

MODELING OF THE NONISOTHERMAL IMPREGNATION OF WOOD AND OTHER POROUS MEDIA BY FLUIDS

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A mathematical model and results of the calculations of the kinetics of impregnation of porous materials by a fluid, whose viscosity essentially depends on temperature, are given. Modeling of the technological process of protective treatment of wooden articles is carried out using, as an example, the impregnation of wood under pressure by a water-oil antiseptic emulsion heated to 40°C. The efficiency of different methods of deep impregnation is analyzed in the context of both the absorption of a protective substance and the uniformity of its distribution in wood.

Introduction. Saturation of porous materials by a fluid is the case in many industrial and technological processes. Among those are the modifying impregnation of wood and leather, preparation of fuel for catalytic combustion and of ceramics wood, filling of the windings of electric motors and transformers with insulation composites, elimination of the welding defects of metallic articles, and so on.

Impregnation of the porous material by hot melts (metals, waxes), viscous oils, and other high-molecular materials involves preliminary heating-up of an impregnating fluid. The traditional technology of protective impregnation of wood (columns, ties) by antiseptic oils [1] necessitates heating of creosote or the other similar antiseptic substances up to the temperature at which its viscosity undergoes a manifold decrease, thus allowing the antiseptic substance to penetrate deep into wood. When a fluid moves in a porous structure, the temperature-dependent properties of the fluid change as a consequence of the heat transfer between the fluid and the cellular structure, which, in turn, influences the impregnation process. Moreover, a change in the temperature of the air in wood leads to pressure redistribution in the wood, which also influences the dynamics of impregnation.

Physicomathematical Model. Previously we have suggested a macroscopic physical and mathematical model of the process of saturation of a porous structure of wood by liquid solutions [2] and emulsions [3] under isothermal conditions.

The main parameters of the state in the model considered are the mass of the fluid ρ_f and of air ρ_a , respectively, contained in unit volume of wood (the effective density) satisfying the continuity equations. The velocity of substance displacement \mathbf{v}_s is assumed to be proportional to the local pressure gradient:

$$\mathbf{v}_s = \sigma_s \nabla P, \quad (1)$$

where pressure P is related to the density ρ_a by the equation of state, while for the tensor of conductivity σ_s in [2, 3] relations are suggested that account for the actual structure of softwood and make it possible to adequately describe the experimentally observed characteristics of the process.

Below we provide supplements to the model developed previously [2, 3] that allow calculation of the processes of impregnation under variable thermal conditions.

The influence of nonisothermality on the dynamics of impregnation is taken into account by introducing conductivity σ and pressure P as a function of local temperature T :

$$\sigma = \sigma_{T_0} \frac{\mu(T_0)}{\mu(T)}, \quad P = P_{T_0} \frac{T}{T_0}, \quad (2)$$

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where T_0 is the initial temperature of wood, σ_{T_0} and P_{T_0} are the values of conductivity and pressure corresponding to the isothermal model, and μ is the dynamic viscosity of an impregnating fluid.

For determination of the temperature distribution in a porous structure a system of equations describing isothermal impregnation is supplemented with the equation of energy

$$\frac{\partial E}{\partial \tau} + \sum_s \operatorname{div}(\mathbf{v}_s E_s) + \operatorname{div} \mathbf{q} = 0, \quad (3)$$

with the Fourier law

$$\mathbf{q} = \lambda \nabla T, \quad (4)$$

with the caloric equations of state

$$E = E_w + E_f + E_a, \quad E_s = c_s \rho_s T, \quad (5)$$

and with the corresponding initial and boundary conditions for temperature

$$T|_{\tau=0} = T_0, \quad T|_{\mathbf{x} \in \Gamma} = T_{\text{ext}}(\tau), \quad (6)$$

where $E(\tau, x, y, z)$ is the density of internal energy, \mathbf{v} is the fluid velocity, \mathbf{q} is the density of a conductive heat flux, λ is the tensor of thermal conductivity, Γ is the sample surface, and $T_{\text{ext}}(\tau)$ is the prescribed temperature of an impregnating fluid.

Determination of the Effective Thermal Conductivity of Wood. In the two-dimensional coordinate system with axes oriented along and across the fibers of wood, the thermal conductivity tensor entering into the expression for specific heat flux (4) is

$$\lambda = \begin{pmatrix} \lambda_{\perp} & 0 \\ 0 & \lambda_{\parallel} \end{pmatrix}. \quad (7)$$

The choice of a model for calculation of thermal conductivity of anisotropic porous ordered structures is based, as a rule, on subdivision of the structure into unit cells [5] followed by subsequent calculation of their total thermal resistance. The effective thermal conductivity of wood in the longitudinal and transverse directions depends on the thermal conductivities of the material of the cell walls λ_w , the impregnating fluid λ_f , and air λ_a , and on the ratio of the volumes occupied by these substances, which, in turn, is determined by the air capacity of wood ε [4] and by the relative local moisture content ρ_f .

As regards the softwood, the cell-tracheid represents a unit cell of the structure. Since the tracheid length is much larger than its cross dimension, in calculating the effective thermal conductivity the influence of transverse cell walls can be ignored and wood can be considered as a system of longitudinal capillaries. If we assume that an impregnating fluid is distributed as a uniform layer along a tracheid wall (which occurs, as a rule, owing to the cellular fibrillar structure of the cell walls [4]), then thermal conductivity in the longitudinal direction is

$$\lambda_{\parallel} = \alpha_w \lambda_w + \alpha_f \lambda_f + \alpha_a \lambda_a, \quad (8)$$

where α_w , α_f , and α_a are the portions of the cross-sectional area of a unit cell pertaining, respectively, to the cell wall, to the fluid, and to air. The values of α_s can be expressed in terms of the air capacity of wood ε and density ρ : $\alpha_w = 1 - \varepsilon$, $\alpha_f = \rho_f / \rho_f^0$, $\alpha_a = \rho_a / \rho_a^0$.

To calculate the thermal conductivity in the transverse direction λ_{\perp} , we will consider the structure of a unit cell shown schematically in Fig. 1a (for reasons of symmetry it is sufficient to consider only 1/4 of the cross section). By definition the thermal conductivity is

$$\lambda_{\perp} = \frac{Q/(rl)}{\Delta T/r} = \frac{Q}{\Delta T l} = \frac{1}{Rl},$$

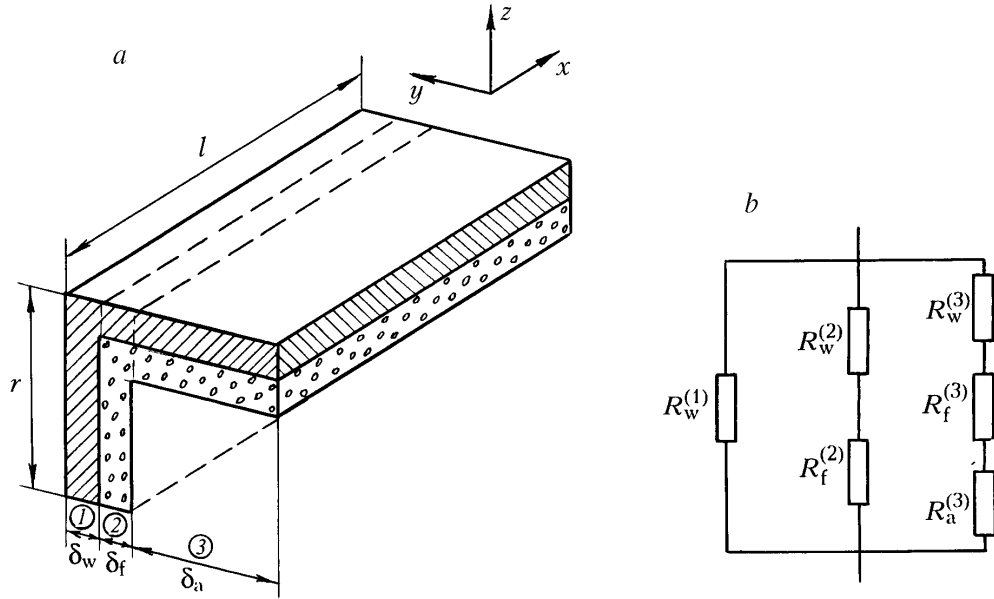


Fig. 1. Schematic of a fragment of the porous structure (wood tracheids) (a) and a schematic diagram of conductivity (b).

where Q is the heat flux across the region considered in the z -direction, ΔT is the corresponding temperature drop, R is the thermal resistance, and l and r are the longitudinal and transverse (in the y - and z -direction) dimensions of the considered region (Fig. 1a). If a heat flux in the y -direction is ignored, then Q can be represented as the sum of independent fluxes passing through three zones, including, respectively, the cell wall, the fluid, and air, which are denoted in Fig. 1a by the corresponding Arabic figures $Q = Q^{(1)} + Q^{(2)} + Q^{(3)}$. An equivalent schematic diagram is shown in Fig. 1b. Then

$$\frac{1}{R} = \frac{1}{R_w^{(1)}} + \frac{1}{R_f^{(2)} + R_w^{(2)}} + \frac{1}{R_a^{(3)} + R_w^{(3)} + R_f^{(3)}}. \quad (9)$$

The quantities $R_s^{(n)}$ are related to the thermal conductivities of substances λ_s and geometric parameters by the following expressions:

$$\frac{1}{R_w^{(1)}} = \lambda_w \frac{\delta_w l}{r}; \quad \frac{1}{R_f^{(2)}} = \lambda_f \frac{\delta_f l}{r - \delta_w}, \quad \frac{1}{R_w^{(2)}} = \lambda_w \frac{\delta_f l}{\delta_w}; \quad \frac{1}{R_a^{(3)}} = \lambda_a \frac{\delta_a l}{\delta_a} = \lambda_a l, \quad \frac{1}{R_f^{(3)}} = \lambda_f \frac{\delta_a l}{\delta_f}, \quad \frac{1}{R_w^{(3)}} = \lambda_w \frac{\delta_a l}{\delta_w}. \quad (10)$$

The parameters r , l , and δ_s are related to ε and ρ_a as follows:

$$\varepsilon = \frac{(r - \delta_w)^2 l}{r^2 l} = \left(1 - \frac{\delta_w}{r}\right)^2, \quad \frac{\rho_a}{\rho_a^0} = \frac{V_a}{V} = \frac{(\delta_a)^2 l}{r^2 l} = \left(\frac{\delta_a}{r}\right)^2, \quad (11)$$

whence

$$\delta_w = r(1 - \sqrt{\varepsilon}), \quad \delta_a = r\sqrt{\rho_a/\rho_a^0}, \quad \delta_f = r - (\delta_w + \delta_a). \quad (12)$$

Analysis of the Calculated Results. In deep impregnation of wood by oil antiseptic substances (e.g., creosote, shale and anthracene oils), to decrease the viscosity the fluid is heated up to a temperature higher than 85°C, at which its viscosity decreases tens of times. A substantial drawback of this "hot" technology is the high level of liberation of harmful substances (phenols, anthracene, etc.) into the atmosphere. A decrease in the temperature of such substances to

TABLE 1. Influence of the Temperature of the Impregnating Fluid on Its Viscosity

Impregnating fluid	Kinematic viscosity ν , cSt, at temperature, °C					
	15	22	30	40	50	85
Shale oil	–	192.3	87.8	46.8	22.8	7.7
Emulsion	48.3	19.6	5.7	3.5	–	–

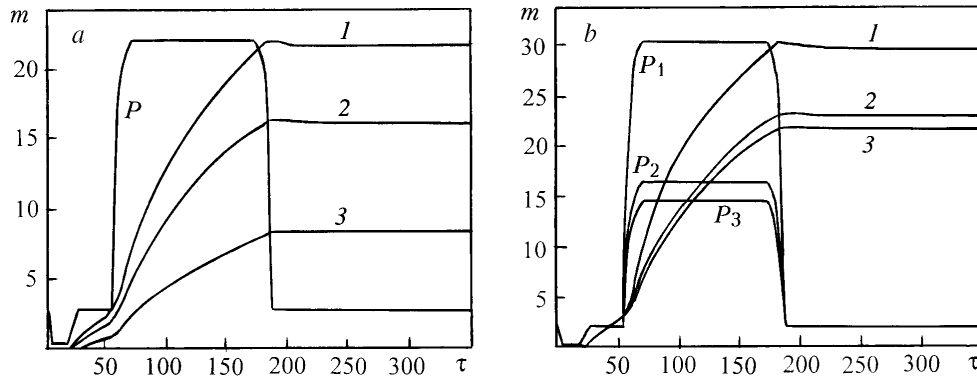


Fig. 2. Influence of the temperature (a) and the pressure (b) on the kinetics of emulsion absorption by wood: a: 1) mass of the absorbed fluid at the impregnating fluid temperatures $T_f = 40^\circ\text{C}$, 2) 30, 3) 20; b: 1) mass of the absorbed fluid at the pressures $P_1 = 1.7$ MPa; 2) $P_2 = 0.9$; 3) $P_3 = 0.8$; $T_f = 40^\circ\text{C}$. m , kg; τ , min.

35–40°C decreases the level of harmful exhaust substances several times. For this purpose, it seems promising to use the water-oil emulsion based on creosote (shale oil) and water. Measurements have shown [4] that the viscosity of the water-emulsion composition is substantially lower as compared with the initial oil antiseptic substance and it rapidly decreases with growth of the temperature (Table 1).

Figure 2a provides the results of modeling of the kinetics of impregnation of a cylindrical wooden sample (a pinewood column with $L = 28$ m, $D = 0.2$ m) with the water-oil emulsion with account for the temperature dependence of its viscosity. A calculation was carried out for the two-dimensional problem of impregnation of the porous structure of wood with the emulsion at the initial pressure $P_0 = 20$ kPa, the impregnation pressure $P = 0.8$ MPa, and $T_0 = 5^\circ\text{C}$. Thermal conductivity was determined by formulas (10)–(12) with the use of the structural parameters of the wood determined for the isothermal problem [2]; the heat capacity and the thermal conductivity of the wood substance were $c_w = 1.55$ kJ/(kg·deg) and $\lambda_w = 0.5$ W/(m·deg), and its density $\rho_w = 1530$ kg/m³.

In analyzing absorption curves 2, 3, and 4 (Fig. 2a), it should be taken into account that heating of the sample begins after evacuation of the wood when the cylinder with the wood is poured with an impregnating solution at $T_f = 40^\circ\text{C}$. As follows from the figure, absorption of the emulsion depends on its temperature, and this dependence is manifested even to a greater degree than on the pressure of the impregnating solution (Fig. 2b).

At the present time, the limited absorption method or the Rueping process (the pressure–pressure–vacuum (PPV) method [1] finds wide application for wood treatment. We will consider the possibilities of its use for the low-temperature protective treatment of wood by water-oil emulsion proceeding from specifications of the available impregnation technologies where the working pressure in cylinders is 0.8–1.2 MPa. We will evaluate the influence of the methods and the parameters of the impregnation process on the quality of treatment of articles determined both by the general level of absorption (the increase in weight) and by the distribution of the impregnating solution in the bulk of wood (the depth of impregnation).

Figure 3 gives the calculated results of emulsion absorption and temperature in a cylindrical pinewood sample. Here, fragments of the sample (the fourth part of the longitudinal section) are shown, where the colored zone illustrates distribution of the impregnating solution in the article. A calculation was carried out using a two-layer (sapwood–core) model, the core diameter of the wood amounting to 2/3 of the overall diameter of the article. Figure 3a

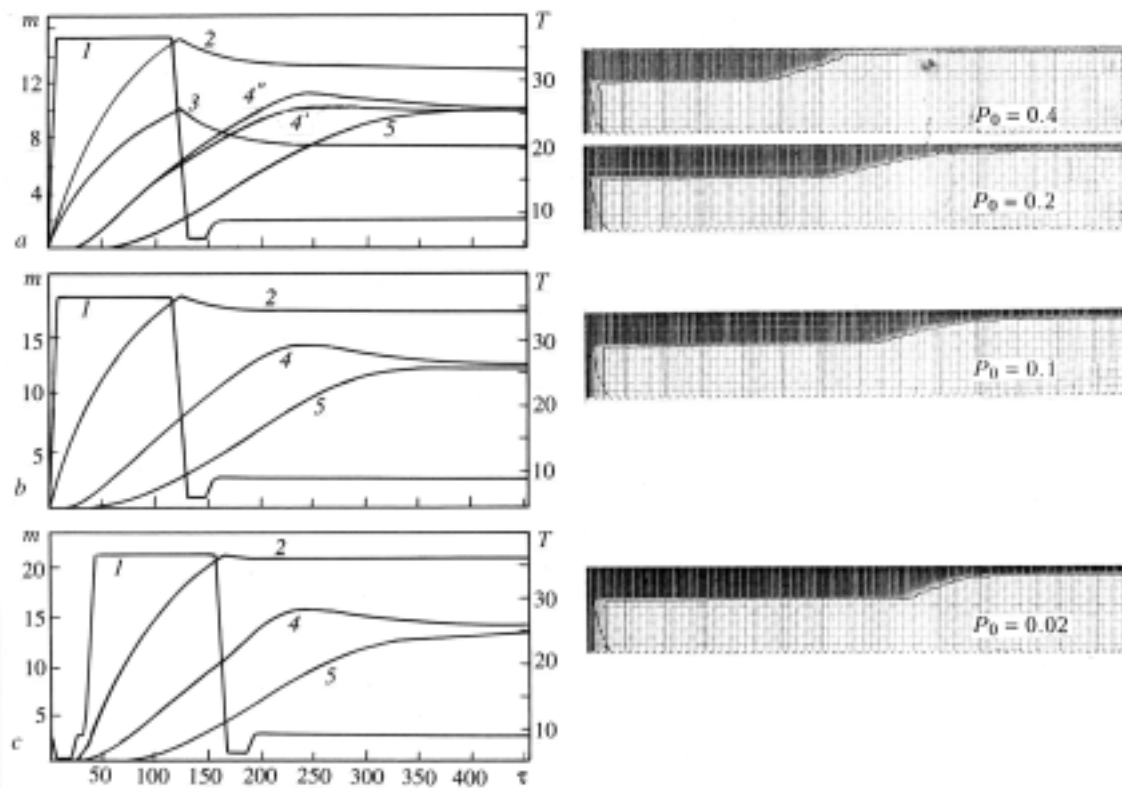


Fig. 3. Kinetics of the emulsion absorption and the distribution of the impregnating fluid in different impregnation methods (the cylindrical pinewood sample, $L = 2.8$ m, $D = 0.2$ m): a) limited absorption (the PPV method or the Rueping process); b) semilimited absorption (the APPV method or the Lowry process); c) maximum absorption (the VPV method or the Bethell process); 1) pressure; 2) absorption of the impregnating fluid; 3) absorption at $P_0 = 0.4$ MPa; 4 and 5) temperature at the center of the isolated fragment and at the sample center, respectively; 4' and 4'') temperature at $P_0 = 0.4$ and 0.2 MPa, respectively. m , kg; τ , min.

represents the results of modeling of impregnation for the limited adsorption method when an excess pressure of the air is preliminarily created in wood (two variants are shown: the upper distribution for $P_0 = 0.4$ and the lower one, for $P_0 = 0.2$ MPa); next the pressure of the impregnating fluid acts ($P_{\max} = 0.8$ MPa) and then the wood is subjected to evacuation (20 kPa). Figure 3b shows calculated results for the semilimited absorption method when the impregnating fluid is poured into the impregnation cylinder at atmospheric pressure (the atmospheric pressure–pressure–vacuum (APPV) method). Here (Fig. 3c), the maximum absorption method (the vacuum–pressure–vacuum (VPV) method) is presented. All the conditions of the process (thermal, structural, etc.) were retained for the calculations and only the method of pressure action (curve 1) was varied. The initial temperature of the wood was $T_0 = 5^\circ\text{C}$; the temperature of the impregnating fluid was $T_f = 40^\circ\text{C}$; after pressure relief, evacuation, and unloading, the temperature on the article surface became $T_{\text{fin}} = 25^\circ\text{C}$. In Fig. 3, curves 4 show the temperature at the points corresponding to the center of the depicted fragment and curve 5, the temperature at the sample center. In Fig. 3a, the curves of pressure 1 and of temperature 5 for $P_0 = 0.2$ and 0.4 MPa virtually coincide in the scale of the drawing. Temperature curves 4' and 4'' pertain to different values of the initial pressure P_0 . As is seen from the figures, the temperature at the indicated points depends on the impregnation method; the heating-up of the wood bulk proceeds slowly and under the prescribed conditions this temperature does not exceed 25°C within the entire process.

The data obtained make it possible to compare the qualitative characteristics of impregnation of the wood treated by different methods (Table 2). In so doing, it should be taken into consideration that the wood core subjected only to the end-type impregnation to a depth of about 4 cm occupies only 44% of the overall volume of the sample.

TABLE 2. Comparison of the Efficiency of Wood Treatment ($L = 2.8$ m, $D = 0.2$ m) under Pressure by Different Impregnation Methods

Impregnation method	Absorption of the impregnating fluid m , kg	Depth of impregnation for sapwood (mean), cm	Portion of the impregnated wood bulk	Quantity of the fluid in the wood, kg/m^3	Local degree of saturation
Maximum absorption	21	100	0.497	201	0.7–0.8
Semilimited absorption	16.9	96	0.488	162.5	0.6–0.7
Limited absorption, $P_0 = 0.2$ MPa	12.9	87	0.446	124	0.55
The same, $P_0 = 0.4$ MPa	7.36	68	0.351	70.8	0.5

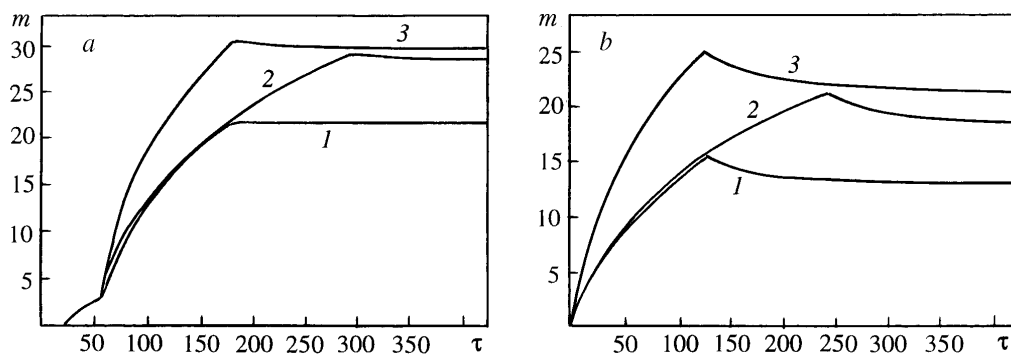


Fig. 4. Comparison of the pressure effect and the time of its action for different impregnation methods: a) the maximum absorption method (mass of the absorbed impregnated fluid after impregnation: $m_1 = 21.6$ kg; $m_2 = 28.6$ kg; $m_3 = 29.6$ kg); b) the limited absorption method ($m_1 = 12.9$ kg, $m_2 = 18.1$ kg, $m_3 = 21.2$ kg); 1) $P_{\max} = 0.8$ MPa; $\tau_p = 2$ h, 2) $P_{\max} = 0.8$ MPa, $\tau_p = 4$ h; 3) $P_{\max} = 1.7$ MPa, $\tau_p = 2$ h. m , kg; τ , min (m_1 , m_2 , and m_3 correspond to curves 1, 2, and 3).

In the sapwood zone of the wood, in variants *b* and *c* (Fig. 3) the concentration of the impregnating fluid is seen to distribute nonuniformly; in variant *a* the concentration of the impregnating fluid changes slightly in the impregnated zone (the intensity of coloring). The degree of saturation of the impregnated zone by the impregnating fluid strongly depends, as follows from Table 2, on the impregnation method; the saturation is at its maximum when the VDV method is used. We will determine the local degree of saturation (filling) L_f as the local ratio of the volume of the impregnating fluid to the accessible (initially filled with air) bulk of wood (L_f can acquire values from 0 to 1). For the limited absorption method ($P_0 = 0.4$ MPa) the impregnating fluid is virtually uniformly distributed (uniform saturation) throughout the entire impregnated bulk. The highest nonuniformity of distribution of the impregnating fluid in the impregnation zone is observed in the sample impregnated by the maximum absorption method, though it differs in the maximum value of L_f .

From an analysis of the results given in Fig. 3 and Table 2, it follows that all the considered impregnation methods provide deep absorption of the protective substance. However the second (APPV) and third (VPV) methods demonstrate the high flow rate of the impregnating fluid. The first (PPV) method with the initial pressure $P_0 = 0.2$ MPa can also be workable in the case where highly effective protective fluids are used. Owing to the forcing-out of some portion of the impregnating fluid by air under pressure relief inside the wood after the period of absorption this method provides the saving of impregnating substances though the quality of impregnation deteriorates.

Figure 4 gives results of a comparative analysis of the efficiency of influence of the basic parameters of the process of protective treatment of wood, namely, the impregnation time and the impregnation pressure. In Fig. 4a, such

a comparison is carried out for the maximum absorption method, and in Fig. 4b, for the limited absorption method ($P_0 = 0.2$ MPa). The pressure and the vacuum were prescribed the same as in Fig. 3a and b. The curves in Fig. 4 represent the time dependence of the fluid mass absorbed by the samples at different pressures and time of their action. Here, the values of mass of the absorbed fluid after completion of the impregnation process are given. It is seen that for both methods of wood impregnation the influence of pressure action is slightly more substantial than the increase in duration of the process. This regularity is especially pronounced for impregnation by the limited absorption method.

CONCLUSIONS

1. A physical and mathematical model of nonisothermal saturation of a porous medium (wood) by a fluid with pronounced dependence of the fluid viscosity on temperature is developed.

2. With protective impregnation of wood taken as an example, the possibility of calculating the kinetics of absorption of water-oil emulsion and the distribution of its concentration and temperature in the volume of the porous medium is shown.

3. An analysis of the efficiency of different methods of wood impregnation has shown that the use of the limited absorption method makes it possible to provide the most uniform, as compared with the methods considered, fluid distribution in the impregnated region.

NOTATION

x, y, z , coordinates; c , specific heat, J/(kg-deg); D , diameter, m; L , sample length, m; V , volume; L_f , local degree of filling by a fluid; m , mass of the absorbed fluid, kg; P , pressure, MPa; T , temperature, °C; ν , kinematic viscosity, cSt; τ , time, min; λ , thermal conductivity, W/(m-deg); δ , layer width; APPV, atmospheric pressure–pressure–vacuum; VPV, vacuum–pressure–vacuum; PVP, pressure–vacuum–pressure. Subscripts: f, fluid; a, air; w, wood substance; P , pressure; s, substance ($s = f, a, w$); c, critical; ext, external; 0, initial value; max, maximum; fin, final.

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