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INVESTIGATION OF RADIATIVE CONTRIBUTION IN A HIGH TEMPERATURE FLUIDIZED-BED USING THE ALTERNATE-SLAB MODEL

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Abstract – The modified alternate-slab model of Gabor is examined for the prediction of radiative contribution to the total heat transfer from a high temperature fluidized-bed system of air–sand to an immersed surface. The results are compared with the predictions of other models and experimental data on average heat transfer coefficient, and percentage radiative contribution as a function of various influencing parameters. The heat transfer coefficients are overestimated by the model within reasonable limits and approach the experimental data for high values of heat transfer surface temperature. The percentage radiative contribution is substantial for large values of particle diameter, surface and bed temperatures. The model is found reliable and simple to handle over a wide temperature range. Results are also presented for air–ash and air–dolomite systems in view of their practical significance.

NOMENCLATURE

Ar, Archimedes number, $Ar = g\rho_g(\rho_s - \rho_g)d_p^3/\mu_g^2$;
c_{ps}, heat capacity of solid;
d_p, particle diameter;
e_p, emissivity of solid particles;
e_s, emissivity of immersed surface;
f_0, fractional surface area exposed to bubbles;
g, acceleration due to gravity;
h, heat transfer coefficient;
h_w, total heat transfer coefficient;
h_{wce}, conductive coefficient in emulsion phase;
h_{wcemax}, maximum conductive coefficient in emulsion phase;
h_{wmax}, maximum total heat transfer coefficient;
h_{wr}, total radiative coefficient;
h_{wrb}, radiative coefficient in bubble phase;
h_{wre}, radiative coefficient in emulsion phase;
h_{wrmax}, maximum total radiative coefficient;
i, identification of slab face;
k_e, effective thermal conductivity of emulsion;
k_g, thermal conductivity of gas;
k_s, thermal conductivity of solid;
l_g, gas layer thickness;
Re_{opt}, Reynolds number at optimum fluidizing velocity, $Re_{opt} = \frac{U_{opt}d_p\rho_g}{\mu_g}$;
s, immersed surface;
T_b, bed temperature;
T_s, immersed surface temperature;
t, time;
t_r, residence time;
U, fluidizing velocity;
U_{opt}, optimum fluidizing velocity;
U_{mf}, minimum fluidizing velocity;
x, distance from immersed surface into the bed.

Greek symbols

Δt, step size in time direction;
Δx_g, gas slab thickness;
Δx_s, solid slice thickness;
α_s, thermal diffusivity of solid;
ε, bed voidage;
ε_{mf}, bed voidage at minimum fluidization;
μ_g, dynamic viscosity of gas;
ρ_g, density of gas;
ρ_s, density of solid;
σ, Stefan–Boltzman constant.

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INTRODUCTION

THE RADIATIVE contribution, h_{wr}, to total heat transfer coefficient, h_w, between a fluidized bed and either its containing vessel walls or an immersed surface has been the subject of investigation ever since Jolley [1] estimated it to be of the order of about 0.5 h_w at a bed temperature of 1273 K. Kharchenko and Makhorin [2] conclude that radiative contribution is insignificant up to bed temperatures of 1023 K, and Szekeley and Fisher [3] agree with them. The opposite view is held by Il' Chenko *et al.* [4], Botterill and Sealey [5], Baskakov *et al.* [6] and Vedamurthy and Sastri [7]. According to these investigators [4–7], the radiative contribution is significant and the relative contribution depends on the properties of the bed material, the particle size, bed and surface temperatures and fluidizing velocity. At one time, there was some uncertainty over the importance of radiation but now a majority of the studies predict significant radiative contribution.

It is, therefore, necessary to develop a suitable theoretical model which can reliably predict the radiative contribution in high temperature beds as a function of various parameters and operating conditions. It may be remarked that even for relatively low temperature beds where radiative contribution is insignificant, no single model predicts, in general, the heat transfer characteristics satisfactorily. Furthermore, the models contain one or more empirical parameters which have to be adjusted to reproduce experimental data. The complexity of the heat transfer phenomenon in fluidized beds justifies the development of these approximate models and their extension to include radiation. Such models have been assessed for their applicability to high temperature systems by comparison with high temperature data and a brief review of such limited efforts is given below.

Szekeley and Fisher [3] using the concept of unsteady state heat conduction to a single spherical particle in contact with a hot surface, as proposed by Botterill and Williams [8], have obtained a simple expression for the radiative component and have concluded that its contribution is insignificant below a bed temperature of 1273 K. Yoshida *et al.* [9] have proposed an emulsion layer model in which they have accounted radiation through the bubbles and through the emulsion on the concept of effective thermal conductivity. They conclude that radiative contribution is insignificant up to a bed temperature of 1473 K.

Vedamurthy and Sastri [10] have used the features of the Mickley–Fairbanks model [11] and the Wicke–Fetting model [12] to investigate the radiative contribution in an air–ash system up to bed temperatures of 1173 K for various fluidizing velocities and particle sizes. The bed and surface are considered as black bodies and the gas as radiatively transparent. They found that, for a particle diameter of 0.5 mm, the radiative contribution is between 17 and 30% at a bed temperature of 1173 K.

Bhattacharya and Harrison [13] have adopted the features of the Vedamurthy–Sastri model [10] and, by considering the gas to be radiatively absorbing and emitting and the bed to be gray, have computed the surface temperature dependence of radiative contribution for an air–sand system. They have found that, for a particle diameter of 0.35 mm at $T_b = 1123$ K, the contribution increases from about 10% at $T_s = 473$ K to about 20% at $T_s = 1073$ K.

Thring [14] has examined the Vedamurthy–Sastri model with a smaller value of the surface film resistance. The model predictions are in good agreement with the experimental data for air–sand system. He has also investigated the spherical particle and cubical particle models of Botterill and Williams [8] and concluded that the three models predict widely different values for the radiative contribution but almost the same result for maximum total heat transfer coefficient.

It is clear from the above that, in addition to the in-depth study of the packet model, the emulsion layer, the spherical particle and cubical particle models have also been employed to establish the contribution of radiative heat transfer. Gabor [15] has proposed an alternate-slab model according to which heat flows between the surface and the bed through alternate slabs of gas and solid. He has demonstrated the applicability of this model for moving packed [15] and fluidized [16] beds at low temperatures. We have further examined this model on the basis of the elaborate experimental data of Ozkaynak and Chen [17]. Figure 1 shows the comparison of our computed average heat transfer coefficients, using the alternate-slab model, for an air–glass system with the experimental data [17]. These workers [17] have also given the values of the packet residence time, t_r, and the fractional heat transfer surface area exposed to bubbles, f_0, using a capacitance probe, and these have been used in our calculations. It can be seen from Fig. 1 that the agreement between the model predictions and experimental data is good for fluidizing velocities greater than about twice the minimum fluidizing velocity. In this region of high fluidizing velocity, the alternate-slab model underestimates the heat transfer coefficient by about 10%. The simplicity of the alternate-slab model, both in its conception and numerical computation, constitutes a strong case in its favor for an in-depth study of its extension to beds at high temperatures.

Zabrodsky *et al.* [18] have recognized the merits of the alternate-slab model but made only a limited investigation on its basis to determine the contribution of instantaneous radiation coefficient for air–graphite, air–glass and air–corundum systems. Their calculations recognize only the emulsion phase of the fluidized bed and hence comparison with experimental data is not made. Although particle diameters greater than 1 mm are considered, the contribution of gas convection is not included. The effect of various parameters which influence the radiative contribution is not studied. They adopted a surface film thickness of $0.05d_p$ as suggested by Gabor [15]. However, in a recent study, Kolar *et al.* [19] have determined that a film thickness of $0.65d_p$ is more appropriate in the model to obtain good agreement with experimental

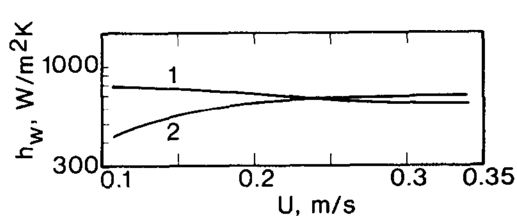

FIG. 1. Comparison of the alternate-slab model predictions with experimental data of Ozkaynak and Chen [17]. Air–glass system; $d_p = 0.245$ mm, $T_b = 360$ K, $T_s = 303$ K, U_{opt}. 1—Present, 2—Okzaynak and Chen.

data. In view of this, we have examined the alternate-slab model, as modified in [19], to predict the radiative contributions in an air–sand system as functions of various parameters for which experimental data are available and the findings are reported here. Model predictions are also given for air–ash and air–dolomite systems in view of their practical importance.

HEAT TRANSFER COEFFICIENTS

Heat is transferred between the bed and the immersed surface by (i) conduction and radiation through the emulsion phase, and by (ii) radiation through the bubble phase. The heat transfer coefficients for each of these processes will be denoted by h_{wce}, h_{wre} and h_{wrb}, respectively. Assuming radiative and conductive components to be additive the total heat transfer coefficient, h_w, can be written as

$$h_w = (h_{wce} + h_{wre})(1 - f_0) + h_{wrb} f_0 \qquad (1)$$

where f_0 is the fractional heat transfer surface area which is exposed to bubbles. The bubble phase heat transfer coefficient is calculated following Yoshida *et al.* [9]

$$h_{wrb} = \frac{2\sigma(T_b^4 - T_s^4)}{\left(\frac{1}{e_p} + \frac{2}{e_s} - 1\right)(T_b - T_s)}. \qquad (2)$$

The total radiative heat transfer coefficient, h_{wr}, is given by

$$h_{wr} = h_{wre} + h_{wrb}. \qquad (3)$$

The alternate-slab model of Gabor [17], as modified by Kolar *et al.* [19], is used in its extended form to calculate h_{wce} and h_{wre} and is explained briefly below. The extension of the model arises due to its use for high temperatures where radiation contribution is important. The details of the calculation necessary for a proper appraisal of the model are given below. The heat transfer coefficient as expressed by equation (1) neglects the contribution due to gas convection and, as a result, the analysis presented here is limited for its application to unpressurized systems comprising particles smaller than 1 mm in diameter.

THE EXTENDED ALTERNATE-SLAB MODEL

The modified alternate-slab model of Gabor [19] assumes the bed to be made up of alternate slabs of gas and solid, Fig. 2. The solid slabs are each $(2/3)d_p$ thick and are further subdivided into a convenient number of slices, in this case eight, each of thickness $d_p/12$. The first gas layer adjacent to the surface, which is at a temperature, T_s, lower than the bed temperature, T_b, is $0.065d_p$ thick and all other gas slabs are $0.13d_p$ thick. The bed and heat transfer surface are considered gray while the gas is radiatively transparent. The properties of the gas are taken as temperature dependent and the same are evaluated at an average temperature equal to the mean of the temperature of the two bounding surfaces of the gas slab.

Following the method explained in [19], the temperatures of the solid slices are calculated by

$$T_i' = [T_{i-1} + (M - 2)T_{i+1}]M^{-1}. \qquad (4)$$

The temperature of the first face of each solid slab is computed from the following equation in which the contribution due to radiation is included:

$$T_i' = \{2.5NT_{i-1} + [M - (2.5N + 2.5)]T_i + 2.5T_{i+1}\}M^{-1} - \frac{P}{R}(T_i^4 - T_{i-1}^4) \qquad (5)$$

where

$$P = \frac{2\sigma\,\Delta x_s}{k_s} \qquad (6a)$$

$$M = \frac{(\Delta x_s)^2}{\alpha_s\,\Delta t} \qquad (6b)$$

$$N = \frac{h_g\,\Delta x_s}{k_s} \qquad (6c)$$

$$h_g = \frac{k_g}{\Delta x_g} \qquad (6d)$$

$$R = \frac{1}{e_{p.i-1}} + \frac{1}{e_{p.i}} - 1. \qquad (6e)$$

To calculate the temperature of the first face of the first slab, we have $i = 1$, and

$$T_{i-1} = T_s, \quad e_{i-1} = e_s, \quad e_i = e_p, \qquad (7)$$

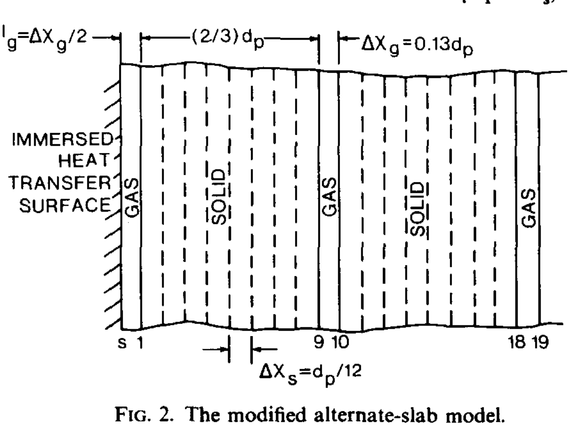

FIG. 2. The modified alternate-slab model.

and h_g and R are now defined as follows:

$$\left.\begin{aligned} h_g &= \frac{2k_g}{\Delta x_g} \\ R &= \frac{1}{e_p} + \frac{1}{e_s} - 1. \end{aligned}\right\} \quad (8)$$

The temperature of the last face of each solid slab is calculated from the relation

$$T_i' = \{2.5NT_{i+1} + [M - (2.5N + 2.5)] + 2.5T_{i-1}\}M^{-1} - \frac{P}{R}(T_i^4 - T_{i-1}^4). \quad (9)$$

Here all the parameters are as given by equation (6). The temperatures of successive slices are calculated starting from the heat transfer surfaces. The calculation in the x-direction at a particular time step is terminated at the slice whose calculated temperature differs from the core bed temperature only by a very small pre-fixed amount. This calculation procedure is in contrast with similar computations performed in the literature in which the thickness of the pocket is *a priori* fixed. The present calculations in the time direction are terminated when the residence time of the emulsion phase is reached. A uniform residence time for the emulsion phase is assumed. The instantaneous heat transfer coefficients thus calculated are next integrated to yield average heat transfer coefficients.

The various heat transfer coefficients and the radiative contribution, determined according to the model and the computational procedure described above, as functions of particle diameter, fluidization number, bed and surface temperatures, are presented and discussed later in the paper.

BED PARAMETERS

Various correlations employed to determine the bed parameters needed in the heat transfer calculations are as follows:

1. The minimum fluidization velocity, U_{mf}, is calculated from the equation suggested by Wen and Yu [20]

$$U_{mf} = \frac{\mu_g}{\rho_g d_p}\{[(33.7)^2 + 0.0408\,Ar]^{1/2} - 33.7\}. \quad (10)$$

2. The optimum fluidizing velocity, U_{opt}, is determined as given by Saxena *et al.* [21]

$$Re_{opt} = \frac{U_{opt} d_p \rho_g}{\mu_g} = \frac{Ar}{18 + 5.22\sqrt{Ar}}. \quad (11)$$

3. Bed voidage, ε_f, at a given fluidizing velocity, U, is evaluated from the following [21]:

$$\varepsilon_f = \frac{1}{2.1}\left[0.4 + \left(\frac{U\rho_g}{U_{mf}\rho_g}\,\frac{\varepsilon_{mf}^3}{1-\varepsilon_{mf}}\right)^{1/3}\right]. \quad (12)$$

4. The residence time, t_r, is obtained by the correlation suggested by Thring [14]

$$t_r = 8.932\left[\frac{g d_p}{U_{mf}^2\left(\frac{U}{U_{mf}} - 1\right)^2}\right]^{0.0756}\left(\frac{d_p}{0.0254}\right)^{0.5}. \quad (13)$$

5. The fractional surface area exposed to bubbles, f_0, is determined according to Thring [14]

$$f_0 = 0.08553\left[\frac{U_{mf}^2\left(\frac{U}{U_{mf}} - 1\right)^2}{g d_p}\right]^{0.1948}. \quad (14)$$

Further, the bed height at minimum fluidization velocity, H_{mf}, is assumed to be 250 mm and the bed voidage at minimum fluidization velocity, ε_{mf}, to be 0.4.

RESULTS AND DISCUSSION

The variation of maximum heat transfer coefficient, h_{wmax}, with particle diameter, d_p, is presented in Fig. 3 for an air–sand system along with the experimental results of Broughton [22], Kharchenko and Makhorin [2] and the theoretical results of Thring [14]. It is seen that the alternate-slab model, for a gas gap of 0.065 d_p, overestimates the values of h_{wmax} within a maximum departure of about 15% from the experimental results. This is considered reasonable in view of the simplicity of the model. Thring's packet model predictions are in better agreement with the data. However, it is to be noted here that Thring adjusted the gas gap thickness to $0.08d_p$ to reproduce the experimental data satisfactorily. We may, however, point out that the value of the gas gap thickness in this model can be regarded as somewhat arbitrary. The present model predictions can be brought closer to the data by adjusting the gas gap. From the figure it is observed that for a gap of

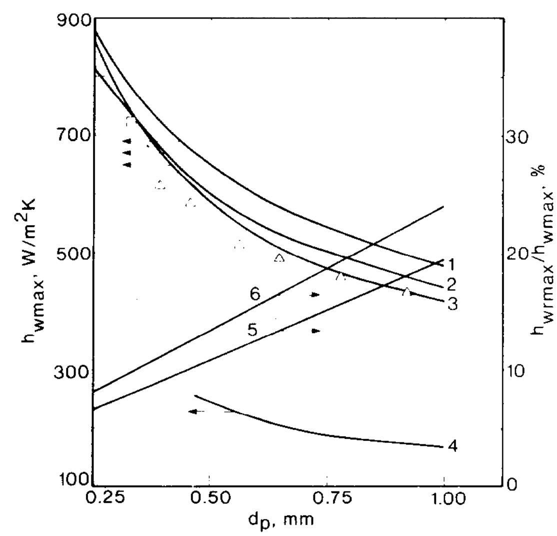

Fig. 3. Effect of particle diameter on heat transfer coefficients. Air-sand, T_b = 1173 K, T_s = 303 K, $U = U_{opt}$. 1—Present model, $l_g = 0.065d_p$; 2—Present model, $l_g = 0.08d_p$; 3—Thring's packet model, $l_g = 0.08d_p$; 4—Vedamurthy and Sastri model $l_g = 0.5d_p$; 5—Present model, $l_g = 0.065d_p$; 6—Present model, $l_g = 0.08d_p$; Δ—Broughton; □—Kharchenko and Makhorin.

$0.08d_p$, the present model gives almost as good an agreement with data as does Thring's model. The predictions of the model of Vedamurthy and Sastri [10] are also reproduced in the figure as given by Thring [14]. These values are comparatively low, as is to be expected, because a large value of $0.5d_p$ for the gas gap was assumed. A general observation from the figure is that h_{wmax} decreases with increase in particle diameter. Further, the predictions based on the alternate-slab and Thring's models approach each other for low values of d_p.

Some discussion here is in order regarding the contact resistance between the surface and emulsion phase. Vedamurthy and Sastri [10] adopted a surface-packet resistance of $(0.5d_p/k_g)$ which is equivalent to a gas layer of $0.5d_p$ in thickness. On the other hand, Baskakov *et al.* [6] employed a resistance of $(0.5d_p/k_e)$ which is equivalent to an emulsion layer of $0.5d_p$ in thickness. Values of k_e are always greater than k_g, thereby implying that the authors of [10] employed a higher resistance than that used by the authors of [6]. This would result in an underestimation of the conductive heat transfer for actual systems by the authors of [10]. Bhattacharya and Harrison [13] assumed a contact resistance equal to that used by Baskakov *et al.* [6] and also included the absorption and emission of radiation by the gas at high temperatures. However, though their model [13] gives satisfactory agreement with experiments at low surface temperatures, it underestimates the conductive heat transfer at high surface temperatures. For the model of [13] to give satisfactory predictions at high temperatures it is imperative that a smaller value of contact resistance be employed than given by $(0.5d_p/k_e)$. Thring [14] employed a surface resistance of $(0.08d_p/k_g)$ and obtained good agreement with experimental data. The present model employs a surface resistance of $(0.065d_p/k_g)$.

The radiative contribution as a percentage of total heat transfer is also shown in Fig. 3. For a gas gap of $0.065d_p$, it increases from about 6.5 to 18% for the range of particle sizes studied. The increase in gas gap to $0.08d_p$ results in an increase of the radiative contribution and it varies between 9 and 24% for the same particle size range. This implies that other conditions being the same, the gas gap thickness controls the radiative contribution.

According to Il' Chenko *et al.* [4] the properties of sand and chamotte are about the same. This prompted Bhattacharya and Harrison [13] to overlap their calculations for air–sand system with Baskakov *et al.* [6] experiments on chamotte. The radiative contribution as reported by these two studies, for d_p = 0.35 mm, as a function of T_s, are presented in Fig. 4. The alternate-slab model results are also shown. The model of [13] consistently overestimates the contribution which, according to [6], varies nonlinearly from about 6 to 17% in the surface temperature investigated. The present model, while overestimating the radiative contribution at low values of T_s as does that of [13], approaches the experimental data at high

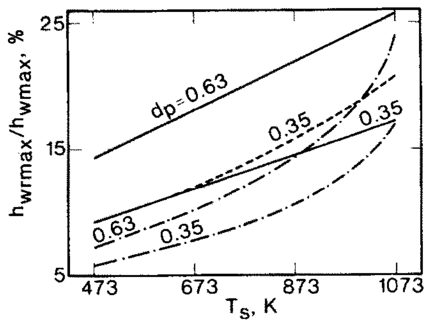

FIG. 4. Effect of surface temperature on heat transfer coefficients. Air–sand, T_b = 1123 K, U = U_{opt}. Present ———; Bhattacharya and Harrison – – – – –; Baskakov *et al.* – · – · – · –.

values of T_s. The maximum deviation is about 3.5%. The curves for d_p = 0.63 mm show that the present model overestimation is considerably higher than at smaller values of d_p. However, the predictions approach the experimental data for large T_s values. The present model predictions are in better agreement with experimental data than those of [13].

The effect of bed temperature, T_b, on maximum heat transfer coefficient, h_{wmax}, and radiative contribution is shown in Fig. 5, for d_p = 0.34 mm and T_s = 303 K. It is observed that the present model overestimates the experimental data of Kharchenko and Makhorin [2] while the packet model of Thring [14] consistently underestimates the same. However, the agreement between the predictions of the spherical particle model of Thring [14] and experiments is excellent. In the same figure is shown the radiative contribution which varies nonlinearly from about 3 to 10% in the bed temperature range of 573–1273 K.

The instantaneous heat fluxes, as predicted by the present model, are compared with those of Thring's packet model in Fig. 6 for d_p = 1 mm, $U = U_{opt}$, T_b = 1173 K and T_s = 303 K. It is seen that, while the alternate-slab model predictions are higher for the maximum total flux, they are lower for the conductive flux. This would imply a larger radiative contribution

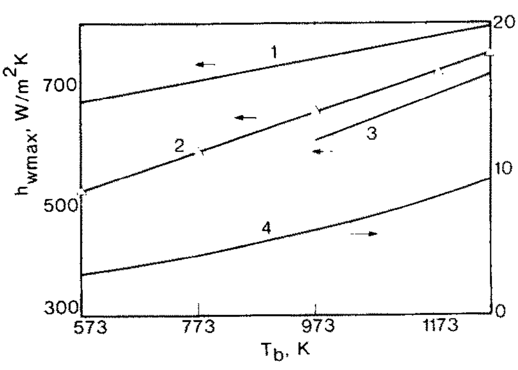

FIG. 5. Effect of bed temperature on heat transfer coefficients. Air–sand, d_p = 0.34 mm, T_s = 303 K. 1—Present; 2—Thring's spherical particle model; 3—Thring's packet model; 4—Present; Δ—Kharchenko and Makhorin.

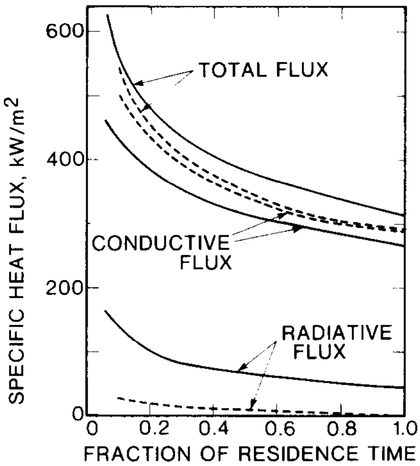

FIG. 6. Variation of specific heat flux with fraction of residence time. Air–sand, d_p = 1 mm, T_b = 1173 K, T_s = 303 K, U = U_{opt}. Present ———; Thring's packet model ------.

for the present model than for the Thring's packet model. The spherical and cubical particle models of Thring (not reproduced in Fig. 6) predict smaller values for the maximum and conductive fluxes than the packet model. The radiative fluxes, however, are similar for the spherical, cubical and alternate-slab models.

Figure 7 presents the effect of surface temperature on the radiative coefficient for d_p = 1 mm and T_b = 1173 K as predicted by the alternate-slab model and Thring's packet model. Also shown are the estimated values from the experimental results of Baskakov *et al.* [6] for the same particle size. The overestimation by the present model and the underestimation by the packet, as was the case with bed temperature variation, is to be noted here also. However, while the deviations are consistent in the case of radiative coefficients, the radiative contribution of the alternate slab model approaches the experimental results for larger values of T_s. The packet model predictions show an increasing disagreement for larger values of T_s.

Thring [14] concludes that all the three models he has investigated give satisfactory values for total heat transfer coefficient while the predicted radiative contributions varied widely from each other. The predictions of the models proposed by Vedamurthy and Sastri [10], Bhattacharya and Harrison [13] and the present one also differ from one another. No single model so far proposed can reliably predict the variation of radiative contribution for all the controlling parameters such as d_p, T_b and T_s. To rely on the predictions of radiative contribution of a model, it is essential that it should be able to reproduce the absolute values of conductive and total heat transfer coefficients. A comparison of these two coefficients, as predicted by the model of [13] and the alternate-slab model, with the experimental data of Baskakov *et al.* [6] for d_p = 0.35 mm and T_b = 1123 K is shown in Fig. 8. It is observed that, while the former model [13] gives good agreement with data for low T_s values up to about 673 K only, the latter model agrees well only for high values of T_s. Although the present model overestimates the values of h_w in the low temperature range, the model predicts the radiative contribution as well as does the model of [13], Fig. 4. This implies that the predictions of the alternate-slab model are useful guides over the entire T_s range. A proper appraisal of the model of Bhattacharya and Harrison [13] is possible only after detailed calculations of heat transfer coefficient are performed as a function of T_b and d_p and by employing similar correlations for f_0 and t_r as adopted in the present and Thring's [14] work.

Figures 9–12 present results for radiative contributions for an air–ash system for various parameters

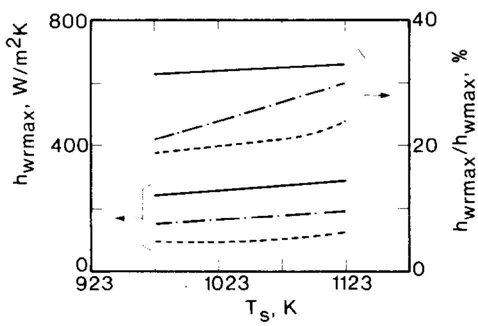

FIG. 7. Effect of surface temperature on heat transfer coefficients. Air–sand, d_p = 1 mm. T_b = 1173 K, U = U_{opt}. Present ———; Thring's packet model ------; Baskakov *et al.* –·–·–·–.

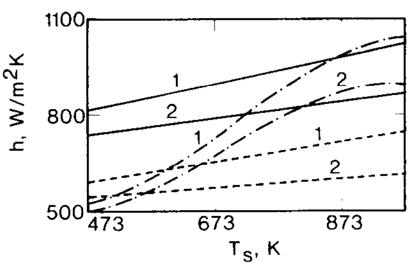

FIG. 8. Effect of surface temperature on heat transfer coefficients. Air–sand, d_p = 0.35 mm, T_b = 1123 K, U = U_{opt}. 1—h_{wmax}; 2—h_{wcemax}; Present ———; Baskakov *et al.* –·–·–·–; Bhattacharya and Harrison ------

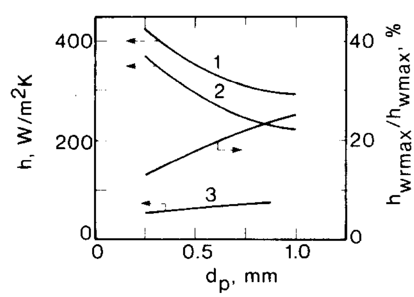

FIG. 9. Effect of particle diameter on heat transfer coefficients. Air–ash, T_b = 1173 K, T_s = 973 K, U = U_{opt}. 1—h_{wmax}; 2—h_{wcemax}; 3—h_{wrmax}.

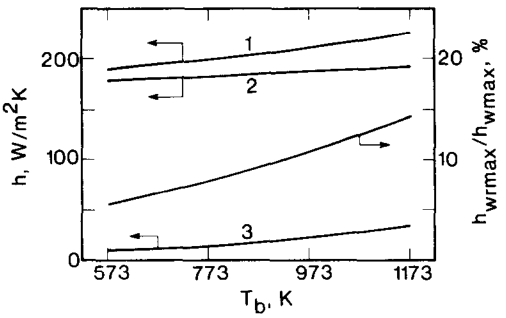

FIG. 10. Effect of bed temperature on heat transfer coefficients. Air–ash, d_p = 1 mm, T_s = 373 K, U = U_{opt}. 1—h_{wmax}; 2—h_{wcemax}; 3—h_{wrmax}.

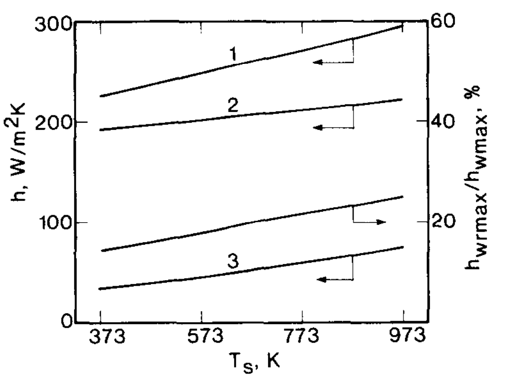

FIG. 11. Effect of surface temperature on heat transfer coefficients. Air–ash, d_p = 1 mm, T_b = 1173 K, U = U_{opt}. 1—h_{wmax}; 2—h_{wcemax}; 3—h_{wrmax}.

as predicted by the alternate-slab model. From Fig. 9 it is seen that radiation can contribute as much as 25% to the total heat transfer for a high bed and surface temperature system of particle diameter 1 mm. The maximum conductive and radiative heat transfer coefficients exhibit the expected dependence on particle diameter. From Fig. 10, it is to be noted that 6–15% of total heat transfer is by radiation for T_s = 373 K and bed temperature variation from 573 to 1173 K. It is seen from Fig. 11 that the radiative contribution varies from 15 to 25% with surface temperature for T_b = 1173 K. Figure 12 presents the variation of heat transfer coefficients and radiative contribution with the fluidization number, U/U_{mf}. The trend is similar to that obtained by Vedamurthy and Sastri [10]. The maximum and conductive coefficients initially increase with U/U_{mf} and after reaching a maximum exhibit a gradual decrease. The radiative contribution shows a steady increase with velocity, varying from about 8 to 17% for T_s = 373 K. With a rise in T_s, the radiative contribution also increases, the corresponding values being 12–22% for T_s = 573 K, with T_b = 873 K.

The calculated maximum heat transfer coefficients and radiative contribution for an air–dolomite system are reported in Fig. 13, for T_b = 1173 K and T_s = 1073 K at U = U_{opt}. It should be noted that the radiative contribution is quite significant, increasing from about 18% for d_p = 0.25 mm to about 43% for d_p = 1 mm. While the total and conductive heat transfer coefficients decrease with increase in d_p, the radiative coefficient increases with d_p, in conformity with other systems. These estimations will be of help in the design of fluidized bed coal combustors where about 90% of the bed comprises dolomite.

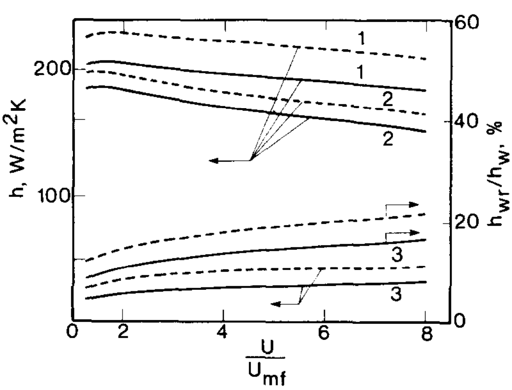

FIG. 12. Effect of fluidization number on heat transfer coefficients. Air–ash, d_p = 1 mm, T_b = 873 K, T_s = 373 K: ———, T_s = 573 K: ------. 1—h_w; 2—h_{wce}; 3—h_{wr}.

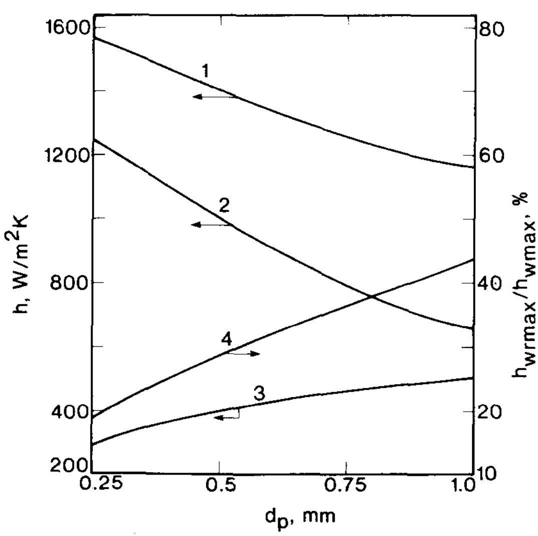

FIG. 13. Effect of particle diameter on heat transfer coefficients. Air–dolomite system, d_p = 1 mm, U = U_{opt}, T_b = 1173 K, T_s = 1073 K. 1—h_{wmax}; 2—h_{wcemax}; 3—h_{wrmax}.

CONCLUSIONS

The alternate-slab model, proposed by Gabor [15] and modified in [19], is examined for prediction of radiative contribution in an air–sand system for various bed and operating parameters. Comparisons are made with available experimental data and analytical model predictions. The percentage radiative contribution is substantial for large values of particle diameter, surface and bed temperatures, and varies directly with them. The radiative contribution is more sensitive to variation of T_s than that of T_b. The alternate-slab model generally overestimates the radiative contribution and average heat transfer coefficients but within reasonable limits and gives good agreement at high T_s and T_b values. The contact resistance at the surface determines the magnitude of percentage radiative contribution. Prediction of radiative contribution is also made for air–ash and air–dolomite systems.

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ETUDE DE LA PARTICIPATION DU RAYONNEMENT DANS UN LIT FLUIDISE A HAUTE TEMPERATURE, A PARTIR DU MODELE DE GABOR

Résumé — Le modèle de Gabor modifié est utilisé pour déterminer la contribution du rayonnement au transfert thermique global entre le système fluidisé à haute température sable–air et une surface immergée. Les résultats sont comparés avec les prévisions d'autres modèles et avec les données expérimentales sur le coefficient moyen de transfert, en s'interessant au pourcentage de la part radiative fonction des différents paramètres. Les coefficients de transfert thermique sont surestimés par le modèle dans des limites raisonables et s'approchent des valeurs expérimentales pour les grandes valeurs de la température de la surface. Le pourcentage de la contribution radiative est substantiel pour les grands diamètres de particule et les fortes températures du lit et de la surface. Le modèle est utile et maniable pour un large domaine de température. Des résultats sont présentés aussi pour des systèmes air–cendre et air–dolomite en vue de leur application pratique.

UNTERSUCHUNG DES STRAHLUNGSBEITRAGS IN EINEM HOCHTEMPERATUR-FLIEßBETT MIT DEM ALTERNIERENDEN PLATTENMODELL

Zusammenfassung—Es wird das alternierende Plattenmodell von Gabor für die Beschreibung des Strahlungsbeitrags für den Gesamtwärmeübergang in einem Hochtemperatur-Fließbett-System aus Luft und Sand an eine eingetauchte Oberfläche untersucht. Die Ergebnisse werden mit den Aussagen anderer Modelle und Versuchsergebnissen des mittleren Wärmeübergangskoeffizienten und des prozentualen Strahlungsbeitrags als Funktion von verschiedenen Einflußparametern verglichen. Mit dem Modell werden die Wärmeübergangskoeffizienten zu groß berechnet; die Ergebnisse liegen jedoch in vernünftigen Grenzen und kommen den Versuchsergebnissen mit hoher Oberflächentemperatur des Wärmeübertragers recht nahe. Der prozentuale Strahlungsbeitrag ist wesentlich bei großen Teildurchmessern, Oberflächen- und Bett-Temperaturen. Das Modell erwies sich als zuverlässig und ist in einem weiten Temperaturbereich einfach zu handhaben. Es werden auch Ergebnisse für Luft–Asche-Systeme und Luft–Dolomit-Systeme im Hinblick auf ihre praktische Bedeutung angegeben.

ИССЛЕДОВАНИЕ ЛУЧИСТОГО ТЕПЛОПЕРЕНОСА В ВЫСОКОТЕМПЕРАТУРНОМ ПСЕВДООЖИЖЕННОМ СЛОЕ С ПОМОЩЬЮ МОДЕЛИ ЧЕРЕДУЮЩИХСЯ ПРОСЛОЕК

Аннотация — Рассматривается возможность использования габоровской модели чередующихся прослоек для расчёта доли лучистого переноса в общем процессе переноса тепла от сильно нагретого псевдоожиженного воздухом слоя песка к погруженной поверхности. Полученные результаты сравниваются с расчётами, проведенными с помощью других моделей, а также с экспериментальными данными по усредненному коэффициенту теплообмена. Рассматривается влияние различных параметров на долю лучистого переноса в процентном выражении. Модель завышает коэффициенты теплообмена в диапазоне допустимых пределов, а при больших значениях температуры поверхности теплообмена даёт значения, близкие к экспериментальным. Процентная доля лучистого переноса довольно существенна при больших значениях диаметра частиц, поверхности и температуры слоя. Найдено, что модель надёжна и проста при использовании в широком диапазоне температур. Приведены также результаты для систем воздух–зола и воздух–доломит в связи с их практической значимостью.