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Thermal Transport in Two-Phase Gas–Solid Suspension Flow Through Packed Beds

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SUMMARY

A method to evaluate the overall Nusselt numbers for heat transfer rates in a packed bed with gas–solid suspension flow through it is presented. The model based on earlier work of the authors on heat transfer in single-phase fluid flow through packed beds, includes separation of the overall heat transfer coefficient into conduction, convection and radiation contributions and their interactions. Numerical results indicate that the heat transfer rates increase with loading ratios and Reynolds number, as expected, but the increase varies with different bed materials. This dependence on the properties of the bed material is discussed and predictions using the present model are compared with a correlation available in the literature. For the special case where the bed materials are the same, the literature correlation prediction and the present model agree and the differences obtained where other bed materials are used further illustrates the importance of considering the properties of the bed materials in evaluating the total heat transfer rates.

INTRODUCTION

In order to achieve high heat fluxes, the addition of solid particles to a gas stream was seen as an answer to the deficiencies of both gases and liquids as heat transfer media (low thermal transport properties of the former and the tendency to undergo phase change and hence instability or burn out in the latter). This was convincingly demonstrated by the extensive and well-organised experiments of Farber and Morley [1]. Depew and Kramer [2] have reviewed much of the work on heat transfer in gas–solid flowing mixtures in pipes and conduits. In addition, gas–solid suspension flow through packed beds is important in chemical engineering, as this phenomenon is encountered in several processes such as the pyrolysis of coal, where fine coal particles are passed in a suspension in air through an incandescent bed of pebbles [3] and other solid catalysed gas-phase reactions with pronounced heat effects. There have been a very large number of studies on the heat transfer phenomenon in packed beds when only a single-phase fluid is flowing through the bed. Much of this work has been reviewed by Barker [4], Balakrishnan and Pei [5], Wakao *et al.* [6] and Burns [7] among others. However, information on heat transfer rates in two-phase gas–solid suspension flow through packed beds is limited and there is a need for reliable and adequate methods and correlations for estimating such heat transfer rates for design purposes. Apart from solid catalysed gas–solid reactions such as the pyrolysis of coal mentioned earlier, gas–solid suspension flow through packed bed systems finds application in solid-catalysed gas-phase reactions with pronounced heat effects where the high heat fluxes obtained by the addition of inert fines to the gas stream (solids loading) help in achieving temperature control of the reactor system.

In earlier work, Balakrishnan and Pei [5] proposed a model based on theoretical and empirical correlations to compute the total heat transfer rates in packed beds subject to

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gas flow (without entrained fines). This paper extends this method for use in the case of gas–solid suspension flow through packed beds.

THE MODEL

The detailed description of the Balakrishnan and Pei model and the derivation of the equations that follow from it are given elsewhere [5]; the expression for the total heat transfer coefficient for gas flow through packed beds was

$$h_t = h_{rcd} \frac{\Delta T}{\bar{T}} \frac{1}{\pi} + h_{fp} \quad (1)$$

where h_{rcd} defined as the heat transfer coefficient representing both conduction and radiation was evaluated using the following expressions:

$$h_{rcd} = h_{cd} + h_r \frac{\pi}{4} \quad (2)$$

$$h_r = \frac{0.227}{\dfrac{2}{e} - 0.264} \left(\frac{\bar{T}}{100}\right)^3 \quad (3)$$

$$h_{cd} = \frac{1}{R_{cd}{}^i} \frac{1}{A_s{}^i} \quad (4)$$

(i = 1 or 2 for simple and body-centred cubic packing geometries, respectively.)

$$R_{cd}{}^1 = \frac{2a}{k_s \pi r_c{}^2} \sum_{n=1}^{\alpha} \frac{P_{2n-1}(x_o) - P_{2n}(x_o)}{(2n-1) + Bi} \quad (5)$$

$$R_{cd}{}^2 = \frac{1}{4} R_{cd}{}^1 \quad (6)$$

The convective heat transfer coefficient h_{fp} for gas (without entrained fines) flowing through the packed bed was determined by an earlier empirical correlation (Balakrishnan and Pei [8]). Using this correlation and eqns. (1) to (6), they evaluated the total heat transfer rates in adiabatic packed beds, *i.e.*, (i) axial conduction with convective effects, (ii) convection from bed to fluid and (iii) radiation between bed particles, and found agreement with literature data. Subsequently, Balakrishnan and Pei [9] extended their empirical correlation for convective or fluid–particle heat transfer to gas–solid suspension flow through packed beds, *i.e.*, gas stream with entrained fines. Their expression was

$$Nu_{fp} = 0.016[Ar_m]^{0.25}[Re_p]^{0.5}[1 + \eta]^{0.68}\phi_s{}^{3.76} \quad (7)$$

In this paper, the convective heat transfer coefficient obtained by this correlation is used with the model equations (1) to (6) and the overall heat transfer rates obtained. The results are discussed vis-à-vis. (i) the effect of the loading ratio on the total Nusselt number, (ii) the contribution to the total Nusselt number of the effect of convection on the conduction mode at various Reynolds numbers and loading ratios and (iii) the comparisons of the model predictions with the earlier correlations by Royston [10].

EFFECT OF REYNOLDS NUMBER

The total heat transfer rates were evaluated as above for 0.635-cm iron oxide spheres and 1.27-cm nickel oxide spheres at various loading ratios and Reynolds numbers. Figure 1 shows a plot of Nusselt number (overall) at various loading ratios and Reynolds numbers for 0.635-cm iron oxide spheres. The loading ratio η is defined as the ratio of the mass flow rate of fines to the mass flow rate of the gas. As might be expected the heat transfer rates increase with loading ratio and Reynolds number. A similar plot was obtained for 1.27-cm nickel oxide spheres; however, computations revealed that 1.27-cm nickel oxide spheres yield higher values of Nu_t than the 0.635-cm iron oxide spheres (at approximately the same Reynolds number and loading ratio). This is due to the fact that the nickel oxide spheres have a larger Archimedes number and this gives rise to higher heat transfer rates, both convective and conductive. The reason for this was explained by Balakrishnan and Pei [9] in terms of the definition of the Archimedes number,

$$Ar_m = \frac{D_p{}^3 g \rho_f(\rho_p - \rho_f)(1-\epsilon)^2}{\mu_f{}^2}$$

$$= \frac{\text{gravitational force}}{\text{viscous force}}$$

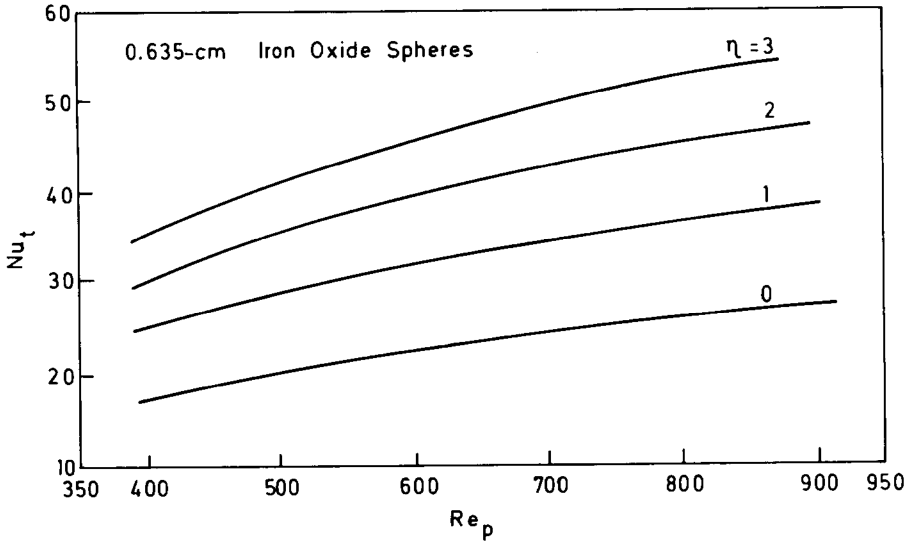

Fig. 1. Total Nusselt number *versus* Reynolds number (0.635-cm iron oxide spheres).

When the gravitational force is large, the contact spots between the bed particles will also be large. The size of the contact spot depends on the force or load between two particles and is obtained from Hertzian elasticity theory [5]. Furthermore, in a randomly packed bed there may be several contact spots. The heat transfer coefficient is defined on the basis of the entire surface area of the particles including the area of the contact spots. But the actual surface area for the convective heat transfer is relatively small for beds with large Archimedes number particles, *i.e.*, where particles are of large diameters and densities and thereby have large contact spots. Large contact spots also increase the conductive mode. This is because the smaller the contact spot, the greater is the resistance to heat transfer by conduction — the resistance being caused by the bending of the heat flow lines through the narrow aperture. For large Archimedes numbers, of course, the contact spots are larger and the resistance to conduction is less or conductive heat transfer is greater. It may be noted that when the Reynolds number is extrapolated to zero, $Re_p \rightarrow 0$, the Nu_t-value is not zero. This is because at zero Reynolds number, although the convective heat transfer no longer exists, there can still be conduction heat transfer between the particles.

EFFECT OF LOADING RATIO

It is obvious that an important parameter in suspension flow through packed beds is the loading ratio. It has been shown earlier [9] that the loading ratio increases the convective heat transfer coefficient h_{fp}, which in turn increases the conduction coefficient h_{cd} as well. This increase of h_{cd} with h_{fp} has been demonstrated earlier [5] and is said to be the effect of convection on the conduction mode, *i.e.*, the two modes are interactive. To study the effect of η on the total Nusselt number, the fractional increase in Nu_t due to solids loading was determined for various values of η. The fractional increase in Nu_t is defined by

$$Nu_{ts} = \frac{Nu_t\ (\text{with fines}) - Nu_t\ (\text{without fines})}{Nu_t\ (\text{without fines})} \tag{8}$$

where Nu_t-values are evaluated using the method described earlier in this paper. Computations reveal that the fractional increase in Nu_t is independent of Reynolds number for a particular loading ratio but dependent on η. Furthermore, the dependence on η varies with bed material. A plot of Nu_{ts} *versus* η is shown in Fig. 2 for three different bed materials — namely 0.635-cm iron oxide spheres, 1.27-cm nickel oxide spheres and 0.635-cm steel

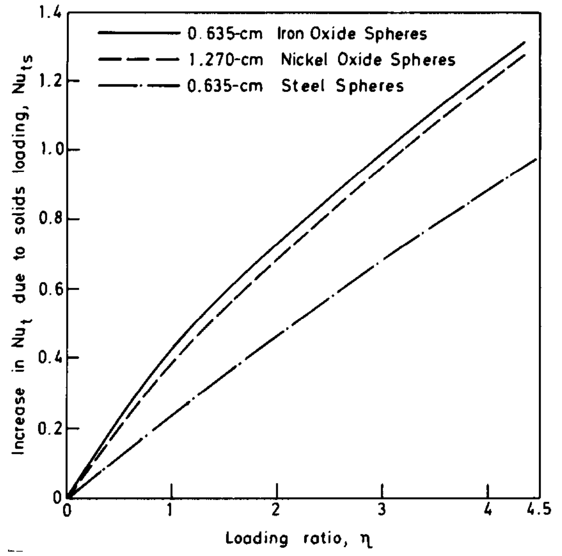

Fig. 2. Effect of loading ratio on total Nusselt number.

spheres. 0.635-cm iron oxide spheres and 1.27-cm nickel oxide spheres were used in the computations because these were among the commercial catalyst samples used in the earlier study [9] to obtain the correlation given by eqn. (7). The 0.635-cm steel spheres were used in order to compare the model results with earlier literature data, which are described later in the paper. The plots indicate that for steel spheres the augmentation of heat transfer rates is approximately uniform with increasing fines loading ratio, but for iron oxide and nickel oxide spheres, the increase in augmentation is pronounced up to a loading ratio of about 1, after which it tends to become approximately uniform with loading ratio. The above observations demonstrate two important characteristics of suspension flow heat transfer in packed beds. Firstly, the augmentation of heat transfer depends both on loading ratio and on the properties of the bed materials. Secondly, at a given loading ratio, the augmentation is independent of Reynolds number. This means the per cent increase in heat transfer due to a fixed amount of solids loading is the same at any gas flow rate for a given bed.

The dependence of Nu_{ts} on bed materials but not on Reynolds number can be explained as follows. The Reynolds number and the loading ratio affect the convective heat transfer coefficient h_{fp}, which in turn affects the conduction mode. The conduction mode has been shown earlier [5] to vary approximately linearly with h_{fp}, and this is proportional to Ar_m, Re_p and η, as is evident from eqn. (7). Therefore, for a particular bed material (Ar_m constant)

$$Nu_t \text{ (with fines)} \propto Re_p{}^m \eta^n \tag{9}$$

$$Nu_t \text{ (without fines)} \propto Re_p{}^m \tag{10}$$

where m and n are constants. Hence, from eqn. (8),

$$Nu_{ts} \propto \frac{Re_p{}^m(\eta^n - 1)}{Re_p{}^m}$$

$$\propto (\eta^n - 1) \tag{11}$$

which shows Nu_{ts} is independent of Re_p and dependent on η only.

On the other hand, varying the bed materials not only changes the convective effects (Ar_m changes) but also the conduction mode (at $Bi \to 0$), since the conductivity of the bed material also changes. The elastic properties of the bed material also change, resulting in different contact angles used in eqn. (5). Therefore,

$$Nu_t \text{ (with fines)} \propto \underset{Bi \longrightarrow 0}{(\text{conduction}} + Ar_m{}^c\eta^n) \tag{12}$$

$$Nu_t \text{ (without fines)} \propto \underset{Bi \longrightarrow 0}{(\text{conduction}} + Ar_m{}^c) \tag{13}$$

where c is a constant and hence, from eqn. (8),

$$Nu_{ts} \propto \frac{Ar_m{}^c(\eta^n - 1)}{\underset{Bi \longrightarrow 0}{(\text{conduction}} + Ar_m{}^c)} \tag{14}$$

which clearly indicates that the fractional increase in Nu_t due to fines depends on the bed material properties too.

IMPORTANCE OF CONVECTIVE EFFECTS ON CONDUCTION MODE IN EVALUATING OVERALL HEAT TRANSFER RATES

The conduction heat transfer coefficient evaluated by eqn. (5) has incorporated in it the effects of convection (through the Biot modulus). To examine the importance of the convective effects on conduction, the total

Nusselt number was determined for 0.635-cm iron oxide spheres using the present model. Nu_t was again determined using Biot modulus, $Bi \rightarrow 0$ (Biot modulus being determined using h_{tp} obtained from eqn. (7)). The difference (hereafter referred to as the 'difference') was evaluated for various Reynolds numbers and loading ratios. These are plotted in Fig. 3. The figure reveals that the 'difference' increases gradually with Reynolds number. Moreover, the slope is steeper with higher values of η. However, at Reynolds number higher than about 700 (in this case), there seems to be a tendency to level off.

This may be explained by noting the similarity between this figure and the behaviour of the convective heat transfer rate with Reynolds number at various loading ratios as experimentally determined by the earlier study of the authors [9]. Furthermore, as stated earlier, they have shown [5] that the increase in conduction due to convective effects is linearly proportional to h_{tp}, the convective heat transfer coefficient. Hence, it is apparant that the 'difference' has a similar dependence on Reynolds number and loading ratio as the convective heat transfer coefficient. The above discussion brings out two points. The Reynolds number and the loading ratio are important parameters not only for the convective contribution, but also for the conduction mode through the effect of convection on conduction. Secondly, ignoring the effect of convection on conduction (as was done by setting $Bi \rightarrow 0$) will result in appreciable underestimation of the overall heat transfer rates. This observation is in line with the view of Vortmeyer and Adam [11] that the effective conductivities of packed beds consist of two parts, namely a contribution for no flow conditions and another which depends on the flow conditions.

COMPARISON OF PRESENT STUDY WITH LITERATURE CORRELATION

Royston [10] studied the increase in Nu_t in a bed of steel spheres using different materials as fines. The correlation based on this work is

$$Nu_{ts} = 0.26 \frac{c_{ps}}{c_{pf}} \eta \tag{15}$$

where Nu_{ts} is the increase in heat transfer as defined in eqn. (8) and depends on the ratio of specific heats of fines and fluid and on the loading ratio. The range of c_{ps} in Royston's experiments is only 0.2 to 0.45 and it is believed that more experiments are required to examine the true dependence of Nu_{ts} on this parameter over a wider range. In the present study, glass fines were used and therefore eqn. (15) for glass reduces to

$$Nu_{ts} = 0.25\eta \tag{16}$$

This shows that the augmentation of heat transfer is dependent only on solids loading ratio, but by eqn. (14) it has been demonstrated that the physical properties of the bed material are also important.

Nu_{ts}-values for steel spheres (at η = 1, 2, 3 and 4) were obtained using eqn. (16) and

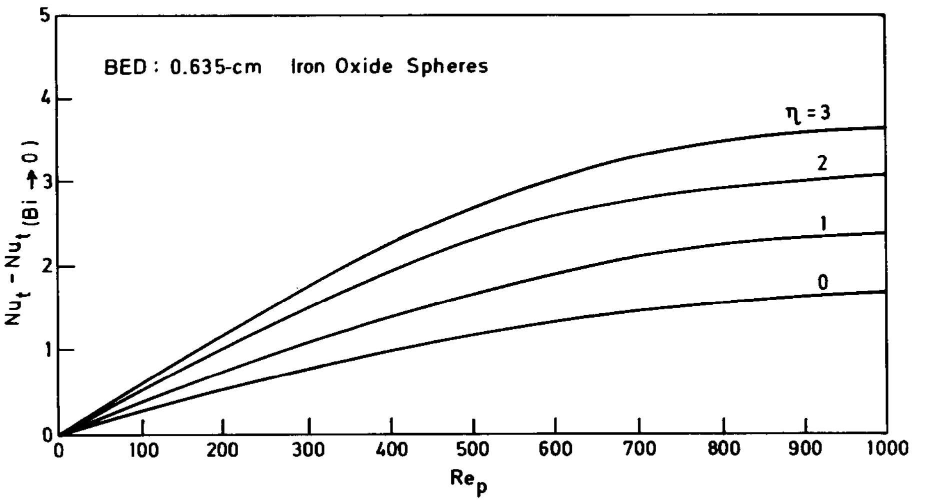

Fig. 3. Effect of convection on conduction mode.

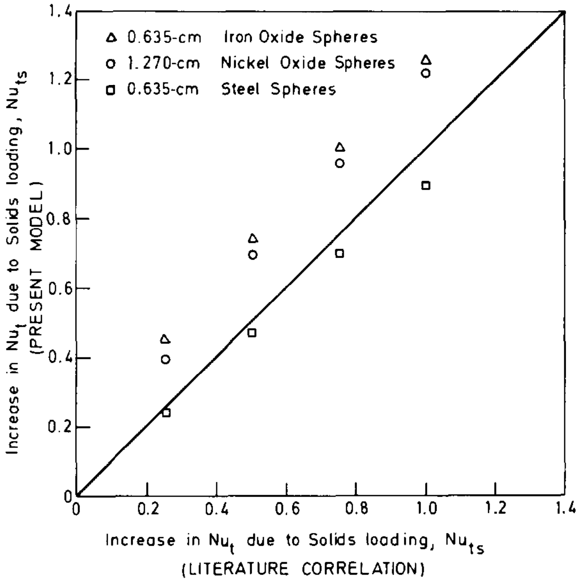

Fig. 4. Increase in Nu_t due to solids loading — comparison between present model and literature correlation.

again using the present model and these are plotted against each other in Fig. 4. (It may be noted that Royston's correlation was obtained from experiments performed on a bed of steel spheres.) The good agreement between the predictions is obvious from the figure. An attempt was made to make similar comparisons for the iron oxide and nickel oxide spheres. These comparisons are also plotted in Fig. 4. It is obvious that the agreement for these two bed materials is less satisfactory, the inference being that Royston's correlation cannot be extended to bed materials other than steel spheres. Furthermore, this correlation relates only the augmentation of heat transfer and the absolute value has to be determined independently. The present method has no such limitation and can be used at any loading (including $\eta = 0$).

CONCLUSIONS

The correlation by Royston [10] for the total heat transfer agrees very well with the present model for the bed material (0.635-cm steel spheres) on which it is based, confirming the validity of the present model to predict the total heat transfer rates in packed beds subject to gas–solid suspension flow. The differences obtained, for bed materials other than steel spheres further illustrates the importance of considering the properties of the bed materials in evaluating the total heat transfer rates. Finally, the conclusions that can be drawn from this study are summarized below:

(1) The total heat transfer rates from a packed bed to flowing gas–solid suspension has been determined using a semi-empirical approach.

(2) Impressive heat transfer augmentation is achieved by increasing fines loading.

(3) The important correlating parameters for heat transfer in gas–solid suspension flow through packed beds are Reynolds number, loading ratio and Archimedes number.

LIST OF SYMBOLS

a radius of sphere in packed bed, m
$A_s{}^i$ cross-sectional area of bed per sphere, m^2
Ar_m Archimedes number, $D_p{}^3 g \rho_f(\rho_p - \rho_f) \times (1-\epsilon)^2/\mu_f{}^2$, —
Bi Biot modulus, $h_{fp}\, a/k_s$, —
c_p specific heat, J/(kg·K)
D_p particle diameter in bed, m
e emissivity, —
G mass velocity, kg/(m^2·s)
h heat transfer coefficient, W/(m^2·K)
$\dot{m}$ mass flow rate, kg/s
Nu Nusselt number, hD_p/k_f, —
P_n Legendre polynomial of order n, —
r_c radius of contact spot, m
$R_{cd}{}^i$ resistance to heat transfer by conduction, s·K/J
Re_p Reynolds number, $D_p G/\mu_f$, —
T temperature, K
u_f fluid velocity, m/s
x_o argument of Legendre polynomials (= cosine of contact angle)

Greek symbols
ϵ bed porosity, —
η loading ratio, $\dot{m}_s/\dot{m}_f$, —
μ fluid viscosity, N·s/m
ρ density, kg/m^3
ϕ_s shape factor, —

Subscripts
f of fluid
p of particles in bed
s of fines in gas suspension

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