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EXPERIMENTAL INVESTIGATION OF NONSTATIONARY HEAT TRANSFER IN A POROUS LAYER WITH A LIQUID PERCOLATING IN THE LAYER

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The solution of problems involving heat and mass transfer in porous layers is distinguished by great complexity. This complexity stems from the hydrodynamic and thermal interaction of the percolating flow with the medium filling the layer and with the surrounding mass (or channel walls).

At the present time, several approaches are available for solving such problems. A widely used model of such a flow is one in which it is assumed that the thermal resistance of the solid particles that make up the layer is small, i.e., a certain homogeneous medium is examined in which the actual characteristics of a nonuniform medium are replaced by equivalent characteristics. Such a model of the flow is used in [1-3] and in other studies. In another approach [4, 8], the thermal resistance of the elements of the layer is taken into account and the basic equations become integrodifferential equations. These equations are solved in terms of series and complicated integrals. Calculations based on the solutions obtained in complicated physical situations become difficult.

Recently, a solution has been proposed for this problem involving a nonstationary temperature field in a porous stratum based on reduction of the integrodifferential equation to an equivalent heat conduction equation [5].

The purpose of the present work is to check different theories and the equivalent heat conduction equation method.

An experimental setup was prepared for studying nonstationary heat exchange with percolation of a liquid in a porous medium. The basic element of the setup was a cylindrically-shaped tank with a diameter of 0.6 m and height 0.6 m with a removable cover. The tank was filled with small glass spherules with various diameters. In order to establish uniform percolation, a parallelepiped was separated out in the center of the volume with length, width, and height dimensions equal to 0.3, 0.42, and 0.44 m, respectively. The volume that was separated out was isolated from the surrounding mass from below, above, and on all sides with the help of a thin sheet of vinyl plastic, which is a material that has a low thermal conductivity. A fluid was introduced into one side of the isolated volume and removed from the other side. The liquid was introduced through perforated pipes with diameter $d = 10^{-2}$ m with a long perforated part equal to the height of the isolated volume. These pipes were distributed uniformly over the entire depth of the inlet and outlet cross sections with a step of $5 \cdot 10^{-2}$ m. The perforated pipes were connected with collectors outside the isolated volume. A frame containing 25 nichrome–constantan thermocouples (five rows distributed over

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TABLE 1

Form of fill	cm^3/min	m/h	m/h	C°	C'	C'
Glass spherules $d=3,2\cdot10^{-3}$ m $\sigma=5600$ m^2/m^3	3000 2030	0,95 0,65	3,8 2,6	5,0 10,0	17 10	22 20
Glass spherules $d=19\cdot10^{-3}$ m $\sigma=590$ m^2/m^3	3000 2030	0,95 0,65	2,7 1,9	11,0 8,0	24 25	35 33

TABLE 2

Bi	μ_1	μ_2	μ_3	μ_4	μ_5	μ_6
0,05	0,3854	4,5045	7,7317	10,9087	14,0697	18,6650
0,1	0,5425	4,5157	7,7382	10,9133	14,0713	17,2266
1,5	1,8366	4,8158	7,9171	11,0409	14,1724	17,3076
2	2,0278	4,9132	7,9787	11,0856	14,2075	17,3364
10	2,8363	6,7172	8,6587	11,6532	14,6870	17,7481
101	3,1105	6,2211	9,3317	12,4426	15,5537	18,6650

Note. μ_n are the roots of the characteristic equation $\operatorname{tg}\mu_n = -\mu_n/(Bi-1)$.

the height with five thermocouples in each row) was placed in the center of the vertical plane inside the volume being studied. The distance between the thermocouples both along the height of the layer as well as along the flow equalled $5.5\cdot10^{-2}$ m. The thermocouples were made out of wires with diameters of 100 μm. The size of the thermocouple beads was 150 μm. The thermocouples exited the tank between two rubber layers under the tank cover. The temperature at the inlet was measured by two thermocouples d_T = 200 μm, placed in the inlet pipe. The inlet pipe was externally insulated by string asbestos. The circuit for measuring the emf of the thermocouples includes the following: a manual switch, electronic F-30 ampere voltmeter, a F-30-50 transcriber, a F-30-K coupling block, and a digital printing device. This system permitted fixing the indications of the thermocouple after desirable time intervals depending on the rate at which the temperature was measured. The fill consisted of two types of glass spherules. The properties of the fill and the basic characteristics of the experiments are presented in Table 1.

At first, water with constant temperature was pumped through the entire setup until the temperature was uniform over the entire fill volume. Then, an electric heater was turned on, but the hot water was discharged bypassing the setup. After a stationary regime was achieved, the F-30-K measuring system was switched on, the shutoff valve was opened, and the hot water was introduced into the setup.

The experiments were carried out for different fluid flow rates and temperature heads. For high fluid flow rates and low temperature heads, all the thermocouples located along a single vertical line indicated the same temperature. When the flow rate of the fluid was decreased and the initial temperature head increased, the temperature along the height of the layer changed, which is related, evidently, to the appearance of free convection flows. In order to make comparisons with computational methods, only experiments in which free convection flows were absent were chosen (presented in Table 1). In order to analyze the nature of the temperature change with time, we used the indications of the thermocouples located at distances 0.08, 0.135, and 0.3 m from the fluid inlet into the volume being studied.

In order to compare the experimental results with theory, we used the expression obtained based on the solution of the equivalent heat conduction equation [5], when boundary conditions of the third kind are satisfied on the surface of a fill element:

$$\Theta = 1 - \frac{1}{2}\left\{\operatorname{erfc}\left[\frac{F_0^* - AGX}{2\sqrt{BGX}}\right] + e^{\frac{A}{B}F_0^*}\operatorname{erfc}\left[\frac{F_0^* + AGX}{2\sqrt{BGX}}\right]\right\}, \quad (1)$$

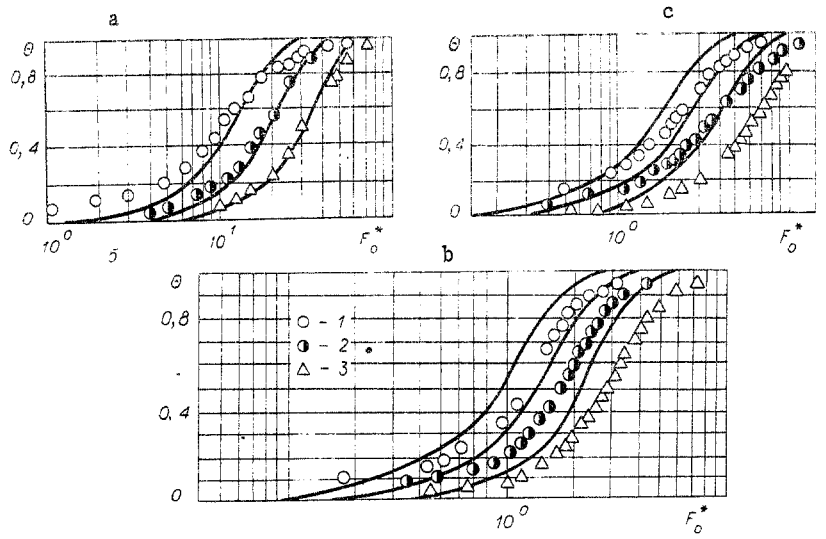

Fig. 1

where

$$A=\sum_{n=1}^{\infty}(-1)^{n+1}\frac{2\mathrm{Bi}^2\sqrt{\mu_n^2+(\mathrm{Bi}-1)^2}\sin\mu_n}{\left(\mu_n^2+\mathrm{Bi}^2-\mathrm{Bi}\right)\mu_n^2};$$

$$B=\sum_{n=1}^{\infty}(-1)^{n+1}\frac{2\mathrm{Bi}^2\sqrt{\mu_n^2+(\mathrm{Bi}-1)^2}\sin\mu_n}{\left(\mu_n^2+\mathrm{Bi}^2-\mathrm{Bi}\right)\mu_n^4};$$

$$G=\frac{R\sigma\rho_f C_f}{\rho_b C_b};\quad \Theta=\frac{t-T_0}{t_0-T_0};\quad F_0^*=F_0-X;\quad F_0=\frac{a\tau}{R^2};\quad X=\frac{ax}{R^2U_e};$$

t_0-T_0 is the initial temperature difference; u_e is the effective velocity of the fluid; R is the radius of a spherule; ρ_b, and C_b are the density and heat capacity of the fluid; ρ_f, C_f, and a_f are the density, heat capacity, and coefficient of thermal diffusivity of the fill; σ is the surface area of the particles per unit volume of fluid; $\mathrm{Bi}=2\alpha R/\lambda_f$; α is the heat transfer coefficient; λ_f is the coefficient of thermal conductivity of the fill. The values of the coefficients μ_n are presented in Table 2.

In order to calculate the coefficients of heat transfer to the particles, we used the function [7]

$$\mathrm{Nu}=0.5+0.068\ \mathrm{Re_r Pr},\ \mathrm{Nu}=\alpha d/\lambda_b,\ \mathrm{Re_r}=u_e d/\nu_b,\ \mathrm{Pr}=\nu/a_b.$$

It was shown in [5] that the solution of the equivalent heat conduction equation coincides exactly, in the range of Bi and GX studied, with the results of the exact solution obtained in [4, 6]. For this reason, based on a comparison between experiment and calculations carried out using Eq. (1), we can judge the correctness of the so-called exact formulation. Figure 1 shows the results of a comparison of experiment with calculations (solid line) based on the equivalent heat conduction equation. The results of the experiment are analyzed in terms of the coordinates $\Theta - F_0^*$ with the parameter GX.

The conditions for carrying out the experiments in Fig. 1 were as follows: a) u_f = 95 m/h, u_e = 3.8 m/h, $d_r = 3.2\cdot10^{-3}$ m, GX = 47 for point 1, GX = 80 for point 2, and GX = 140 for point 3; b) u_f = 0.95 m/h, u_e = 2.7 m/h, $d_r = 19\cdot10^{-3}$ m, GX = 1.2 for point 1, GX = 2.0 for point 2, and GX = 3.5 for point 3; c) u_f = 0.38 m/h, u_e = 1.1 m/h, $d_r = 19\cdot10^{-3}$ m, GX = 3.0 for point 1, GX = 5.0 for point 2, and GX = 8.6 for point 3. It is evident that Eq. (1) with the use of boundary conditions of the third kind agrees satisfactorily, within the limits of its applicability, with the experimental data.

We will compare the experimental data with the Klinkenberg's equation

$$\Theta = \frac{1}{2}\left[1 - \operatorname{erfc}\left(\sqrt{Z} + \frac{1}{8\sqrt{Z}} - \sqrt{Y} + \frac{1}{8\sqrt{Y}}\right)\right], \quad (2)$$

where

$$Z = \alpha\sigma x / \rho_1 C_1 u_1; \; Y = \alpha\tau / \rho_2 C_2 R.$$

It is well known that (2) approximates Shuman and Antselius' solution for $Z \geqslant 1.0$ and $Y \geqslant 2.0$ to within 0.6% [9]. The results of the calculation based on Eq. (2) are presented in Fig. 2 (dashed lines with cross marks); the results of the calculation using the homogeneous model are shown here as well. If it is assumed that the temperature of the fluid and solid phases equalize instantaneously, then the energy equation can be written in the form [10]

$$C_0 \partial\Theta/\partial\tau + C_1\rho_1 u \partial\Theta/\partial x = \lambda_0 \partial^2\Theta/\partial x^2,$$

where the coefficients C_0 and λ_0, called effective coefficients, are determined from the following equations:

$$C_0 = \rho_1 C_1 m + \rho_2 C_2 (1 - m), \; \lambda_0 = \lambda_1 m + \lambda_2 (1 - m). \quad (3)$$

The boundary conditions have the form

$$\Theta = 1, \; x = 0, \; \tau > 0, \; \Theta = 0, \; \tau = 0, \; x > 0.$$

Using the solution of the differential equation (4) presented in [11], it is possible to obtain for the homogeneous heat exchange model

$$\Theta = \frac{1}{2}\left\{\operatorname{erfc}\left[\frac{x - \frac{C_1\rho_1 u}{C_0}}{2\left(\frac{\lambda_0}{C_0}\tau\right)^{1/2}}\right] + \exp\left(\frac{C_1\rho_1 u}{\lambda_0}\right)\operatorname{erfc}\left[\frac{x + \frac{C_1\rho_1 u}{C_0}}{2\left(\frac{\lambda_0}{C_0}\tau\right)^{1/2}}\right]\right\}.$$

Since all experimental data were obtained for values Re < 10, in this case, the coefficient of longitudinal thermal conductivity can be calculated according to the equation [12]

$$\lambda_{eff} = 1.5 \, \lambda_0. \quad (4)$$

The following notation is used in Fig. 2: the dashed and dot–dash lines indicate the results of a calculation using the homogeneous model for the case when the thermal conductivity is determined from Eqs. (3) and (4), respectively; the solid lines indicate the results of a calculation using the equivalent equation; the numerals I-III correspond to calculations for the conditions of experiments 1-3; and the remaining notation is the same as in Fig. 1. It is evident from Fig. 2 that taking into account longitudinal dispersion and determining λ_{eff} from Eq. (4) results in better agreement between the calculations based on the homogeneous model and the experimental result, but do not change significantly the overall picture and the fact that flow models (of the Shuman type), in which the thermal resistance of the solid material is not taken into account, agree poorly with the experimental data for a given heat transfer coefficient. Of course, choosing the magnitudes of the coefficient in Shuman's equation it is possible to make the calculations coincide with some of the experimental curves, but then, this coefficient will no longer have the meaning of a heat transfer coefficient, determined by classical methods. The basic role in heat exchange with small percolation rates in a porous medium consisting of large elements is played by the effect of thermal resistance from the side of the liquid and the elements of the medium. This can be seen in Fig. 2. Comparing the different curves, we see that by decreasing the permeability of the medium (which is proportional to $\sim d^2$) and increasing the percolation rate, the influence of the thermal resistance from the side of the liquid decreases. For high percolation rates, the effective longitudinal heat capacity will play the main role. In this case, apparently, it is possible to use, in the case of a fill consisting of monodispersed material with good conduction the homogeneous heat exchange model with thermal conductivity coefficients that depend on the percolation rate of the heat carrier and the sizes of the elements of the medium. In Fig. 2, it is evident that in some cases, some deviation of our experi-

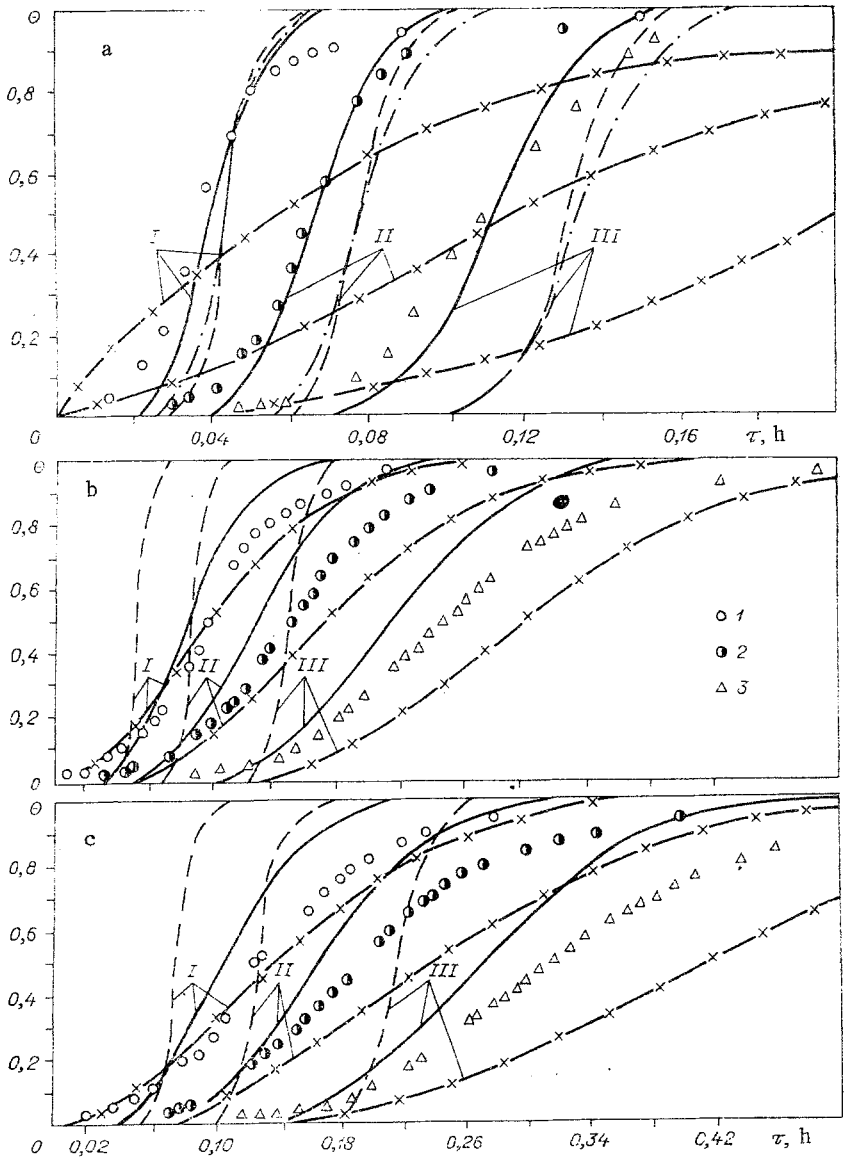

Fig. 2

mental results from the curves computed using the equivalent equation is observed. This can be related to the absence of a term with longitudinal effective diffusion in the equation. Apparently, in some cases, longitudinal diffusion can have a much greater effect on the spreading of the temperature front, than the effect of the thermal resistance of the structural elements of the porous medium.

Thus, it has been shown in the present work that in the range of characteristic parameters investigated here, the nature of the change of the temperature field in a porous layer can be best calculated using an equivalent heat conduction equation, in which the coefficients correspond to boundary conditions of the third kind. Taking into account the longitudinal thermal conductivity of the layer can lead to even better agreement between theory and experiment for large Reynolds numbers ($Re_r > 200$).

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CAPILLARY PERMEATION OF HYDROPHOBIC OIL-SATURATED ROCKS BY A SOLUTION OF AN ACTIVE ADMIXTURE

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It is well known (see, e.g., [1-3]) that capillary permeation plays an important role in extracting oil from heterogeneous (layered-nonuniform, fractured-porous, and so on) strata. As a result of capillary permeation, water penetrates to the less permeable parts of the stratum, in which oil turns out not to have been displaced by frontal flooding. This mechanism assumes that water has better wetting ability than oil (i.e. the rocks are hydrophilic), and for this reason, under conditions of capillary balance, water predominately fills regions with small pores. In a number of cases, the rocks turn out to be hydrophobic as a result of adsorbing active components in oil on their surfaces and the process of capillary permeation cannot proceed, which decreases the oil recovery from the stratum.

One of the means for increasing oil recovery in such cases is adding surfactants to the water that is pumped in [4, 5], which, being adsorbed on the surface of the porous framework, make the surface hydrophilic. Since the process of making the surface hydrophilic must precede permeation, the surfactant must be soluble to some extent (even a small extent) in oil.

In the present work, we examine the simplest description of such a permeation process for an initially hydrophobic rock by a water solution of an active admixture that makes the rock hydrophilic. This case differs from the previously examined [6] problem of counterflow capillary permeation of a porous medium by a solution of an active admixture by the fact that it is necessary to take into account the solubility of the active admixture in oil and the change in the sign of the capillary pressure (the medium becomes hydrophilic); as will be evident from the results, the permeation rate in the case being examined depends in a characteristic way on the rate of the diffusion of the active admixture.

1. We will write the equations for two-phase flow in a porous medium in the presence of an active admixture, assuming that local conditions for thermodynamic equilibrium between the admixture dissolved in water and in oil and that adsorbed by the porous medium are satisfied:

$$ms_{,t} + \operatorname{div} \mathbf{u}_1 = 0, \ \operatorname{div}(\mathbf{u}_1 + \mathbf{u}_2) = 0; \tag{1.1}$$

$$[mc_1 s + m(1 - s)c_2 + a]_{,t} + \operatorname{div}(c_1\mathbf{u}_1 + c_2\mathbf{u}_2) + \operatorname{div}\mathbf{q} = 0; \tag{1.2}$$

$$c_1 = c, \ c_2 = \varphi(c), \ a = a(c, s), \ \mathbf{q} = -D\nabla c, \ D = D(c, s); \tag{1.3}$$

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