

Heat Transfer Mechanisms in a Gas – Liquid-Solid Fluidized Beds

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Abstract

Three-Phase Fluidized Beds have found an important place in processing technology as Reactors. Gas-Liquid-Solid fluidization is considered in the present paper as operating bed of fluidized solid particles simultaneously with co-current upward flow of a continuous liquid phase and a gaseous phase dispersed in the form of bubbles. In the present study, the experimental work of the author on heat transfer from the Wall-to-Bed Three-Phase Fluidization is described. The mechanistic models based on Double Thermal Resistance, Surface Renewal and Capillary Tube models are discussed and compared with the author data. After discussing the possible reasons for the discrepancy, a generalized correlation for the wall-to-bed heat transfer coefficient is developed. It was noted that the limitations of Semi-theoretical models and important conclusions are presented. A good understanding of heat transfer mechanism should further aid the design and optimization process.

Key Words: capillary tube, mechanistic model, surface renewal, three-phase, thermal resistance.

1. Introduction

TPFBs with cocurrent upward flow of gas and liquid are recently receiving greater attention because of their wide variety of industrial applications. Many industrial process for hydro treating and conversion of heavy petroleum and synthetic, H – Oil, H – Coal process for coal liquefaction, Catalytic wet oxidation, Methanation, Washing of Uranium ore, Electrolytic tinning process, Bio-Fluidization and waste water purification and alkaloid production with immobilized cells. Recent progress in research and development for TPFBs was reviewed by Kim and Laurant

[1]. The influences of the liquid properties on the htcs in TPFBs were examined by Kato [2], Kang [3], Saberian – Broudjenni [4], Kim [5], Magilioutou [6], Zaidi [7], Rao Patnaik K.S.K [12], [13], Li, H and A Prakash, [15], Yang, G.Q, [17]. Recently Nigam K.D.P and Schumpe. A [14] has reviewed the TPSRs and it's fundamentals and analysis of practical systems.

2. Literature review – Mechanistic models

2.1 Thermal Resistance model

Chiu and Ziegler [8] proposed a model based on thermal resistance of the Fluidized bed. This implies that existence of two resistances of heat transfer, on near the heating surface and the other located inside the bed. The htc was calculated from the following equations

$$h = \frac{Q_w}{A(T_w - T_B)} \quad (1)$$

$$Q_w = m c_p (T_{Bout} - T_{Bin}) \quad (2)$$

Where T_B is the bulk steam temperature bed at the level of the main heater and T_w is the wall temperature. They observed that the temperature distributions flattened with increasing gas velocity. This inference radial mixing in TPFBs increases with increasing gas velocity.

Muroyama, K [9] examined the htc data by the equation of the Colburn type

$$j'_H = 0.137 Re'_{LG}{}^{-0.271} \quad (3)$$

$$\text{with } j'_H = h_w / (\rho_L C_{PL} U_L) \epsilon_L Pr^{2/3}$$

$$Re'_{LG} = [Re_L(\epsilon_G + \epsilon_L)] / [\epsilon_L(1 - \epsilon_G - \epsilon_L)] \quad (4)$$

The plots of j'_H Vs Re'_{LG} for the TPFBs are presented. The correlation is almost

independent of solid properties within the accuracy of heat transfer experiments.

2.2 Surface Renewal model

In TPFBs the continuous splitting and recombination of liquid stream around bubbles and particles generate the radial flow of the liquid phase between the heater surface and the bed. The liquid elements will stay for a certain period of time at the surface and leave it and enter the bulk fluid again. In the liquid elements adjacent to wall, unsteady heat diffusion may take place. The rate of heat transfer is controlled by the rate of renewal of liquid element which depend on the intensity of turbulence.

The mathematical representation of the above mechanism is

$$\frac{\partial T}{\partial t} = \alpha_L \frac{\partial^2 T}{\partial r^2} \quad (5)$$

subject to the boundary conditions

$$\begin{aligned} T &= T_w, r = 0, t \geq 0, \\ T &= T_B, r > 0, t = 0, \\ T &= T_B, r = \infty, t > 0, \end{aligned}$$

The mathematical solution of the above equation leads to the temperature profile. Therefore the average heat flux during the contact time θ of the liquid eddy at the exchanger surface is given by

$$q = 2 \sqrt{\frac{\alpha_L}{\pi \theta}} \rho_L C_{PL} (T_w - T_B) \quad (6)$$

The htcs in TPFBs can be represented by $h = C$

$$[k_L \rho_L C_{PL} \{ (U_L + U_G)(\epsilon_S \rho_S + \epsilon_L \rho_L + \epsilon_G \rho_G) - U_L \rho_L \} g / (\epsilon_L \mu_L)]^{0.5} \quad (7)$$

where C is the proportionality constant.

2.3 Capillary Tube model

The heat transfer in TPFBs is influenced by the hydrodynamics effects of the gas – liquid and solid – phase and the thermophysical properties of the liquid phase and can be represented by the following relationship

$h = f$ (hydrodynamic variables, liquid thermophysical properties)

The hydrodynamic variables can be represented by Reynolds number Re and Froude number Fr and the thermophysical properties by Prandtl number Pr. The above relationship, therefore, is described as follows:

$$St = F(Re, Fr, Pr) \quad (8)$$

if Stanton number St is used for the htcs. For TPFBs, however it is not easy to define clearly the characteristic velocity and length scale due to the presence of gas phase. Kato [2], therefore, employed Reynolds number for the hydrodynamic contribution of liquid phase and an additional dimensionless number, i.e., Froude number due to the presence of gas phase. All the correlations for the heat transfer in TPFBs based on the capillary tube model are reduced to a relationship for h in LSFBS,

$$h \sim c_{PL}^a k^b L \rho_L^c \mu_L^d d_S^e d_R^f u_L^g \epsilon_S^h \epsilon_L^i \quad (9)$$

The energy dissipation rate per unit mass of liquid has been used widely for developing a unified correlation of transport parameter in multiphase reactors. From a macroscopic viewpoint Suh, [10] the energy dissipation rate per unit cross sectional area of a TPFB with a bed height of H_R is calculated as the rate of the energy input into the system minus the rate of the potential energy recovery by the fluid phases

$$E = (u_L + u_G) \Delta P_{HR} - H_{Rg}(u_L \rho_L + u_G \rho_G) \quad (10)$$

In which ΔP_{HR} is the pressure drop across the bed height H_R and representation as follows

$$\Delta P_{HR} = (\epsilon_S \rho_S + \epsilon_L \rho_L + \epsilon_G \rho_G) g H_R \quad (11)$$

A less rigorous method determining the energy dissipation rate in TPFBs adopted by Yasunishi [11], however, the superficial liquid velocity instead of the interstitial liquid velocity for the relative velocities between the liquid and particles and between bubbles and the liquid.

3. Experimental

The experimental set up is used for investigating the htcs in TPFBs is the same on that used for heat transfer experiments described elsewhere. The complete experimental construction, explanation and procedure is therefore omitted here.

In the present observation, nearly 500 experimental runs are conducted covering different particle sizes, different bed weights with Water – Air and Aqueous glycerol – Air as Fluidizing media.

4. Results and Discussion

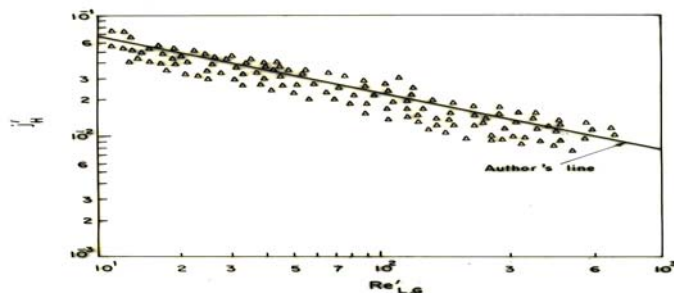


Figure 1. Author's correlation plot on thermal resistance model

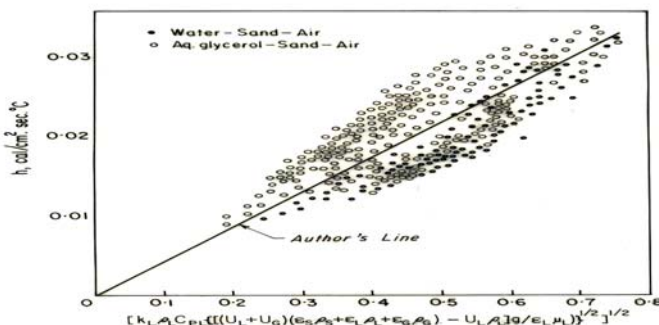


Figure 2. Correlation of Author's data on surface renewal model

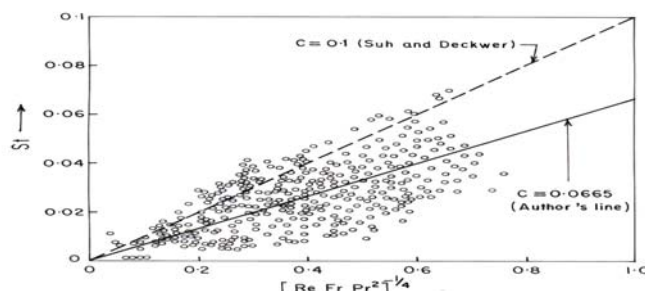


Figure 3. Parity plot – Author's line compared with Suh and Deckwer

Table I: The following range of parameters are covered in the present author's data

Particle sizes	0.17, 0.20, 0.25, 0.36, 0.46, 0.50, 0.66 mm
Bed material	Fine river sand
Fluid mass	Water, Aq-glycerol (5% to 40% wt%), Air
Superficial liquid velocity	$0.30 < u_L < 5$ cm/sec
Superficial gas velocity	$0 < u_G < 3$ cm/sec
Air pressure	0.65 kg/cm ² (gauge)
Diameter of the fluidized column	10.16 cm
Heating length of the fluidized column	100 cm
Viscosity of Aq. Glycerol	$0.01 < \mu_L < 0.0355$ pa.s
Solid hold up	$0.10 < \epsilon_s < 0.3$
Liquid hold up	$0.16 < \epsilon_L < 0.95$
Gas hold up	$0.08 < \epsilon_G < 0.65$

Figure.1 represents the relation between the j'_H vs Re'_{LG} for the TPFBs are presented. The author's data is scattered and below the Muroyama, K (9) predicted value. The correlation is almost independent of the particle properties with in the accuracy of heat transfer data. The author's correlation for the whole range of data is with in the $\pm 15\%$ deviations. Figure. 2 represents the relation between the h Vs x where $x =$ and also 'h' increases with variable 'x'.

The author's data having large scatter and fall below the Suh, (10) line. This clearly shows that the constant 'c' cannot be predicted from theory. It may be concluded that surface renewal model is purely a semi-theoretical requiring further development. However, at this stage it is difficult to substantiate the validity of these semi-empirical models. Figure. 3 indicates the relation of Capillary tube model which is based on hydrodynamic and thermophysical properties of liquids i.e Stanton number, St Vs $[Re Pr^2 Fr]^{-1/4}$ directly reads the proportionality constant $C = 0.0665$ from the author's data. If the value of $C = 0.0647$ Suh et, al (16) instead of 0.1 is used in general equation gives a constant value of the relative apparent bed viscosity

5. Conclusions

1. The author's data show the same trend as that of Muroyama. K, [9] on j'_H factor Vs Re'_{LG} correlation plot. The author's data fall below the muroyama correlation. The author's data is represented by $j'_H = 0.175 Re'_{LG}$ with $\pm 10\%$ deviation (12)
2. The author's data show a large scatter. The author's data is represented in accordance with the surface renewal model as

$h = 0.042$

$$[k_L \rho_L c_{PL} \{ (U_L + U_G)(\epsilon_s \rho_s + \epsilon_L \rho_L + \epsilon_G \rho_G) - U_L \rho_L \} g / (\epsilon_L \mu_L) \}^{0.5}]^{0.5} \quad (13)$$

With $\pm 20\%$ deviations.

3. The author's data show an excellent agreement with the Suh and Deckwer [16] based on capillary tube model. The author's data is represented by

$$St_t = 0.0665 [Pr^2 Re Fr \frac{\mu_b}{\mu_l} \frac{1}{P_v^*}]^{-1/4} \quad (14)$$

4. The fact that the constant C cannot be predicted from the theory.
5. It may be concluded that these models (Double Thermal Resistance, Surface Renewal and Capillary tube) are purely a semi-empirical requiring further development.

Notation

- A = geometric surface area for heat transfer
- Q = power dissipated by the heating surface
- q = heat flux
- m = mass flow rate
- c_p = heat capacity at constant pressure
- u_G = Superficial gas velocity
- u_L = Superficial liquid velocity
- h = wall-to-bed heat transfer coefficient
- c = proportionality constant
- K = Thermal conductivity
- j'_H = modified Chilton-Colburn factor for heat transfer at the wall
- Re'_{LG} = modified Reynolds number
- t = real time
- T = temperature difference
- K_{er} = effective thermal conductivity
- d_s = particle diameter
- d_R = reactor diameter

U_t = radial velocity component
 η_b = relative apparent bed viscosity
 μ_b = apparent effective bed viscosity
 g = acceleration due to gravity
 H_R = bed height
 μ_l = liquid viscosity
 E = energy dissipation per unit cross-sectional area
 ΔP_{HR} = pressure drop across the bed height
 P_v = mechanical energy dissipation rate per unit volume of liquid in TPFB

P_v^* = dimensionless group

TPFBs = Three-Phase Fluidized Beds

TPSRs = Three-Phase Sparged Reactors

htc = heat transfer coefficient

LSFBs = Liquid-Solid Fluidized Beds

Greek symbols

ϵ = phase holdup
 μ = dynamic viscosity
 ρ = density
 α = thermal diffusivity
 Θ = contact time

Subscripts

G = gas phase
 L = liquid phase
 S = solid phase
 P = particle
 B = bed
 W = wall

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