CALCULATION OF THE NONSTATIONARY TEMPERATURE OF A BODY IMMERSED IN A DISPERSED MEDIUM

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The problem of the nonstationary temperature of bodies immersed in a dispersed medium is investigated.

It is well known that the coefficient of heat transfer between a fluidized bed and a surface is a pulsating function of time [1]. The amplitude of these pulsations is very large; the value of α varies from a maximum when the surface is washed by the solid phase to a minimum, sometimes a negligibly small quantity, when the surface is washed by the continuous phase. Accordingly, the temperature of the surface varies. If the heat capacity of the immersed body is small as, for example, for transducers used to measure heat-transfer coefficients in a bed [2, 3], the temperature pulsations are rather large both on the surface and within the body.

However, bodies subjected to thermal processing or chemical heat treatment in a fluidized bed are generally rather massive with a large heat capacity and it is of interest to examine the dependence of the magnitude of the temperature pulsations at the surface of such bodies on their thermophysical characteristics and the amplitude and frequency of the pulsations of the heat-transfer coefficient.

The general problem of the change of temperature of a body with a change in the heat-transfer coefficient is posed and solved in [4], but the solution obtained is complicated and inconvenient for estimates. Therefore, we use an approximate treatment. We consider a quasistationary process; i.e., we assume that each successive pulsation is the same as the preceding. We assume also that the temperature pulsations in the body are harmonic with a period $2\pi/\omega$, and that their amplitude depends only on the distance from the surface. We limit ourselves to a semiinfinite body. At a distance of a wavelength $l \sim 2\sqrt{\pi a/f}$ from the surface the amplitude of the temperature oscillations is decreased by more than a factor of 50 [5], and for thermal processing in a fluidized bed the value of l is ordinarily less than the half-thickness of the body. For example, according to data in the literature, the most typical pulsation frequency of α in a fluidized bed is f = 5Hz, and for this frequency calculations give $l \approx 0.56 \times 10^{-3}$ m for glass and $l \approx 4 \times 10^{-3}$ m for steel.

The magnitude of the temperature pulsations of a body immersed in a fluidized bed can be estimated by taking account of the fact that under the restrictions indicated above, the amplitude of the oscillations of the heat flux is related to the amplitude of the surface temperature oscillations by the familiar relation

$$q_a = \sqrt{\omega c\rho\lambda}\, t_{sa} \, . \tag{1}$$

Using the fact that the heat flux is given in terms of the heat-transfer coefficient by $\alpha(t_m - t_s)$ we obtain

$$\frac{t_{sa}}{t_m - t_s} \approx \frac{\alpha_a}{\sqrt{\omega c\rho\lambda}} \, . \tag{2}$$

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It is not difficult to compute from (2) that if the heat-transfer coefficient pulsates with a frequency of 5 Hz and the peak value of α_a is 300 W/(m · deg), $t_{sa}/(t_m - t_s) \approx 0.0065$ for steel and ≈ 0.05 for glass.

Equation (2) must be regarded as an approximation. In particular, it does not take account of the complex character of nonstationary heat transfer between the fluidized bed and the surface. Therefore, for a more accurate analysis of the change in temperature of a body immersed in a fluidized bed a numerical model of heat transfer between a body and a fluidized bed was constructed. The mechanism of the heat-transfer process was considered according to the packet model [2]. The situation of a packet was interpreted as the contact of a body with a dense dispersed medium. When the gas traverses the surface of the body the heat-transfer coefficient is assumed zero.

Nonstationary heat transfer between the body and a dense bed was investigated first. In this case the physical model and the corresponding system of differential equations proposed in [6, 7] were used. Taking account of the temperature distribution within the body this system has the form

$$\begin{gathered} c_1\rho_1(1-\varepsilon)\frac{\partial t_1}{\partial \tau} = \lambda_1\left(\frac{\partial^2 t_1}{\partial r^2} + \frac{1}{r}\frac{\partial t_1}{\partial r}\right) + S\alpha^*(t_2 - t_1), \\ c_2\rho_2\varepsilon\frac{\partial t_2}{\partial \tau} = \lambda_2\left(\frac{\partial^2 t_2}{\partial r^2} + \frac{1}{r}\frac{\partial t_2}{\partial r}\right) - S\alpha^*(t_2 - t_1), \\ c_3\rho_3\frac{\partial t_3}{\partial \tau} = \lambda_3\left(\frac{\partial^2 t_3}{\partial r^2} + \frac{1}{r}\frac{\partial t_3}{\partial r}\right) \end{gathered} \tag{3}$$

in cylindrical coordinates.

Boundary conditions of the fourth kind were taken for the gaseous phase. The dispersed medium was assumed infinite. Therefore, at the outer boundary of the bed the temperatures of the particles and the gas were assumed constant and equal to the initial temperature of the filling. Thus in the presence of a packet of particles at the surface the boundary conditions were the following:

$$\begin{gathered} \frac{\partial t_3}{\partial r}(\tau,\ 0) = 0,\ \lambda_2\frac{\partial t_2}{\partial r}(\tau,\ R) = \lambda_3\frac{\partial t_3}{\partial r}(\tau,\ R), \\ t_2(\tau,\ R) = t_3(\tau,\ R),\ \frac{\partial t_1}{\partial r}(\tau,\ R) = 0,\ t_2(\tau,\ \infty) = t_1(\tau,\ \infty) = t_a\,. \end{gathered} \tag{4}$$

In agreement with the results of [8] it was assumed that $S\alpha^* = 4\lambda_2/d^2$.

The problem was solved by the net-point method using the Crank–Nicholson implicit scheme [9]. For economy of calculation a linear-fractional coordinate transformation was used, permitting a concentration of nodes of the net close to the surface of the body. The difference scheme approximated the initial system of equations with an accuracy $O(h^2 + s)$. The problem was solved numerically with the pivotal method. The temperature distributions, the heat fluxes, and the heat-transfer coefficient were calculated for various times.

The calculations were performed for bodies having various thermophysical properties (nickel, steel, glass) but the same radius R = 0.1 m. The dispersed medium consisted of a system of 0.5-mm-diameter slag spheres in air. The thermophysical coefficients, assumed independent of temperature, were calculated from the data of [10-15].

Figure 1 shows the results of solving problems (3) and (4). It is clear from the figure that after a dimensionless time Fo = 10 the temperatures at the centers of the steel and glass cylinders remain constant, while the temperature at the center of the better conducting nickel body varies. The surface temperatures of the bodies change sharply at the very beginning of the heat-transfer process (Fo < 0.5), and then the steady-state temperature drop between the center and the surface remains constant up to Fo = 10. The change in surface temperature depends on the kind of material of the body but it is not affected by the intensity of the heat transfer; the Nu vs Fo curve is the same for all bodies.

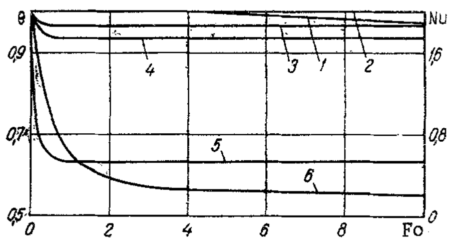

Fig. 1

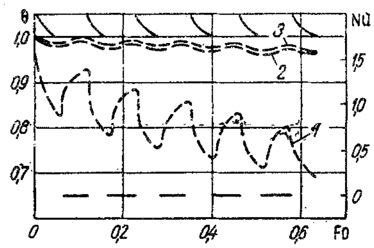

Fig. 2

Fig. 1. Dimensionless temperature θ and Nu as functions of dimensionless time in the heat-transfer process of bodies in a dense bed: 1) dimensionless temperature at center of nickel body; 2) the same for steel and glass bodies; 3, 4, 5) dimensionless surface temperature of nickel, steel, and glass bodies, respectively; 6) Nu.

Fig. 2. Pulsations of the dimensionless temperature θ and Nu in the heat-transfer process of bodies in a fluidized bed. The open curves are the pulsations of the dimensionless temperature, and the solid curves are for Nu; 1, 2, 3 are the pulsations of the dimensionless temperature at the surface of glass, steel, and nickel bodies, respectively.

The relations obtained can be interpreted as the result of close contact of a packet with the surface; they permit an estimate of the magnitude of the temperature pulsations of a body placed in a fluidized bed. Actually, the pulsation frequencies of α in a fluidized bed correspond to values of Fo of the order of 10^{-1}. After this time the surface temperatures of the nickel and steel cylinders change by a few percent, and that of glass by 10 times as much. A temperature gradient develops in the heat-transfer process within the body and the amplitude of the pulsations changes. In this connection calculations were performed assuming that packet and gas cavity alternated with one another at the boundary of the body.

The frequency of replacement of a packet by a cavity was assumed equal to 5 Hz as before. Mathematically, the contact with a gas cavity corresponds to replacing the boundary condition at the surface in Eqs. (4) by the condition

$$\frac{\partial t_3}{\partial r}(\tau,\ R) = 0. \tag{5}$$

Figure 2 shows the results of a numerical solution of the heat-transfer problem of bodies in a fluidized bed. It is clear from the figure that the dimensionless amplitude of surface temperature oscillations of nickel and steel bodies is 0.005, while that of glass is 0.05, in good agreement with estimates made by using Eq. (2).

The results obtained can be used in investigations and calculations of thermal processes and chemical heat treatment of bodies in a fluidized bed.

NOTATION

ρ, density; c, specific heat; λ, thermal conductivity; α, heat-transfer coefficient; α*, interphase heat-transfer coefficient; r, distance in the radial directions; x, distance; R, radius of cylindrical body; d, particle diameter; t, temperature, °C; θ, dimensionless temperature; f, frequency; ω, angular frequency; m, emissivity of body; h, space step; s, time step; ε, porosity; a, thermal diffusivity; $Fo = a_e\tau/d^2$; $Nu = \alpha d/\lambda_e$; $\lambda_e = \lambda_1 + \lambda_2$; $a_e = \lambda_e/(c_1\rho_1 + c_2\rho_2)$. Indices: 1, solid particles of dispersed medium; 2, gaseous phase of dispersed medium; 3, body; m, dispersed medium; i, initial value; a, amplitude value; e, effective value; s, surface of body.

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HEAT TRANSFER IN A DENSE MOVING LAYER IN A CYLINDRICAL CHANNEL

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Analytical results are presented on the heat transfer to the layer with rod-type direct motion of the components in a cylindrical pipe; the solutions are analyzed and a comparison is made with experiment.

Our knowledge of heat transfer in moving layers with fluid through flow is inadequate, particularly for the conditions occurring in chemical reactors and other plants. A mathematical description has been given [1], together with the general dimensionless heat-transfer equation and certain approximate relationships. The latter were derived by considering the layer as a pseudocontinuous medium with the components equal in temperature. However, in the general case the temperatures of the gas and solid components are not the same [1-3].

Here we calculate the temperature distribution and heat transfer for a dense layer of this type moving in a cylindrical pipe, with the layer considered as a discrete two-component system, with each of the components acting as a pseudocontinuous medium. The heat transport in each component is represented by the corresponding effective thermal conductivities ($\lambda_g^☆$, $\lambda_s^☆$), which incorporate the actual flow structure. A working cell contains a number of particles sufficient for these effective properties to be applicable. The effective thermal conductivity of the solid component incorporates the heat transport by conduction in the particles, as well as by contact between the particles and conduction through the immobile gas near the contacts, in addition to radiative transfer between the surfaces of adjacent particles.

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