per unit volume of the mixture; $f = F + p\,\mathrm{grad}\,m$; d, particle diameter; c_V, c_p, and c_s, heat capacities of the gas and of the particles; μ, coefficient of viscosity of the gas, $\varkappa = c_p/c_v$, $h^2 = (\varkappa+1)/(\varkappa-1)$; A, ratio of the reduced densities of the particles and of the gas; $\varepsilon = Ac_s/c_p$ with $T_s = T$ and $\varepsilon \equiv 0$ with $\alpha = 0$, $A \neq 0$; $\chi(t)$, an arbitrary function of t; β, γ, constants expressed in terms of A, $\varkappa$, ε; s, entropy of the gas; M and λ, Mach and Khristianovich numbers; λ_*, subsonic velocity of the gas, corresponding to the critical velocity of the pseudogas; φ and ψ, velocity potential and the stream function; θ, angle of inclination of the velocity vector to the x axis; $P = 1/\lambda$, $Q = \rho_0/\rho_1\lambda$; $\sqrt{K}$ and σ, coefficient and independent variable of the system of Chaplygin's equations. Indices: 1, pseudogas, i.e., the equilibrium mixture; ∞, quantities in the unperturbed flow at infinity; 0, values at the point of stagnation of the flow; *, critical values of the quantities.

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STATIONARY EXCHANGE BETWEEN AN INFILTRATED GRANULAR BED AND A BODY IMMERSED IN IT

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Stationary heat and mass outflow from a body in an infiltrated granular bed is studied taking into account the effect of the high-porosity zone near the surface of the body.

Problems concerning the stationary transfer of heat or mass from bodies placed in a filtrational flow were first posed and studied for bodies with a simple shape in [1, 2]. In [3] this formulation was extended to nonstationary transfer processes with absorption in the volume of the granular bed. Here the presence of a thin zone, in which the transfer coefficients differ considerably from their effective values outside it, on the surface of the immersed body was completely ignored. This is completely justified, if the characteristic size of the body is much greater than the structural size of the bed (diameter of the particles), and Peclet's number, constructed based on the size of the body, the filtration velocity, and the effective transfer coefficient, is not too large (see, for example, the experiments in [4]). When any of these conditions is violated, however, the existence of the indicated zone significantly changes the observed heat or mass flows compared to those determined theoretically neglecting this zone.

The idea of a layer of high thermal resistance near the surface of a body has been introduced repeatedly in different semiempirical variants of the theory and has been discussed in connection with the problem of external heat transfer in fluidized systems (see the review in [5, 6]). In application to exchange between bodies and filtration flows in stationary granular fills, it was recently used in [7, 8], where the zone near the wall was viewed as

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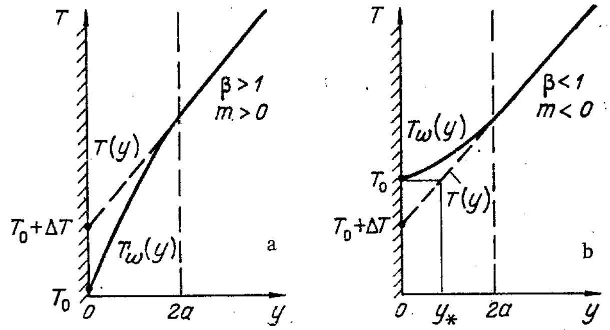

Fig. 1. Profiles of the true and asymptotic average temperature at a solid wall with high (a) and low (b) thermal resistance of the zone near the wall.

an analog of a viscous sublayer of a turbulent boundary layer in a single-phase medium. It is shown in this work that for a fixed temperature of the surface of the body in the flow in the granular bed, the presence of the surface zone can be taken into account by introducing a boundary condition of the third kind on the surface, if the indicated zone has a high thermal resistance, and by giving a boundary condition of the first kind, not on the surface of the body itself, but rather at some distance away from it, if the resistance to heat transfer in the zone is lower than the resistance of the granular bed far from the body. In the first case, expressions are obtained for the stationary local and total heat flows from a flat plate, a cylinder, and a sphere.

1. Temperature Jump at a Solid Wall. We shall study the distortion of the temperature field in a dispersed medium, associated with the presence of a solid surface bounding the region occupied by the medium, with the help of the models and methods developed in [9]. For simplicity, we first assume that the solid boundary is flat, the process of heat conduction is stationary, the temperature of the wall and the temperature field perturbed by the wall do not depend on the longitudinal coordinates, and there is no flow in the granular bed. If the linear scale of the problem is much larger than the radius a of particles in the bed, then the filled granular bed can be considered to be an approximately homogeneous uniform medium, characterized by an effective coefficient of thermal conductivity λ, and at distances of the order of a from the wall

$$T(y) \approx T_0 + \Delta T + Ey,\ T_0 + \Delta T = T|_{y\to 0},\ E = \left.\frac{dT}{dy}\right|_{y\to 0}, \tag{1}$$

where ΔT and E do not depend on the transverse coordinate y. The flow of heat to the wall is, by definition, equal to λE. The problem consists of determining the relationship between ΔT and E.

Since the wall is impermeable to particles, the porosity and therefore the thermal conductivity in the thin zone near the wall differ from their values outside this zone. This leads to the fact that the average temperature of the dispersed medium $T_w(y)$ near the wall (coinciding with the average temperatures of the phases of the medium, if the contact conduction between the particles is neglected) differs from the asymptotic field T(y), as shown in Fig. 1. The effect of the wall reduces to imposing on the possible configurations of the system of particles an additional nonholonomic coupling and is manifested primarily in the form of the single-particle distribution function. This function usually oscillates with increasing y, and the oscillations damp out at distances of the order of several a. For a layer which is nearly monodispersed, it is sufficient to assume in the first approximation that there exists at the wall a "forbidden" region of thickness a into which the centers of the particles (which are assumed to be spherical) cannot enter, while outside this region different positions of the centers are equally probable. We then obtain the following expression for the volume concentration of particles near the wall:

$$\rho_w(y) = \rho\sigma(\eta),\ \sigma(\eta) = 1 - (1+\eta)\left(1 - \frac{\eta}{2}\right)^2, \qquad 0 \leqslant \eta = \frac{y}{a} \leqslant 2, \tag{2}$$

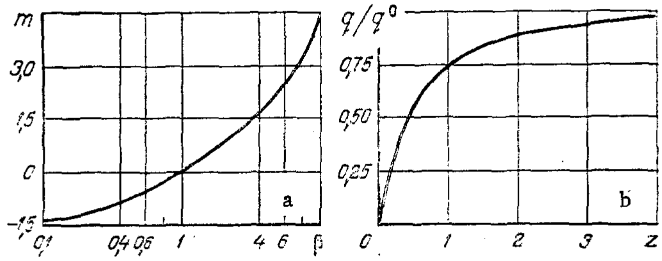

Fig. 2. Dependence of the parameter m on β (a) and of the relative heat flux q/q° on $z = \delta/2ma$ (b).

and $\sigma(\eta)$ is identically equal to unity in the region $\eta > 2$. The function in (2) is analogous to the function examined in [9] in the calculation of the conditional volume concentration of particles near some individual particle.

With the help of the method in [9] we can obtain the following relation for the average thermal conductivity in the region near the wall:

$$\lambda_w(y) = \lambda_0 [1 + (\beta - 1)\sigma(\eta)], \; \beta = \lambda/\lambda_0, \tag{3}$$

which transforms into the well-known formula for the effective thermal conductivity of a homogeneous medium, modeling the filled granular bed, for $y \geqslant 2a$. For a monodispersed layer, β depends only on ρ and λ_1/λ_0. There are a large number of studies concerned with the determination of this dependence; it was determined in [10-12] based on the method in [9] for concentrated systems with different assumptions on the form of the binary distribution function for particles in the granular bed.

The equation of stationary thermal conductivity at the wall, which taking into account (3) assumes the form

$$\frac{d}{dy}\left\{\left[1 + (\beta - 1)\sigma\left(\frac{y}{a}\right)\right]\frac{dT_w}{dy}\right\} = 0,$$

with obvious boundary conditions $T_w(0) = T_0$ and $dT_w/dy = E$ at $y = 2$, has the following solution, taking into account (1),

$$T_w(y) = T_0 + aE\beta \int_0^{y/a} \frac{d\eta}{1 + (\beta - 1)\sigma(\eta)}. \tag{4}$$

The relations (1) and (4) together with the requirement $T_w = T$ at $y = 2$ permit finding the jump in the temperature ΔT at the wall

$$\Delta T = maE, \; m = \beta \int_0^2 \frac{d\eta}{1 + (\beta - 1)\sigma(\eta)} - 2, \tag{5}$$

and the function $\sigma(\eta)$ is defined in (2). The dependence of the coefficient m on β is shown in Fig. 2a. If the thermal conductivity of the particle material is greater than the thermal conductivity of the liquid phase, then $\beta > 1$, $m > 0$; in the opposite case, $\beta < 1$, $m < 0$.

It is first necessary to describe the external heat exchange, examining only the asymptotic field T(y) in the uniform homogeneous medium with thermal conductivity λ. In the two cases shown in Fig. 1, this must be done with the help of different methods. If $\beta > 1$, i.e., the zone near the wall is characterized by a high thermal resistance (see Fig. 1a), then a boundary condition of the third kind at the wall, obtained automatically from the definitions of T and ΔT in (1) and (5),

$$T - ma\frac{dT}{dy} = T_0, \; y = 0 \tag{6}$$

must be imposed on the solution of the heat-conduction equation.

If $\beta < 1$, i.e., the resistance to transfer in the zone near the wall is lower than the resistance outside the zone (see Fig. 1b), then the boundary condition must be a boundary condition of the first kind, but imposed not at the wall itself at $y = 0$, but rather at the surface located at a distance $y = y_*$ away from it, and in addition the expression for y_* is once again obtained from (1) and (5):

$$T = T_0,\ y = y_* = |m|\,a. \tag{7}$$

Relations (6) and (7) evidently remain in force also in the case when T_0 and T depend on the longitudinal coordinates and time, but the characteristic linear and time scales of this dependence are much greater than a and a^2c/λ, respectively. Thus, the presence of a zone near the wall with different properties and with a fixed wall temperature can be taken into account within the framework of a boundary-value problem of heat conduction or convective heat conduction in the homogeneous medium with uniform thermophysical properties. With a high thermal resistance in this zone, the analysis reduces to the solution of a standard boundary value problem of the third kind, and with a low resistance it reduces to the solution of the problem of the first kind, but in a region with a deformed boundary. We examine below only the first problem. With regard to the second problem we indicate only that its solution can be obtained with the help of the perturbation theory and, in addition, the solution of the standard boundary value problem of the first kind with the boundary condition given directly on the surface of the body can be used as the zeroth-order approximation.

In the presence of filtrational flow, in the general case, together with the molecular thermal conductivity it is also necessary to take into account heat transfer due to convective dispersion as a result of mixing and exchange between elementary streams, appearing with the flow past the particles in the bed. Because the molecular and convective dispersive transfer processes are statistically independent the corresponding transfer coefficients can be added. The coefficients of thermal conductivity, associated with convective dispersion, form axisymmetrical tensors, whose principal values corresponding to longitudinal and transverse transfer (i.e., in the directions of the local filtration velocity vector **u** and normal to it), can be approximately written in the form

$$\lambda^{(i)} = 2k^{(i)}c_0d_0au,\quad k^{(2)} = k^{(3)} \neq k^{(1)},\ i = 1,\ 2,\ 3. \tag{8}$$

The coefficients $k^{(i)}$ for small values of the Reynolds number, characterizing the flow around the particles, depend on it (see, for example, the review in [13]), which apparently reflects the effect of this number on the efficiency of exchange between separate elementary streams. To simplify the problem, we shall assume that these coefficients are constants, taking $k^{(1)} = 0.76$ and $k^{(2)} = 0.19$ in accordance with the theory in [14].

As the solid wall is approached, the constituent components of the convective heat-conduction tensors change from their limiting values (8) to zero. This is a result primarily of the corresponding change in the tangential component $u_w(y)$ of the filtration velocity from the value u, formally obtained from the solutions of the equations of the theory of filtration, to zero. To describe this phenomenon, it is necessary to take into account the tangential stresses in the filtration flow in the region near the wall as well as the dependence of the local average porosity on the distance to the wall in accordance with (2). For small Reynolds numbers for particles in the bed, the filtering liquid can be viewed as a simple Newtonian medium with an effective viscosity, whose dependence on the dynamic viscosity of the liquid and concentration of the granular bed was studied in [12]. For large Reynolds numbers an additional momentum transfer, arising due to the convective dispersion, must be taken into account and a component of the total effective viscosity of the filtering liquid, analogous to (8), must be introduced, which has still not been done.

If the dependence $u_w(y)$ were known, then in the immediate vicinity of the surface it would be necessary to replace (8) by

$$\lambda_w^{(i)}(y) = \lambda^{(i)}\tau(\eta), \tag{9}$$

regarding the quantity $\tau(\eta)$, increasing from zero at $\eta = 0$ to unity as $\eta \to \infty$, as a known function. The components (9) of the total thermal conductivity would also have to be included in determining the temperature jump at the surface. As a result, we would obtain the following expression for the coefficient m in (5)-(7):

$$m = \lim_{\eta\to\infty}\left\{\left(\beta + \frac{\lambda^{(2)}}{\lambda_0}\right)\int_0^\eta \frac{d\eta}{1 + (\beta - 1)\,\sigma(\eta) + (\lambda^{(2)}/\lambda_0)\,\tau(\eta)} - \eta\right\}. \tag{10}$$

Thus, for a known function $\tau(\eta)$ the parameter m must be viewed as some empirical quantity. From general considerations, however, it is clear that the functions τ and σ vary in the same way as the distance from the wall increases and the difference between them probably falls within the limits of accuracy of the proposed analysis. If it is assumed that $\tau = \sigma$, then the coefficient m, calculated from (10), for $\beta + \lambda^{(2)}/\lambda_0 \gg 1$ is close to the coefficient determined from (5). In view of the approximate nature of Eqs. (9) this assumption is apparently completely admissible for $\beta \gg 1$, which corresponds, for example, to a granular bed into which gas infiltrates.

Boundary conditions of the third kind with constant m were also applied in the study of the strongly nonstationary heat exchange between a solid wall and a gas-filled granular medium [5]. In reality, in this case, the coefficient m must depend on time, which is associated, first of all, with the presence of nonstationary fields of the average temperatures of the phases and, second, with the time dependence of the coefficient of interphase heat exchange. The fact that the results of the calculations with m = const agree quite well with the experimental data, even at short times after the beginning of the heat-exchange process, can be viewed as a good indirect confirmation of the reliability of the indicated boundary condition.

2. Heat Flow Away from Submerged Bodies. We shall study below only the stationary convective heat-transfer processes neglecting the absorption of heat within the granular bed. In accordance with the results of the preceding section, the asymptotic temperature field in a uniform homogeneous medium surrounding a body with a fixed surface temperature can be found from the solution of the problem

$$(\mathbf{u}\nabla)T = \nabla(\mathbf{D}_e\nabla T),\ \mathbf{D}_e = \boldsymbol{\lambda}_e/c_0 d_0,$$
$$T|_{y\to\infty} \to 0,\ T - ma\partial T/\partial y|_{y=0} = T_0. \tag{11}$$

The temperature is measured with respect to its value far away from the body. It is also necessary to impose the condition that the temperature vanish at the point at which the filtrational flow hits the body. The quantity λ_e in (11) is the tensor of total effective coefficients of thermal conductivity with principal values $\lambda_e^{(i)} = \lambda + \lambda^{(i)}$, where $\lambda^{(i)}$ are determined in (8).

The "macroscopic" Peclet number, determined according to the linear size of the body in the flow, is usually much larger than one. In this case, the temperature changes considerably only within a thin thermal boundary layer and the problem (11) is greatly simplified. For example, for a flat plate oriented parallel to the stream lines, we have

$$U\frac{\partial T}{\partial x} = (1+\gamma)D\frac{\partial^2 T}{\partial y^2},\quad D = \frac{\lambda}{c_0 d_0},\ \gamma = 0.38\frac{aU}{D},$$
$$T|_{x=0} = T|_{y\to\infty} = 0,\quad T - ma\left.\frac{\partial T}{\partial y}\right|_{y=0} = T_0, \tag{12}$$

where x is the longitudinal coordinate, measured from the front edge of the plate downstream along the flow, and γ is a "microscopic" Peclet number, determined with respect to the structural scale a of the granular bed. With m = 0 the solution of this problem is self-similar and has the form

$$T = T^\circ = T_0\,\mathrm{erfc}\frac{y}{\delta},\quad \delta = 2\left[\frac{(1+\gamma)Dx}{U}\right]^{1/2},$$
$$q = q^\circ = -(1+\gamma)Dc_0d_0\left.\frac{\partial T^\circ}{\partial y}\right|_{y=0} = (1+\gamma)Dc_0d_0\frac{2T_0}{\sqrt{\pi}\,\delta}. \tag{13}$$

The dependences of T° on y/δ and of q° on δ for bodies with a different shape coincide with m = 0 with (13); the form of the body only affects the dependence of δ on the coordinates introduced on the surface of the body. For a cylinder in a flow moving normally to its axis and for a sphere the dependences of δ on the corresponding tangential coordinate are determined in [1-3].

If m $\neq$ 0, then the solutions of the problem (12) and analogous problems for bodies with a different shape are no longer self-similar, which is attributable to the appearance of an additional linear scale ma in the boundary condition. In this case, the temperature field depends not only on y/δ but also, for example, on y/ma, and the corresponding local

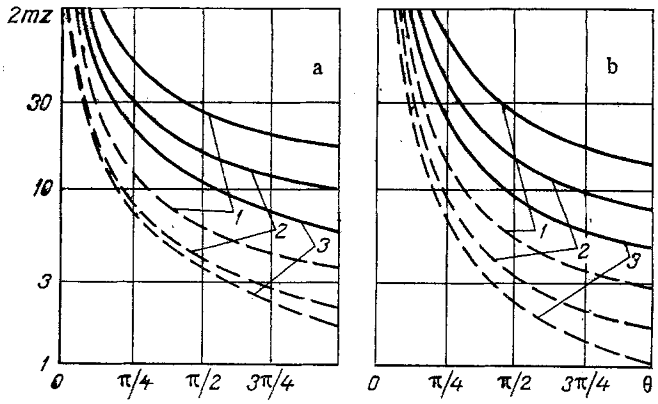

Fig. 3. Variation of the dimensionless thickness of the thermal boundary layer 2mz = δ/a along the surface of a cylinder (a) and of a sphere (b) with α = 0.01 and 0.05 (solid and broken curves, respectively); 1-3) Pe = 30, 100, and 300.

heat flow from the surface of the body depends not only on δ but also on the ratio of the scales ma/δ, transforming into q° only in the limit ma/δ → 0. This flow, however, is determined only by the local situation at distances of the order of a or δ from the surface of the body. Since both of these dimensions are assumed to be much smaller than the characteristic size of the body, it may be assumed that the dependence of the local heat flux on δ and δ/ma will be the same for bodies with different form. The latter permits determining the indicated dependence by studying only the simplest problem (12) for a flat plate.

Assuming that m ≠ 0, applying the Laplace transformation to (12), solving the problem obtained for the ordinary differential equation, and calculating the inverse transform, we obtain instead of (13)

$$\frac{T}{T_0} = \operatorname{erfc}\frac{y}{\delta} - \exp\left[\frac{y}{ma} + \frac{1}{4}\left(\frac{\delta}{ma}\right)^2\right]\operatorname{erfc}\left(\frac{y}{\delta} + \frac{\delta}{2ma}\right), \tag{14}$$

and for δ(x) the formula in (13) is valid as before. The local flow of heat from the surface corresponding to (14) has the form

$$q = (1+\gamma) Dc_0 d_0 \frac{T_0}{ma}\exp(z^2)\operatorname{erfc} z, \qquad z = \frac{\delta}{2ma}. \tag{15}$$

From (13) and (15) it is easy to obtain an expression for the relative change in the local heat flow as a result of replacing the boundary condition of the first kind on the surface of the body by a condition of the third kind, i.e., as a result of taking into account the presence of the zone near the surface with a high thermal resistance. We have

$$\varphi = q/q^\circ = \sqrt{\pi}\, z \exp(z^2)\operatorname{erfc} z. \tag{16}$$

This quantity has the following asymptotic forms:

$$\varphi \approx \sqrt{\pi}\, z\left(1 - \frac{2}{\sqrt{\pi}} z\right), \ z \ll 1; \quad \varphi \approx 1 - \frac{1}{2z^2}, \ z \gg 1.$$

The dependence (16) is illustrated in Fig. 2b, whence it is evident that the presence of an additional ("contact") resistance at the surface leads to a considerable decrease in the heat given off by the body in the flow, which increases as the thickness of the thermal boundary layer decreases. The total heat flux from one side of the plate of unit width and length x, measured from the front edge, is obtained by integrating the quantity (16) with respect to dx taking into account the dependence of the quantity z on x. It is convenient to study the ratio of this flow to its value with m = 0. We have

$$\frac{Q(x)}{Q^\circ(x)} = \left(\int_0^x q^\circ[z(x)]\,dx\right)^{-1}\left(\int_0^x q[z(x)]\,dx\right) = \left(\int_0^x \frac{dx}{z(x)}\right)^{-1}\left(\int_0^x \frac{\varphi[z(x)]}{z(x)}\,dx\right) = 1 - \frac{1}{2z}\left[1 - \exp(z^2)\operatorname{erfc} z\right], \tag{17}$$

where z is determined along the coordinate x of the back edge of the plate.

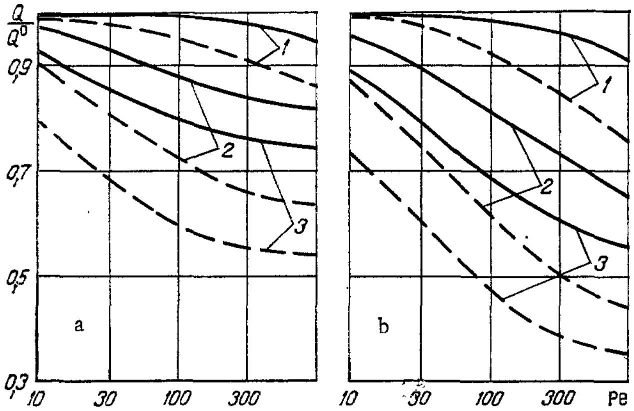

Fig. 4. Total relative heat flow away from a cylinder (a) and a sphere (b) as a function of the Peclet number of the filtrational flow with m = 1.0 and 2.1 (solid and broken curves, respectively); 1-3) α = 0.01, 0.05, and 0.09.

The dependences (15) and (16) are also valid for bodies with a more complicated form, but with definitions of γ and δ (or z) which differ from those for a flat plate. Using the results of [1-3], we can immediately write down:

for a cylinder $\gamma = 0.76\ (aU/D)\sin\theta$ and

$$mz = \frac{1}{\alpha\sqrt{2\mathrm{Pe}}\sin\theta}\left[1+\cos\theta+0.38\alpha\,\mathrm{Pe}\left(\pi-\theta+\frac{\sin 2\theta}{2}\right)\right]^{1/2}, \tag{18}$$

for a sphere $\gamma = 0.57\ (aU/D)\sin\theta$ and

$$mz = \frac{1}{\alpha\sin^2\theta}\left(\frac{2}{3\mathrm{Pe}}\right)^{1/2}\left\{\frac{2}{3}+\cos\theta-\frac{\cos^3\theta}{3}+0.14\alpha\,\mathrm{Pe}\left[\frac{3}{2}(\pi-\theta)+\sin 2\theta-\frac{\sin 4\theta}{8}\right]\right\}^{1/2}. \tag{19}$$

Here θ is the polar angle of a cylindrical or spherical coordinate system (the point at which the flow hits the body corresponds to $\theta = \pi$), $\alpha = a/R$ and Pe = RU/D; in addition, U is the velocity of filtration of the unperturbed flow far away from the body. The angular dependences of the quantities (18) and (19) for different values of α and Pe are presented in Fig. 3. It is evident that the increase in both of the indicated parameters leads to a decrease in z and, therefore, to a decrease in the local heat flow away from the body, which is especially large in the bow region of the body, where the thickness of the thermal boundary layer is minimum. This leads, in particular, to the fact that the maxima of q as a function of θ, attained for values of aU/D which are not small at some distance downstream away from the point at which the flow hits the body [1-3], become sharper.

For the total heat flow away from the body we have the following expressions:

for a cylinder

$$\frac{Q}{Q^\circ} = \left(\int_0^\pi \frac{1+0.76\alpha\,\mathrm{Pe}\sin\theta}{z(\theta)}d\theta\right)^{-1}\int_0^\pi \frac{1+0.76\alpha\,\mathrm{Pe}\sin\theta}{z(\theta)}\varphi[z(\theta)]\,d\theta, \tag{20}$$

for a sphere

$$\frac{Q}{Q^\circ} = \left(\int_0^\pi \frac{1+0.57\alpha\,\mathrm{Pe}\sin\theta}{z(\theta)}\sin\theta d\theta\right)^{-1}\int_0^\pi \frac{1+0.57\alpha\,\mathrm{Pe}\sin\theta}{z(\theta)}\varphi[z(\theta)]\sin\theta d\theta, \tag{21}$$

where $\varphi(z)$ is determined in (16) and $z(\theta)$ in (18) and (19), respectively. The total flux Q° from a cylinder and a sphere in the flow in the absence of a high resistance in the zone near the wall was calculated in [1-3]. The dependences of Q/Q° on Pe for different values of m and α are presented in Fig. 4, whence it follows that the presence of a zone with a high thermal resistance leads to a considerable drop in the heat flow away from the body. This effect becomes stronger as m, α, and Pe increase, because in this case the relative role of the indicated zone in the heat transfer process increases. An analysis shows that the indicated effect enables a satisfactory qualitative explanation of the experimental results in [4, 8].

In conclusion, we note that the results obtained are also valid for mass transfer between bodies in a granular bed and the filtrational flow moving past them.

NOTATION

a, radius of the particles; c and c_0, specific heat capacities of the bed and of the liquid phase; D, thermal diffusivity (or the coefficient of diffusion) in the layer; d_0, density of the liquid phase; E, gradient of the temperature at the wall; $k^{(i)}$, coefficients introduced in (8); m, a parameter determined in (5) or (10); Q and q, total and local heat flows away from the body; R, radius of the cylinder or sphere; T and T_0, temperature and its value over the surface of the body; $\mathbf{u}$, local filtration velocity vector; U, velocity of filtration of the unperturbed flow; x and y, longitudinal and transverse coordinates; z, dimensionless thickness of the thermal boundary layer; $\alpha = a/R$; $\beta = \lambda/\lambda_0$; γ, a parameter or a function characterizing the role of the convective dispersion; δ, thickness of the thermal boundary layer; η, dimensionless coordinate; λ, λ_0, λ_1, thermal conductivities of the bed, of the liquid phase, and of the particle material; ρ, volume concentration of particles; σ and τ, functions introduced in (2) and (9); φ, relative local heat flux; Pe = RU/D; the subscript w refers to quantities determined for the zone near the wall, the superscript ° refers to quantities calculated neglecting the zone near the wall.

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