Fluid-Particle Heat Transfer In Gas Fluidized Beds

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The heat transfer coefficient in a fluidized bed may be divided into three modes namely, fluid-particle, particle-particle and bed to wall. However, most of the experimental studies reported in the literature were limited to the measurements of total heat transfer coefficient only; this was due primarily to the difficulty in designing experiments to investigate any one mode independently. It is very difficult to obtain a single generalized correlation for the total heat transfer in a fluidized bed owing to the fact that each of the three modes are controlled by different interacting parameters.

Chang and Wen[1] in 1966 were the first to measure fluid-particle heat transfer coefficients under transient conditions. Their experiments involved the heating of the bed with hot air and subsequently cooling it by switching to cold air and this procedure may involve some error due to inertial effects of the flow system. Recently, the use of microwave heating which results in the bed attaining a uniform temperature almost instantaneously was investigated[2]. This eliminates temperature gradients within the bed and hence the particle-particle heat transfer. Using this technique and by maintaining adiabatic wall conditions Bhattacharyya and Pei[2] collected fluid-particle heat transfer data. Their bed materials consisted of 0.126 in. dia. Fe_2O_3 spheres and 0.2 in. dia. Fe_2O_3 cylinders with $L/D = 1$. The purpose of this note is to present additional data on the effects of the physical, thermal and transport properties of the bed materials on the fluid-particle heat transfer in gas fluidized beds. Seven commercial catalysts whose properties are listed in Table 1 were used.

The same equipment described by Bhattacharyya and Pei[2] was used in this investigation. The fluidized solids are heated to a constant temperature by microwave radiation and then cooled by the fluidizing gas which enters the bed at a constant temperature. Heat is transferred from the surface of the particles to the gas by convection and from the centre of the particle to the surface by conduction. The temperature of the bed is monitored by tagging a particle to a copper constantan thermocouple. The tagged solids were introduced at various locations inside the bed and were provided with enough thermocouple wire so that in fluidized conditions they could move freely within the bed. The surrounding fluid temperature was measured by inserting separate thermocouples placed inside glass tubes with the tips just lying within the tubes. Thus the thermocouple tips did not touch the solids and measured the gas temperature. The differential equation describing the temperature profile at the centre of a tagged particle is

$$\frac{\partial T_a}{\partial \tau} = \frac{1}{\eta^2} \frac{\partial}{\partial \eta} \left[\eta^2 \frac{\partial T_a}{\partial \eta} \right] \qquad (1)$$

The boundary conditions are

$$\frac{\partial T_a (1, \tau)}{\partial \eta} + Bi \left[T_a(1, \tau) - T_f(\tau) \right] = 0$$

$$T_a(\eta, 0) = 1$$

$$T_a(0, \tau) = \text{finite}$$

Balakrishnan[3] solved this equation and obtained

$$T_a(\tau, 0) = 1 + 2Bi \sum_{n=1}^{\alpha} e^{-\lambda_n^2 \tau} \left[\frac{\lambda_n \, . \, Sin\lambda_n \, (Bi - 1)}{Bi - Sin^2\lambda_n} \right] x \int_0^{\tau} e^{\lambda_n^2 \tau} \left[T_f(\tau) - 1 \right] d\tau \qquad (2)$$

TABLE 1

THERMO-PHYSICAL PROPERTIES OF THE CATALYSTS

Catalyst	Shape	Size in.	c_{ps} Btu/(lb.) (°F)	α ft.²/hr.	k_s Btu/(hr.) (ft.) (°F)	ρ_s lb./ft.³
Vanadium Pentoxide (Type 1)	Cylinders $L/D = 1$	7/32	0.415	0.0075	0.2614	84
Vanadium Pentoxide (Type 2)	Cylinders $L/D = 1.5$	7/32	0.263	0.0206	0.3027	54.31
Nickel-Molybdenum Oxide	Cylinders $L/D = 2$	1/8	0.325	0.0065	0.1077	51.8
Cobalt-Molybdenum Oxide	Cylinders $L/D = 2$	1/8	0.297	0.0083	0.128	51.6
Iron Oxide	Sphere	1/4	0.208	0.014	0.3525	121.06
Nickel Oxide	Sphere	1/4	0.39	0.0058	0.1569	52.76
Vanadium Pentoxide	Sphere	3/16	0.42	0.0034	0.12	82.98

The catalysts were supplied by:
The American Cyanamid Co.
Monsanto Enviro-Chem Systems Inc.
The Harshaw Chemical Co.
The Chemetron Corp.

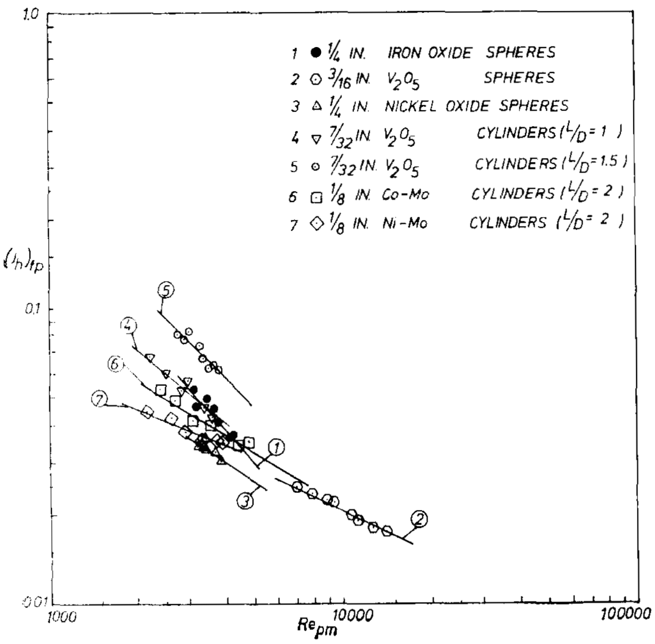

Figure 1 — Fluid-particle heat transfer data.

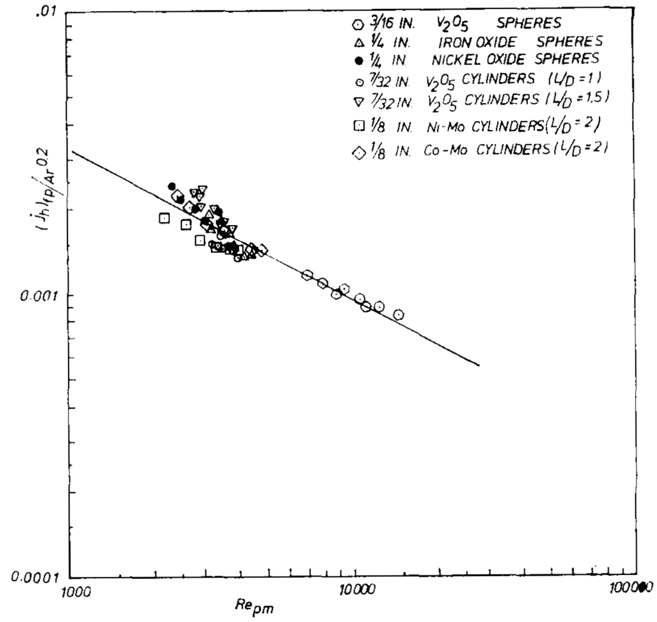

Figure 2 — Comparison of present data with Chang and Wen's correlation.

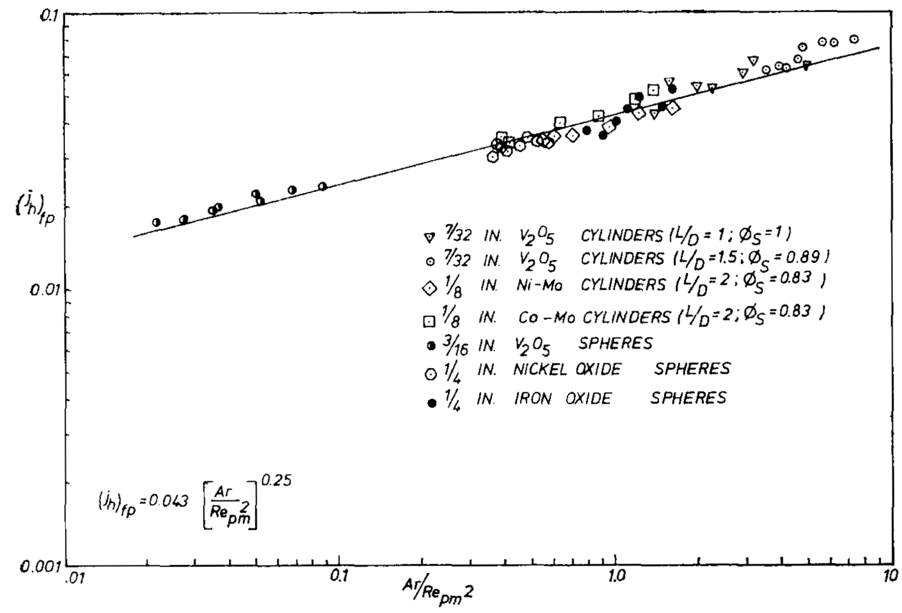

Figure 3 — Fluid-particle heat transfer correlation.

where the eigenvalues λ_n, are the roots of

$$\mu_n \cdot Cot\lambda_n = 1 - Bi \qquad (3)$$

Chang and Wen[1] solved the same equation and obtained an expression numerically identical to Equation (2). Equation (2) with the eigenvalues obtained from Equation (3) was used to determined B_i and hence h_{fp} from the cooling profiles of the tagged pellet, T_a, and the fluid, T_f, which are obtained by allowing the air flow rate and the solid and gas temperatures to reach steady state and then cutting off the microwave radiation. The results are shown in Figure 1 as a plot of a fluid-particle colburn-J factor, $(jh)_{fp}$ against a modified particle Reynolds number, Re_{pm}.

It is noted that a simple correlation between $(jh)_{fp}$ and Re_{pm} is not possible. This is due to the fact that while j factor in heat transfer includes the viscous force term and the inertial force term another equally important parameter which includes the gravity force term is not present. Therefore, to correlate fluidized bed heat transfer data, Chang and Wen[1] used

$$(jh)_{fp} = 0.097\,(Re_{pm})^{-0.5}\,(Ar)^{0.2} \qquad (4)$$

where Ar is the Archimedes number. The data appears to fit expression (4) reasonably well; however, on close observation it appears that there is some further dependence of jh factor on Archimedes numbers as reported by Bhattacharyya and Pei[2].

Bhattacharyya and Pei[2] recommended the following correlation

$$(jh)_{fp} = 0.043 \left[\frac{Ar}{Re_{pm}^2}\right]^{0.25} \qquad (5)$$

This is shown in Figure 3 and the data fits very well in the range $0.02 < \frac{Ar}{Re_{pm}^2} < 10$, with a variance, σ^2, of 1.89×10^{-4} and an average deviation of 8.5%. Moreover, the Archimedes number is defined as

$D_p^3 g\, \rho_f\, (\rho_p - \rho_f)/\mu_f^2$ and Re_{pm} is $D_p u_f \rho_f/\mu_f(1 - \epsilon)$

Therefore

$$\frac{Ar}{Re_{pm}^2} = \frac{D_p g}{u_f^2} \frac{(\rho_p - \rho_f)\,(1 - \epsilon)^2}{\rho_f}$$

$$= \frac{1}{Fr^2} \frac{(\rho_p - \rho_f)\,(1 - \epsilon)^2}{\rho_f} = \frac{1}{Fr_{pm}^2}$$

where Fr is the well known Froude number and Fr_{pm} a modified Froude number for gas-solid particulate systems. Hence, the proposed correlation (5) may also be written as

$$(jh)_{fp} = 0.043\,(Fr_{pm})^{-0.5} \qquad (6)$$

The gravity force represents the free movements of the solids in the fluidized bed. The inertia force is responsible for the fluid motion. Therefore, the ratio of gravity-to-inertial force $1/Fr_{pm}^2$ is an important parameter in correlating fluid-particle heat transfer data with jh factor which includes the viscous force term.

Finally, it may be noted that in fluidized beds the shape of the bed material does not have any effect on the jh factor. In the case of fixed beds the shape factor was found[4] to be an important correlating parameter. In fixed beds the gravity force represents the compactness of the bed and the particle-particle contact depends on the shape of the individual particles which is absent in fluidized beds.

In summary, the fluid-particle heat transfer coefficients were determined for a wide variety of sizes, shapes, densities, thermal and transport properties. The present data shows that $(Fr_{pm})^{-0.5}$ is the controlling parameter in correlating the experimental data.

Nomenclature

A_s	= total surface area of particles in the bed.
Ar	= archimedes number = $D_p^3 g \rho_f(\rho_s - \rho_f)/\mu_f^2$
Bi	= biot modulus = $h_{fp}\, D_p/k_s$
C_{ps}	= specific heat of solids.
C_{pf}	= specific heat of fluid.
D_p	= diameter of pellets.
g	= acceleration due to gravity.
G_f	= fluid mass velocity
h_{fp}	= fluid-particle heat transfer coefficient.
$(jh)_{fp}$	= colburn heat transfer factor = $(h_{fp}/c_{pf}G_f)\, Pr_f^{2/3}$.
k_f	= fluid thermal conductivity.
k_s	= thermal conductivity of solids.
Pr_f	= prandtl number = $C_{pf}\mu_f/k_f$.
r	= distance from centre of sphere.
R	= radius of sphere.
Re_{pm}	= modified Reynolds number = $D_p G_f/\mu_f(1 - \epsilon)$.
t_a	= solid temperature.
t_{ao}	= initial solid temperature.
t_f	= fluid temperature.
T_s	= t_a/t_{ao}.
T_f	= t_f/t_{ao}.
u_f	= fluid velocity

Greek letters

α	= thermal diffusivity of solids
ϵ	= porosity of bed
η	= r/R
θ	= time
μ_f	= fluid viscosity
ρ_f	= fluid density
ρ_s	= solid density
τ	= time = $k_s\theta/\rho_s C_{ps} R^2$

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