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INFLUENCE OF HEAT AND MASS TRANSFER ON WOOD IMPREGNATION KINETICS

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We have further developed the nonstationary mathematical model of two-phase filtration in an anisotropic porous medium — wood — by a fluid, taking into account the temperature dependence of its viscosity. The results of the calculations of the temperature and kinetics of wood impregnation under the action of vacuum and excess pressure for the problem of internal and external heat transfer are presented. The process of preservative impregnation of woodworks with a water-oil emulsion for various degrees of filling of the autoclave, including the maximum one, has been simulated.

Introduction. This investigation is devoted to the modeling of the process of nonisothermal impregnation of woodworks with oily antiseptic fluids under the action of the pressure gradient. The traditionally used creosote (coal-tar or shale oil) in the technology of preservative impregnation of the wood of ties, poles, etc. in order to decrease the viscosity requires heating up to a temperature of 85–100^{o}C. Since the viscosity strongly depends on the temperature, it is important to study the influence on the quality of impregnation of the heat exchange between the wood article and the heated fluid penetrating into the porous structure of the body under the action of the pressure gradient.

In the last few years, in Australia and in a number of European countries ecologically safer water-oil emulsions based on the PEC (Pigment Emulsion Creosote)-type creosote have been used for such purposes. These emulsions contain a high-temperature creosote — up to 65%, oxide pigments — up to 5%, water, and other components [1, 2]. Such compositions permit impregnation at a temperature of 60–70^{o}C, which is lower than in the creosote and thus reduces the danger of environmental pollution.

With the same aim, at the Heat and in Mass Transfer Institute of the National Academy of Sciences of Belarus jointly with the Belarusian State University a water-emulsion composition based on shale oil (WSOC) for tie impregnation has been developed [3]. It is a water-in-oil emulsion containing 60% shale oil and about 30% water. Experimental measurements have shown that the viscosity of such a water-oil composition rapidly decreases with increasing temperature. For instance, when the temperature is increased from 10 to 40^{o}C, it decreases from 70 to 3.5–5 cSt [4–6], which permits conducting the technological process of wood impregnation at a temperature of 40^{o}C.

The present paper is restricted to the consideration of the saturation kinetics of wood specimens with a WSOC-type preservative composition with regard for the internal and external heat exchange between the wood and the heated fluid, although the proposed method of numerical simulation can also be used to calculate the parameters of wood treatment with other impregnating compositions.

Earlier [6] we considered a two-dimensional problem of saturation of the porous structure of wood with a water-emulsion composition at a given fixed temperature of the surrounding fluid medium T_{ext} (boundary condition of the first kind). At the same time, as the experimental studies of [4, 5] have shown, under conditions where the external volume of the impregnating fluid is comparable to the volume of the fluid absorbed by the wood in the process of impregnation, the value of T_{ext} can change markedly due to the heat exchange between the fluid and the specimen being impregnated.

This paper presents the results of calculations of the impregnation process performed with the use of a modified model taking into account both the heat exchange inside the wood and the influence of the heat exchange with the specimen on the temperature of the impregnating external fluid.

Model. The estimate of the Biot number (Bi = hr/λ_w) during the fluid motion in the impregnating volume has shown that its value for large-sized specimens — ties, poles — amounts to dozens of unities even for heat exchange

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under the conditions of natural convection. This means that the heat exchange is limited to the process in the woodwork itself [7], and to describe the change in T_{ext}, one can use the energy equation in the integral form*)

$$\frac{d\varepsilon_{ext}(\tau)}{d\tau} = c_f G\,(T_{in} - T_{ext}) + \int\limits_{\Gamma} (q_{conv} + q_{cond})\,dS\,, \quad \varepsilon_{ext} = \rho_f c_f T_{ext} V_{ext}\,, \tag{1}$$

where V_{ext} is the external volume of the impregnating fluid per wood product and G is the mass flow of the impregnating fluid due to the induced convection per specimen.

Equations (1) complement the mathematical model given in [6] that describes the heat exchange at a filtration fluid and gas flow in the porous structure of wood:

$$\frac{\partial E}{\partial \tau} + \sum_{s} \mathrm{div}\,(\mathbf{v}_s E_s) + \mathrm{div}\,\mathbf{q} = 0\,, \quad E = E_w + E_f + E_a\,, \quad E_s = c_s \rho_s T\,, \quad \mathbf{q} = -\lambda \nabla T\,. \tag{2}$$

The expressions for the thermal conductivity tensor λ and the equations for $\mathbf{v}_s$ are presented in [6, 8] and, for brevity, are not given here.

Equations (1) and (2) are complemented with the initial conditions at $\tau = 0$

$$T = T_0\,, \quad T_{ext} = T_{ext0} \tag{3}$$

and the boundary condition on the specimen surface

$$T(\tau, \mathbf{x})\big|_{\mathbf{x}\in\Gamma} = T_{ext}(\tau)\,. \tag{4}$$

The quantities q_{conv} and q_{cond} entering into (1) are related to the state parameter $\mathbf{v}_s$, T, and T_{ext} as follows;

$$q_{conv} = \begin{cases} \rho_f c_f T_{ext} v_{f,n}\,, & (v_{f,n} < 0)\,, \\ \sum\limits_{s} \rho_s c_s T v_{s,n}\,, & (v_{f,n} > 0)\,, \end{cases} \quad q_{cond} = q_n\,,$$

where v_n and q_n are, respectively, the components of the heat flow rate and density normal to the surface.

Results and Discussion. The calculations were made for the process of impregnation by the method of Bethell maximum absorption or VPV (vacuum–pressure–vacuum). In such a method of impregnation, in the impregnating cylinder — an autoclave containing a batch of wood materials — a vacuum (P = 20 kPa) is created for 20–40 min and after the cylinder is filled with a heated fluid a pressure of P = 1.6 MPa is maintained in it for 2 h. Subsequent to the action of the pressure and the removal of the fluid from the cylinder, postimpregnation vacuum treatment (P = 30 kPa) is carried out, and then the wood is drawn from the cylinder.

Figure 1 presents the results of the calculation of the wood impregnation kinetics and the mean temperature of the fluid contacting the specimen. Curve 5 shows the character of the change in the external pressure of the fluid P_{ext}. Vacuum-treated specimens of wood with the initial temperature T_w = 0^oC are embedded with the impregnating compound with a temperature T = 40^oC. In the process of compound absorption by the wood, new portions of heated fluid enter the cylinder and the total amount of the fluid external with respect to the specimen remains unchanged.

In the calculations, the initial values of the specific heat of the wood c_w = 1550 J/(kg·deg) and of the fluid c_f = 2970 J/(kg·deg) were taken. It was assumed that the fluid density was invariable — ρ_f = 1000 kg/m^3. The parameters of the impregnating compound viscosity used for the calculations, the method of determining the thermophysical coefficients, and the structural parameters of the wood are shown in [6, 8]. As an example — a specimen for

*) It should be noted that, depending on the specific technical realization of the impregnation process, in some cases conditions preventing temperature equalization in the impregnating volume can arise. To describe such situations, it is necessary to consider the processes of hydrodynamics and heat exchange of the fluid inside the specimen and in the external volume in the complete formulation.

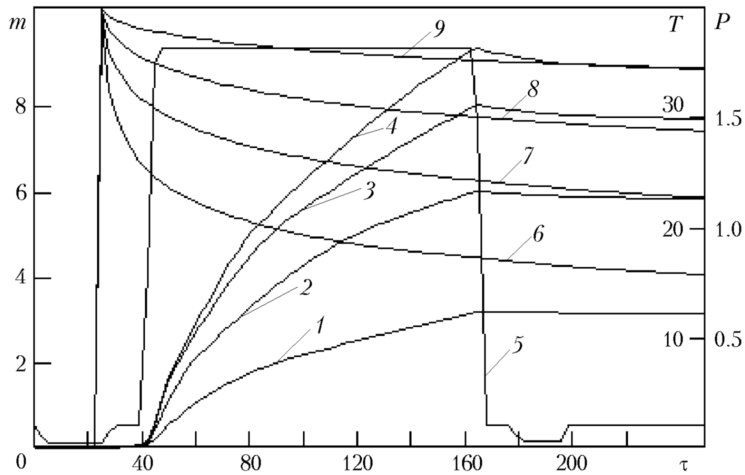

Fig. 1. Influence of the fluid volume V_{ext} participating in the heat exchange with the wood specimen on the fluid absorption and temperature: 1, 6) mass of the fluid absorbed by the specimen and its mean temperature at K_u = 0.9; 2, 7) 0.75; 3, 8) 0.6; 4, 9) 0.5; 5) fluid pressure. m, kg; T, ^{o}C; P, MPa; τ, min.

modeling — we chose a pine cylinder of L = 2.8 m and r = 0.10 m with a ratio of the core radius to the total radius of 3/5. At this stage, the fact that with decreasing temperature the emulsion can display the properties of a Newtonian fluid and its viscosity may depend on the shear deformation rate was ignored [9].

The data presented permit investigating the influence of the degree of filling of the impregnation cylinder volume on the quality of impregnation due to the nonisothermal character of the process. By analogy with the notion of the degree of loading of the autoclave, which is determined as the ratio of the total volume of the wood to the total working volume of the impregnation cylinder, we introduce a similar quantity for a single article:

$$K_u = V_w / (V_w + V_{ext}) \ .$$

In the case of a uniform distribution of wood articles in the impregnation cylinder volume, this quantity coincides with the degree of loading of the autoclave.

It should be noted that with the boundary condition under which the specimen surface temperature was kept constant [6] (T_{ext} = 40^{o}C = const) the value of absorption of the compound by the specimen after impregnation was m = 9.22 kg. Comparison of this result with curve 4 (see Fig. 1) has shown that even at K_u = 0.5, i.e., at an equal volume ratio of the wood and its contacting fluid, the absorption decreased to m = 8.86 kg. The results presented in Fig. 1 demonstrate the necessity of taking into account the conditions of the heat exchange in the impregnation process: the higher the degree of loading K_u, the lower the fluid temperature $T^{*)}$ and the smaller the absorption m. This imposes certain constraints on the volume of autoclave filling and, accordingly, on the efficiency of the technological process.

The calculations show a strong dependence of the absorption on the size of clearances between the specimens at impregnation. Figure 2 gives the isotherms for fragments of the wood specimen (a fourth part of the longitudinal section of the column) at the end of the impregnation process (τ = 250 min). This figure also shows the distributions of the impregnating compound concentration. The figure illustrates a marked difference in the heating of the wood specimen under conditions where the fluid volume interacting with the sample is approximately equal to the volume absorbed by the wood (Fig. 2a, b) and where this volume considerably exceeds the volume of the specimen and the fluid is practically not cooled (Fig. 2c, d). The distribution patterns of the impregnating composition corresponding to the given temperature fields show a direct relation between the heating depth and the impregnation depth, which corroborates the conclusion that it is necessary to take into account the heat exchange of the specimen surface with the

*) The calculation data for the wood-surface temperature at the end of the process before the drawing from the autoclave can be useful in practice in estimating the ecological state of the production.

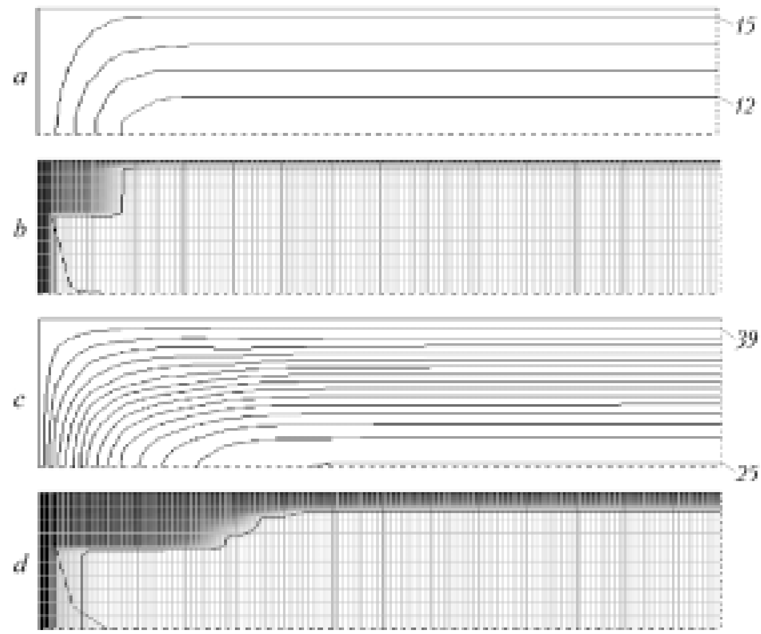

Fig. 2. Temperature and impregnating composition distribution in the wood specimen after impregnation: a and c) temperature levels in the specimen (isotherms have a step of 1^{o}C); b and d) fluid mass distribution (1-cm step of the grid lines); a and b correspond to the impregnation with regard for the cooling of the fluid contacting the specimen (K_u = 0.9); c and d show the impregnation ignoring the cooling T_{ext} = 40^{o}C. Figures show temperatures, ^{o}C.

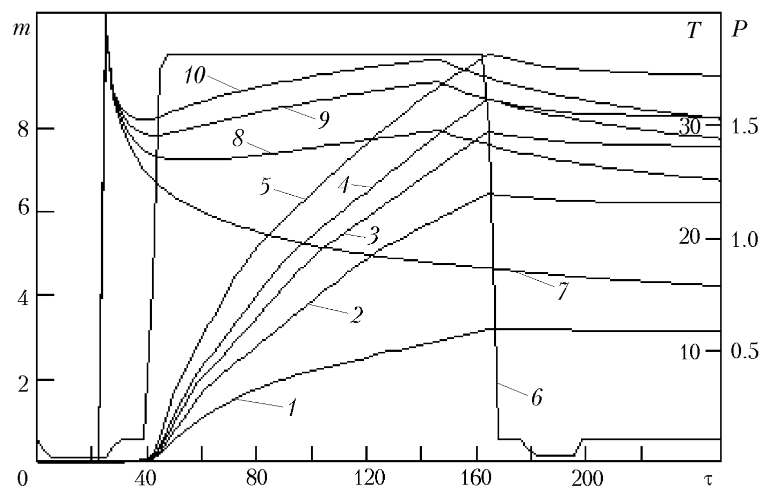

Fig. 3. Influence of the circulation (running) on the absorption kinetics and temperature of the fluid (K_u = 0.9): 1, 7) absorbed fluid mass and temperature T_{ext} in the absence of circulation; 2, 8, in the presence of circulation Rf = 1; 3, 9) 2; 4, 10) 3; 5) T_{ext} = 40^{o}C; 6, fluid pressure. m, kg; T, ^{o}C; P, MPa; τ, min.

fluid. The variant given in Fig. 2c, d at T_{ext} = 40^{o}C corresponds to the impregnation where the volume of the fluid contacting the specimen $V_{ext} >> V_w$, which in practice can be realized only at large distances (clearances) between specimens and a low degree of loading of the autoclave.

Obviously, running of the heated fluid from the heating zone through the impregnating cylinder (fluid circulation) permits an additional heating of wood materials and makes it possible to increase the fluid absorption by the

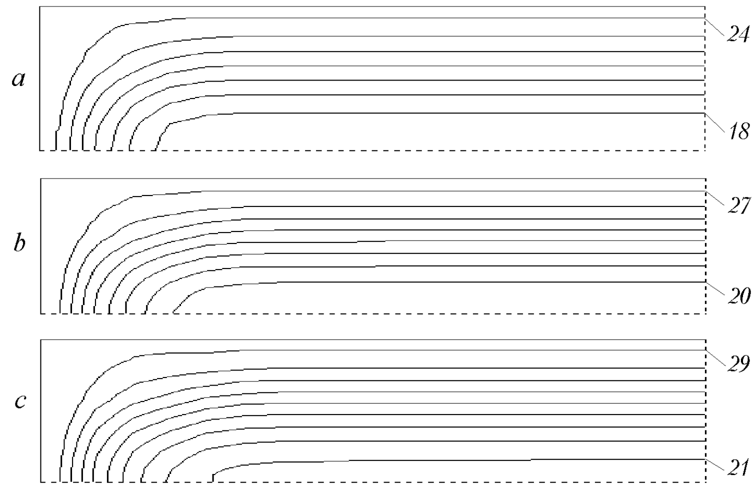

Fig. 4. Temperature distribution in the specimen at various flows of the circulating fluid in the process of impregnation (K_u = 0.9): a) Rf = 1; b) 2; c) 3. Figures show temperatures, ^{o}C.

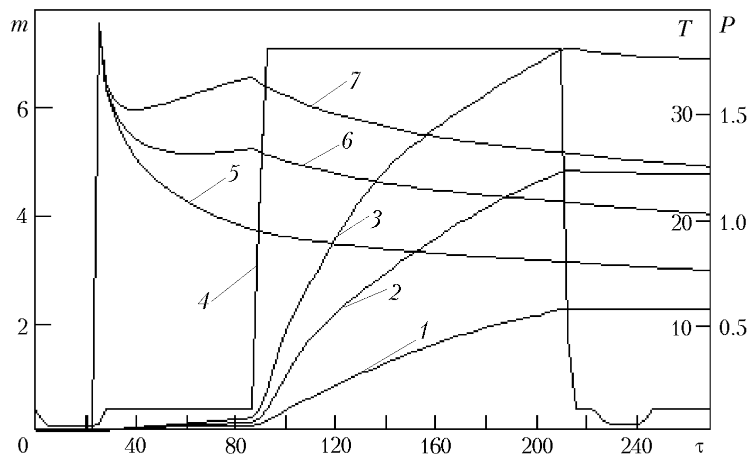

Fig. 5. Influence of the circulation in the heating period on the absorption kinetics and temperature T_{ext} of the fluid (K_u = 0.9): 1, 5) absorbed fluid mass and temperature in the absence of circulation; 2, 6) in the presence of circulation Rf = 1; 3, 7) 3; 4) fluid pressure. m, kg; T, ^{o}C; P, MPa; τ, min.

wood. The calculation data for the impregnation kinetics of the specimen in the case where the fluid incoming from the impregnating composition heating zone or from the thermostatic vessel for composition storage at a temperature T_{in} = 40^{o}C is run are given in Fig. 3. This figure shows the case of maximum loading of the impregnation cylinder with wood K_u = 0.9 where the fluid volume V_{ext} and its heat content are minimal. This example corresponds to the closest possible placement of cylindrical specimens in the impregnating vessel and for specimens of rectangular profile (ties, beams, boards) — to the placement with a clearance of a few millimeters. Figure 3 also gives the absorption calculation data for the fluid with a fixed temperature T_{ext} = 40^{o} (curve 5) — a perfect heating when the specimen warm-up and its saturation with the fluid are only determined by the internal heat exchange in the wood and are independent of the external fluid volume V_{ext}. We introduce the coefficient characterizing the fluid-exchange multiplicity due to the circulation during 1 h, Rf = $3600G/(\rho_f V_{ext})$. From Fig. 3 it is seen that the impregnation kinetics largely depends on the fluid circulation: for instance, at Rf = 1, i.e., at a circulation of one volume V_{ext} per hour (curve 2) the fluid absorption by the wood is twice as high as than without circulation (curve 1), and at a circulation of three volumes (Rf = 3) it is higher by a factor of 2.6. This is due to the better heating of the specimens as a result of the increase in T_{ext} (curves 7–10), which is evidenced by the temperature distributions in the wood volume given in Fig.

4. From Fig. 4, as well as from Fig. 2a and c, it is seen how the heating of the specimen occurs under various external conditions. The data presented show a high efficiency of the influence of the circulation (running) of the heated fluid on the impregnation process, which can ensure the required quality of treatment of wood materials at the highest possible degree of loading of the autoclave.

Taking into account that in a real technological process it is not always possible to run the fluid in the period of impregnation at a high pressure, we consider the variant of preheating the wood loaded into the autoclave by running the heated fluid incoming from the heating zone at a temperature $T_{in} = 40^{o}C$ just before the impregnation. Data on the influence of the heated compound circulation with a different flow rate in the heating period (τ = 60 min) are given in Fig. 5. It should be noted that for the VPV (Bethell) process wood impregnation begins simultaneously with the pouring of the impregnating fluid under the action of the fluid column and atmospheric pressure after the stage of vacuum-treatment of the wood. The results of the numerical simulation demonstrate a strong influence of fluid heating (circulation) on its absorption by the specimen: for instance, with a circulation of one volume in the heating period (Rf = 1) the absorption is 1.4 times higher than without circulation, and with a circulation of three volumes it is 1.7 times higher, which is much lower than the calculation data given in Fig. 3. Obviously, to increase these indices, it is necessary to increase the heating time.

The simulation of the impregnation process without vacuum pretreatment of specimens by the methods of APPV (atmospheric pressure–pressure–vacuum or Lowry process) and PPV (air pressure–pressure–vacuum or Rueping process) has shown an analogous dependence of absorption on V_{ext} and as high an efficiency of the influence of the composition circulation.

CONCLUSIONS

1. The kinetics of impregnation of large-sized woodworks (poles, ties) with heated oily compositions depends on many parameters that are not so important in impregnating with preservative water solutions: the degree of loading of the autoclave, the spacing between the wood specimens, and the circulation (running) rate of the impregnating fluid in the clearances between the specimens.

2. The value of the volume of the heated fluid contacting the specimen strongly influences the heating rate and depth of the specimen, which determines the amount of fluid absorbed by it and the impregnation depth.

3. The heat exchange can be intensified and, accordingly, a high quality of impregnation can be attained by circulating the fluid incoming from the heating zone into the clearances between lumbers, which becomes particularly important with increasing degree of loading of the autoclave.

NOTATION

c, specific heat, J/(kg·deg); *E*, internal energy density, J/m^3; *G*, mass flow of the impregnating fluid, kg/sec; *h*, heat-exchange coefficient, W/(m^2·deg); K_u, ratio of the specimen volume to the total volume of the wood and external fluid pertaining to this specimen; *L*, specimen length, m; *m*, mass, kg; *P*, pressure, Pa; *q*, heat flow density, J/(sec·m^2); *r*, cylindrical-specimen radius, m; Rf, fluid-exchange multiplicity per hour; *T*, temperature, ^{o}C; **v**, velocity of travel of substance, m/sec; *V*, volume, m^3; **x**, coordinates; ε, internal energy, J; Γ, specimen surface; *S*, specimen surface area; λ, thermal conductivity tensor; τ, time; ρ, effective density (mass contained in a unit volume of wood), kg/m^3. Subscripts: a, air; f, fluid; w, wood substance; s, substance (s = a, f, w); cond, conductive; conv, convective; n, normal; ext, external; 0, initial value; u, unit; in, incoming.

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