particle density, and increase with particle diameter. A correlation was also suggested for Nusselt number as

$$N_{up} = 0.014\, (Re_p)^{1\cdot 1}\ [(1-\varepsilon)/\varepsilon\,]^{0\cdot 4}$$

Varma et al (2) studied the heat transfer characteristics of semifluidized beds using liquid-solid systems, and reported similar observations as marked by Rao et al (1) in gas-solid systems. Heat transfer coefficient was claimed to be a function of bed expansion ratio in preference to the particle concentration represented by overall bed-porosity. From experimental observations, correlations have been developed and compared with the experimentally obtained values. The equations are, for glass beads

$$N_{up} = 0.00285\, (Re_p)^{1\cdot 21}\, (Pr)^{0\cdot 33}\, (R)^{-1\cdot 1}\, (D_p/D_t)^{-00\cdot 58}$$

and for aluminium particles.

$$N_{up} = 0.0032\, (Re_p)^{1\cdot 21}\, (Pr)^{-0\cdot 33}\, (R)^{-1\cdot 1}\, (D_p/D_t)^{-0\cdot 58}$$

Agreement between calculated and experimental values was good for the aluminium particles.

DISCUSSION:

In the correlations given by earlier investigators, Nusselt number has been expressed at a function of porosity or expansion ratio of the semifluidized bed. But these do not take into consideration the variations in the contributions of heat transfer possible due to different combinations of height of fluidized bed and. packed bed sections for the same value of either porosity or bed expansion ratio. So, it is desirable to include a factor which would take these variations into consideration. It has been stated that heat transfer coefficient depends on the properties

*The authors are with Regional Engineering College. Rourkela.

of the solid-like thermal conductivity, particle density etc. but these were not incorporated in the correlations. Proper accounting for these properties may explain the difference in coefficients of Nusselt number obtained for glass and aluminium particles by Varma et. al. (2).

CONCLUSIONS :

The effect of the variables on heat transfer rate as reported by earlier investigators may be summarized as follows :

1. The heat transfer coefficients increase with increase in the concentration of solids within the bed.
2. The values of heat transfer coefficient decrease with increase in the dia. of the particles.
3. Heat transfer coefficients for semifluidized beds can be predicted from a knowledge of flow through packed and fluidized beds.
4. Heat transfer coefficients for semifluidized beds can be predicted knowing the heights of the various zones in the semifluidized beds and the heat transfer coefficients of the individual zones separately.

Scopes:

The earlier work done is very meagre to assess the effect of the variables namely fluid properties, properties of the solid particles and operating conditions. So, a rigorous work is demanded in this field to study the effect of the above variables on heat transfer rate.

It is desirable to formulate equations based on theoretical background of the flow through packed beds and fluidized bed to predict heat transfer rates rather than to depend on empirical relations which may not be valid beyond experimental conditions.

MASS TRANSFER:

Wen et. al. (3) initiated the studies in the field of mass transfer. They conducted experiments with Benzoic acid-water system and correlated the mass transfer data in terms of j_D-factor and the modified N_Be. The mass transfer coefficients were calculated on the basis of the overall logarithmic mean driving force for both packed and fluidized bed sections. The correlation is as follows:

$$j_D = 1.865\,(Re_m)^{-0.48} \text{ where } Re_m = \frac{Re_p}{(1-\varepsilon)}$$

$$\text{for } Re_m > 5 \text{ and } < 30$$

Linear variation of mass transfer coefficients is claimed possible within the limits of a completely fixed bed and a fully fluidized bed by means of bed expansion alone.

Shirai presented a correlation of the mass transfer data in the particle beds on the basis of boundary layer theory. It is given by

$$N_{sh}\,\varepsilon = 2.0 + 0.75\,N_{Re}^{1/2}\,N_{sc}^{1/3}$$

Fan et al (4) have given correlations in terms of Sherwood Number and Reynold's Number for packed bed, fluidized bed and for combination of fluidized and packed bed based on the method sujggested by Shirai. They are given by

$$N_{sh} = 2.0 + 0.424\,Re_p^{0.558}\,N_{sc}^{1/3} \text{ – (Packed bed)}$$

$$N_{sh} = 2.0 + 0.23\,Re_p^{0.659}\,N_{sc}^{1/3} \text{ – (Fluidized bed)}$$

and

$$N_{sh} = 2.0 + 0.312\,Re_p^{0.608}\,N_{sc}^{1/3} \text{ – (Semifluidized bed)}$$

Rai et al (5) have undertaken the work to study the effect of variables, namely, properties of the solid particles (size, shape and density), properties of the fluid (density and viscosity) and operating conditions (fluid velocity and diffusivity). Benzoic acid, cinnamic-acid and 2-Naphthol have been used as the solid particles and water as the fluidizing medium.

As they have used only one fluidizing medium, the effect of the physical properties of fluid could not be ascertained. From the possible influence of the variables mentioned earlier, the following correlation in terms of dimensionless groups was suggested.

$$N_{sh} = C\left[(\rho_s - \rho_f)/\rho_f \cdot (D_p/D_t)\right]^x (N_{Rep})^y\,(N_{sc})^z$$

They have predicted exponential dependence of Sherwood number on Reynold's number.

On the basis of the penetration theory which concludes that kf a $D_f^{0.5}$, Schmidt index is 0.5 and from the consideration of analogy between heat and mass transfer the index is 0.33. The correlations using both the indices were compared with the experimental data. It was found that the correlation based on penetration theory agreed better with the experimental data.

An attempt was also made to propose correlations in terms of jD factor and NRep, for the systems studies. It was found that the relation was linear for all the systems with a difference in coefficient 'C in the correlation given below.

$$j_D = C\,(N_{Rep})^{-0.084}$$

The change in coefficient was attributed to hardness and crystalline structure of the pellets rather than to the difference in diffusion coefficients.

Govindrajan (6) obtained mass transfer data for benzoic acid-water systems for various particle sizes (10 to 30 BSS) and initial static bed heights. Based on these data a correlation was proposed to predict volumetric mass transfer coefficient in terms of the modified Reynold's number and bed expansion ratio. The correlation is given by

$$k_L a = 2.512 \times 10^{-5}\left[\left(\frac{D_p\,G}{\mu_f}\right)^{2.51} (R)^{-1.03}\right]$$

The deviation of the calculated values from experimental values was of the order of 16 per cent.

CONCLUSIONS:

The following conclusions may be made, based on the earlier studies to understand the effect of variables on mass transfer rate.

1. Mass transfer rate increased with increase in Reynold's number or flow rate of the fluid.
2. The values of KL of semifluidized bed lie between the limits corresponding to the fixed bed at one end and the fluidized bed at the other.
3. Mass transfer rate is affected by the characteristics of the particles, fluids, flow rate, and by the amount of expansion the bed allowed.
4. Hardness and crystalline structure of the particle also effect mass transfer rate.
5. The magnitudes of mass transfer coefficients can be controlled approximately linearly and within the limits of a completely fixed bed and a fully fluidized bed by means of bed expansion alone.

Scope:

The work reported earlier does not reveal the effect of all the variables on mass transfer rate. It is desirable to propose theoretical background as well, along with empirical correlations to predict the effect of these variables on mass transfer rate.

INDUSTRIAL IMPORTANCE :

The utility of semifluidized beds may be found, in industry as catalytic reactors, ion exchange columns, solvent extractors and other process equipments.

Cholette and Blanchet (7, 8) have shown that a combination of mixed and tubular reactors is often theoretically more efficient than either of these reactors operated independently. It was also shown that for endothermal reactions the tubular reactor is superior to C.S.T.R. and for exothermic reactions the C.S.T.R. is superior to the tubular reactor upto a certain Conversion after which the tubular reactor is more efficient.

The theoretical advantage of the mixed and tubular reactors' combination can be practically realized in a simple reactor system utilizing the principle of semifluidization. This has been discussed by Babu Rao et al (9). For example, this type of reactor may be used in the manufacture of Phthalic Anhydride from Naphthalene or Oxylene by oxidation or in the manufacture of Acrylonitrite from acetylene and hydrogen cyanide.

So, work in the field of heat and mass transfer will be of very much use in future.

SCOPE FOR STUDIES OF INDUSTRIAL IMPORTANCE:

It will be a very useful study if an attempt could be made to predict optimum heights of fluidized sections and packed bed section in semifluidized reactor to carry out reactions for the manufacture of chemicals of industrial importance.

NOMENCLATURE :

a = Specific surface of the particle (cm^2/cm^3).

C_{pf} = Specific heat of fluid (cal./gm.°C).

D = Diffusivity (cm^2/sec.).

D_p = Diameter of the particle (cm.).

D_t = Diameter of the tube (cm.).

k_f = Thermal conductivity of the fluid (cal./cm. sec.°C).

k_L = Mass transfer coefficient (cm./sec.).

L_e = Length of the empty section of the tube (cm.).

L_f = Length of fluidized section (cm.).

L_o = Initial static bed height (cm.).

L_{pa} = Length of the packed section (cm.).

= Height of the semifluidized bed (cm.).

G = Mass velocity of fluid (gm./cm^2 sec.).

h_c = Heat transfer coefficient of empty section (cal./cm^2. hr.°C).

h_f = Heat transfer coefficient of fluidized section.

h_{pa} = Heat transfer coefficient of packed section.

h_{sf} = Heat transfer coefficient for semi-fluidized bed.

N_{up} = Particle Nusselt Number ($h\, D_p/k_f$), (Dimensionless).

N_{sh} = Sherwood Number ($k_L\, L/D$), (Dimensionless).

Pr = Prandit Number ($Cp_f\, \mu_f / k_f$)

R = Bed expansion ratio, (Dimensionless)

S_c or N_{sc} = Schmidt's Number ($\mu_f/P_f D$). (Dimensionless).

N_{Re} or Re_p = Particle Reynold's Number $D_p v_o \rho_f / \mu_f$ (Dimensionless).

V_o = Superficial velocity of the fluid (cm./sec.).

GREEK LETTERS :

ε = Porosity of the bed (Dimensionless).

ρ_s = Density of the solid particles (gm./c.c.).

ρ_f = Density of the fluid (gm./c.c.).

μ_f = Viscosity of the fluid (gm./cm. sec.).

REFERENCES:

1. Heat Transfer in Semifluidized Beds, S. Purnachandra Rao and Ramalingam Kaparthi. Indian Chemical Engineer, April, 1969.
2. Heat Transfer in Semifluidized Beds, R. L. Varma, G. N. Pandey and G. Tripathi. Indian Journal of Technology, 19, Jan. 1972, pp. 11-15.
3. Semifluidization: Mass Transfer in Semifluidized Beds, Liang-Tseng Fan, Yung-Chia Yang and Chin-Yungnen, A.I.Ch.E. Journal, 5, No. 3, 1959, pp. 407-409.
4. Mass Transfer in Semifluidization, Liang-Teseng Fan et al. A.I.Ch.E. Journal, 1960.
5. Studies of Particle—Fluid Mass Transfer in Semifluidized Beds. H. S. Rao, G. N. Pandey and G. Tripathy. Paper presented in 23rd Annual Session of I.I.Ch.E.
6. Mass Transfer in Semifluidization. M.Tech. Thesis, P. N. Govindrajan.
7. Cholette, A., and J. Blanchet, Can.J.Chem. Eng., 39, 192 (1961).
8. Chollette, A., and L. Cloutier, ibid., 37, 105 (1959).
9. A New Adiabatic M.T. Reactor System, K. Babu Rao, S. P. Mukherjee and L. G. Doraiswamy. A.I.Ch.E. Journal, 11, No. 4, July (1965) pp. 741-742.
10. Leva, M. Weintranb, M. Grummer & Clark, R. R. I.E.C., 40, 747 (1948).
11. Urie, R. W., M.S. Thesis, Cambridge, M.I.T. (1948).
12. Process Heat Transfer, Kern, D. Q., McGraw-Hill Publications.

AMA-UC-44

UNISTAR®

offers India's FIRST

Flexo Cable for Air Field Lightining and other high wattage lighting equipment

This sophisticated Silicone Rubber Insulated Cable Lead Assembly works with unfailing reliability under most severe environmental conditions and therefore is most suited for air field lighting and other very exacting applications.

Whilst pioneering the manufacture of this cable Unistar have not only saved valuable foreign exchange, but have once again proved that Indian technology is capable of developing such item.

In the past also Unistar have been the first to manufacture in India other speciality cables, such as, aluminium screened railway signalling cables, split conductor cables etc. Unistar design engineers will be happy to receive such challenging assignments to develop other speciality cables on your demand.

Unistar Range include:—Elastomeric Insulated Cables upto and including 11 KV grade. Paper insulated power cables upto 33 KV. □ Unistar Thermoplastic cables upto 11 KV. Unistar copper conductor control and Railway Signalling Cables. AAC and ACSR as well as Special Cables to client's specifications. □ Unistar Properzi rods. Paper capacitors for Fans, Lighting, Motors and other domestic appliances. HT and LT Power Factor Improvement Capacitors.

Universal Cables Ltd.
Birla Colony, Satna. (M.P.)

For further information refer readers' service card.