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# Heat transfer between gas fluidized beds and immersed surfaces

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**Abstract**—Various models of heat transfer between the emulsion phase of a gas fluidized bed and immersed surfaces are discussed. It is shown that certain features of these models, such as the contact resistance or a gas film between the surface and the solid particles, are related to the statistical variation of the thermal properties of the emulsion phase in the vicinity of the heat transfer surface. The variation of the thermal properties of the emulsion phase is accounted for directly in models using the concept of the property boundary layer.

## INTRODUCTION

A NUMBER of theoretical models are available in the literature for predicting heat transfer rates between gas fluidized beds and immersed surfaces. The most useful models are those which are based on transient conduction between the bed and the immersed surface. The models can be conveniently classified into two groups according to the approach they adopt.

The models of the first group consider the bed microscopically, and thus try to evaluate heat transfer between the surface and the individual bed particles. The simplest model of this kind was developed by Botterill and Williams [1], who assumed that an isolated spherical particle contacts the heat transfer surface for a certain time during which the heat is transferred to it by transient conduction. However, there are several disadvantages associated with this model. First, the solutions can only be obtained numerically; secondly, the model will only be accurate for short particle residence times, when the heat does not penetrate beyond the first layer of particles and thirdly, in order to reconcile the theoretical results with the available experimental evidence a gas film must be introduced between the surface and the first layer of particles.

These limitations have been long recognized and further development has taken place. For example, solutions have been obtained for additional layers of particles [2, 3] to make the model applicable for longer particle residence times, and the behaviour of the particles near the wall has been modelled in more detail [4, 5] so that the gas film between the surface and the first layer of particles is no longer required to reconcile the theoretical results with the experimental data.

The models of the second group consider the bed macroscopically by assuming that the bed consists of continuous emulsion of the particles and the fluidizing gas, and gas bubbles which constitute the discrete phase. The first, and the simplest model of this group was developed by Mickley and Fairbanks [6], who regarded the emulsion as a continuum with constant voidage and thus constant thermophysical properties. They calculated heat transfer rates between the immersed surface and a packet of constant voidage emulsion phase swept to the surface by, for example, the passing gas bubbles. The advantage of this model is its simplicity and a reasonable agreement with the experimental evidence for large packet residence times. The major disadvantage of this model is that the assumption of constant voidage emulsion does not hold in the vicinity of the surface, which leads to unrealistically high heat transfer rates for short packet residence times when the heat penetration is confined to the region equivalent to the first layer of particles.

The above limitation has been investigated and the model has been considerably refined to extend its validity to short packet residence times. Initially, this was achieved by introducing a concept of additional time-independent contact resistance at the bed–surface interface to account for the increased voidage in the vicinity of the surface [7–10]. With this modification the models give good agreement with available experimental results.

The gas film and the contact resistance discussed above are introduced to compensate for the increased voidage of the bed in the vicinity of the surface. Since there is no conclusive experimental evidence of either stagnant gas film or time-independent contact resistance, both concepts must be regarded as mathematical expedients which allow for the complicated variation of the voidage and thermophysical properties near the surface. The variation of the voidage of the bed in the vicinity of the surface can be used directly in the modification of the basic Mickley–Fairbanks model. The modified model was originally developed by Kubie and Broughton [11]. They examined the emulsion phase statistically and used the variation of the voidage in the vicinity of the surface to evaluate the variation of the thermosphysical properties there: the concept is analogous to the boundary layer. The model requires a reasonable approximation to the voidage field near the surface, and gives excellent agreement with experimental results without recourse to the use of the gas film or contact

**NOMENCLATURE**

| | |
|---|---|
| $c$ | specific heat |
| $d$ | particle diameter |
| $F_W$ | wall heat flux |
| $h$ | instantaneous heat transfer coefficient |
| $\bar{h}$ | time-mean heat transfer coefficient |
| $k$ | thermal conductivity |
| $R_C$ | contact resistance |
| $t$ | time |
| $T$ | temperature |
| $T_W$ | wall temperature |
| $T(0)$ | temperature at $x = 0$ |
| $x$ | distance from the surface. |

Greek symbols

| | |
|---|---|
| $\varepsilon, \varepsilon_p$ | voidage |
| $\kappa$ | thermal diffusivity |
| $\rho$ | specific density |
| $\tau$ | mean packet residence time. |

Subscripts

| | |
|---|---|
| E | emulsion phase |
| F | constant wall heat flux |
| G | gas |
| S | solid particles |
| T | constant wall temperature. |

resistance discussed above [11, 12]. The major disadvantage of this model is that the solution must be obtained numerically.

It is the purpose of this paper to show that the concept of the property boundary layer is related to the thickness of the gas film used in the models of the first group and to the contact resistance used in the models of the second group. The additional contact resistance is calculated and the results are compared with the results of previous investigations. The advantages and disadvantages are also discussed.

## PROPERTY BOUNDARY-LAYER MODEL

The model is described more fully elsewhere [11] and thus only the major results are quoted here.

The major assumptions are as follows.

(i) The emulsion phase in the bulk of the bed has constant voidage and is isothermal.

(ii) Packets of emulsion phase are transferred to the heat transfer surface by bubble-induced circulation, stirring or flow of the solids. The heat transfer mechanism is one of transient conduction during the time of emulsion residence on the surface.

(iii) The only constraint on the position of the particles at the surface is provided by the surface itself, which influences the local particle packing and hence alters the local thermosphysical properties.

(iv) The variation of voidage is confined to the plane normal to the heat transfer surface.

The governing equation then takes the following form:

$$\rho(x)c(x)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[k(x)\frac{\partial T}{\partial x}\right] \tag{1}$$

subject to

$$t = 0, x \geqslant 0 \qquad T = 0 \tag{2}$$

$$t \geqslant 0,\ x = 0 \quad -k(x)\frac{\partial T}{\partial x} = F_W \tag{3a}$$

$$T = T_W \tag{3b}$$

where the boundary condition (3a) is applicable to the constant wall heat flux case and the boundary condition (3b) to the constant wall temperature case.

The instantaneous and the time-mean heat transfer coefficients for the case of constant heat flux are given respectively as

$$h_F = F_W/T(0) \tag{4}$$

$$\overline{h_F} = F_W/\overline{T(0)} \tag{5}$$

where

$$\overline{T(0)} = \frac{1}{\tau}\int_0^\tau T(0)\,dt \tag{6}$$

and where $T(0)$ is the emulsion phase temperature at the surface.

The instantaneous and the time-mean heat transfer coefficients for the case of constant wall temperature are given respectively as

$$h_T = \left[-k(x)\frac{\partial T}{\partial x}\right]_{x=0} \Big/ T_W \tag{7}$$

$$\overline{h_T} = \frac{1}{\tau}\int_0^\tau h_T\,dt. \tag{8}$$

As shown in [11] the variation of the voidage in the vicinity of a surface $\varepsilon(x)$ can be expressed as follows

$$x \leqslant d \quad \varepsilon(x) = 1 - 3(1-\varepsilon_E)[(x/d) - 2(x/d)^2/3] \tag{9}$$

$$x > d \quad \varepsilon(x) = \varepsilon_E \tag{10}$$

where $\varepsilon_E$ is the emulsion phase voidage in the bulk of the bed.

The variation of the thermophysical properties in the vicinity of the surface depends on the variation of the voidage there [i.e. equations (9) and (10)] and on the thermosphysical properties of the solid particles and the fluidizing gas. This is discussed further in ref. [11], where it is shown that the dominant parameter is the ratio $k_S/k_G$ where $k_S$ and $k_G$ are the thermal conductivities of the solid particles and the fluidizing gas respectively.

The governing equations must be solved numerically. The numerical results for the instantaneous and

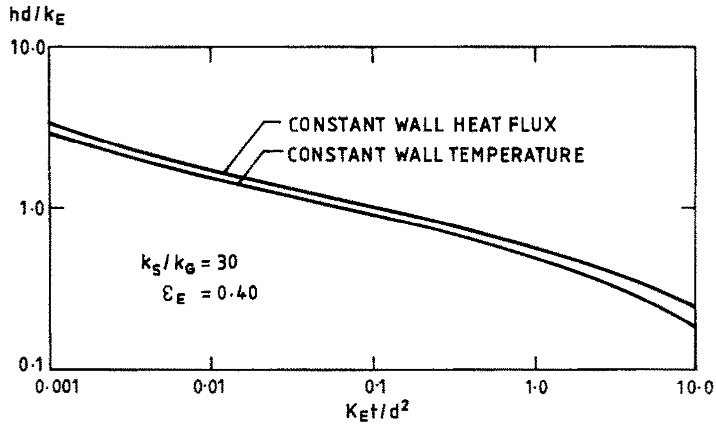


FIG. 1. Comparison of the instantaneous heat transfer coefficients for the case of (i) constant wall heat flux and (ii) constant wall temperature.

the time-mean heat transfer coefficients for the case of constant wall heat flux are presented in [11]. Figure 1 of this paper compares the theoretical results of the instantaneous heat transfer coefficient for the case of constant wall heat flux and the case of constant wall temperature. Similarly, Fig. 2 compares the theoretical results of the time-mean heat transfer coefficient for the two cases. An examination of these two figures indicates that the results are relatively insensitive to the choice of the boundary condition.

The theoretical results are compared with experimental data in refs. [11] and [12]. In both cases good agreement between the theoretical predictions and the available experimental evidence can be observed.

## COMPARISON WITH THE CONTACT RESISTANCE MODEL

The concept of the contact resistance was introduced by Baskakov [7, 13] who derived the expressions for the instantaneous and the time-mean heat transfer coefficients assuming time-independent contact resistance and constant wall temperature. The exact results are rather complex, but the time-mean heat transfer coefficient $\bar{h}_T$ can be approximated by [13]

$$\frac{\bar{h}_T d}{k_E} = \left[\frac{k_E R_C}{d} + \frac{\sqrt{\pi}}{2}\left(\frac{\kappa_E \tau}{d^2}\right)^{1/2}\right]^{-1} \quad (11)$$

where $R_C$ is the contact resistance, and $k_E$ and $\kappa_E$ are respectively thermal conductivity and thermal diffusivity of the emulsion phase in the bulk of the bed.

Similar equations can be derived for the case of constant wall heat flux; the instantaneous heat transfer coefficient $h_F$ and the time-mean heat transfer coefficient $\bar{h}_F$ are then given as

$$\frac{h_F d}{k_E} = \left[\frac{k_E R_C}{d} + \frac{2}{\sqrt{\pi}}\left(\frac{\kappa_E t}{d^2}\right)^{1/2}\right]^{-1} \quad (12)$$

$$\frac{\bar{h}_F d}{k_E} = \left[\frac{k_E R_C}{d} + \frac{4}{3\sqrt{\pi}}\left(\frac{\kappa_E \tau}{d^2}\right)^{1/2}\right]^{-1}. \quad (13)$$

It can be seen from equations (11) and (13) that for the two cases considered the time-mean heat transfer coefficients are similar.

The property boundary-layer model described

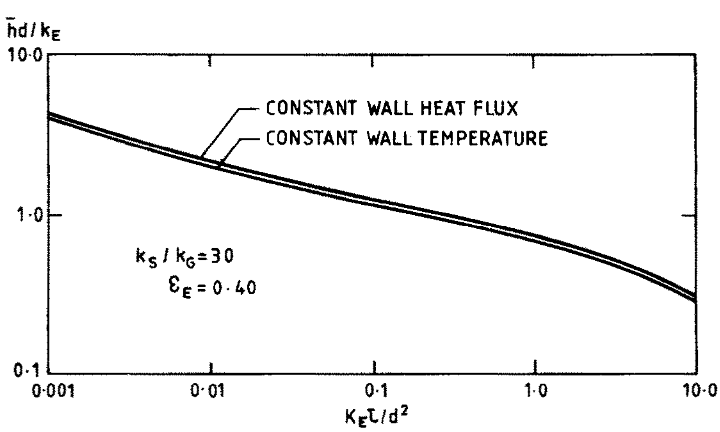


FIG. 2. Comparison of the time-mean heat transfer coefficients for the case of (i) constant wall heat flux and (ii) constant wall temperature.

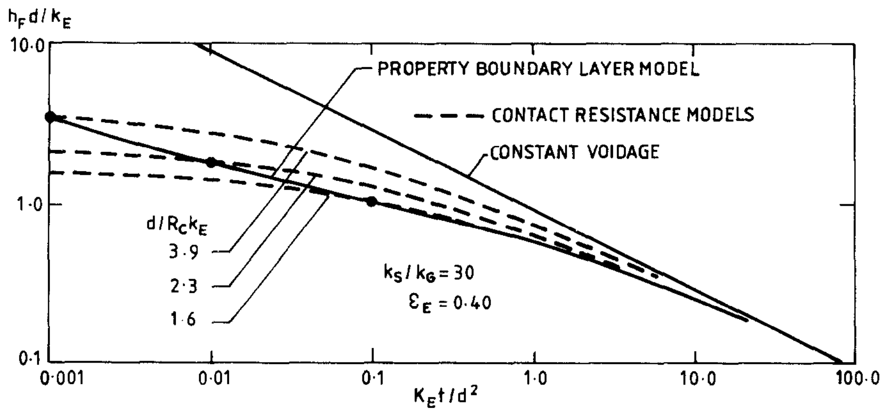


FIG. 3. Comparison of the property boundary-layer model with the contact resistance models.

above can be used together with equations (12) and (13) to estimate the value of the contact resistance. However, it should be pointed out that because the two approaches are physically different the contact resistance will not have a unique value for a particular case of a gas fluidized bed. As shown in Fig. 3 the contact resistance does not depend only on the voidage of the emulsion phase and the properties of particles and the fluidizing gas, but also on the value of the contact time (or the packet residence time) chosen for correspondence between the two models. Furthermore, it also depends on whether it is calculated from the instantaneous or the time-mean heat transfer coefficients.

The contact resistance is plotted in Fig. 4 against the ratio $k_S/k_G$ for $\varepsilon_E = 0.4$ and different values of either the contact time or the packet residence time chosen for correspondence between the two models. The contact and the residence times used in Fig. 4 are the typical values found in practice. The theoretical results of Fig. 4 are re-plotted in Fig. 5 against the ratio $k_E/k_G$ which is calculated from $k_S/k_G$ and $\varepsilon_E = 0.4$ using the method of Kunii and Smith [14]. Figure 5 demonstrates that the contact resistance is a relatively strong function of the ratio $k_E/k_G$ and hence should never be taken as a constant.

Baskakov [13, 15] concludes that for stationary beds the contact resistance expressed as a Nusselt number $d/R_C k_E$ is equal to 2, but that if there is appreciable particle movement in the vicinity of the heat transfer surface, different values may result. It should be noted that Baskakov derived his contact resistance for gas–particle systems for which the values of the ratio $k_E/k_G$ are typically about 5. This agrees with the results of the present analysis since Fig. 5 indicates that for $k_E/k_G$ equal to about 5 the contact resistance Nusselt number is approx. 2.

The problem has been recently investigated again by Gloski *et al.* [10]. Their aim was to study the mechanism of heat transfer for very short emulsion phase residence times. They developed a transient technique which can provide data at low Fourier numbers $\kappa_E t/d^2$. Furthermore they claim that their technique allows them to measure the contact resistance for both packed and fluidized beds, and for a variety of particle sizes and gas velocities. Their work can be summarized as follows:

(i) For short emulsion phase residence times of 20 ms or less very high heat transfer coefficients were observed. This they claim is due to direct heat transfer between particle asperities and the heat transfer surface.

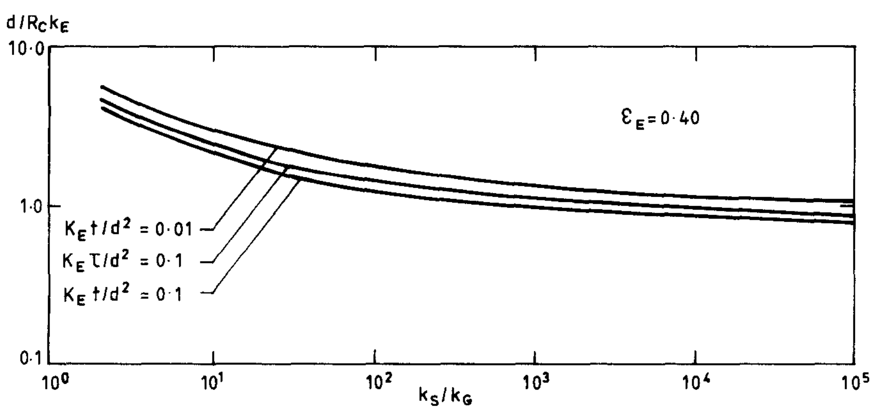


FIG. 4. A plot of the contact resistance as a function of the ratio $k_S/k_G$ for $\varepsilon_E = 0.4$.

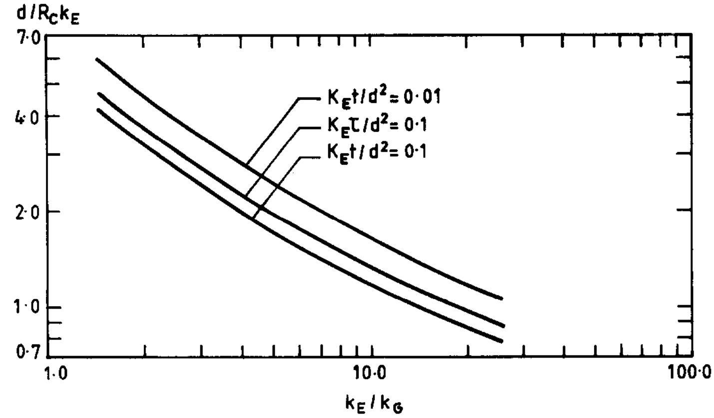


FIG. 5. A plot of the contact resistance as a function of the ratio $k_E/k_G$ for $\varepsilon_E = 0.4$.

They suggest that in this case a model of heat transfer using a single row of particles at uniform temperature separated from the surface by a thermal contact seems appropriate.

(ii) For emulsion phase residence times of between 20 ms and about 100 ms the observed heat transfer coefficients were lower and nearly invariant with time. They suggest that in this case heat transfer takes place primarily through the fluid separating the particles and the surface. They conclude that the contact resistance model is the most appropriate in this regime.

(iii) They extended the property boundary-layer model of Chandran [16] to low values of the Fourier number $\kappa_E t/d^2$. They noted that the theoretical results obtained from this extension deviated significantly from the experimental data. They conclude that this reflects the inadequacy of the property boundary-layer model which, they suggest, is due to the neglect of the inhomogeneous distribution of thermal properties in the vicinity of the surface.

It is shown below that the property boundary-layer model is not inconsistent with the experimental evidence of Gloski *et al.* [10]. Figure 1 above, which represents the theoretical results of the property boundary-layer model for glass particles fluidized by air (i.e. $k_S/k_G = 30$, $\varepsilon_E = 0.4$), is replotted in Fig. 6. Figure 6, which uses linear scales, gives the variation of $hd/k_G$ with the emulsion phase residence time $t$ assuming that $k_E/k_G = 5.7$ [14], $\kappa_E = 1.2 \times 10^{-7}$ m$^2$ s$^{-1}$ [11] and $d = 1$ mm. Figure 6 indicates behaviour similar to that of Gloski *et al.* [10]. During the first 30 ms or so the heat transfer coefficients are very high and they decrease rapidly with time. During the subsequent period of about 100 ms the heat transfer coefficient decreases by about 50%. Figure 6 also includes the experimental results of Gloski *et al.* [10]. However, it should be noted that the theoretical results of this work and the experimental results of Gloski *et al.* are not strictly comparable since the experimental results are corrected "to account for changes in the mean particle

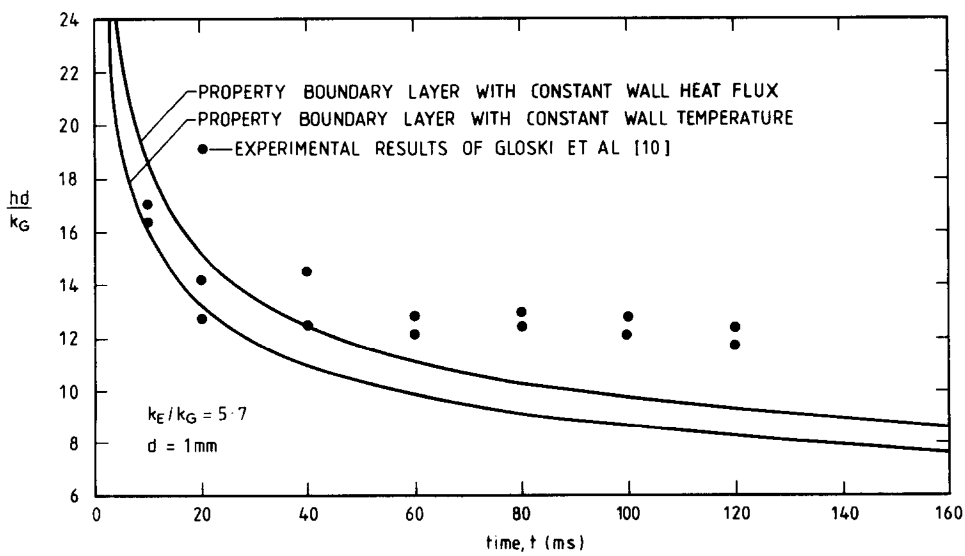


FIG. 6. Comparison of the theoretically derived instantaneous heat transfer coefficients with the experimental data of Gloski *et al.* [10].

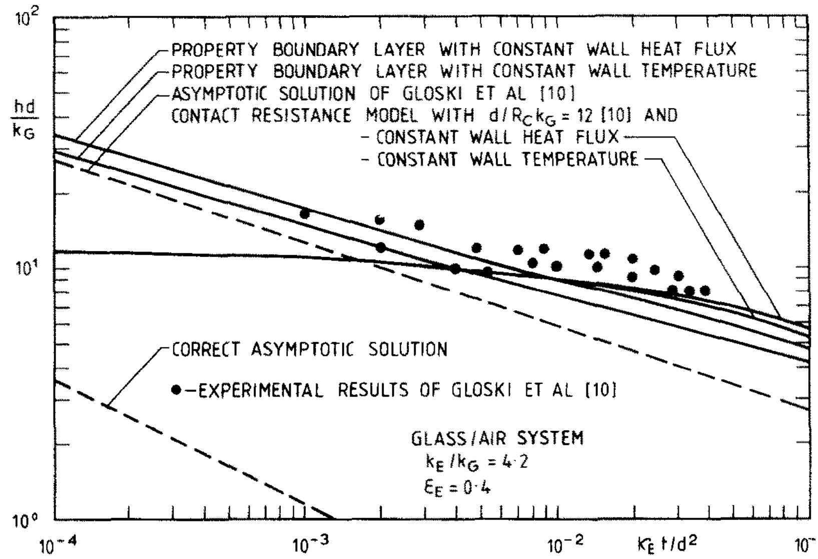


FIG. 7. Comparison of the theoretical results of various models with the experimental data of Gloski *et al.* [10].

temperature with time" [10]. Hence the experimental heat transfer coefficients are not based on the difference between the temperature of the surface and the bulk bed temperature, and the exact physical meaning of the correction is ambiguous. Since the effect of the correction is to increase heat transfer coefficients with increasing emulsion phase residence time, the correction may account for the heat transfer coefficients being constant between 20 and 120 ms.

Experimental results of Gloski *et al.* [10] are compared in Fig. 7 with the theoretical results of the property boundary-layer model for the case of constant wall heat temperature and the case of constant wall heat flux. The theoretical results were obtained for $k_E/k_G = 4.2$, which is the value used in [10]. It should be noted that this value seems rather low, since assuming $k_S/k_G = 30$ (for a glass/air system) and $\varepsilon_E = 0.4$ the method of Kunii and Smith [14] gives $k_E/k_G = 5.7$. This latter value of $k_E/k_G$ would give better agreement between experimental and theoretical results.

Gloski *et al.* [10] also present an extension of the variable property boundary layer to low Fourier numbers, but their analysis is incorrect. They used the property variations assumed by Kubie and Broughton [11] and for short residence times approximated the heat capacity as

$$\rho(x)c(x) \sim 3\frac{x}{d}(\rho c)_E. \tag{14}$$

However, in deriving the variation of the heat capacity in the vicinity of the heat transfer surface Kubie and Broughton [11] assumed that the heat capacity of the fluidizing gas could be neglected. This assumption is reasonable for calculating the heat transfer rates for all but the very short residence times. For the very short residence times the heat capacity of the gas must be included and thus

$$\rho(x)c(x) \sim (\rho c)_G + 3\frac{x}{d}(\rho c)_E \tag{15}$$

which can be approximated once again as

$$\rho(x)c(x) \sim (\rho c)_G. \tag{16}$$

Hence it follows that the correct asymptote is given by transient heat conduction to the fluidizing gas. The theoretical results, as given by Carslaw and Jaeger [17], are also included in Fig. 7. This figure also shows the asymptotic solution of Gloski *et al.* [10]. The correct asymptotic solution may or may not over-predict the empirical results, but the well-controlled experiments of Gloski *et al.* do not support the suggestion that the property boundary-layer model is inadequate. Only the experimental data of Dunsky *et al.* [18] are not described well by the property boundary-layer model, but the probable reasons for this discrepancy were discussed elsewhere [11].

Finally, Gloski *et al.* suggest a contact resistance Nusselt number $d/R_C k_G$ of 12. The present work indicates a figure of about 10.

## COMPARISON WITH THE SINGLE PARTICLE MODEL

Consider a flat surface with a single layer of spherical particles packed on it and assume that the particles are arranged either in a triangular pitch or a square pitch packing. If it is further assumed that the voidage in the vicinity of the surface $\varepsilon_P(x)$ is equal to the mean voidage of the two packings, $\varepsilon_P(x)$ can be calculated as

$$\varepsilon_P(x) = 1 - \pi(0.5 + 1/\sqrt{3})[(x/d) - (x/d)^2]. \tag{17}$$

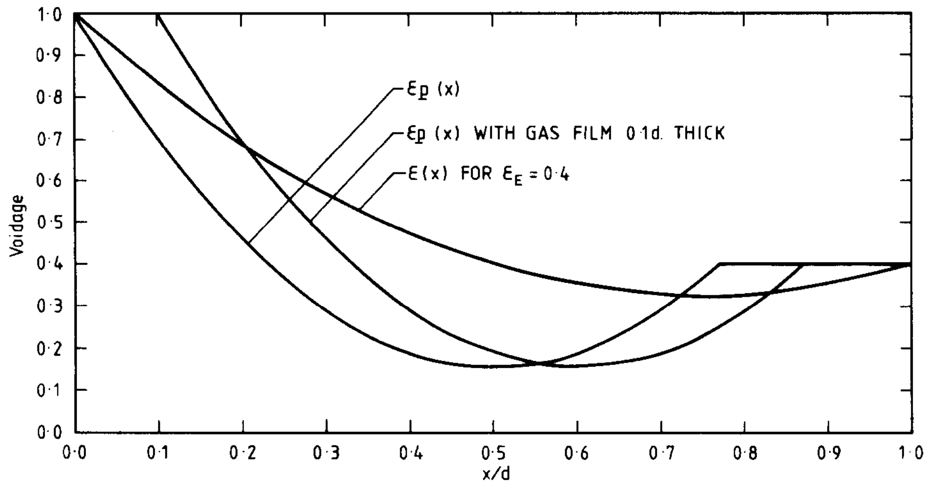


Fig. 8. Variation of the emulsion phase voidage in the vicinity of a surface.

The voidage $\varepsilon_P(x)$ of equation (17) is plotted in Fig. 8 together with the voidage of the property boundary-layer model, i.e. voidage $\varepsilon(x)$ of equation (9) with $\varepsilon_E = 0.4$. Figure 8 demonstrates that the voidage $\varepsilon_P(x)$ decreases too rapidly near the surface compared with the voidage $\varepsilon(x)$, which is based on experimental evidence [19, 20].

The voidage $\varepsilon_p(x)$ of equation (17) can be used in the property boundary-layer model. However, since this voidage is only meaningful in the vicinity of the heat transfer surface it is assumed that for $x/d > 0.77$, when the voidage reaches 0.4, the voidage $\varepsilon_P(x)$ stays constant and equal to the emulsion phase voidage in the bulk of the bed, $\varepsilon_E = 0.4$. Such defined voidage $\varepsilon_P(x)$ is then used in the property boundary-layer model instead of the recommended voidage of equations (9) and (10). The theoretical results for the instantaneous heat transfer coefficient for the case of constant heat flux are plotted in Fig. 9. Theoretical results were also obtained for the situations when there is a gas film separating the first layer of particles from the heat transfer surface. (The voidage distribution for gas film 0.1 $d$ thick is also shown in Fig. 8.) The theoretical results for gas film thicknesses of 0.1 $d$, 0.05 $d$ and 0.02 $d$ are also plotted in Fig. 9. Finally, Fig. 9 also shows the theoretical results using the recommended voidage of equations (9) and (10), and the asymptotic solution discussed in the previous section.

Figure 9 demonstrates why the single particle model gives such high values of the heat transfer coefficients

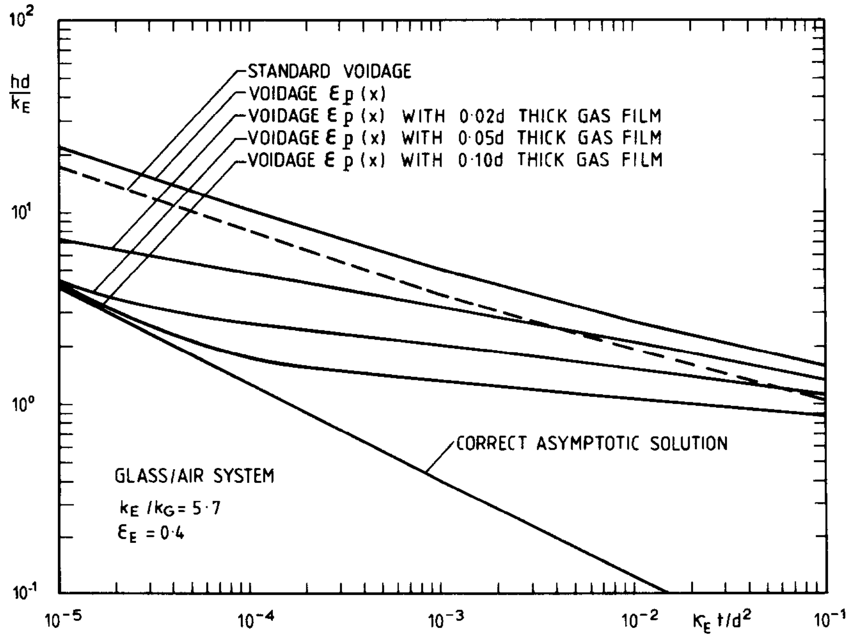


Fig. 9. Influence of the variation of the emulsion phase voidage on the heat transfer coefficient obtained from the property boundary-layer model.

when the first layer of particles is assumed to contact the heat transfer surface, and why a gas film between the heat transfer surface and the first layer of particles is required to reconcile the theoretical results with the experimental data.

## DISCUSSION

The truly fundamental model of heat transfer between a heat transfer surface and the emulsion phase in its vicinity would model the transfer processes between the surface and the fluidizing gas and *all* the solid particles which can influence the heat transfer process. Hence the model would have to consider not just the particles on the surface, but also those particles which are separated from the surface by a gas film, since statistical examinations of particle packing indicate that not all the particles in the nearest layer contact the surface and are arranged in regular pitch packing. Thus random particles packing near the surface would have to be taken into account and their full behaviour, such as their rotation and slipping, would have to be analysed.

The fundamental approach described above is not practicable and approximations must be considered. If the heat transfer surface is comparable to the size of the solid particles, the heat transfer rates may vary in nominally identical experiments. If, however, the heat transfer surface is large compared with the size of the solid particles, the heat transfer rates will become invariant because the very large number of solid particles near the surface will result in particle packing with some mean properties from the statistical point of view. Hence it follows that in the latter case the emulsion phase in the vicinity of the heat transfer surface may be approximated by a single phase medium with variable thermal properties in the vicinity of the surface. The variation of the thermal properties can in theory be determined by averaging the thermal properties of the individual solid particles immersed in the fluiding gas. However, in the development of the property boundary-layer model a different approach was used. First, the variation of the voidage was determined by analysing the available experimental evidence [19, 20], and the variation of the voidage was then used to calculate the variation of thermal properties.

Hence it is not the case, as suggested by Gloski *et al.* [10] that the inhomogeneous distribution of thermal properties is neglected in the development of the property boundary-layer model. As discussed above it is very much taken into account in the development of the model. What could be criticised is the calculation of the thermal properties from the variation of the voidage. This may not be very accurate in the region of high voidage, but it does not detract from the general principles of the property boundary-layer model.

It should be noted that the averaging process discussed above suggests that single particle models cannot give accurate heat transfer characteristics if the particles are assumed to contact the heat transfer surface. Reliable heat transfer rates can only be obtained if the average particle position is assumed, that is when the particle is separated from the surface by a thin gas film.

The major disadvantages of the property boundary-layer model is its numerical complexity. However, the major advantages are that it is physically feasible and, furthermore, that it agrees well with available evidence. Finally, the model can be used to estimate the value of the contact resistance (say from Fig. 5) to be employed in the much simpler contact resistance models.

## CONCLUSIONS

Two conceptually different models of heat transfer between gas fluidized beds and immersed surfaces have been discussed. The two models are based on (i) the consideration of single particles and (ii) the consideration of packets of emulsion phase.

It has been shown how certain features of the two models, such as the gas film between the surface and the solid particles or the contact resistance, are related to the concept of the property boundary layer, which takes into account the statistical variation of the thermal properties of the emulsion phase in the vicinity of the heat transfer surface.

Finally, it has been shown that the contact resistance sometimes used in the models of the second group is a relatively strong function of the conductivity ratio $k_E/k_G$.

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## TRANSFERT THERMIQUE ENTRE DES LITS FLUIDISES GAZEUX ET DES SURFACES IMMERGEES

**Résumé**—On discute différents modèles de transfert thermique entre une phase dispersée d'un lit fluidisé gazeux et des surfaces immergées. On constate que certains aspects de ces modèles, tels que la résistance de contact ou un film gazeux entre la surface et les particules solides, sont liés à la variation statistique des propriétés thermiques de la phase émulsionnée au voisinage de la surface. La variation des propriétés thermiques de la phase émulsionnée est considérée dans des modèles utilisant le concept de la couche limite de propriété.

## WÄRMEÜBERGANG ZWISCHEN GASDURCHSTRÖMTEN WIRBELSCHICHTBETTEN UND ÜBERFLUTETEN OBERFLÄCHEN

**Zusammenfassung**—Verschiedene Modelle, die den Wärmeübergang zwischen der Emulsionsphase eines gasdurchströmten Wirbelschichtbettes und überfluteten Oberflächen beschreiben, werden diskutiert. Es wird gezeigt, daß gewisse Besonderheiten dieser Modelle, so z. B. der Kontaktwiderstand oder ein Gasfilm zwischen der Oberfläche und den Feststoffpartikeln durch die statistische Variation der thermophysikalischen Stoffdaten der Emulsionsphase in der Nähe der Wärmeübertragungsfläche zustandekommen. Der Variation der thermophysikalischen Stoffdaten der Emulsionsphase wird direkt in den Modellen durch Anwendung des Konzepts der 'Stoffdaten-Grenzschicht' Rechnung getragen.

## ТЕПЛООБМЕН МЕЖДУ ПСЕВДООЖИЖЕННЫМ ГАЗОМ И ПОГРУЖЕННОЙ ПОВЕРХНОСТЬЮ

**Аннотация**—Рассматриваются различные модели теплообмена между эмульсионной фазой псевдоожиженного газа и погруженными поверхностями. Показано, что определенные характеристики этих моделей, такие как контактное сопротивление или газовая пленка между поверхностью и твердыми частицами, связаны со статическим изменением тепловых свойств эмульсионной фазы вблизи поверхности теплообмена. Изменение тепловых свойств эмульсионной фазы учитывается непосредственно в моделях, использующих понятие характерного пограничного слоя.