Journal of Engineering Physics and Thermophysics, Vol. 72, No. 4, 1999

KINETICS OF THE WOOD IMPREGNATION PROCESS. MODELING AND EXPERIMENT

M. A. Brich, V. P. Kozhin, and
V. K. Shchitnikov

UDC 532.546:674.048

A physical and mathematical model of deep impregnation of wood by a fluid which allows for motion of the fluid and air in its porous structure is developed. The results of calculations of the kinetics of pressure-gradient impregnation of wood are reported. An experimental impregnation bench intended for investigations of different impregnation conditions and for measurements aimed at refinement of the impregnation parameters is described.

Introduction. Intensification of saturation of the free volume of porous bodies by a fluid under pressure is of interest in solving some scientific and engineering problems of wood processing [1], chemical technology [2], mechanical engineering, etc. The present work provides the results of an investigation of the process of deep impregnation of wood by liquid compositions (aqueous solutions, oils, melts, polymers) for the purpose of wood modification including imparting fire and bioprotection properties to it, improving its strength characteristics and resistance to the action of water, acids and alkali, changing its decorative quality, and preparation of fuel for catalytic combustion [3], sorbents, etc. from wood.

A wood sample represents an anisotropic capillary-porous body with a complicated texture. The complete description of the dynamics of impregnating fluid motion in wood due to a pressure gradient and, as a result, design of the governing parameters of the equipment and the impregnation technology encounter considerable difficulties. The latter are related, first of all, to the complicated internal structure of wood and to the choice of an adequate physicomathematical model of impregnation [4, 5].

The impregnation depth and fluid absorption by wood depend on a number of factors: pressure of an impregnating solution, the impregnation time, timber dimensions, the structural, physical, and chemical properties of the wood, the moisture content, the characteristics of the solutions used, impregnation conditions, and so on.

Proceeding from the general structure of wood as a capillary-porous structure, when investigating the process of fluid penetration into wood, the majority of investigators considered wood as a system of parallel capillaries [6, 7]. However, the results obtained and the physical models suggested were rough; they described satisfactorily only one-dimensional end-type timber impregnation of some species of hardwood having long water-conducting vessels. For softwood species such a calculation model leads to considerable discrepancies with experimental data.

In the present work we suggest a refined macroscopic physical and mathematical model of the process of wood impregnation, which phenomenologically allows for specific features of softwood structure, motion of gas and liquid phases, the presence of entrapped air, and the Zamain effect [8] on fluid absorption by wood.

Model. Softwood structure can be schematically presented as a system of tracheids connected by micropores (Fig. 1a). Correspondingly, the process of fluid motion in wood includes its flow along the tracheids and overflow through the pores connecting the neighboring tracheids.

Consider fluid motion in a system consisting of two tracheids connected with one pore (Fig. 1b). For steady flow

---

Academic Scientific Complex "A. V. Luikov Heat and Mass Transfer Institute" of the National Academy of Sciences of Belarus, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 72, No. 4, pp. 618-626, July-August, 1999. Original article submitted September 28, 1998.

 1062-0125/99/7204-0590$22.00

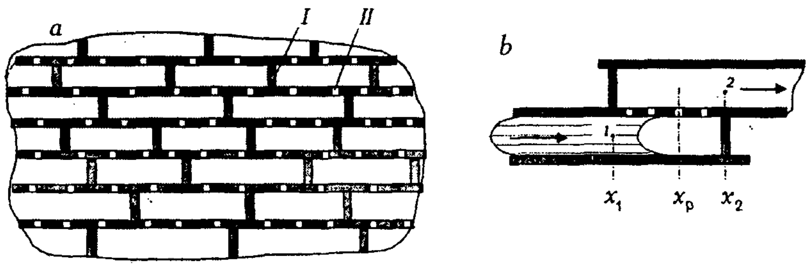

Fig. 1. Schematic of softwood structure: a) I is the cell walls, II is the pores; b) x_1, x_2, x_p are the coordinates of the ends of tracheids and a pore, respectively.

$$Q = (P_1 - P_2)/R\,, \tag{1}$$

where Q is the bulk of the fluid flowing through the system per unit time; P_1 (P_2) is the fluid pressure at point 1 (2); R is the hydraulic resistance of the section between points 1-2. It is obvious that the total hydraulic resistance is

$$R = R_{1p} + R_p + R_{2p}\,, \tag{2}$$

where R_{1p} (R_{2p}) is the resistance to fluid motion over section $x_1 - x_p$ ($x_p - x_2$); R_p is the hydraulic resistance of a pore. As in works [2, 6], we assume that for flow along a tracheid the Poiseuille formula is valid. Then

$$R_{1p} = b\,(x_p - x_1)\,, \quad R_{2p} = b\,(x_2 - x_p)\,, \quad b = \frac{8\mu}{\pi r^4}\,, \tag{3}$$

and

$$R = b\,(x_2 - x_1) + R_p \approx b\,\frac{l_t}{2} + R_p\,. \tag{4}$$

It can be assumed that if tracheids are connected by N pores rather than by one pore, then formula (4) remains valid with replacement of R_p by R_p/N:

$$R = b\,\frac{l_t}{2} + R_p/N\,. \tag{5}$$

As regards the hydraulic resistance, a macroscopic wood sample with length L_x and cross dimensions L_y, L_z with fibers oriented along the sample can be considered as the sequence n_x of successive layers consisting of $n_y n_z$ elements connected in parallel, each of which is described by formula (5). Since

$$n_x = \frac{L_x}{l_t/2}\,, \quad n_y = \frac{L_y}{2r}\,, \quad n_z = \frac{L_z}{2r}\,, \tag{6}$$

then

$$R_x^s = R\,\frac{n_x}{n_y n_z} = \left(b\,\frac{l_t}{2} + R_p/N\right)\frac{4r^2 L_x}{L_y L_z l_t/2}\,. \tag{7}$$

In the transverse, relative to the tracheid axis, the direction of the wood resistance is attributed mainly to the resistance of pores. It is obvious that

$$R_y^s \approx \frac{R_p}{N}\,\frac{n_y}{n_x n_z}\,, \quad R_z^s \approx \frac{R_p}{N}\,\frac{n_z}{n_x n_y}\,. \tag{8}$$

Thus, for the wood sample

$$Q^s = \Delta P / R^s , \tag{9}$$

where ΔP is the pressure drop; R^s is determined by formulas (7) or (8) depending on the direction of the fluid motion relative to the orientation of fibers.

Using the limiting-transition procedure, we obtain the expression for the specific fluid flow

$$\mathbf{q} = -\sigma \nabla P . \tag{10}$$

In the coordinate system with the x-axis directed along the fibers, σ has the form

$$\sigma = \begin{pmatrix} \sigma_x & 0 & 0 \\ 0 & \sigma_y & 0 \\ 0 & 0 & \sigma_z \end{pmatrix} , \tag{11}$$

where

$$\sigma_x = \frac{l_t}{8r^2 \left(b \frac{l_t}{2} + R_p / N \right)} ; \quad \sigma_y = \sigma_z = \frac{l_t}{2} \frac{R_p}{N} . \tag{12}$$

The conductivity σ is related to the commonly used penetration factor C [8] by the following expressions $\sigma_x = C_x/\mu$, $\sigma_y = \sigma_z = C_y/\mu$.

Air motion is described by equations similar to (10), (11), (12) with replacement of $\mu \to \mu_a$.

Figure 1b depicts the situation when the fluid moving along tracheid 1 overlaps a part of the pores connecting tracheids 1 and 2. Here, the overflow of both the fluid and air are seen to overflow from tracheid 1 to 2. Thus, the number of pores covered with the fluid gradually increases. We can assume that due to the wetting effect all pores will be overlapped earlier than all air will be forced out of tracheid 1. Starting from this moment only the fluid will overflow from tracheid 1 but air remains trapped in this tracheid and only undergoes compression with increasing pressure.

Denote the part of the tracheid volume occupied by the fluid by α and the critical value of α at which pores are completely overlapped with the fluid by α_c. Since $\mu_a << \mu_f$, then at $\alpha < \alpha_c$ we can neglect the fluid overflow. Then

$$\mathbf{q}_f = \begin{cases} 0 , & \alpha < \alpha_c , \\ -\sigma_f \nabla P , & \alpha \geq \alpha_c , \end{cases} \quad \mathbf{q}_a = \begin{cases} -\sigma_a \nabla P , & \alpha < \alpha_c , \\ 0 , & \alpha \geq \alpha_c . \end{cases} \tag{13}$$

The effective density of the fluid and air per unit volume of wood is equal to

$$\rho_f = \alpha \varepsilon \overset{0}{\rho_f} , \quad \rho_a = (1 - \alpha) \varepsilon \overset{0}{\rho_a} \frac{P}{P^0} , \tag{14}$$

respectively, where ε is the air capacity of wood (the share of the volume free of cell walls [5]); P_0 is atmospheric pressure; $\overset{0}{\rho_f}$, $\overset{0}{\rho_a}$ is the density of the impregnating fluid and air at atmospheric pressure, respectively. The parameters ρ_f and ρ_a must satisfy the equations of the mass conservation law

$$\frac{\partial \rho_f}{\partial \tau} = -\operatorname{div} (\rho_f \mathbf{q}_f) , \quad \frac{\partial \rho_a}{\partial \tau} = -\operatorname{div} (\rho_a \mathbf{q}_a) . \tag{15}$$

Thus, in the context of the model suggested the process of wood impregnation is described by a system of Eqs. (13), (14), (15) which should be supplemented with the following initial and boundary conditions

TABLE 1. Wood Penetration Factors and Conductivities of Pine and Fur-Tree Timber

Kind of wood	Sapwood		Core	
	C, Darcy	$\log\sigma$	C, Darcy	$\log\sigma$
Pine:				
along the fiber	30.2	−7.5	1.88	−8.7
across the fiber	$21\cdot10^{-4}/3.7\cdot10^{-4}$	−11.6/−12.4	$3.6\cdot10^{-4}/0.79\cdot10^{-4}$	−12.4/−13.1
Fur-tree:				
along the fiber	0.58	−9.2	0.03	−10.5
across the fiber	$0.76\cdot10^{-4}/8\cdot10^{-6}$	−13.1/14.1	$8\cdot10^{-6}/1\cdot10^{-7}$	−14.1/−16

$$\rho_f(0, x) = \rho_{f0}, \quad \rho_a(0, x) = \rho_{a0}, \tag{16}$$

$$P|_{x\in\Gamma} = P_{ext}(\tau) \tag{17}$$

(P_{ext} is the prescribed external pressure, Γ is the sample surface). The conductivities σ entering Eqs. (13) can be either calculated by formulas (12) in terms of the microstructure parameters of wood or determined experimentally.

For further development of the model we take into account the effects of wetting of cell walls by an impregnating fluid and the wetting hysteresis. These factors must be manifested, in particular, in the influence of the process prehistory on the dependence of a local fluid flow on a pressure gradient. In a first approximation, the wetted state of a cell wall can be characterized by the step function W taking the value 0 or 1:

$$W(\tau, x) = \theta\left\{\int_0^{\tau} \theta\,[\alpha(\tau', x) - \alpha_c]\,d\tau'\right\}, \tag{18}$$

where $\theta(\xi)$ is the Heaviside function. The initial state corresponds to $\alpha < \alpha_c$ and, correspondingly, $W = 0$. Henceforth W acquires the value 1 at those points of space and at those instants when α begins to exceed α_c. The reverse transition $W = 1 \to 0$ occurs under wood drying conditions which are not considered in the present work.

The influence of W on the specific fluid flow q_f includes:

1) the dependence of α_c on the state of a cell wall:

$$\alpha_c = \begin{cases} \alpha_1 & \text{at} \quad W = 0, \\ \alpha_2 & \phantom{\text{at}} \quad W = 1; \end{cases}$$

2) the residual pressure gradient attributable to multiple formation of menisci (the Zamein effect):

$$q_f = -\sigma_f \begin{cases} \nabla P & \text{at } W = 0 \\ \nabla P\,(1 - G/|\nabla P|) & \text{at } W = 1, \quad |\nabla P| > G \;(\alpha > \alpha_c). \\ 0 & \text{at } W = 1, \quad |\nabla P| \le G \end{cases} \tag{19}$$

The parameter G represents the limiting pressure gradient attributable to the wetting hysteresis. Its maximum value can be determined based on the assumption that one tracheid is one meniscus and from the literature data [8] for the pressure drop per meniscus. Refinement of the G value is made from a comparison of the calculated and experimental results.

Along with anisotropy the essential feature of wood is its inhomogeneity (for instance, early- and latewood, wood core and sapwood, moist and dry zones). Therefore the parameters of the model suggested must be considered, generally speaking, as functions of coordinates.

In monograph [8] the penetration factors obtained experimentally are generalized for the wood of pine and fur trees (Table 1).

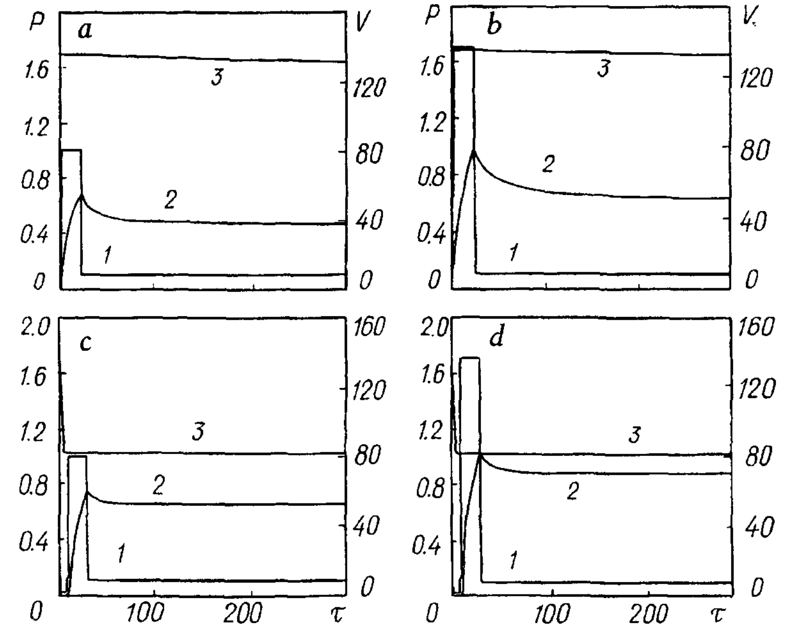

Fig. 2. Influence of the pressure and preliminary evacuation on absorption of the impregnating fluid and air release from the wood sample (pine 15 × 6 × 3 cm): a) P_{max} = 1.0 MPa; Δm_f = 38.3 g; ΔV = 1.8 mliter; b) 1.7; 51; 2.1; c) P_{max} = 1.0 MPa; Δm_f = 50.3 g; d) 1.7; 65; 1 is the pressure of the impregnating fluid; 2 is the fluid volume in the wood; 3 is the air volume in wood. P, MPa; V, mliter; τ, min.

In the table the denominator gives the penetration factors for radial/tangential directions across the fibers. The log σ columns give the conductivities corresponding to the indicated penetration factors.

The results of calculations of the kinetics of wood impregnation by the model suggested are given in Fig. 2 for two pressure values (10 and 17 atm) of the impregnating fluid. They make it possible to analyze the influence of pressure and vacuum on the kinetics of fluid absorption and air release from the bulk of wood under impregnation. In the calculations, the following values of the governing parameters were adopted: log $\sigma_x = -7.5$; log $\sigma_y = -12$; $\varepsilon = 0.5$, which correspond to sapwood impregnation. Curves 2 and 3 in the figure correspond to the volumes (in mliter) of air and the fluid contained in the wood sample in the course of impregnation.

As is seen, with increasing pressure P the volume V of the impregnating fluid absorbed increases considerably. Here, a portion of the fluid forced out of wood after pressure relief increases as well but air liberation from the wood bulk is insignificant. To decrease the release of the fluid from wood and, correspondingly, to increase its absorption, prior vacuum treatment was performed. A comparison of Fig. 2a, b and c, d confirms that the prior vacuum treatment considerably decreases the amount of fluid discharged from the wood bulk after pressure relief due to relaxation of the air pressure in the wood pores. In the latter case (Fig. 2c, d) the impregnation conditions corresponded to the technique of complete (maximum) absorption of the fluid, while the version a, b pertains to the method of limited (semilimited) absorption.

Experimental Bench. Experimental Procedure. The choice or development of a technique and a regime of impregnation and the choice of an impregnating solution must involve their testing on laboratory benches. For this purpose we have developed and manufactured a laboratory test bench providing wide possibilities for investigation and development of an impregnation technology for different methods tested.

A schematic diagram of the bench is shown in Fig. 3. The internal diameter of the impregnation cylinder was 127 mm; the total capacity was 2 liters. In the course of an experiment the amount of impregnating fluid absorbed by a sample in time (kinetics of the process) can be controlled both by the weight method and by a level gauge of the cylinder.

Now consider in succession the operational principles of the bench for different methods of pressure impregnation of wood.

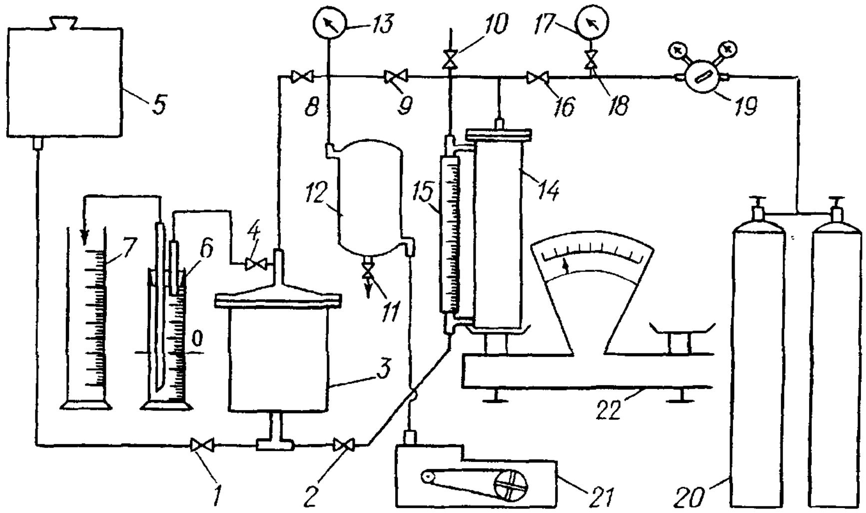

Fig. 3. Schematic of the impregnation test bench: 1) filling valve; 2) connecting valve; 3) impregnation tank; 4) valve connecting the impregnation tank with the measuring unit; 5) filling vessel; 6, 7) air and fluid measuring cylinders, respectively; 8, 9) vacuum valves; 10) valve of pressure relief in the system; 11) atmospheric valve; 12) vacuum receiver; 13) vacuum gauge; 14) pressure vessel; 15) level gauge; 16) pressure valve; 17) manometer; 18) manometer valve; 19) pressure regulator; 20) gas cylinders; 21) vacuum pump; 22) balance.

Impregnation by the Limited Absorption Method (the Atmospheric Pressure–Pressure (APP) Method). Prior to impregnation the air in wood is at atmospheric pressure (it can also be at a higher pressure); then a pressure of the impregnating fluid is created.

With hermetically sealed impregnation vessel 3 and with valve 4 shut the imprègnating fluid is poured into filling vessel 5. By means of pressure regulator 19 and manometer 17 the prescribed pressure is set, which is then smoothly transferred to pressure vessel 14 by means of valve 16. The sample is placed into impregnation cylinder 3, the cover of which is hermetically sealed. Opening sequentially valves 4, 1, the impregnation cylinder is filled. The initial readings of the balance and the level gauge (or one of the measuring units used under the experimental conditions) are recorded. Next, valve 2 is opened thus connecting the pressure vessel with the impregnation tank. Simultaneously, time is recorded and the amount of the fluid absorbed by the sample is periodically measured.

The system for measuring the amount of the impregnating fluid and air released (returned) by the sample after pressure relief in the impregnation tank consists of two glass cylinders 6 and 7, one of which is vented to the atmosphere while the second cylinder is sealed with a rubber plug with two (inlet and outlet) pipes. When the fluid and the gas arrive in hermetically sealed cylinder 6, the internal pressure in the latter changes and squeezes out an equivalent volume of the fluid to cylinder 7, thus restoring the equilibrium state in cylinder 7, in which the amount of air increases and the fluid level lowers correspondingly to the volume of the air introduced.

The experimental data in Fig. 4a demonstrate the high intensity of pressure impregnation reached over small times. With pressure relief an insignificant amount of air is released. According to the measurement data for various dry wood samples for the first hour of relaxation after pressure relief 40 to 70% of the fluid absorbed by the sample is removed. The fluid remaining in the sample is retained in the porous wood skeleton by capillary forces and is due to moisture sorption by the cell walls. The preliminary experiments have shown that due to capillary impregnation the amount of fluid absorbed by the samples immersed in the latter is from 2 to 12% of the initial mass of the sample for a period equal to the experiment time and depends on its initial moisture content and structure. For the reference samples no more than 10–15 mliter was absorbed in this experiment owing to capillary impregnation under wood steeping conditions.

Impregnation by the Maximum Absorption Method (Vacuum–Pressure (VP) Method). Saturation is attained by preliminary evacuation of wood followed by its pressure impregnation.

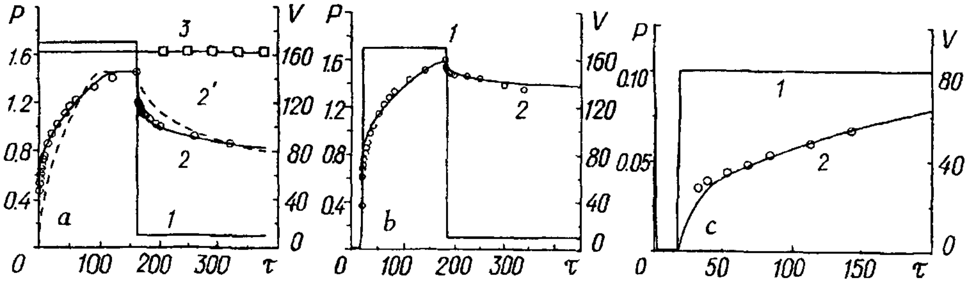

Fig. 4. Comparison of the calculated curves and experimental data for different impregnation methods (pinewood 150 × 60 × 30 mm): a) limited absorption (the APP method); b) complete absorption (the VP method); c) vacuum–atmospheric pressure (the VAP method): 1) pressure of the impregnating fluid; 2) volume of the fluid absorbed by the wood (the two-layer model); 2') the same for the one-layer calculation model; 3) air volume in the wood.

For preliminary evacuation of wood vacuum pump 21 is switched on. With valve 4 being shut, value 8 is opened and vessel 3 is evacuated for 10–15 min to attain a vacuum of about 0.016–0.02 atm (1418–2026 Pa). Then valve 8 is shut; the pump is switched off. The next stages are repeated as in the previous case.

The preliminary evacuation affects the pressure-relief stage. A small residual amount of air in the pores after evacuation is responsible for the small amount of fluid released from the sample after pressure relief. As is seen from Fig. 4, preliminary evacuation allows an almost twofold increase of absorption of the impregnating fluid by the sample.

Impregnation by the "Vacuum–Atmospheric Pressure (VAP)" Method. Wood is at first evacuated, then the impregnating fluid enters the cylinder, and impregnation is accomplished at atmospheric pressure.

Experimental data for this impregnation technique are provided in Fig. 4c. This method can be efficient for practical applications when penetration of an impregnating solution to great depths is not needed.

Analysis of the Calculated and Experimental Results. Figure 4 also provides the results of numerical calculations for the impregnation methods described above in which the wood characteristics (the calculated parameters) have been determined from the experimental data. The satisfactory correlation of the experimental points and the theoretical curves is indicative of the wide possibilities of the physical and mathematical model used.

A comparison of the calculation results reveals the interrelationships of the air capacity ε, being a function of the initial moisture content and the structure of the wood sample, with the mass increment of the sample and the volume of the fluid discharged after pressure relief of the impregnating fluid. For dry wood the air capacity coincides with porosity [5]. It is obvious that for extended impregnation times upon establishing a pressure equilibrium of the air and the fluid in the wood bulk the total absorption by the wood will be determined by its air capacity minus the volume of the air compressed. With increasing impregnation pressure or upon deep evacuation of the wood the absorption volume and the air capacity differ insignificantly. The longitudinal and transverse conductivities σ_x, $\sigma_y = \sigma_z$ determine the rate and depth of longitudinal and transverse impregnation and, correspondinly, the fluid distribution within the wood volume. The critical volume α_c characterizing the amount of trapped air in a tracheid exerts an influence on the rate of air release from the wood and the fluid distribution in the volume.

A comparison of the experimental and calculated results has revealed that the governing parameters of impregnation can vary within rather wide ranges: $\varepsilon = 0.4$–0.6, $\log \sigma_x = -6$ to -8.7, $\log \sigma_y = -8$ to -12.5, $\alpha_c =$ 10–90%, as a consequence of the large scatter of the experimental data due to the difference in structural characteristics of the samples. These data are satisfactorily consistent with the data of [8] given in Table 1. The value of the pressure gradient of capillary forces G that mainly determines the amount of fluid remaining in the wood after pressure relaxation due to the menisci forces is $G_x = 0.015$–10 kPa/m, $G_y = G_z = 1$–1000 kPa/m. The difference of the experimental and theoretical dependences of the kinetics of impregnation (Fig. 4a, curve 2') can be attributed to the use of averaged parameters in the calculations. Considerably better agreement is attained in

TABLE 2. Comparison of the Absorption Volumes of the Impregnating Fluid by Pinewood for Different Impregnation Methods

Impregnation method	Maximum absorption, liter/m^3	Fluid discharge with pressure relaxation, $\frac{\text{liter/m}^3}{\%}$	Fluid remaining in wood, $\frac{\text{liter/m}^3}{\%}$
APP (limited absorption)	580	238/41	342/59
VP (maximum absorption)	645	120/19	525/81
VAP	258	–	258/100

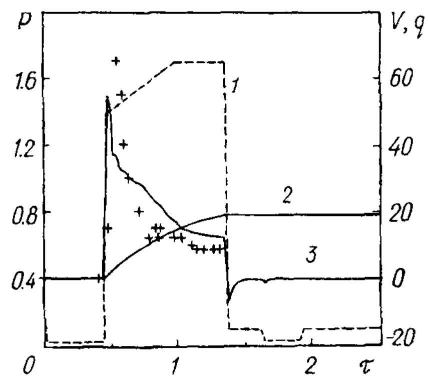

Fig. 5. Modeling of the impregnation process of the wooden tie and comparison of the calculated results and experimental data (pinewood, 280 × 24 × 16 cm): 1) pressure of the impregnating fluid; 2) volume of the solution absorbed by the tie; 3) flow rate of the fluid absorbed by the tie (curves are the calculation, the points are the experiment). V, liter; q, liter/h; τ, h.

the calculations made by the two-layer model assuming that the sample has a core and a sapwood part (curve 2 where for 60% of the sample thickness $\log \sigma_x = -7.8$; $\log \sigma_y = -12.0$, but for 40% of the thickness $\log \sigma_x = -6.0$; $\log \sigma_y = -10.0$).

Thus, the model suggested allows calculation of the impregnation process with a satisfactory accuracy and determination of the wood properties from measurement results.

Table 2 gives generalized data on impregnation aimed at achieving the maximum saturation of dry pine wood with a core of 30–50% by different methods at a fluid pressure of 1.6 MPa for 160 min including evaluation for 15 min at an air pressure of 1.5 kPa. For the internal pressure of air to relax, the samples were held after impregnation for no less than two days under conditions preventing their drying. In practice, to speed up the process of internal pressure relaxation and, correspondingly, to decrease the impregnating fluid loss timbers are usually exposed to postimpregnation evacuation [9]. The table illustrates the capabilities of each of the impregnation methods and allows the choice of the method expected to be most efficient for particular tasks.

Figure 5 presents the data calculated by the two-layer model for impregnation with maximum saturation of a railway tie consisting of sapwood (20%) and a core (80%) by the vacuum–pressure–vacuum (VPV) method. Here, the measurement results obtained for industrial antiseptic impregnation of pine ties by an aqueous protective solution are presented. In the calculation, the pressure is determined from the experimental data; the calculated parameters of the process were found from the laboratory measurements described above. The total amount of wood in the impregnation cylinder was about 21 m^3 (210 ties). Figure 5 gives experimental values of the fluid flow absorbed by the wood, obtained by measurements by a flow meter, recalculated per tie. Solution absorption by a tie after impregnation was determined by control weighing of an arbitrarily chosen 12 ties followed by averaging the increase in weight. In terms of the volume indices this value was 18.2 ± 4.5 liters, which agrees well with the calculated results.

The consistency observed between the calculated and experimental data for different methods of impregnation allows us to draw the conclusion that the physical and mathematical model suggested can be used to describe the process of pressure saturation of wood by a fluid and that the calculation procedure above shows promise for modeling of the technological processes of wood impregnation.

NOTATION

P, pressure; Q, total fluid flow; R, hydraulic resistance; V, volume; G, pressure gradient due to wetting hysteresis (the Zamein effect); Δm, ΔV, change in the mass and volume, respectively; r, l_t, tracheid radius and length, respectively; x, y, z, coordinates; ε, air capacity of wood; μ, dynamic viscosity; ρ, density; σ, conductivity; τ, time. Sub- and superscripts: a, air; c, critical; ext, external; f, fluid; max, maximum; p, pores; s, sample; 0, initial value.

REFERENCES

1. S. N. Gorshin, *Wood Preservation* [in Russian], Moscow (1977).
2. G. M. Ostrovskii, A. Yu. Ivanenko, and E. G. Aksenova, *Teor. Osnovy Khim. Tekhnol.*, **29**, No. 6, 607-611 (1995).
3. N. N. Grinchik and V. P. Kozhin, in: *Modern Problems of Combustion and Its Applications*, Proc. of the IInd School-Seminar, Minsk (1997), pp. 93-94.
4. V. E. Vikhrov, *Diagnostic Wood Criteria of the Main Forestry and Timber Species in the USSR* [in Russian], Moscow (1959).
5. B. N. Ugolev, *Wood Science and Fundamentals of the Science of Timber Commodities* [in Russian], Moscow (1986).
6. V. I. Patyakin, Yu. G. Tishin, and S. M. Bazarov, *Engineerinng Hydrodynamics of Wood* [in Russian], Moscow (1990).
7. B. S. Chudinov, *Water in Wood* [in Russian], Novosibirsk (1984).
8. N. A. Osnach, *Penetrability and Conductivity of Wood* [in Russian], Moscow (1964).
9. P. S. Sergovskii and A. I. Rasev, *Hydrothermal Processing and Preservation of Wood* [in Russian], Moscow (1987).