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MODELING OF IMPREGNATION OF WOOD WITH PROTECTIVE SOLUTIONS AND EMULSIONS

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A calculational model for the process of deep impregnation of wood with solutions and water-polymer emulsions is developed that takes account of the motion of the fluid, the polymer particles, and the air in the porous structure. Calculated results for the kinetics of impregnation of wood under the action of a pressure gradient and the distribution of the fluid in the material volume are presented. A comparison with experimental data for dry and wet wood is performed.

Introduction. Saturation of porous materials with a fluid under the action of pressure is widely used in many processes of chemical engineering (such as leaching and the introduction of catalysts into a porous structure), in hydraulic stabilization of building materials (for example, cellular concrete), in filtration of a liquid in rocks in hydrogeology, in withdrawal of mold cores from castings in machine building, etc. Among the problems that are most frequently encountered in practice is the problem of impregnation of wood to impart fire- and bioproof properties to it and improve its strength, decorative, and other qualitative characteristics [1]. Impregnation of wood with combustion catalysts permits production of high-rank charcoal [2].

In impregnation of wood articles with protective solutions of water-soluble salts, washing-out is decreased by introducing insoluble polymer additives – synthetic resins, oils, and other heavy fractions of oil refining – into the solution. In this case, the protective composition is prepared in the form of water-oil or water-polymer emulsions. After impregnation and drying, water-resistant films form on the surface and in the volume of the wood, which noticeably decreases the washing-out of protective components. The sizes of the particles in the emulsion depend on its type and the method of preparation and are 0.5–20 μm. Depending on the size, the particles can be filtered in the porous structure and be retained in a thin layer or penetrate to various depths.

In analysis of the quality of the modifying impregnation of wood, apart from the magnitude of the absorption of the fluid by the material during its saturation under pressure, no less important is the uniformity of the distribution of the impregnating composition in its volume. Wood is an anisotropic and inhomogeneous medium with an intricate structure that has a substantial effect on the impregnation quality. To determine the internal distribution of the fluid, generally specimens are sawed or split, fragments are sawed from various sections of the articles, holes are drilled with the aid of special bores, etc. Wood articles are up to several meters long and the cross section measures tens of centimeters; therefore experimental investigations in the full volume present major difficulties. In the current work, a method of complex modeling is used that consists in carrying out investigations on small wood specimens, setting up a calculational model, refining the parameters, and modeling the impregnation for articles of any size.

Model. In [3], a macroscopic physicomathematical model of impregnation of wood is proposed that takes account of the motion of gas and liquid phases and the structural features of softwood. In the present work, a more complete model based on it is set forth that makes it possible to find the concentration fields

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of the impregnating composition in the volume of the wood and to calculate the kinetics of saturation of the wood volume with both solutions and emulsional and disperse compositions doped with insoluble liquid or solid substances.

Qualitative analysis of the fluid and air motion in the system of bound wood cells – tracheids – with allowance for their microstructure [3] and the need for describing the experimentally established effect of the presence of entrapped air led to introduction, into the model, of a state variable α equal to the portion of the internal volume of a tracheid that is occupied by the fluid. The effective densities of the fluid and the air per unit volume of the wood are calculated in terms of this variable:

$$\rho_f = \alpha\varepsilon\rho_f^0 , \quad \rho_a = (1 - \alpha)\, \varepsilon\rho_a^0 \frac{P}{P^0} , \tag{1}$$

where ε is the air capacity of the wood (the portion of the volume that is not occupied by the cell walls or the free fluid [4]), P^0 is the atmospheric pressure, and ρ_f^0 and ρ_a^0 are respectively the densities of the impregnating fluid and the air at atmospheric pressure. The parameters ρ_f and ρ_a must satisfy equations that express the law of conservation of mass:

$$\frac{\partial\rho_f}{\partial\tau} = -\operatorname{div}(\rho_f \mathbf{v}_f) , \quad \frac{\partial\rho_a}{\partial\tau} = -\operatorname{div}(\rho_a \mathbf{v}_a) , \tag{2}$$

with the fluid and air velocities $\mathbf{v}_f$ and $\mathbf{v}_a$ defined by expressions [3] that take account of the change in the character of the motion depending on α:

$$\mathbf{v}_a = \begin{cases} -\sigma_a \nabla P , & \alpha < \alpha_c , \\ 0 , & \alpha \ge \alpha_c ; \end{cases} \tag{3}$$

$$\mathbf{v}_f = \begin{cases} -\sigma_f \nabla P \ \text{ for } \ W = 0 \ \text{ and } \ \alpha > \alpha_c , \\ -\sigma_f \nabla P\, (1 - G/|\nabla P|) \ \text{ for } \ W = 1 , \ |\nabla P| > G \ \text{ and } \ \alpha > \alpha_c , \\ 0 \ \text{ for } \ W = 1 , \ |\nabla P| \le G \ \text{ or } \ \alpha < \alpha_c ; \end{cases} \tag{4}$$

$$\alpha_c = \begin{cases} \alpha_1 \ \text{ for } \ W = 0 , \\ \alpha_2 \ \text{ for } \ W = 1 , \end{cases} \tag{5}$$

where the function

$$W(\tau, \mathbf{x}) = \theta \left\{ \int_0^\tau \theta\, [\alpha(\tau', \mathbf{x}) - \alpha_c]\, d\tau' \right\} , \tag{6}$$

which assumes the value 0 or 1, characterizes the state of wetness of the cell wall, $\theta(\cdot)$ is the Heaviside function, and α_1 and α_2 are model parameters.

Depending on the viscosity and the particle size, insoluble additives can penetrate into the depth of the wood or concentrate in the surface zone of the article. Experimental measurements of impregnation of wood with protective emulsions doped with bitumen particles have demonstrated that the penetration of bitumen particles into the depth of the wood is restricted to a thin surface layer with a thickness of the order of tracheid sizes (3–4 mm). This is attributed to the fact that the sizes of the particles prevent them from penetrating through the pores in the cell walls, and they occupy only near-surface tracheids. As the filling proceeds, the pores are blocked by particles that connect tracheids, which leads to a decrease in the wood permeability, which is also observed experimentally.

To describe impregnation with emulsions, the model is supplemented with equations for the dynamics of the suspension. Furthermore, a local dependence of the coefficient of conductivity on the volume content of the polymer material is introduced. The state of the system is additionally characterized by the quantity ρ_p (the polymer mass in unit volume of the wood). To take account of adhesion of the polymer particles to the cell walls during impregnation, we separately consider the dynamics of the polymer suspended in the carrying fluid and moving along with it (the "free" polymer with the volume density ρ_p^s) and the change in the amount of the polymer that has adhered to the wood (the "bound" polymer with the volume density ρ_p^b). Obviously,

$$\rho_p = \rho_p^s + \rho_p^b . \tag{7}$$

For a quantitative description, we adopted the following simplified scheme of the process: 1) as the emulsion is forced into the depth of the wood, a certain portion of the polymer that is defined by the model parameter γ adheres to the cell walls, and the remaining part moves farther; 2) in reverse motion, the part that has settled on the walls remains immobile and its amount remains unchanged, while the remaining part (the free polymer) flows out along with the fluid.

With allowance for the foregoing,

$$\frac{\partial \rho_p}{\partial \tau} = - \operatorname{div} (\rho_p^s \mathbf{v}_f) , \tag{8}$$

$$\frac{\partial \rho_p^b}{\partial \tau} = - \gamma \theta (v_f) \frac{\partial \rho_p}{\partial \tau} , \tag{9}$$

where $\mathbf{v}_f$ is the emulsion velocity defined by expressions (4)–(6).

The change in the wood permeability as the cell pores are blocked by particles during the impregnation is quantitatively described by the dependence of the conductivity on the depth of polymer penetration l, which is defined as

$$l = \frac{1}{\varepsilon \rho_p^0} \int\limits_0^{L/2} \rho_p (x) \, dx . \tag{10}$$

For the dependence $\sigma_f(l)$, we adopted the piecewise-linear approximation

$$\sigma_f = \begin{cases} \sigma^0 (1 - l/l^*) , & x \le l , \\ \sigma^0 , & x > l , \end{cases} \tag{11}$$

where σ^0 is the conductivity for a pure carrying fluid and l^* is the limiting depth of penetration of the polymer (a model parameter). The polymer particles are assumed to fill only the tracheid layer that is closest to the surface. In this connection, Eqs. (9)–(11) are written for one measurement in the direction normal to the specimen surface.

The initial and boundary conditions are

$$\tau = 0 : \ \rho_f = \rho_{f0} , \ \ \rho_a = \rho_{a0} , \ \ \rho_p = 0 ; \tag{12}$$

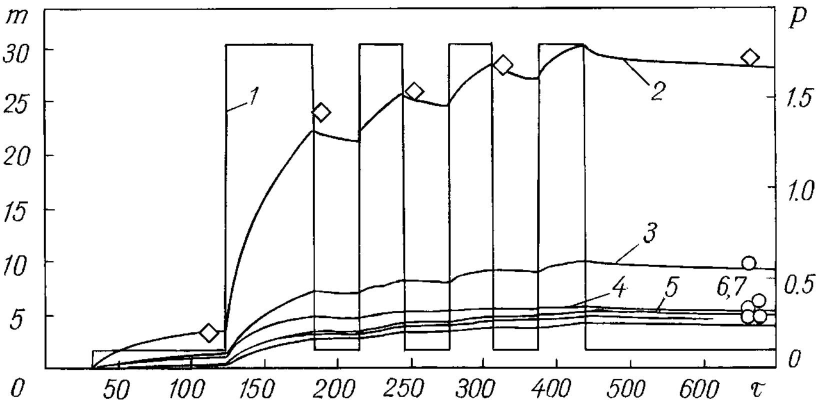

Fig. 1. Impregnation kinetics for 2.5-m-long pine columns: 1) pressure of the impregnating fluid, P_{max} = 1.8 MPa; 2) overall absorption of the fluid by the specimens; 3) absorption by an individual specimen with D = 120 mm and w = 32%; 4) 120 and 63; 5, 6) 100 mm, 56 and 79; 7) 80 and 59. m, kg; τ, min.

$$\mathbf{x} \in \Gamma : \; P = P_{\text{ext}}(\tau) \; ; \; \rho_p^s = c^0 \overset{0}{\rho}_p \, , \; \rho_f = (1 - c^0) \overset{0}{\rho}_f \, , \tag{13}$$

where $\mathbf{\Gamma}$ is the specimen surface, P_{ext} is the specified external pressure, c^0 is the concentration (volume fraction) of the polymer in the initial emulsion, ρ_p^0 is the polymer density, and ρ_f^0 is the density of the carrying fluid.

The calculations for modeling of the kinetics of impregnation of wood specimens and a comparison with data of laboratory investigations [3] permitted refinement of the determining parameters of the process, which then formed a basis for a numerical modeling of saturation of large-size articles with protective solutions and emulsions. It should be noted that the proposed physicomathematical model disregards changes in the volumetric characteristics of the wood (distension) and in the sorption, evaporation, and condensation of the fluid vapor by the cellular structure during the saturation, i.e., corresponds to wood with an initial moisture content of no less than 30% (the saturation limit for the cell wall). It takes account only of the difference in the wood structure within the confines of the entire specimen (a sapwood–core double-layer model) rather than of an annual ring, ignores the additional resistance due to capillary forces in the case of a high initial moisture content of wood, etc. However, since the character of the process parameters (such as σ, α, G, l^*, and γ) is effective and their values are refined with acceptable accuracy using experimental data, impregnation of wood can be modeled for a wider range of its initial moisture content.

Analysis of Calculated Results and Experimental Data. In [3], the laboratory setup and the procedure for studying the kinetics of impregnation of wood specimens are described; the data obtained permitted refinement of the basic process parameters that are used for numerical modeling.

Figure 1 presents calculation results for the kinetics of saturation of a cylindrical pine column in impregnation with an aqueous antiseptic solution by the "vacuum–pressure" method. The pressure had a cyclic character, which offered an opportunity for directly controlling the level of the impregnating fluid in experimental measurements. The impregnation stand, which was designed for experimental verification, consisted of an impregnation cylinder of volume 200 liter and length 3 m, an upright maneuvering cylinder of volume 50 liter, a system for evacuation to 10 kPa, and a system for setting up a pressure of the impregnating fluid of up to 1.8 MPa. Pine columns of length 2.5 m with different diameters (60–140 mm) and initial moisture contents (w = 32–91%) were loaded into the impregnation vessel. The increase in weight for each specimen after impregnation and the distribution of the fluid inside the column were measured. The character of the

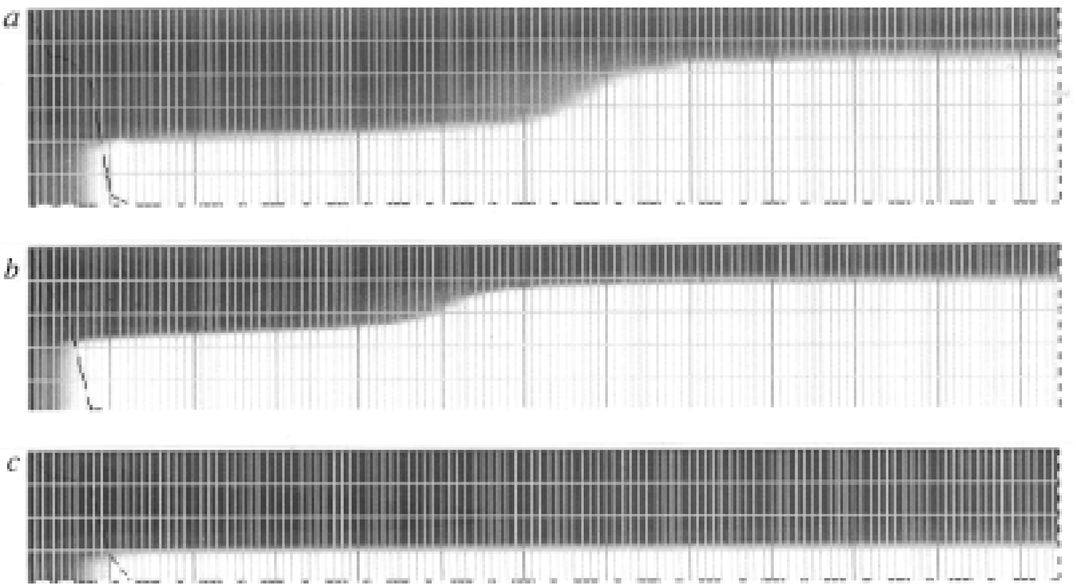

Fig. 2. Distribution of the impregnating solution in the central longitudinal cross section of the columns: a) D = 120 mm, b) 100, c) 80.

distribution was studied by sawing the specimen lengthwise across the diametric section. With the aid of a chemical tracer, the sizes of the core and sapwood parts of the column were also determined for subsequent use in calculations according to a double-layer model.

As follows from Fig. 1, comparison of the data of the numerical and experimental modeling of the impregnation kinetics shows a result that is satisfactory for practical calculations. The vacuum intensity was 10 kPa, and the maximum pressure of the impregnating solution was 1.8 MPa. Figure 2 presents calculated distributions of the solution concentration for column fragments of different diameter (a quarter of the central longitudinal cross section of the articles) that correspond to curves 4, 6, and 7 of Fig. 1. Measurement data on the distribution of the impregnating solution also showed the acceptability of the proposed calculational model. For an initial moisture content of 40–45%, in this method of treatment the sapwood is completely colored (Fig. 2c), which is indicative of through impregnation. For a high initial moisture content, the impregnation is not complete even over the sapwood of the specimens (Fig. 2a and b). The actual size of a grid cell in the figure is 1 cm. The solution distributions presented are in favorable agreement with measurement data for specimens sawed after impregnation. Thus (Fig. 2a), in the experiment, the impregnation depth over the core was 40–50 mm (the calculation showed 60–70 mm), the through impregnation over the sapwood for a column (a) 120 mm in diameter was 50–70 mm (the calculation showed 60–70 mm) and for (b), 40–50 mm (the calculation showed 40–50 mm), and the thickness of the impregnated zone near the central cross section was 16–17 mm (a) (the calculation showed 15–16 mm) and for the case (b), 10–15 mm (the calculation showed 12 mm).

The proposed low-frequency cyclic method of impregnation where the pressure has a cyclic character (see Fig. 1) was also used to increase the absorption of the impregnating solution for articles made of wet cylinder-shaped wood [5], when standard methods of impregnation do not provide sufficient absorption. With a cyclic pressure change, the absorption can be expected to increase as a consequence of the effect detected by Huber and Wertz [6], in which the wood permeability decreases with the time of the pressure action due to closing of some of the pores that connect tracheids because of displacement of tori. It should be noted that there is no common opinion on the question of the efficiency of the action of cyclic pressure on the absorption of the solution in impregnation [7, 8].

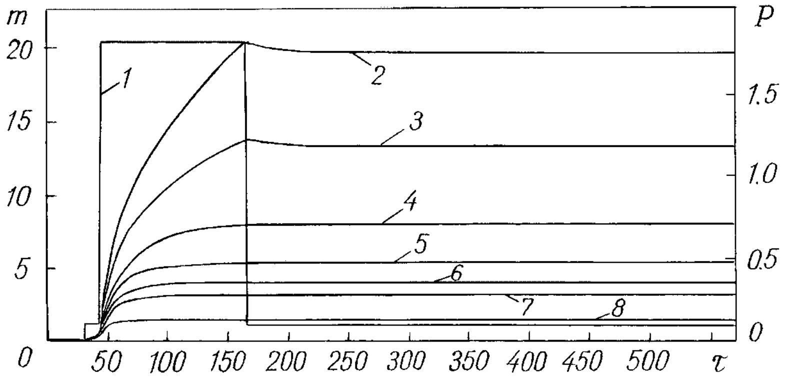

Fig. 3. Kinetics of impregnation of railway crossties (2800 × 240 × 160 mm) with protective compositions containing polymer additives: 1) pressure of the impregnating fluid, $P_{\max}$ = 1.8 MPa; 2) polymer particles are absent from the solution; 3) 2%; 4) 4; 5) 6; 6) 8; 7) 10; 8) 20.

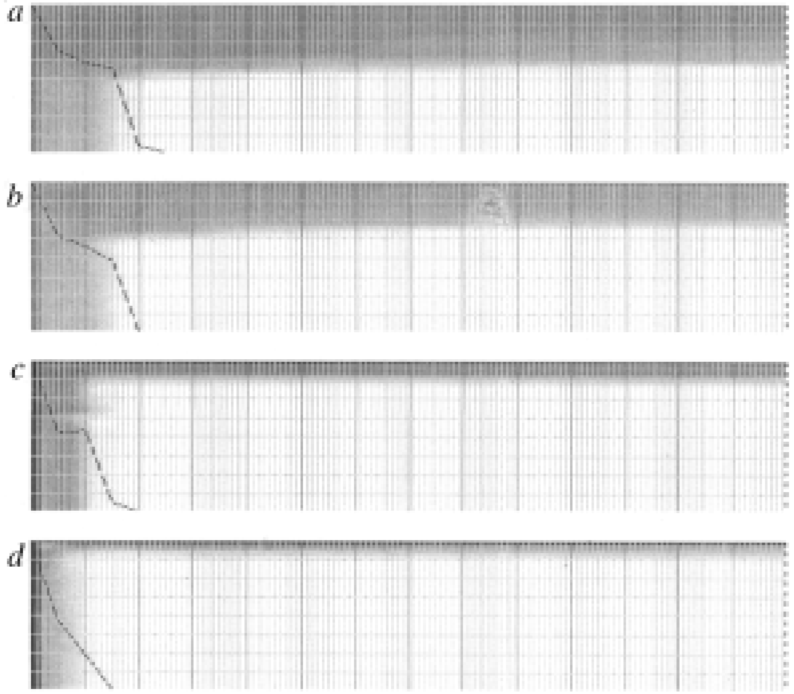

Fig. 4. Distribution of the impregnating fluid in pine railway crossties: a) polymer particles are absent; b) 2%; c) 6; d) 10.

Experiments with a batch of pine columns over a wide range of initial moisture contents of the wood (w = 30–90%) made it possible to draw the conclusion of practical importance that the indicated method of impregnation with the number of cycles of pressure action varying from 4 to 8 provides high absorption of the solution (no less than 200 liter/m^3) for wet wood (with an initial moisture content of up to 90%).

For all the considered specimens of wet cylinder-shaped wood, the impregnating solution spread over a large part of the sapwood (no less than 60% of the area of the longitudinal cross section and 67% of the volume of the wood). Thus, for wet wood it is possible to ensure absorption (an increase in weight) in accordance with requirements of standards for bio- and fireproof wood; however, for an initial moisture content of over 45–50% a thorough distribution (a through impregnation over the sapwood) is not achieved. This may limit somewhat the practical use of wood impregnated by the above method in a medium that is favorable for

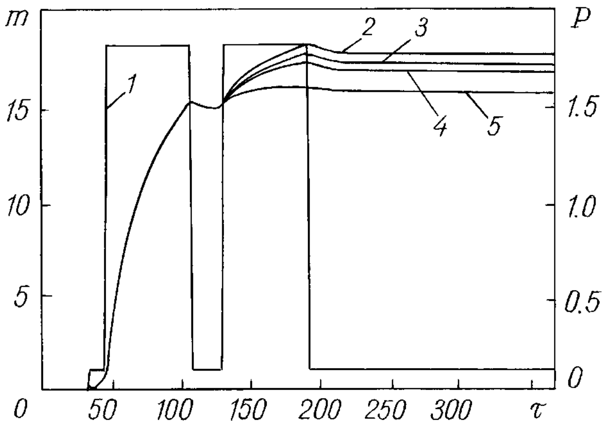

Fig. 5. Two-stage impregnation of crosstie wood (the first cycle of the impregnation is without polymer particles and the second cycle is with an addition of particles): 1) pressure; 2) absorption of a solution with a polymer additive of 6%; 3) 8; 4) 10; 5) 20. *P*, MPa.

the development of biological destructive agents, i.e., under conditions corresponding to a high class of service conditions [1].

Figure 3 presents results of numerical modeling of impregnation with water-polymer emulsions for the wood of pine crossties (2800 × 240 × 160 mm). The maximum fluid pressure was 1.8 MPa and the vacuum intensity was 20 kPa. The curves manifest a strong dependence of the emulsion absorption by the wood on the concentration of polymer particles in the solution of the protective agent. The data of measuring the increase in weight of the crossties in impregnation with a bitumen emulsion with a mean particle size of over 10 μm indicate acceptability of the proposed model and reliability of the calculated results [9]. The distribution of the solution in the volume of the wood is shown in Fig. 4. The data indicate low absorption of the protective composition by the wood for high concentrations of polymer particles in the emulsion. With decrease in the size of the particles and with their going deeper into the wood volume the absorption–concentration dependence weakens, and in the case of particle sizes smaller than 1 μm an insignificant effect of them on the absorption and the distribution of the solution concentration in the material ought to be expected.

For large particles (see Fig. 3), the absorption can be increased by two-stage treatment of the wood material. Relevant calculated data are presented in Fig. 5. In the first stage of the impregnation the wood absorbs a protective composition without polymer particles, and in the next stage a water-polymer emulsion is absorbed. A comparison with data for single-stage impregnation shows a marked increase in the absorption of the protective agent in separate treatment of large-sized wood articles by two compositions. Within the framework of the calculational model considered, a certain decrease in the absorption of polymer particles by the surface layer of wood tracheids from 0.4 kg per crosstie in single-stage impregnation to 0.3 kg in two-stage impregnation is noted.

CONCLUSIONS

1. The developed physicomathematical model of impregnation of wood with solutions and water-polymer emulsions makes it possible to determine not only the fluid absorption by the porous structure but also the concentration distribution in the volume of the wood with an accuracy sufficient for engineering calculations (no worse than 15%) using the method of computer modeling.

2. A low-frequency cyclic method of impregnation of wet-wood articles offers high absorption of the protective solution by a material with an initial moisture content of up to 90% (no less than 200 liter/m^3); the

protective solution spreads over a large part of the wood volume (no less than 67%), however, the impregnation is not uniform.

3. A significant decrease in the absorption of the protective composition by wood is noted in impregnation with water-polymer emulsions that contain large polymer particles. The absorption can be increased using a two-stage impregnation method in which in the first stage the impregnation is effected with an aqueous protective solution, and in the second stage the impregnation is effected with a water-polymer emulsion. The layer of polymer particles that is formed here in a thin zone of the wood guards the protective agent in the volume of the wood against the action of atmospheric precipitation.

NOTATION

$\mathbf{x}$, coordinates; τ, time; D, diameter; P, pressure; ρ, effective density (mass of the substance contained in unit volume of the wood); α, portion of the internal volume of a tracheid occupied by the impregnating fluid; $\mathbf{v}$, velocity of motion of the substance; σ, conductivity; G, pressure gradient due to the hysteresis of the contact wetting angle (Jamin effect); γ, portion of the polymer that has adhered to the cell walls of a tracheid; l, depth of penetration of the polymer; L, length of the specimen; w, moisture content. Subscripts: f, fluid; a, air; p, polymer; c, critical; ext, external; 0, initial value; max, maximum. Superscripts: s, free; b, bound; 0, pertaining to initial substances.

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