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BRIEF COMMUNICATION

HEAT TRANSFER COEFFICIENTS IN THREE PHASE FLUIDIZED BEDS

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In order to obtain a semitheoretical correlation for the heat transfer coefficients in three phase fluidized beds, Deckwer's semitheoretical correlation for the heat transfer coefficients in the bubble column, which was derived from Higbie's surface renewal theory of interphase mass transfer with the concept of isotropic turbulence, has been extended to three phase fluidized beds with the modification of the energy dissipation rate.

One of the desirable characteristics of three phase fluidized beds is the uniformity of temperature in the bed. The intense longitudinal and transverse turbulent mixing in a fluidized bed may induce the uniform fields of temperature and solids concentration. For highly exothermic reactions, the uniform temperature in the bed is essential to avoid the local hot spots.

In order to control the uniform temperature of three phase fluidized beds, the addition or removal of heat in the bed is required and the information on heat transfer surface and the bed is essential to designing the heat exchanger.

Recently, Chiu & Ziegler (1983) determined wall-to-bed heat transfer coefficients in three phase fluidized bed (5.08 cm ID) of glass beads and cylindrical gamma alumina particles which were fluidized by cocurrent flow of air and water. Their data were correlated in terms of the modified Colburn j factor.

Kato *et al.* (1981) measured wall-to-bed heat transfer coefficients in three phase fluidized beds of 5.2 and 12.0 cm internal diameter. Four different sizes of glass beads (0.42–2.2 mm) were fluidized by air and aqueous carboxymethyl cellulose solutions. The coefficients increased with decrease in liquid viscosity and with increase in gas and liquid velocity.

Heat transfer coefficients have been determined in a 24.0 cm diameter column (Baker *et al.* 1978) in which a coaxially mounted heater was installed. Four different sizes of glass beads (0.5–5.0 mm) were fluidized by air and water. The coefficients in three phase beds were found to be higher than those in the comparable liquid–solid and gas–liquid systems. Also, the coefficients increased with the particle size and gas velocity and went to maximum as the bed porosity increased.

The effects of liquid and gas velocity, particle size and viscosity of liquid on heat transfer coefficient between three phase fluidized beds and a coaxially mounted heater have been studied by Kang *et al.* (1983). They found that the coefficients increased with fluid velocities and particle size and it decreased with liquid viscosity. The bed porosity at which the maximum heat transfer occurred decreased with particle size but increased with liquid viscosity.

Since the heat transfer in three phase fluidized beds may be attributed to the intense mixing of solid phase, the heat transfer coefficients can be correlated from the energy input rate in three phase fluidized bed.

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THEORY

For gas–solid fluidized bed, the mechanism of particle convective transfer accounts for the most part of the total heat transfer. Since the thermal conductivity and volumetric heat capacity are much higher for liquids than for gases, heat transfer by particle convection can be neglected in liquid–solid (Patel & Simpson 1977, Wasmund & Smith 1967) and three phase fluidized beds.

In three phase fluidized beds, the continuous splitting and recombination of the 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 then leave it and enter the bulk fluid again. In the liquid elements adjacent to the wall, unsteady heat diffusion may take place. The rate of heat transfer is controlled by the rate of renewal of liquid element which may depend on the intensity of turbulence. Thus it can be anticipated that the heat transfer characteristics of three phase fluidized bed is similar to the radial mixing characteristics, as reported by El-Temtamy *et al.* (1979).

The mathematical representation of the above mechanism is

$$\frac{\partial T}{\partial t} = \alpha_L \frac{\partial^2 T}{\partial r^2} \qquad [1]$$

subject to the following boundary conditions:

$$T = Tw, \quad r = 0, \quad t \geq 0,$$
$$T = T_B, \quad r > 0, \quad t = 0,$$
$$T = T_B, \quad r = \infty, \quad t > 0.$$

Integration of the above equations by means of Laplace transform leads to the instationary temperature profile. Therefore the average heat flux during the contact time θ of the liquid eddy at the heat exchanger surface can be calculated as follows:

$$q = 2\sqrt{\frac{\alpha_L}{\pi\theta}}\,\rho_L Cp_L\,(T_w - T_B). \qquad [2]$$

The comparison of [2] with the common definition of heat transfer coefficient yields the following relation:

$$h \propto (k_L \rho_L Cp_L/\theta)^{1/2}. \qquad [3]$$

The contact time θ can be related to the length η and velocity scale v of the microscale eddies as follows:

$$\theta = \eta/v. \qquad [4]$$

Kolmogoroff's theory (Hinze 1958) postulates that the energy dissipation by the micro eddies is locally isotropic and mainly governed by the viscous forces. Therefore, the length and velocity scale of micro eddies can be correlated with the kinematic viscosity ν and the energy dissipation rate per unit mass of fluid p_v by dimensional analysis as follows:

$$\eta = (\nu^3/p_v)^{1/4}, \qquad [5]$$

$$v = (\nu P_v)^{1/4}. \qquad [6]$$

By the replacement of [4]–[6] in [3], heat transfer coefficient leads to the following equation:

$$h \propto [k_L \rho_L Cp_L (P_v/\nu_L)^{1/2}]^{1/2}. \qquad [7]$$

Deckwer (1980) derived the same relation for the heat transfer coefficients in bubble column. Because of the negligible effect of particle convective transport on the heat transfer in three phase fluidized beds, the above correlation for bubble column may be extended to three phase fluidized beds by the modification of the energy dissipation rate term p_v which covers the increase of the surface renewal rate resulted from the presence of solid particles in three phase fluidized bed.

Since phase holdups in three phase fluidized beds have been found to be uniform along the bed height (Kato *et al.* 1981, Kim *et al.* 1972, Bergovich & Watson 1978), the energy dissipation rate per unit mass of liquid phase in three phase fluidized beds may be given by the energy input rate minus the energy recovery rate due to the increase of the potential energy of liquid phase as

$$p_v = [(U_L + U_G)(\epsilon_S \rho_S + \epsilon_L \rho_L + \epsilon_G \rho_G) - U_L \rho_L] g/(\epsilon_L \rho_L). \qquad [8]$$

The heat transfer coefficients in three phase fluidized beds can be represented by the replacement of [8] in [7] as

$$h = C[k_L \rho_L Cp_L \{[(U_L + U_G)(\epsilon_S \rho_S + \epsilon_L \rho_L + \epsilon_G \rho_G) - U_L \rho_L] g/(\epsilon_L \mu_L)\}^{1/2}]^{1/2}, \qquad [9]$$

where C is the proportionality constant which can be determined from the heat transfer coefficient data obtained from wall-to-bed (Chiu & Ziegler 1983, Kato *et al.* 1981) and a coaxially mounted heater to bed (Kang *et al.* 1984, Baker *Et al.* 1978) in three phase fluidized beds. In addition, it may be assumed that these heat transfer coefficients from the above cited studies are independent of heater dimension since Lewis, *et al.* (1982) have found that once a vertical dimension greater than 4.0 cm is reached, the heat transfer becomes independent of heater dimension and orientation in bubble columns.

CORRELATION

A multiple regression analysis on the published experimental data (Baker *et al.* 1977, Chiu & Ziegler 1983, Kato *et al.* 1981, Kang *et al.* 1984) of the heat transfer coefficient in

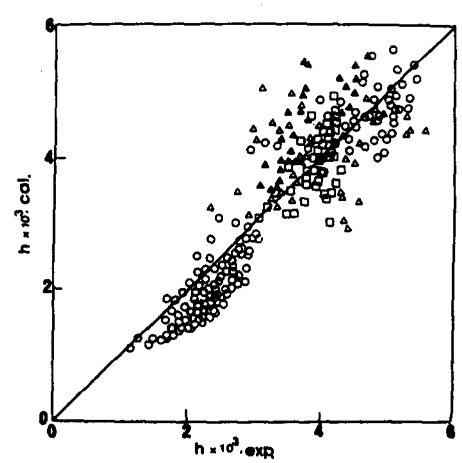

Figure 1. Comparison of observed and calculated values of heat transfer coefficients. O: Kang *et al.* (1983)—301 data points. □: Chiu and Ziegler (1983)—107 data points. △: Kato *et al.* (1981)—55 data points. ▲: Baker *et al.* (1978)—50 data points.

three phase fluidized beds results in the following form:

$$h = 0.0647[k_L \rho_L C p_L \{[(U_L + U_G)(\epsilon_S \rho_S + \epsilon_L \rho_L + \epsilon_G \rho_G) - U_L \rho_L] g/(\epsilon_L \mu_L)\}^{1/2}]^{1/2} \qquad [10]$$

with the correlation coefficient of 0.91.

The goodness of fit between experimental and calculated values of h is shown in figure 1 for 513 data points. This correlation covers the range of variables, $0.6 < U_L < 16.0$ cm/s, $0.8 < U_G < 18.0$ cm/s, $0.001 < \mu_L < 0.039$ Pa s, $0.06 < \epsilon_S < 0.59$, $0.25 < \epsilon_L < 0.86$, $0.007 < \epsilon_G < 0.25$. The values of k_L, ρ_L and C_{pL} have been assumed as of water since the concentrations of carboxymethyl cellulose in water were very small (Perry 1963). The available experimental data from the literature (Baker *et al.* 1978, Kato *et al.* 1981, Chiu & Ziegler 1983, Kang *et al.* 1984) are well represented by the proposed heat transfer mechanism. Further work is of course necessary to extend this correlation to the wider range of experimental variables in three phase fluidized beds.

NOTATION

C_p Heat capacity, J/kg K
g Gravitational acceleration, m/s^2
h Heat transfer coefficient, W/m^2 K
k Thermal conductivity, W/m K
P_v Energy dissipation rate per unit mass of continuous phase, m^2/s^3
q Heat flux, W/m^2
r Direction of heat flow
t Time, s
T Temperature, K
T_B Bed temperature, K
T_W Wall temperature, K
u Superficial velocity, m/s
v Velocity scale of micro eddy, m/s

Greek letters
α Thermal diffusivity, m^2/s
ρ Density, kg/m^3
ν Kinematic viscosity, m^2/s
μ Dynamic viscosity, Pa s
η Length scale of micro eddy, m
θ Contact time, s
ϵ Phase holdup

Subscript
G Gas phase
L Liquid phase
S Solid phase

REFERENCES

Baker, C. G. J., Armstrong, E. R., & Bergougnou, M. A. 1978 Heat Transfer in Three Phase Fluidized Beds. *Powder Technol.* **21,** 195–204.

Bergovich, J. M. & Watson, J. S. 1978 Hydrodynamic Characteristics of Three Phase Fluidized Beds, Fluidization. *Proc. of 2nd Eng. Found. Conf.,* 190–195.

Chiu, T. M. & Ziegler, E. N. 1983 Heat Transfer in Three Phase Fluidized Beds, *AIChE J.* **29,** 677–685.

DECKWER, W. D. 1980 On the Mechanism of Heat Transfer in Bubble Column Reactors, *Chem. Eng. Sci.* **35**, 1341–1346.

EL-TEMTAMY, S. A., EL-SHARNOUBI, Y. O. & EL-HALWAGI, M. M. 1979 Liquid Dispersion in Gas–Liquid Fluidized Beds, Part II: Axial and Radial Dispersion. The Dispersed Plug Flow Model. *Chem. Eng. J.* **18**, 161–168.

HINZE, J. O. 1958 *Turbulence*. McGraw-Hill, New York.

KANG, Y., SUH, I. S. & KIM, S. D. 1984 Heat Transfer Characteristics of Three Phase Fluidized Beds. *Chem. Eng. Commun.* (to be published).

KATO, Y., UCHIDA, K., KAGO, T. & MOROOKA, S. 1981 Liquid Holdup and Heat Transfer Coefficient Between Bed and Wall in Liquid–Solid and Gas–Liquid–Solid Fluidized Beds. *Powder Technol.* **28**, 173–179.

KIM, S. D., BAKER, C. G. J. & BERGOUGNOU, M. A. 1972 Holdup and Axial Mixing Characteristics of Two and Three Phase Fluidized Beds. *Can. J. Chem. Eng.* **50**, 695–701.

LEWIS, D. A., FIELD, R. W., XAVIER, A. M. & EDWARDS, D. 1982. Heat Transfer in Bubble Columns. *Trans IChem E.* **60**, 40–47.

PATEL, R. D. & SIMPSON, J. M. 1977 Wall to Fluid Heat Transfer in Aggregative and Particulate Liquid-Fluidized Beds. *Chem. Eng. Sci.* **32**, 67–74.

PERRY, J. H. 1963 *Chemical Engineers' Handbook*. 4th Ed., p. 3–225, McGraw-Hill, New York.

WASMUND, B. & SMITH, J. W. 1967 Wall to Fluid Heat Transfer in Liquid Fluidized Beds—Part 2. *Can. J. Chem. Eng.* **45**, 156–165.