MODEL FOR HEAT EXCHANGE BETWEEN A WELL-DEVELOPED FLUIDIZED BED AND A SURFACE WITHIN THE BED

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UDC 621.785:66.096.5

A physical model for heat exchange between a fluidized bed and a surface in contact with it is proposed and discussed. The heat exchange is due to heat transfer by oscillating particles.

The "external" heat and mass transfer between a fluidized bed and surfaces are of considerable interest in connection with the widespread applications of such systems. As examples we can cite not only heat exchange between a bed and the walls bounding it, but also the many exchange processes with inserts, heat exchangers, articles being processed, etc., which lie within the bed; such systems are found in several technological applications.

Much experimental information is now available on external heat transfer in beds of various types, and models have been worked out which explain the essential features of certain phenomena accompanying heat transfer. These models also give a physical interpretation of the mechanism for this transfer (see, e.g., the review in [1-4]). Qualitatively, the existing models can be classified in three groups: First, there is the Leva–Richardson–Levenspiel model [5-7], which is based on the concept of a localization of the thermal head in a thin gas film or in liquid drops on the heat-exchange surface. Second, the Wicke–Fetting–Zabrodskii model [8, 9] incorporates, in addition to this film, heat transfer by conduction in a boundary layer of particles [8] or in successive rows of particles adjacent to the surface. Exchange of inindividual particles between these rows is taken into account [9]. Finally, in the Mickley–Fairbanks–Baskakov "packet" model [10, 11], the heat transfer is dominated by packets of particles in correlated motion which come briefly into contact with the surface.

Although some of these models have clearly been successful in giving a qualitatively correct description of heat exchange in certain particular situations or over narrow ranges of parameters, they do not give a complete physical picture of the process, and they are sometimes contradictory. The contradiction arises because one particular model focuses on one of the competing heat-exchange mechanisms, to the detriment of other possible mechanisms. In order to use these particular but simple models in a knowledgeable manner, we clearly need a more complete model, giving a descritpion of the general behavior of the heat-transfer coefficient of the surface as a function of the various parameters and specifying which particular heat-transfer mechanism is predominant in a particular situation.

There are a large number of physical factors which affect heat transfer, and a detailed analysis of each of these factors is quite complicated. It is therefore worthwhile to initially examine simply the qualitative behavior of the various heat-transfer mechanisms under certain simplifying assumptions. In the present paper we report the basic results of such a study for the case in which the primary mechanism is heat transfer by particles of the disperse phase which are heated in a surface layer.

We consider a granular bed under conditions of well-developed fluidization. We assume the thermal conductivity of the particles, λ_1, to be higher than that of the cooling agent, λ_0. This approach restricts the scope of an analysis of beds which are cooled by gases, but it does permit us to neglect heat removal at parts of the surface which are in contact with gas bubbles at a particular instant in comparison with heat

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Institute of Problems of Mechanics, Academy of Sciences of the USSR. Moscow Institute of Chemical Machinery. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 29, No. 3, pp. 410-418, September, 1975. Original article submitted June 17, 1974.

removal at parts of the surface in contact with the dense phase of the bed. The statistical fraction of the surface area in direct contact with the dense phase, s, depends on the hydrodynamic situation in the bed and on the arrangements, shape, and orientation of the surface. This fraction plays an important role in a systematic theory. For large surface areas, this quantity can be thought of as the instantaneous value of the surface area averaged over the area; for small surfaces, it can be thought of as the average over time.*

In a well-developed fluidized bed the particles are entrained in a well-developed oscillatory motion. In accordance with the extensive experimental information available [1-4], we can assume that, first, there is an ideal mixing among particles in the sense that the particles are at a homogeneous temperature, which is equal to the bed temperature far from the surface, T_∞, and, second, the average time spent by a particular particle in the immediate vicinity of the surface is short. In other words, exchange of particles between the surface region and the core of the bed occurs quite rapidly. Clearly, this assumption is consistent with the models in [9-11]. However, this assumption makes the theory inapplicable for describing heat transfer in steady-state or minimally fluidized beds, in which the particle oscillations are weak. We emphasize that it is completely irrelevant whether the particles approach the surface in groups, i.e., in packets, or alone. The only important consideration is that these particles penetrate into the surface region, are heated in this region (where they act as a heat sink), and then migrate into the core of the bed.

Intense oscillations of the particles prevent the formation of an ordinary thermal boundary layer at the surface; these oscillations constantly disrupt this boundary layer, so that the situation can be assumed approximately the same at various elements of a large surface under identical conditions. Then we can neglect heat convolution during tangential motion of the gas and particles at the surface. Since the temperature drop is concentrated in a thin layer near the surface, where the average normal velocity of both phases of the bed vanishes, we can also neglect the average convection in the direction normal to the surface. This of course does not mean that we are neglecting heat transfer due to random oscillations of the gas at the surface; this transfer can be extremely important. This latter process is typically diffusive in nature, however, and can be described by introducing an additional term in the equation for the effective thermal conductivity of the gas filtering through the pore volume of the porous object formed by the moving particles (see the discussion below). We note that the first of these assumptions may turn out to be incorrect if the scale dimension of the surface in contact with the bed is comparable to the scale dimension of the microstructure of the bed (e.g., for heat exchange of a bed with thin tubes or wires, with a diameter comparable in magnitude to the average distance between particles).

Under these assumptions, the problem of steady-state heat conduction in the fluidizing gas which is part of the dense phase – a problem whose solution yields the average characteristics of heat exchange of a bed with a temperature T_∞ with a surface maintained at a temperature T_W – can be written on the basis of the analysis in [12] in the following form:

$$\lambda \frac{d^2T}{dx^2} - k(T - T_\infty) = 0, \quad T|_{x=0} = T_w, \quad T|_{x\to\infty} \to T_\infty. \tag{1}$$

Here k is the coefficient of the heat transfer from the gas to the particles per unit volume of the dense phase; this coefficient can be found from the known solutions of the problem of unsteady heat exchange between a single particle and a medium [13]. Here also, λ is the effective thermal conductivity of the gas containing the oscillating particles; it can be written

$$\lambda = \lambda' + \sigma c_0 d_0 a (1-\varepsilon)^{-1/3} u, \quad \lambda' = \lambda_0 F(\varepsilon, \lambda_1/\lambda_0). \tag{2}$$

The first term in the sum in (2) describes the effective apparent thermal conductivity of a steady-state granular bed, for which an equation follows from [12, 14, 15]; the second term describes the convective heat dispersion due to the fine-scale gas motion in the pore volume of the dense phase, with a scale dimension $a(1-\varepsilon)^{-1/3}$. The theory of this dispersion is set forth, e.g., in [16]. For complete mixing of the elementary streams of gas in the pores – which is extremely probable in the case of well-developed fluidization – we have $\sigma \approx 1$; if the mixing is incomplete (in particular, in steady-state granular beds), this coefficient can be much smaller [17]. The function F in (2) was calculated in [12, 14, 15]; for values of

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*We emphasize that an immediate consequence of this assumption is that this model turns out to be inapplicable not only for describing heat exchange in beds which are fluidized by liquid in drops, but also for analyzing mass transfer in any beds. In the latter case, mass transfer of parts of the surface in contact with a pure gas or a gas carrying a few particles can even exceed the transfer at regions in contact with the dense phase, because the solid particles are impenetrable to the diffusing impurity.

ε characteristic of the dense phase of the bed and under the condition $\lambda_1/\lambda_0 \gg 1$, this function is given in order of magnitude by $F \sim 10$. We note that the apparent thermal conductivity of the gas, λ', should be distinguished from the effective thermal conductivity of the granular bed which this gas fills [12, 14, 15].

Equation (1) is strictly correct under conditions such that the scale length of the field of the average gas temperature T is much larger than $a(1-\varepsilon)^{-1/3}$. In the case under consideration here, this condition is not always satisfied, so that this equation must be treated as approximate. Two more approximations have been used to simplify the calculations and the analysis. The component of the heat dispersion due to fluctuations in the gas velocity, due to random inhomogeneities of the porosity, has been neglected. This component was taken into account in [18] for randomly packed granular beds and in [19] for fluidized beds, and it can in principle be incorporated in the analysis. In addition, the effective gas "film" at the surface, which plays such an important role in the models of [5-8], has been neglected. The reason for this film is that the wall exerts a limiting effect on possible configurations on the system of particles, so that the average porosity of the dense phase near the wall turns out to be slightly higher than far from the wall [20]. This effect can also turn out to be important in hydrodynamic [21] and thermal [5-8] problems, if the particles are large enough. This film can be easily taken into account without introducing any new fundamental difficulties.

The solution of problem (1) is

$$T = T_\infty + (T_w - T_\infty)\exp\left(-\sqrt{\frac{k}{\lambda}}\,x\right), \tag{3}$$

from which we see that the thickness of the layer within which the gas temperature is inhomogeneous is

$$\delta \approx (\lambda/k)^{1/2}. \tag{4}$$

Then the average heat flux from the surface and the corresponding heat-transfer coefficient become

$$q = s\sqrt{\lambda k}\,(T_w - T_\infty), \quad \alpha = s\sqrt{\lambda k}. \tag{5}$$

To evaluate k we use the assumption that the average time τ spent by the particles in the surface region is small; then we can assume the particle to be in an infinite medium with a thermal conductivity λ_0, and we can use the solution of the problem of unsteady heat exchange between two half-spaces [13]. The average heat absorbed by a single particle over the time τ is

$$q_\tau = 4\pi a^2 \frac{2}{\sqrt{\pi}} (c_0 d_0 \lambda_0 \tau)^{1/2} \left[1 + \left(\frac{c_0 d_0 \lambda_0}{c_1 d_1 \lambda_1}\right)^{1/2}\right]^{-1} (T - T_\infty). \tag{6}$$

To convert from q_τ to the average absorbed by all the particles in a unit volume of the dense phase, we must multiply (6) by the number density of particles ($1-\varepsilon$ divided by the volume of a single particle) and by the frequency of particle interchange in the heat-transfer zone, $f = \tau^{-1}$. As a result, we find the following equation for k:

$$k = \frac{6}{\sqrt{\pi}} \frac{1-\varepsilon}{a} \left(\frac{c_0 d_0 \lambda_0}{\tau}\right)^{1/2} \left[1 + \left(\frac{c_0 d_0 \lambda_0}{c_1 d_1 \lambda_1}\right)^{1/2}\right]^{-1}. \tag{7}$$

This equation and the equation

$$\alpha = s\left(6\lambda \frac{1-\varepsilon}{a}\right)^{1/2} \left(\frac{c_0 d_0 \lambda_0}{\pi\tau}\right)^{1/4} \left[1 + \left(\frac{c_0 d_0 \lambda_0}{c_1 d_1 \lambda_1}\right)^{1/2}\right]^{-1/2}, \tag{8}$$

which follows from (5) and (7), have the form of the equations from packet theory [4, 10, 11]. Both contain the unknown time τ or the frequency f. These latter quantities are functions of not only the properties of the particles in the gas and the state of the bed, but also the hydrodynamic environment near the surface. For this reason, much caution must be used in drawing conclusions about the particular values of these quantities under various conditions.

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*We note in this connection that the identification of f as the observed frequency of global oscillations of a fluidized bed, discussed in [3], would be erroneous in general. This latter frequency is a measure of a certain macroscopic process (e.g., regular circulation of the disperse phase in the bed or the frequency at which large bubbles are burst), while f corresponds to microscopic oscillations of particles or packets of particles.

If the surface in contact with the bed does not cause any significant disruption of the layer structure, the time τ can be evaluated as the scale time for motion of a fluctuating particle of the dense phase over a distance δ in the direction normal to the part of the surface under consideration. If the mean free path of a particle having an rms fluctuation velocity u' in this direction is comparable to or larger than δ, then we have $\tau \approx \delta/u'$. Otherwise, we have an alternative means for determining τ, specifically, the relation $\tau \approx \delta^2/2D$, where D is the effective dispersion coefficient of the particles in the direction normal to the surface. The values of u' and D have been estimated, e.g., in [19], while an estimate of δ follows from (4). For the first estimate of τ to be approximately correct, the quantity δ must be comparable in magnitude to a. The second estimate is correct if δ is much larger than a. Analysis of the experimental data shows that the first estimate seems to be better, i.e.,

$$\tau \approx \frac{\delta}{u'} \approx \frac{C}{u}\left(\frac{\lambda}{k}\right)^{1/2}, \tag{9}$$

where C is a coefficient which is a complicated function of the arrangement of the surface, the Reynolds number corresponding to the flow around a single particle of the dense phase, and the porosity. Without going into the extraneous details, we note that the coefficient C is on the order of 0.1-1 for nearly vertical surfaces, for realistic values of the porosity.

Combining (7) and (9), we find the following expression for k:

$$k \approx \lambda^{-1/3}\left(6\,\frac{1-\varepsilon}{a}\right)^{4/3}\left(\frac{uc_0d_0\lambda_0}{\pi C}\right)^{2/3}\left[1+\left(\frac{c_0d_0\lambda_0}{c_1d_1\lambda_1}\right)^{1/2}\right]^{-4/3}. \tag{10}$$

Substituting this into (8) and using (2), we can write

$$\alpha \approx s\,[\lambda_0F+\sigma c_0d_0a\,(1-\varepsilon)^{-1/3}\,u]^{1/3}\left(6\frac{1-\varepsilon}{a}\right)^{2/3}\left(\frac{uc_0d_0\lambda_0}{\pi C}\right)^{1/3}\left[1+\left(\frac{c_0d_0\lambda_0}{c_1d_1\lambda_1}\right)^{1/2}\right]^{-2/3}. \tag{11}$$

Let us briefly discuss the heat-transfer coefficient α as a function of the conditions prevailing in the bed and of physical properties of the particles and the gas. First, in accordance with the two-phase theory for fluidization, the porosity of the dense phase of the bed and the average gas velocity in it depend on the fluidization rate Q extremely weakly, since nearly all the excess gas (above the amount required for minimal fluidization) breaks through the bed in the form of bubbles. Despite the obviously approximate nature of this theory (see, e.g., the criticism of this theory in [22]), we can make the rough estimate $u \approx Q_m/\varepsilon$ and assume ε to lie in the range 0.4-0.6. Significantly, both these quantities are more properly thought of as characteristics of the gas and the particles rather than characteristics of the conditions prevailing in the bed.

For very small particles (such that the Reynolds numbers is less than or on the order of one), we have

$$u \approx K(\varepsilon)\,\frac{d_1ga^2}{\mu}, \tag{12}$$

and the second time in the first set of brackets in (11) is much smaller than the first. Accordingly, as the particle radius falls to zero, the coefficient α tends toward some finite limit, as is easily seen from (11). This conclusion is of fundamental importance, since such a limit is usually not reached experimentally, and one gets the impression that heat exchange between the bed and the surface can be intensified without restriction if the particle size is reduced.

For light particles (for Reynolds numbers much larger than one) we have

$$u \approx K'(\varepsilon)\left(\frac{d_1}{d_0}\,ga\right)^{1/2}. \tag{13}$$

Using (13) in (11), we see that as the value of a is increased the coefficient α at first begins to fall off in proportion to $a^{-1/2}$ [while the second term in (2) for λ remains small in comparison with the first] and then tends toward a value independent of a. Here we have been ignoring the dependence of C on the Reynolds number (and thus on a). Furthermore, this model neglects the competing heat-transfer mechanisms (e.g., convective transport by the average flow of the filtered gas), which become increasingly important as the particles become larger. A preliminary analysis shows that for sufficiently large values of a the coefficient α should increase slowly with increasing a and should have a minimum at some intermediate value a_*. This "critical" radius can be estimated roughly on the basis of the order of magnitude of the terms in (2):

$$a_* \sim \left(\frac{F}{K'} \cdot \frac{1-\varepsilon}{\sigma}\right)^{2/3} \left(\frac{\lambda_0}{c_0}\right)^{2/3} (d_0 d_1 g)^{-1/3} \sim \left(\frac{\lambda_0^2}{d_0 d_1 c_0^2 g}\right)^{1/3}. \tag{14}$$

A large number of equations have been proposed [1-3] for the quantities K and K' which appear in (12)-(14). The behavior of α as a function of a outlined here agrees with the experimental data available (see [1-3] and also [23-26]).

How is α affected by the physical properties of the gas. For sufficiently small particles, with the first term predominant in Eq. (2) for λ, we have $\alpha \sim \lambda_0^{2/3}$ and $\alpha \sim (c_0 d_0)^{1/3}$. For large particles, on the other hand, in which case the convective heat dispersion is more important in (2), we have $\alpha \sim \lambda_0^{1/3}$ and $\alpha \sim (c_0 d_0)^{2/3}$. Accordingly, if we describe the experimental results with power laws of the type $\alpha \sim \lambda_0^n$ and $\alpha \sim (c_0 d_0)^m$ we should expect the exponents n and m to lie between 0.33 and 0.67. For particles which are not too large, corresponding to most experiments on heat transfer between a bed and a surface, we should have n = 0.5-0.7 and m = 0.3-0.4, in agreement with experiment [1-8].

According to (11), the thermal conductivity and specific heat of the material of the particles have extremely little effect, again in agreement with experiment. In this connection we must emphasize that the dependence of α on λ_1 and $c_1 d_1$ is not fully reflected in (11), because details of the particle migration in the surface region have been neglected and because we have assumed a rapid interchange of particles in this region. A more accurate calculation would lead to new terms in (11), although they would be small, on the order of $c_0 d_0 \lambda_0 / c_1 d_1 \lambda_1$. The specific gravity of the particles affects the value of α indirectly, through the quantity Q, which affects u [see, e.g., (12) and (13)].

The dependence of the heat-transfer coefficient on the fluidization conditions and on the position and orientation of the heat-exchange surface in the bed is concentrated in the factor s in (11). In the spirit of the basic assumption that the heat exchange occurs primarily at surface regions in contact with the dense phase of the bed, this factor can be treated as the average fraction of the area of such regions participating actively in the heat exchange. To determine this quantity we must solve several complicated, purely hydrodynamic problems – beyond the scope of the present paper. However, it is not difficult to carry out a qualitative analysis of the functional dependence of s on the various factors.

The quantity s is proportional to the concentration of the dense phase near the surface. If the presence of the surface does not strongly alter the hydrodynamics of the bed in the region adjacent to this surface, then this concentration is approximately equal to the concentration of the dense phase in a free bed, s_0. This latter quantity falls off with increasing fluidization rate. Working from the concepts of the two-phase fluidization theory, we can write

$$s_0 \approx \frac{U-Q}{U-Q_m}. \tag{15}$$

It is also a simple matter to derive equations like (15) corresponding to refined versions of the two-phase theory, e.g., as in [22] or [27]. The substitution of $s \approx s_0$ from (15) into (11) shows that α falls off with increasing Q. This conclusion is, of course, valid only in the range of applicability of this model, i.e., only for a well-developed fluidized bed. Equation (11) describes only the descending branch of the α(Q) curve, observed experimentally. This model is not valid for describing the ascending branch of this curve or its maximum, since some of the assumptions of the model are not satisfied.

Relation (15) describes the concentration of the dense phase averaged over the volume of the bed. Actually, gas bubbles are distributed nonuniformly in a bed of even a simple geometry, so that s_0 is an inhomogeneous function of the coordinates. Accordingly, we can expect some increase in the bubble concentration $1-s_0$ with increasing distance above the gas distribution grid, since the bubbles in the lower part of the bed are still growing.

We can therefore expect α to fall off slightly with distance above the grid, at least at distances sufficiently far from the grid. Analogously, gas bubbles are distributed nonuniformly in any horizontal cross section of the bed [28]. As a result, α also depends on the horizontal coordinates; the nature of this dependence can, in principle, be predicted by using (11) and results like those in [28]. The decrease of α with height above the gas distribution grid and the complicated dependence of α on the horizontal coordinates have been observed experimentally on several occasions [1-3].

The discussion above has dealt with surfaces whose presence in fluidized beds does not greatly alter the characteristic value of s in comparison with that in the corresponding "free" bed. In other words, this discussion actually holds for surfaces which make small angles with the vertical. If the surface makes a large angle with the vertical, the orientation can have a greater effect on α than the position of the surface in the bed.* For example, an oscillating layer of pure gas, essentially free of particles, forms at the lower surface of a horizontal plate or of a cylinder, sphere, etc., in the flow [29]. It is completely clear that the mechanism for heat exchange between such a surface and the bed is different from that postulated above and, incidentally, different from the external heat exchange adopted in other models. In particular, it is clear that in this case we cannot neglect heat transfer to the pure gas, since this simplification greatly distorts the physical picture of the process. The other limiting case is the upper side of a horizontal plate or of an object in a flow, at which a "cap" of densely packed particles usually forms. Physically, it is obvious that heat transfer from such a surface will be dominated by conduction through the steady-state (perhaps moving) granular bed and by convection by the gas flow, so that the assumption of a rapid interchange of particles in the surface region is quite wrong. For complicated surfaces, the actual situation seems to be described approximately by the arguments of [30], according to which the degradation of the hydrodynamic conditions for heat exchange at individual parts of a surface is offset by the improvement in these conditions at other regions and that this degradation is extremely slight on the whole and does not always have a definite effect on the value of α averaged over the surface. We note, in conclusion, that fluctuations in the porosity of the bed and the associated oscillations of the particles and the gas play a very important role in heat exchange between a bed and a surface immersed in the bed. In the discussion above we took these oscillations (which are by no means small) into account implicitly, through assumptions involved in the model for the process. Presumably, a more thorough and more direct analysis of these oscillations would lead to new fundamental conclusions regarding the nature of the process and regarding possible ways for intensifying the process which were previously not obvious. Accordingly, a detailed theoretical and experimental study of the fluctuations in the surface temperature, in the heat flux from the surface, and in the heat-transfer coefficient is clearly worthwhile.

NOTATION

a	is the particle radius;
C	is the coefficient in (9);
c_0 and c_1	are the specific heats of the gas and particles;
D	is the dispersion coefficient of the particles;
d_0 and d_1	are the densities of gas and particles;
F	is the function in (2);
f	is the frequency;
g	is the acceleration due to gravity;
K and K'	are the coefficients in (12) and (13);
k	is the interfacial heat-transfer coefficient;
m and n	are the exponents;
Q	is the gas flow rate;
Q_m	is the minimum fluidization rate;
q	is the heat flux to surface;
$q\tau$	is the heat absorbed by a single particle over a time τ;
s	is the fraction of surface area in contact with the dense phase of the bed;
s_0	is the volume concentration of gas bubbles in a free bed;
T	is the temperature;
T_W and T_∞	are the temperatures of surface and bed;
U	is the gas velocity in the bubble phase;
u	is the gas velocity in dense phase;
u'	is the rms velocity of particle oscillations in the direction normal to the surface;
x	is the normal coordinate;
α	is the heat-transfer coefficient at surface;

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*In this connection one of the authors (Buevich) would like to express an opinion in connection with the controversy on the adequacy of the packet model of heat transfer. It follows from the present discussion that there is no point in this controversy. The adherents of this model are correct when the subject is heat transfer whose kinetics is actually governed by contacts between the surface and the dense phase and by the rate of heat transfer by particles. The critics of this model are equally correct when the subject is surfaces which alter the local structure of the fluidized system and thereby alter the basic physics of the external heat exchange.

δ	is the thickness of variable-temperature layer near the surface;
ε	is the porosity;
λ and λ'	are the effective thermal conductivity and apparent conductive thermal conductivity of gas in dense phase;
λ_0 and λ_1	are the thermal conductivities of gas and particles;
μ	is the gas viscosity;
σ	is the coefficient in (2);
τ	is the average time spent by a particle near the surface.

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