HEAT TRANSFER IN FLUID FILTRATION IN A CAPILLARY-POROUS BODY WITH VARIABLE PARAMETERS

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The problem of the heat transfer in fluid filtration in a capillary-porous body with variable physical parameters is formulated and a numerical solution is obtained. As an example, the impregnation of wood by antiseptic liquid is considered.

Motion of a heat carrier through a capillary-porous body is accompanied by a change in its parameters — viscosity, temperature, concentration — and this, in turn, leads to change in structure of the body skeleton. Because such processes are so widespread, it is of great practical interest to study them and to develop mathematical models for them, for example, in the control and choice of the optimal technological conditions of hydrothermal treatment of materials, wood, and petroleum extraction [1-6]. In [2-5], the heat transfer in porous bodies with continuous parameters was investigated. Investigation of heat-carrier filtration in capillary-porous bodies with variable parameters of the heat carrier and the skeleton has been extremely inadequate.

The present work is intended to fill a certain gap in the study of such complex distributed heat-transfer processes in capillary-porous bodies with variable parameters.

The example considered in the analysis of the problem is the hydrothermal treatment of wood — impregnation under pressure by antiseptic materials. The technology of the process is relatively simple: The wood (a transmission-line support) is loaded into an autoclave and a solution of antiseptic is fed in at a pressure of 4-15 atm and temperature up to 120°C.

The main measure of impregnation is the radial depth of penetration of antiseptic in the wood: The deeper the penetration, the longer the wood will resist decay. The savings from a means of high-quality impregnation of wood would amount to millions of rubles on a national scale, and hence the theoretical basis and automatic control of this process are of great practical significance.

A mathematical description will now be obtained for the heat-transfer process in the filtration of a liquid heat carrier (creosote, petroleum oil) in a capillary-porous cylindrical body. Under the pressure of the heat carrier in the body, the gas is compressed; the gas is assumed to be close to ideal in its properties. The viscosity of the heat carrier, the rate of filtration, the heat-transfer coefficient, and the permeability of the skeleton depend on the time and space coordinates.

To simplify the analysis, the following additional assumptions are made: The heat loss to the surrounding space is small; phase transitions and internal heat sources are absent; and the heat flux due to heat conduction in the skeleton and the heat carrier is small in comparison with that due to convection by the heat carrier.

As is known, the structure of wood consists of a system of coaxial yearly layers. This structure gives rise to a clearly expressed anisotropy of the skeleton structure in both axial and radial directions. Therefore, if the analysis of the process is to be rigorous, a two-dimensional formulation should be adopted. However, in the autoclave impregnation of transmission-line supports, the axial component may be neglected, since $2r/L \gg 1$ (r and L are the radius and length of the support). To investigate the radial impregnation under laboratory conditions, cylindrical samples are cut from a trunk of wood in the radial direction

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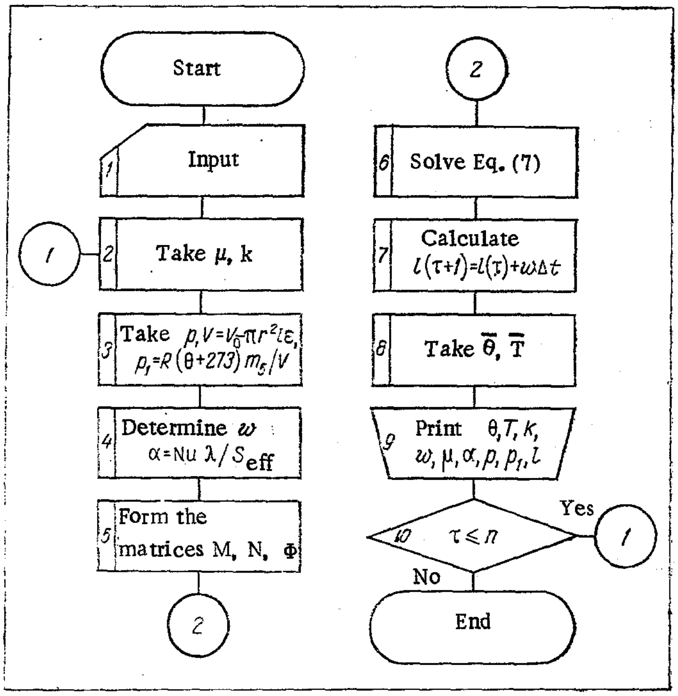

Fig. 1. Block diagram of "Filter" program.

and treated in accordance with [6]. The present work considers the modeling of the heat-transfer process in such samples. This allows the theoretical and experimental investigations to be reliably compared.

Thus, in view of the assumptions made, the initial equations for the cylindrical sample of wood will take the form of relations between the main thermodynamic parameters of the process: pressure, temperature, density, and rate of motion of the heat carrier and the permeability of the skeleton.

1. The equation of motion for the one-dimensional flow of heat carrier (or Darcy's law)

$$w(x,\ t) = -k_f(\bar{T})\,\eta(\bar{\theta})\,\frac{dp}{dx}, \qquad \eta = \mu_a/\mu. \tag{1}$$

2. The energy equation for the heat carrier and the skeleton

$$\frac{\partial \vartheta}{\partial t} + v\frac{\partial \vartheta}{\partial x} + H\vartheta = 0, \tag{2}$$

where

$$\vartheta(x,\ t) = \begin{bmatrix} \theta \\ T \end{bmatrix},\ v = \begin{bmatrix} u & 0 \\ 0 & 0 \end{bmatrix},\ H = \begin{bmatrix} \varkappa_1 & -\varkappa_1 \\ -\varkappa_2 & \varkappa_2 \end{bmatrix},$$

$$u = w/\varepsilon,\ \varkappa_1 = \frac{\alpha}{c_w \rho_w \varepsilon},\ \varkappa_2 = \frac{\alpha}{c\rho(1-\varepsilon)}.$$

3. The interpolation equation for the temperature dependence of the antiseptic viscosity

$$\mu(\bar{\theta}) = \mu_0 \exp[-b(\bar{\theta} - \theta_0)]. \tag{3}$$

4. The equation for the coefficient of heat transfer from the heat-carrier flow to the capillary walls of the skeleton

$$\alpha = f_1(w,\ \mathrm{Re},\ \mathrm{Pr},\ \mathrm{Nu}). \tag{4}$$

5. The equation of state of the gas held in the capillaries of the skeleton at constant mass

$$p_1 = f_2(V,\ T). \tag{5}$$

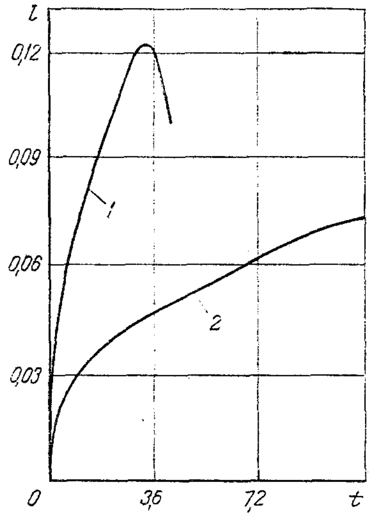

Fig. 2. Depth of antiseptic penetration for different initial temperatures of skeleton (l, m; t, h): 1) T = 60°C; 2) 20°.

6. The temperature dependence of the permeability of the skeleton [6]

$$k_f(\bar{T}) = \sum_{i=0}^{4} a_i \bar{T}^i. \tag{6}$$

It is necessary to add to Eqs. (1)-(6) relations between the density and porosity of the skeleton and its moisture content. Since these relations are adequately investigated and outlined in the specialist literature [7], there is no need to dwell on them here.

The initial and boundary conditions for Eq. (2) are of the form

$$\theta(0, x) = \theta_0(x);\ \theta(t, 0) = \theta_{in}(t);\ T(0, x) = T_0(x).$$

Equation (6) was obtained by analysis of the experimental data of [6] and reflects the temperature effect of both the fluid and skeleton properties on the permeability. Since the true permeability of the skeleton and viscosity of the fluid may be represented in the form

$$k = k_f \mu_a,$$

it is possible to determine k if μ_a is known. The experimental fluid used was nitrogen. In the temperature range 20-120°C the viscosity of nitrogen changes insignificantly. If the mean velocity in this temperature range is taken, the permeability of the skeleton is determined mainly by k_f. From a physical point of view, the change in permeability of the wood skeleton is the result of thermal deformation, partial melting of the resinous material, blocking the capillaries, and other factors whose mechanism remains to be determined.

It is impossible to solve Eqs. (1)-(6) analytically and so a numerical central-difference method is used. The grid is rectangular, with time step Δt and step Δx in the space coordinate. The process is modeled on an M-222 computer using the "Filter" program written in Algol 60. A block diagram of the algorithm is given in Fig. 1.

At the first time step at τ = 0 all the parameters of the process are calculated at the initial temperature of the fluid and the skeleton, together with the elements of the matrices M, N, Φ of the system of equations

$$M(\zeta, \tau)\vartheta(\zeta, \tau+1) = N(\zeta, \tau)\vartheta(\zeta, \tau) + \Phi(\zeta, \tau) \tag{7}$$
$$(\zeta = 1, 2, \ldots, m;\ \tau = 0, 1, \ldots, n),$$

which is obtained by discretizing Eq. (2). After solving Eq. (7), the temperature vector at the (τ + 1)-th time step is determined. The penetration depth of the fluid is calculated from the known rate of motion and the time. At this stage, the mean-integral temperatures of the heat carrier and the skeleton are determined and used at the next time step in calculating Eqs. (1) and (3)-(6). The calculation is then repeated at the (τ + 2)-th time layer and so on.

TABLE 1. Parameters of Heat-Transfer Process

t, h	θ(1, τ), °C	T(1, τ), °C	θ(2, τ), °C	T(2, τ), °C	$u\cdot10^2$, m/h	μ, N·h/m²	α, kJ/m³·h·deg	p, atm	p_1, atm	$k_f\cdot10^2$, m²/h·atm	$k\cdot10^{16}$, m²
0	120	20	0	20	5,40	5,670	8524	9	1	0,108	0,497
1,2	53,7	48,9	0	20	0,40	103,4	2481	11,35	1,478	0,133	0,612
2,4	68,2	65,1	18,10	11,5	0,49	91,80	2775	12,46	1,575	0,139	0,639
4,8	75,3	74,7	57,50	45,6	0,69	73,55	3229	12,97	1,813	0,152	0,699
7,2	83,4	82,6	11,79	20,93	0,45	86,93	2696	11,35	2,141	0,143	0,658
9,6	88,7	88,2	17,80	17,2	0,35	81,72	2456	9,006	2,443	0,147	0,676
12	91,5	91,3	21,80	21,3	0,14	81,72	1722	5,540	2,853	0,147	0,676
14,4	93,3	93,1	25,40	25,0	0,12	80,30	1595	5,192	3,045	0,148	0,681
16,8	95,6	95,2	28,5	27,9	0,23	78,52	2085	7,330	3,318	0,150	0,690
19,2	98,9	98,5	34,9	34,1	0,41	75,42	2617	10,61	4,015	0,152	0,699
21,6	102,5	102,2	43,0	42,0	0,43	77,92	2634	12,79	6,538	0,151	0,695
24,0	104,4	104,1	49,0	48,3	0,25	73,61	2149	12,47	9,603	0,154	0,708
26,4	104,8	105,0	49,1	49,6	—0,11	73,08	1598	9,849	11,42	0,155	0,712
28,8	104,1	104,3	47,3	47,8	—0,17	74,63	1838	6,665	8,836	0,154	0,708
30,0	103,7	103,9	46,2	46,7	—0,16	75,55	1821	5,546	7,828	0,153	0,704

The pressure of the oil (antiseptic) at the sample inlet was represented by different functions of the time (steplike, harmonic) and the effect of various conditions on the impregnation depth was investigated. The initial skeleton temperature has a large effect on the depth of antiseptic impregnation; this is particularly evident in the impregnation of oils in which there is a significant temperature dependence of the viscosity. In the region of the moving front, the viscosity of oil rises sharply and, as a result, filtration of the oil in a cold skeleton is impeded.

The variation in the rate of filtration at different initial values of the skeleton temperature is shown in Fig. 2. It is evident from the results of modeling that in skeletons of higher temperature, with all other conditions the same, the antiseptic penetrates to a greater depth. The values of the other heat-transfer parameters for one of the curves in Fig. 2 (T_0 = 20°C) are shown in Table 1. The variation in the external pressure of transformer oil was of the form $p = 4\sin\omega t + 9$. The moisture content of the wood was 25%. It is evident from Table 1 that the process may run in the reverse direction: Negative values of the filtration rate appear when the pressure of the "gas cushion" inside the body becomes greater than the external pressure applied. In practice, this is observed after impregnation of the wood when the external atmospheric pressure is less than the internal pressure, as a result of which the antiseptic begins to be expelled from the body — "sweating," as it is called.

Values of the penetration depth calculated from Eqs. (1)-(6) were compared with the experimental data of [6]. In a set of 12 creosote-impregnated heartwood samples of pinewood at 90-120°C and p = 4 atm for 1 h, the mean penetration depth was 0.0059 m. Modeling by Eqs. (1)-(6) for 72 min with other conditions equal gives a penetration depth of 0.008 m. The computer time required was about 14 min for a grid with m = 5 and n = 50.

The results of the present work may be used for prediction of the penetration depth, calculation of optimal conditions, control systems, and also in the analysis of heat-transfer processes in other capillary-porous bodies.

NOTATION

θ, T, temperatures of heat carrier and wood skeleton; $\bar{\theta}$, $\bar{T}$, mean-integral temperatures of heat carrier and wood skeleton over a section of length l; t, x, time and space coordinates along axis of body; w, filtration rate of heat carrier; c_w, c, specific heats of heat carrier and skeleton; ρ_w, ρ, densities of heat carrier and skeleton; α, heat-transfer coefficient per unit volume; μ, μ_0, μ_a, viscosity, initial heat-carrier viscosity, viscosity of nitrogen; k, radial permeability of skeleton; ε, porosity; p, p_1, heat-carrier pressure at inlet to sample and pressure of "gas cushion"; V_0, V, initial and current volumes of gas; a, b, constants; θ_0, T_0, θ_{in}, initial distributions of heat-carrier and skeleton temperature and variation in heat-carrier temperature at inlet to porous body; k_f, coefficient characterizing the permeability of the sample for the given liquid or gas; λ, heat-carrier thermal conductivity; S_{eff}, effective heat-transfer surface; R, gas constant; m_s, number of moles of air in porous body; Re, Pr, Nu, Reynolds, Prandtl, and Nusselt numbers.

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