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 individual particles between these rows is taken into account [9]. Finally, in the Micldey—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 description 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 dispersive 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, $\lambda_1$, to be higher than that of the cooling agent, $\lambda_0$. 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...
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, \( T_\infty \), 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 convection 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 \( T_\infty \) with a surface maintained at a temperature \( T_w \)— can be written on the basis of the analysis in [12] in the following form:

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

(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, \( \lambda \) is the effective thermal conductivity of the gas containing the oscillating particles; it can be written

\[
\lambda = \lambda' + \rho_0 \omega_D a (1 - \epsilon)^{-1/3} u, \quad \lambda' = \lambda_0 F(\epsilon, \omega_0/\lambda_0).
\]

(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 \( a(1-\epsilon)^{-1/3} \). 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 \( \omega \approx 1 \); 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

*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.