HEAT EXCHANGE BETWEEN A SURFACE AND AN AGITATED LAYER OF DISPERSED MATERIAL

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An expression is obtained for the heat flux based on the solution of the equation of heat conduction with a source. The results are compared with experiment.

The study of heat exchange between a surface and a layer of agitated dispersed material is of interest for understanding the mechanism for the appearance of transport and obtaining the data necessary for calculating heat exchange for apparatus with agitators. This problem is examined in a series of works [1-6].

In [1], heat exchange between a gravitational sand layer, sinking inside a pipe, and a wall was studied. In [2], the intensity of heat exchange between a layer of finely dispersed materials and a moving vertical surface was measured; in this case, the time interval for contact between the particles and the heat exchange surface was relatively long (Fo > 1).

Of interest are [3, 4] in which results are presented for heat exchange between a layer of dispersed material and a surface, moving relative to one another, when the contact time of the particles with the surface is not long (0.02 < Fo < 1).

However, substantial simplifications are made in the works indicated, since the motion of particles in a direction perpendicular to the heat exchange surface, i.e. agitation, is not taken into account. This simplification permits estimating the value of the maximum heat exchange coefficient of the wall of the apparatus with a moving layer of dispersed material, but does not permit obtaining an expression for heat exchange between the wall and the layer as a function of the agitation intensity.

Thus, at the present time, there are no satisfactory methods for calculating heat exchange between a surface and an agitated layer of dispersed material. An exact solution of this problem is impossible due to the necessity of examining in detail the dynamics and heat exchange of each particle separately. For this reason, a phenomenological approach, based on some model, taking into account the properties of heat exchange of a layer of dispersed material with the surface, is most useful for obtaining practical results. In the present work, we make an attempt to study heat exchange between the surface and the layer of agitated dispersed material based on models [7, 8] developed at the Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, and accepted in practice.

The heat-transfer process in a dense layer of dispersed material can be described by the hyperbolic equation of heat conduction for dispersed systems, as proposed in [8]. In the general case, for a mixed layer of dispersed material, this equation can be written in the form

$$\frac{\partial T}{\partial \tau} + \tau_r \frac{\partial^2 T}{\partial \tau^2} = a \frac{\partial^2 T}{\partial x^2} + \frac{W}{c\rho}. \qquad (1)$$

Let us consider heat exchange between an isothermal flat wall and a layer of agitated dispersed material. In the stationary state, a temperature field is established in the layer that is controlled by the boundary conditions, the thermophysical characteristics of the dispersed material, and the intensity of particle agitation in the layer. The average temperature of the particles will be constant at any point in the layer and will depend on the coordinates of this point. This means that the average temperature of any isolated elementary volume of particles, which is sufficiently large in comparison with the volume of a

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single particle, does not change in time. However, due to particle agitation in the layer, each particle separately or small groups of particles are under conditions of nonstationary heat exchange with the remaining particles, forming the given quasistationary temperature profile in the layer.

Assuming that such a description of heat exchange in a layer of agitated dispersed material is correct, each particle moving toward the wall can be viewed, e.g., as a heat sink, while each particle moving in the opposite direction as a heat source. We will write a heat sink W in the form

$$W = \alpha^* S (T - T_p). \tag{2}$$

Equation (1) in this case is greatly simplified:

$$a \frac{d^2T}{dx^2} - \frac{\alpha^* S (T - T_p)}{(1 - \varepsilon) c_p \rho_p} = 0, \tag{3}$$

and the boundary conditions can be written in the form

$$T = T_0, \quad x = 0 \tag{4}$$

$$T = 0, \quad x = \infty. \tag{5}$$

In order to solve the system of equations (3)-(5), let us express the instantaneous particle temperature T_p in Eq. (3) in terms of the average temperature of the layer T. A rigorous solution of this problem encounters considerable difficulties. For this reason, we will determine T_p with sufficient accuracy from the equation of heat balance of particles in the layer. Neglecting in the first approximation the temperature differential across the cross section of a particle, we write

$$(1 - \varepsilon) c_p \rho_p \frac{dT_p}{d\tau_1} = \alpha^* S (T - T_p). \tag{6}$$

Solving (6), we obtain an expression for the temperature of a particle:

$$T_p = T \left[1 - \exp\left(-\frac{\tau_1}{\tau_r} \right) \right], \tag{7}$$

where

$$\tau_r = \frac{(1 - \varepsilon) c_p \rho_p}{\alpha^* S} \tag{8}$$

characterizes the thermal inertia of particles or the time necessary for equalizing the temperature difference between the particles and the layer. In solving Eq. (7), it is assumed that the temperature in the core of the layer equals 0.

Substituting (7) into (3) we obtain

$$\frac{d^2T}{dx^2} - \frac{1}{\tau_r a} T \exp\left(-\frac{\tau_1}{\tau_r} \right) = 0. \tag{9}$$

We write (9) in dimensionless variables:

$$\frac{d^2\Theta}{dX^2} - \frac{\exp\left(-\frac{\mathrm{Fo}}{\mathrm{Fo}_r} \right)}{\mathrm{Fo}_r} \Theta = 0. \tag{10}$$

The boundary conditions (4) and (5) take the form

$$\Theta = 1, \quad X = 0, \tag{11}$$

$$\Theta = 0, \quad X = \infty. \tag{12}$$

The solution of Eq. (10) with boundary conditions (11) and (12) has the form

$$\Theta = \exp(-\sqrt{B}\, X), \tag{13}$$

where

$$B = \frac{\exp\left(-\frac{\mathrm{Fo}}{\mathrm{Fo}_r} \right)}{\mathrm{Fo}_r}.$$

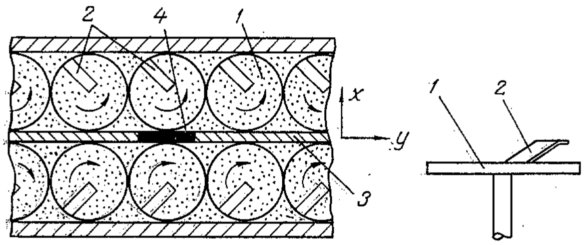

Fig. 1. Diagram of the setup: 1) rotor; 2) blade; 3) central barrier; 4) heater-sensor.

Let us determine the instantaneous value of the dimensionless heat flux Nu at the boundary of an isothermal surface and the layer:

$$\mathrm{Nu} = -\left.\frac{d\Theta}{dX}\right|_{X=0} = \sqrt{B} = \frac{1}{\sqrt{\mathrm{Fo}_r}} \exp\left(-\frac{\mathrm{Fo}}{2\,\mathrm{Fo}_r}\right). \tag{14}$$

In order to find the average heat flux $\overline{\mathrm{Nu}}$, additional assumptions are required concerning the time that a particle spends in the heat-exchange zone or, keeping in mind (14), concerning values of Fo.

As in [9], we will assume that the residence time of particles in the heat exchange zone (at the wall) is described by the gamma function

$$f(\tau_1) = \frac{1}{2\beta} \exp\left(-\frac{\tau_1}{2\beta}\right). \tag{15}$$

Then, $f(\tau_1)d\tau_1$ is the probability that the particle is located in the heat-exchange zone during a time from τ_1 to $\tau_1 + d\tau_1$.

In order to determine $\overline{\mathrm{Nu}}$, we will transform to dimensionless time Fo_β in (15):

$$f(\mathrm{Fo}) = \frac{1}{2\,\mathrm{Fo}_\beta} \exp\left(-\frac{\mathrm{Fo}}{2\,\mathrm{Fo}_\beta}\right). \tag{16}$$

Let us determine the average value of the dimensionless heat flux at the boundary:

$$\overline{\mathrm{Nu}} = \int_0^\infty \mathrm{Nu}\, f(\mathrm{Fo})\, d\,\mathrm{Fo}. \tag{17}$$

Integrating (17) taking into account (14) and (16), we obtain

$$\overline{\mathrm{Nu}} = \frac{1}{\sqrt{\mathrm{Fo}_r\left(1 + \frac{\mathrm{Fo}_\beta}{\mathrm{Fo}_r}\right)}}. \tag{18}$$

Let us analyze expression (18). For $\mathrm{Fo}_\beta \to 0$ (rapid exchange of particles at the wall), $\overline{\mathrm{Nu}} \to 1/\sqrt{\mathrm{Fo}_r}$, which coincides with the solution of the hyperbolic equation of heat conduction for dispersed systems with boundary conditions of the first kind, when $\mathrm{Fo} \to 0$ [8]. From here, based on [8], it follows that the limiting value of the dimensionless heat-exchange coefficient $\overline{\mathrm{Nu}}$ with the surface in the agitated layer of dispersed material does not exceed $\overline{\mathrm{Nu}}$ for a dense layer. The value of $\overline{\mathrm{Nu}}$ in the agitated layer depends on the average residence time Fo_β of particles in the heat-exchange zone and the heat exchange intensifies with decreasing Fo_β. For $\mathrm{Fo}_\beta \to \infty$ (stationary layer), $\overline{\mathrm{Nu}} \to 0$, which coincides with the solution of the classical equation of heat conduction with $\mathrm{Fo} \to \infty$. Thus, it is evident from the solution (18) that heat exchange in the agitated layer of dispersed material is determined by two parameters: Fo_β and Fo_r, the first of which characterizes agitation, and the second takes into account the thermophysical properties of the layer.

In order to check the model, we used heat exchange of a surface with a modification of the agitated layer: a vibrating layer [10]. Experiments were performed with a laboratory setup having a chamber with dimensions 1070 × 210 mm, in which two rows of rotors were placed with blades fixed on their upper surfaces. The diameter of the rotors was 90 mm. The rotors were driven by two asynchronous electric motors. The rate of rotation of the rotors, measured by a TCh-10R tachometer to within 1%, was a constant 390 rpm in the given experiments. A barrier, containing a heater-sensor for measuring the heat exchange intensity, was placed

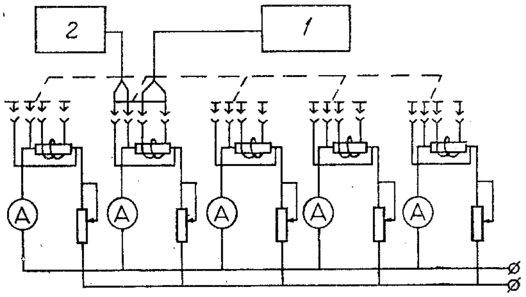

Fig. 2

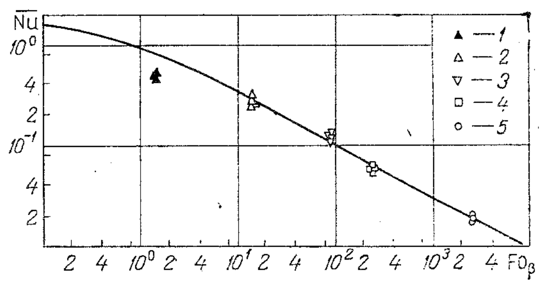

Fig. 3

Fig. 2. Electrical scheme for switching in the heater-sensor: 1) R380 type ohmmeter; 2) digital voltmeter.

Fig. 3. $\overline{Nu}$ at the wall as a function of Fo_β in a vibrating layer: 1) magnesite (d_{av} = 630 μm); 2) magnesite (200); 3) magnesite (80); 4) corundum (50); 5) silicon carbide (14); the curve shows the values computed from (18).

at the center of the chamber. The scheme for the setup is shown in Fig. 1, wherein the direction of rotation of the rotors, the positioning of the heater-sensor, and one of the rotors with a blade fixed on its upper surface are shown.

The heater-sensor consisted of a Getinaks rectangular plate on which five independent heaters were wound loop by loop densely with one another, and on top of them were placed five resistance thermometers made of copper wire with a diameter of 50 μm. All terminals of the windings were flush mounted with the plate with the help of pressed mounting. Prior to the measurements, the heater-sensor was calibrated in the temperature range from 30 to 80°C with temperature control within ±0.1°C. The resistance of the windings was measured with the help of an electronic R380 ohmmeter to within ±0.1%. The dimensions of the heater-sensor were as follows: length $(50.0 \pm 0.1)\cdot 10^{-3}$ m, width $(26.05 \pm 0.01)\cdot 10^{-3}$ m, thickness $(1.55 \pm 0.01)\cdot 10^{-3}$ m. The current in the heater circuit was measured by M1104 type ammeters with precision grade 0.2, while the voltage was measured by a digital R386 voltmeter with precision grade 0.02.

In order to measure the intensity of heat exchange, the heater-sensor was switched into the circuit shown in Fig. 2.

The current in the circuit of each heater was established, with the help of rheostats, at a magnitude so that the temperature of the sections was the same: 70°C. The latter was controlled with the help of the upper windings, which simultaneously played the role of the resistance thermometers, and the heat exchange surfaces. The temperature in the core of the layer was measured with the help of a mercury thermometer to within ±0.1°C. The heat-sensor was located at a distance of 17 mm from the surface of the rotors. The height of the layer in all the experiments equaled 60 mm. The maximum instrumental error for determining the heat exchange coefficient was ±3.6%.

The experiments were carried out with a dispersed material, the characteristics of which are given in Table 1.

In these experiments, the dispersed material was agitated in a single direction on both sides of the heater-sensor. Together with the motion of particles of the material along the wall, the particles also moved in a direction perpendicular to the wall, which is what led to exchange between the core of the layer and the near surface region by the particles.

TABLE 1. Characteristics of the Material Studied

Material	d_{cr}, μm	ρ_p, kg/m³	ε	Particle shape
Magnesite	80	3100	0,52	Irregular
	200	3100	0,50	
	630	3100	0,49	
Corundum	50	4000	0,58	Sharp angled, irregular
Silicon carbide	14	3200	0,68	Irregular

The results on heat exchange that were obtained were analyzed in terms of criteria (Fig. 3).

The effect of the heat conduction and thermal diffusivity of the layer were computed from the formulas presented in [11]. The value of the porosity was taken as equal to the porosity of the dense layer. The average residence time β of particles in the near-wall region, entering into the criteria Fo_β, was chosen empirically as equal to 4.7 sec.

Comparison of the experimental and computed data shows that they agree satisfactorily in the region of large Fo_β. For $Fo_\beta < 4$, which corresponds to large particle diameters, there is considerable disagreement between the experimental and computed data. This can be explained by the fact that for the vibrating layer, Fo_r was chosen to be the same as for the dense layer, which is valid only for $\beta \to 0$.

Thus, the proposed model reflects qualitatively correctly the physical properties of an agitated layer.

In conclusion, we note that further study is required to determine β.

NOTATION

a and λ, effective coefficients of thermal diffusivity and thermal conductivity of the layer; ε, porosity; ρ, effective density of the layer; ρ_p, particle density; c, effective heat capacity of the layer; c_p, specific heat capacity of the particles; d_{av}, average particle diameter; S, surface area of the particles per unit volume; τ, time; τ_1, heating time of the particles; τ_r, relaxation time in the dense layer; T, temperature of the layer; T_0, temperature of the wall; T_p, instantaneous particle temperature; $\Theta = T/T_0$, dimensionless temperature of the layer; x, instantaneous coordinate in a direction perpendicular to the wall; $X = x/d$, dimensionless coordinate; W, heat source per unit volume; α, heat-exchange coefficient; α*, coefficient for heat exchange between phases; β, average residence time of particles in the heat exchange zone; $Fo = a\tau_1/d^2$, dimensionless heating time of the particle; $Fo_r = a\tau_r/d^2$, dimensionless relaxation time; $Fo_\beta = a\beta/d^2$, average dimensionless residence time for particles in the heat exchange zone; $Nu = \alpha d/\lambda$, Nusselt's number.

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