

Simulation of technological process of aerosol wood impregnation

*Vladimir Shamaev**, *Iliya Medvedev*, *Aleksander Russu*, *Nikolai Trubnikov*,
Aleksander Khvorykh, *Valeriy Malikov*, and *Oksana Garkusha*

Voronezh State University of Forestry and Technologies named after G.F. Morozov, 8, Timiryazeva str., Voronezh, 394087, Russian Federation

Abstract. The process of impregnation of timber bars using a dispersed antifriction compound is studied. An air flow, containing inclusions of impregnating liquid, is formed in a special installation. The flow moves mainly in the direction of the fibers. Deposition of liquid particles on the surface of the porous system of wood takes place during this process. A description of a pilot installation performing aerosol impregnation process is presented. Technical conditions of its work to create the optimal content of Biol grease in hardwood specimens are specified. A mathematical model for the non-stationary adsorption of particles of aerodisperse mixture on the surface of a porous wood matrix has been developed, based on the mechanics of multiphase systems. The analysis of the mathematical model for one-dimensional approximation is carried out. It is shown that the calculated averaged values of the volume concentration of precipitated liquid component for different values of wood initial porosity are in satisfactory agreement with the experimental data. The formulated mathematical models enable to predict the distribution dynamics of parameters for aerosol wood impregnation process along the specimen length depending on the operating characteristics and average value of initial wood porosity.

1 Introduction

Modification is the most promising area of comprehensive improvement of wood physical mechanical, tribological and operational properties [1-3]. Modified wood is used in mechanical engineering as a material for manufacture of self-lubricating sleeve bearings [4]. Such bearings can be used for lightly loaded friction units instead of bronze and thermazote ones. There is also increasing interest in modifying the decorative properties of subsidiary wood species [5, 6].

The main technological operations of wood modification are drying, impregnation, and pressing. Dried wood specimens are impregnated with antifriction compounds, for example, Biol lubricant. It is established that the optimum content of the lubricant should be 7-9% relative to the mass of dry wood. The composition should be evenly distributed throughout

* Corresponding author: drevstal@mail.ru

the volume of specimen. Impregnated specimens are pressed into special pressing tools up to a density of $\sim 1250 \text{ kg/m}^3$ [7].

The best known method of wood treatment is impregnation using solutions. This method involves additional technological operation of subsequent removal of the solvent from the porous system of wood. The solvent removal process affects the properties of resulting material. In particular, its tensile strength is significantly reduced.

Patent № 2646612 suggests a fancy technology of aerosol impregnation of wood with a lubricating composition, which does not have the above disadvantages. Special installation delivers lubricant to the capillary-porous system in a dispersed form. At the same time, it is possible to achieve both the required concentration of lubricant and sufficiently uniform impregnation of wood specimens.

The mechanisms for the lubricant droplets deposition in wood material have not been fully studied yet. Summ [8] showed that in spite of the limited ability of the liquid phase to wetting, full spreading of liquid over the surface is still realized in the porous structure. Spreading of oil droplets on the surface of wood porous system is a spontaneous process that occurs due to a decrease in the free surface energy of the system. Deposition of oil droplets on the walls of pores and capillaries occurs under the influence of four types of mechanisms - inertial, impaction, sedimentation and diffusion ones [9].

This paper presents the results of theoretical and experimental study of the laws of wood aerosol impregnation process.

Wood is a heterogeneous system with a complex inhomogeneous structure. The observed patterns of mass transfer in such bodies appear to be the result of fairly complex phenomena occurring at micro and macro levels. Common transfer equations used in continuous homogeneous media cannot be used to study the movement of gases and liquids with irregular structure [10]. Well-known studies [11-13] created scientific approaches taking into account the effects of the mutual influence of individual phases on the patterns of heat and mass transfer in heterogeneous systems. A mathematical model on the basis of the mechanics of multiphase systems for the movement of dispersed fluid in a porous wood system has been formulated in this paper, taking into account partial depositions on the walls of woody cells.

2 Experiment

Birch, aspen and oak wood were used for experiments on aerosol treatment of wood specimens. The scheme of experimental installation is shown in Figure 1.

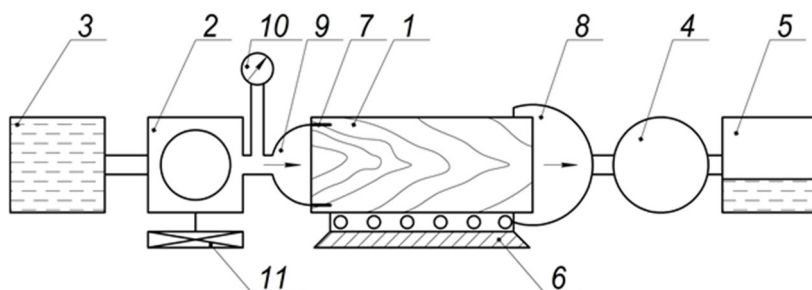


Fig. 1. Installation scheme for wood impregnation. Here 1 - wood specimen; 2 - fuel injection pump; 3 - tank with hot lubrication; 4 - vacuum pump; 5 - separator; 6 - frame; 7 - knives; 8 - vacuum head; 9 - impregnating head; 10 - manometer; 11 - compressor.

The frame 6 is equipped with heating elements. Fuel high-pressure pump (fuel pump) 2 and wood specimen 1 are fixed on it.

The impregnation process is as follows. Wood specimen 1 with dimensions 80x80x700 mm (the last dimension is along the fibers), having a moisture content of 2-4%, is fixed in a heated frame 6. Knives 7 of rectangular section are punched from one end of the specimen, and vacuum head 8 is put on from the other end. Impregnating liquid (from the tank 3 with a temperature of 70-75°C) enters the pump. From here, aerosol mixture with a concentration of 5.7-10% under a pressure of 2.5-6 MPa is fed by the compressor 11 through the nozzles to the end of the work piece. Vacuum pump 4 creates small vacuum of 80 kPa at the opposite side of the specimen. Thus, directed aerosol flow is created. The residual liquid substance is drained into the separator 5 after soaking, where the liquid is separated from the air and then returned to the tank 3.

Experiments have shown that the time of impregnation depends on the length of the specimen and wood species. In particular, the impregnation process takes 20 minutes in case of birch specimen with the length of 0.7 m. The content of the lubricant in the specimen reaches 7-9% (by weight). The concentration difference does not exceed 1% at the ends of the specimens.

3 Mathematical model

3.1 Assumptions and Limitations

Macroscopic description of aerosol wood impregnation process has been built with the following assumptions and limitations:

1. Pore and capillary diameters greatly exceed molecular kinetic dimensions.
2. The size of inhomogeneities is significantly smaller than those distances at which the macroscopic parameters of individual phases vary significantly.
3. The kinetic energy of small-scale motion can be neglected in all phases of the system.
4. The solid phase is incompressible and non-deformable one.
5. The gas mixture can be considered as ideal gas.

The transfer equations for liquid, solid and gaseous phases of the system are obtained by volumetric averaging the equations written for the microparameters over the volume of each phase. The subscripts: 1 - gas phase, 2 - liquid phase, 3 - solid phase are used to designate the values related to the individual phases of the wood system. Each instant micro parameter corresponds to its average value. For example, the average value $\langle x_2 \rangle_2$ for the x_2 parameter, averaged over the liquid macrovolume dV_2 , has the form:

$$\langle x_2 \rangle_2 = \frac{1}{dV_2} \int_{dV_2} x_2' dV.$$

In this expression the sign ' refers to the variables that are defined as averages within the dV microvolume, the value of which is substantially less than the characteristic size of inhomogeneities. The equations written below contain the values of the variables averaged over the volumes of phases 1, 2, 3. To shorten the records, the averaging sign $\langle \rangle_i$ is omitted, i.e. $\langle x_2 \rangle_2$ is indicated below like x_2 .

We believe that wood is demoiustrized. Its initial moisture content corresponds to the presence of only chemically bound water. The liquid phase consists of treating solution inclusions. Additionally, we assume that the liquid phase is incompressible, its density is constant - $\rho_2^0 = const$; crushing, coagulation processes and phase transitions are absent. It is believed that wood substance is a material of the skeleton, it is also incompressible. It is not deformed during the impregnation process and $\rho_3^0 = const$.

We take into account that the specimen and aerosol components are subjected to preliminary heat treatment, so that a uniform temperature distribution is established in the wood and in the aerosol. Phase transitions are absent. The mass transfer process being studied is isothermal on: $T_1 = T_2 = T_3 = T$.

3.2 Conservation equations for a three-phase system

Diffusion-filtration transfer of the dispersed medium and adsorption of the dispersed phase on the pore surface take place in the process of aerosol wood impregnation. Let's write the conservation equations for a three-phase system and show that these equations require clarification for the technological task of aerosol impregnation.

The continuity equations for gaseous and liquid phases of a disperse system impregnating capillary and porous structure of wood are as follows:

$$\frac{\partial(\rho_1^0 \alpha_1)}{\partial t} + \nabla^k (\rho_1^0 \alpha_1 v_1^k) = 0; \tag{1}$$

$$\frac{\partial(\rho_2^0 \alpha_2)}{\partial t} + \nabla^k (\rho_2^0 \alpha_2 v_2^k) = 0, k = 1, 2, 3, \tag{2}$$

where t – time, c ; v – speed, m/s ; ρ_i^0 ($i = 1, 2, 3$) - real density of phases, α_i - volume concentration of the i -phase. Volume concentrations of phases are related by the ratio

$$\alpha_1 + \alpha_2 + \alpha_3 = 1. \tag{3}$$

The equations of change in the variation of momentum are written without taking into account the dynamic effects of the deposition process of droplets on the wood matrix surface.

$$\rho_1^0 \alpha_1 \left(\frac{\partial \vec{v}_1}{\partial t} + v_1^k \nabla^k \vec{v}_1 \right) = \nabla^k \alpha_1 \langle \vec{\sigma}_1^{kl} \rangle + \rho_1^0 \vec{g}_1 + \nabla^k P_1^k + \vec{R}_{21} + \vec{R}_{31}, \tag{4}$$

$$\rho_2^0 \alpha_2 \left(\frac{\partial \vec{v}_2}{\partial t} + v_2^k \nabla^k \vec{v}_2 \right) = \nabla^k \alpha_2 \langle \vec{\sigma}_2^{kl} \rangle + \rho_2^0 \vec{g}_2 + \nabla^k P_2^k + \vec{R}_{12} + \vec{R}_{32}, \tag{5}$$

$$\vec{R}_{ij} = -\vec{R}_{ji}, \vec{R}_{ji} = s_{ij} \left\langle \sigma_i' (n_i^i) \langle \sigma_i^{kl} \rangle_{ij} \langle \sigma_i^{kl} n_i^k \rangle_{ij} \right\rangle, \rho_i^0 \vec{g}_i = \langle \rho_i^0 \vec{g}'_i \rangle_i,$$

where \vec{R}_{ij} – the vector of surface forces acting on the part of the i phase on the j phase per a volume unit of a system, σ_i' - stress tensor acting on the surface of i phase of the selected volume; \vec{g}'_i - vector of external mass forces per unit volume; \vec{n}_i - vector of singular external normal to the interfacial surface between the i -th and j -th phases, directed towards the phase with j number. Tensor Π_i determines pulsation stresses, which are similar to Reynolds stresses during turbulent fluid motion.

Equations (7-8) can be represented in a form being more convenient for analysis. For this, we use the decomposition of stress tensor into ball and deviator components.

$$\langle \sigma_i^{kl} \rangle_i = -\langle p_i' \rangle_i \delta^{kl} + \langle \tau_i^{kl} \rangle_i, \tag{6}$$

And we also present the force interaction of phases, determined by the vectors \vec{R}_{ij} , as a sum of components associated with the resistance of microparticles to changing volume and shape:

$$\vec{R}_{ji} = \vec{R}_{ji}^{(p)} + \vec{R}_{ji}^{(\tau)}; \vec{R}_{ji}^{(p)} = \langle p_i' \rangle_i \nabla \alpha_i + \Delta \vec{R}_{ji}^{(p)}. \tag{7}$$

In the expressions (6, 7) p – pressure, $\langle \tau_i^{kl} \rangle_i$ - tangential stress tensor.

Let us note that the forces of interfacial interaction are associated with small-scale pressure pulsations due to the difference in phase acceleration relative to each other. It can be written:

$$-\Delta \vec{R}_{ji}^{(p)} = \chi_{mji} \rho_i^0 \alpha_i \alpha_j \left(\frac{d_i \vec{v}_i}{dt} - \frac{d_j \vec{v}_j}{dt} \right). \tag{8}$$

where χ_{mji} – mass coefficients, $i, j=1, 2, 3$.

Forces $\vec{R}_{ij}^{(\tau)}$ are connected with viscous forces on interfacial area; their values are given by the formulas:

$$-\vec{R}_{ji}^{(\tau)} = \frac{\mu_i \alpha_i}{K_{i-j}} (\vec{v}_i - \vec{v}_j), \tag{9}$$

where μ - viscosity, K_{i-j} – permeability coefficient of i phase in j phase.

Taking into account (6, 7), the equations of motion (4, 5) can be written as follows:

$$\rho_1^0 \alpha_1 \left(\frac{\partial v_1^l}{\partial t} + v_1^k \nabla^k v_1^l \right) = -\alpha_1 \nabla^l \langle p_1' \rangle_1 + \nabla^k (\alpha_1 \langle \tau_1^{kl} \rangle) + \nabla^k P_1^{kl} + \Delta R_{21}^{(p)} + \Delta R_{21}^{l(\tau)} + \Delta R_{31}^{(p)} + \Delta R_{31}^{l(\tau)} \tag{10}$$

$$\rho_2^0 \alpha_2 \left(\frac{\partial v_2^l}{\partial t} + v_2^k \nabla^k v_2^l \right) = -\alpha_2 \nabla^l \langle p_2' \rangle_2 + \nabla^k (\alpha_2 \langle \tau_2^{kl} \rangle) + \nabla^k P_2^{kl} + \Delta R_{12}^{l(p)} + \Delta R_{12}^{l(\tau)} + \Delta R_{32}^{l(p)} + \Delta R_{32}^{l(\tau)} \tag{11}$$

Obviously, a mathematical model based on equations (1-2, 10-11), enables to control the change in polar concentrations of treating solution in the specimen, but it does not completely eliminate the features of the technological process of aerosol impregnation. The fact is that: the presence of free particles of liquid phase is possible at this point of wood specimen. These particles move with air flow. The presence of liquid phase elements, trapped by filter, is also possible. It is precisely the dynamics of concentration distribution of precipitated liquid phase that is important for the industrial process control of aerosol impregnation.

3.3 Transfer equations in a three-phase system for determining the concentration of precipitated liquid phase

More detailed description of the transfer processes in the liquid phase is needed to determine the concentration of the precipitated component. It is achieved by additionally averaging all dependent variables over the volume of precipitated liquid phase (dV_{2a}) and the volume of the non-precipitated liquid phase (dV_{2n}) according to the method of Dornyak [14-16].

In this case, the representation for some arbitrary variable y_2 in the following form makes sense

$$\langle y_2 \rangle_2 = \alpha_{2a} y_{2a} + \alpha_{2n} y_{2n}, \tag{12}$$

where

$$\alpha_{2a} = \frac{dV_{2a}}{dV_2}, \alpha_{2n} = \frac{dV_{2n}}{dV_2}, \alpha_{2a} + \alpha_{2n} = 1.$$

Here, index $2a$ refers to the adsorbed part of the dispersed aerosol phase; $2n$ refers to the non-adsorbed part.

Volume content of precipitated and non-precipitated liquid is denoted like m_{2a} and m_{2n} , respectively:

$$m_{2a} = \frac{dV_{2a}}{dV}, m_{2n} = \frac{dV_{2n}}{dV}.$$

It is obvious that m_{2a} and m_{2n} values are related to the concentration of liquid phase α_2 as follows: $m_{2a} = \alpha_{2a} \cdot \alpha_2$; $m_{2n} = \alpha_{2n} \cdot \alpha_2$; $m_{2a} + m_{2n} = \alpha_2$.

Let us consider how the system of transport equations changes after the introduction of an additional averaging of the following form (12).

Averaging the continuity equation for a liquid over the volumes of adsorbed and non-adsorbed inclusions, we have:

$$\frac{\partial(\rho_2^0 m_{2a})}{\partial t} + \nabla^k (\rho_2^0 m_{2a} v_{2a}^k) = -J_n; \tag{13}$$

$$\frac{\partial(\rho_2^0 m_{2n})}{\partial t} + \nabla^k (\rho_2^0 m_{2n} v_{2n}^k) = J_n. \tag{14}$$

where J_n - mass of dispersed particles precipitated per time unit in a volume unit of the liquid phase.

Summarizing these two equations, we get

$$\frac{\partial(\rho_2^0 \alpha_2)}{\partial t} + \nabla^k [(\rho_2^0 (m_{2a} v_{2a}^k + m_{2n} v_{2n}^k))] = 0. \tag{15}$$

Assuming that the particles, captured by the wood as a filter, have a speed which is close to zero one, we can write:

$$\vec{v}_{2a} = 0. \tag{16}$$

Taking into account (16), the velocity vector of the dispersed phase, averaged over the liquid volume, is expressed as follows:

$$\vec{v}_2 = \frac{m_{2n}}{\alpha_2} \vec{v}_{2n}. \tag{17}$$

In view of (17), equations (13-15) take the form:

$$\frac{\partial(\rho_2^0 m_{2a})}{\partial t} = -J_n; \tag{18}$$

$$\frac{\partial(\rho_2^0 m_{2n})}{\partial t} + \nabla^k (\rho_2^0 m_{2n} v_{2n}^k) = J_n; \tag{19}$$

$$\frac{\partial(\rho_2^0 \alpha_2)}{\partial t} + \nabla^k (\rho_2^0 \alpha_2 v_2^k) = 0. \tag{20}$$

Value $-J_n$ characterizes the intensity of aerosol particles precipitation in a porous matrix.

Since only two equations from system (18-20) are independent, any two of them should be included in the mathematical model.

The equations of change in the amount of motion are written without taking into account the precipitation dynamic effects, pulsation stresses and mass forces. The effects of viscous friction can also be neglected for the gas phase and equation (10) can be used as follows:

$$\rho_1^0 \alpha_1 \left(\frac{\partial v_1^l}{\partial t} + v_1^k \nabla^k v_1^l \right) = -\alpha_1 \nabla^l \langle p'_1 \rangle_1 + \Delta R_{2n,1}^{l(p)} + \Delta R_{2n,1}^{l(\tau)} + \Delta R_{31}^{l(p)} + \Delta R_{31}^{l(\tau)} + \Delta R_{2a,1}^{l(p)} + \Delta R_{2a,1}^{l(\tau)}. \tag{21}$$

The velocity field of the liquid phase, which is not kept by the porous system of the sample, is determined using the equation derived from (11):

$$\rho_2^0 m_{2n} \left(\frac{\partial v_{2n}^l}{\partial t} + v_{2n}^k \nabla^k v_{2n}^l \right) = -m_{2n} \nabla^l \langle p'_2 \rangle_2 + \nabla^k (m_{2n} \langle \tau_2^{kl} \rangle) + \Delta R_{1,2n}^{l(p)} + \Delta R_{1,2n}^{l(\tau)} + \Delta R_{3,2n}^{l(p)} + \Delta R_{3,2n}^{l(\tau)} + \Delta R_{2a,2n}^{l(p)} + \Delta R_{2a,2n}^{l(\tau)}. \tag{22}$$

It should be pointed out that the added interaction forces between gaseous and liquid phase retained on the walls of woody cells in (21) and (22) are linked with additional averaging (12). The forces of interaction between the phases and the components should be written with reference to the average velocity of the non-precipitated particles \vec{v}_{2n} using the formulas (8-9).

The statement of the problem for studying the process of aerosol impregnation contains 5 differential equations of differential derivatives (1, 19, 20, 21, 22) for dependent variables $p_1(\rho_1), m_{2n}, \alpha_2, \vec{v}_1, \vec{v}_{2n}$. These conservation equations should be supplemented with gas equation and a system of initial and boundary conditions.

3.4 One-dimensional formulation of the problem of non-stationary precipitation of air-dispersed mixture particles on the surface of porous wood matrix

A wood specimen in the shape of a rectangular bar is considered. The material is considered to be transversely isotropic one. The fibers are parallel to one of the bar sides - x_3 axis (Figure 2). The dried specimen is placed in an installation for impregnating wood with an aerosol.

We assume that (in addition to the assumptions made above) the transfer of both components of the dispersion medium occurs mainly along the fibers of the wood specimen and $v_1^1 \ll v_1^3, v_1^2 \ll v_1^3$, and also $v_2^1 \ll v_2^3, v_2^2 \ll v_2^3$. Therein $v_1^3 = v_1^3(x_3)$ and $v_2^3 = v_2^3(x_3)$.

From equations (18-20), one-dimensional mass conservation equations for gas phase, liquid non-precipitated phase, and also for precipitated part of the liquid phase are obtained in the following form:

$$\frac{\partial(\rho_1^0 \alpha_1)}{\partial t} + \frac{\partial(v_1^3 \rho_1^0 \alpha_1)}{\partial x_3} = 0; \tag{23}$$

$$\frac{\partial(\rho_2^0 m_{2n})}{\partial t} + \frac{\partial(v_2^3 \rho_2^0 m_{2n})}{\partial x_3} = J_n; \tag{24}$$

$$\frac{\partial(\rho_2^0 \alpha_2)}{\partial t} + \frac{\partial(v_2^3 \rho_2^0 \alpha_2)}{\partial x_3} = 0. \tag{25}$$

Well-known kinetic equation is used to calculate J_n value:

$$J_n = -\eta \rho_2^0 v_{2n} m_{2n}, \tag{26}$$

where η – "capture coefficient" of dispersed phase in porous system, determined from experiments.

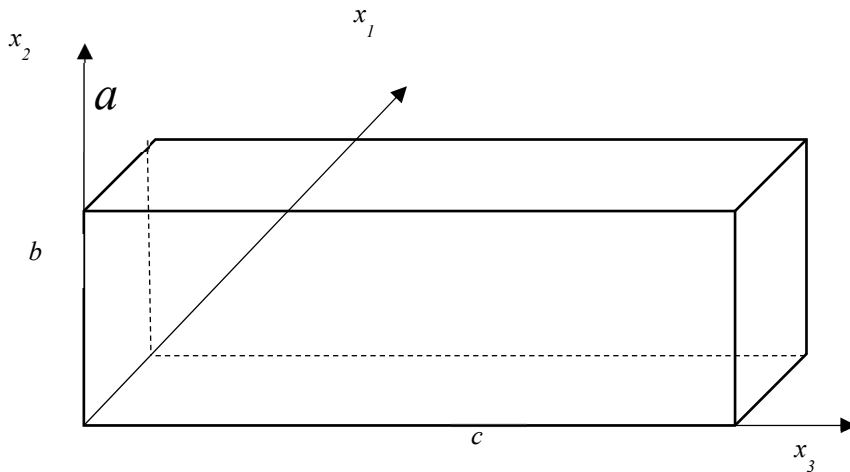


Fig. 2. Choosing a coordinate system.

Let's suppose that the convective terms and capillary effects ($p_2 \approx p_1$) can be neglected in the equations of motion (21-22). Without taking into account the contribution of the pulsating component and viscous friction (it is taken into account at the interphase boundaries), the equations of motion of aerosol gas and liquid phases, written on x_3 axis projection, have the form:

$$\rho_2^0 \alpha_1 \frac{\partial v_1^3}{\partial t} = -\alpha_1 \frac{\partial p_1}{\partial x_3} + \Delta R_{2n,1}^{l(p)} + \Delta R_{2n,1}^{l(\tau)} + \Delta R_{31}^{l(p)} + \Delta R_{31}^{l(\tau)} + \Delta R_{2a,1}^{l(p)} + \Delta R_{2a,1}^{l(\tau)}; \tag{27}$$

$$\rho_2^0 m_{2n} \frac{\partial v_{2n}^3}{\partial t} = -m_{2n} \frac{\partial p_1}{\partial x_3} + \Delta R_{1,2n}^{l(p)} + \Delta R_{1,2n}^{l(\tau)} + \Delta R_{3,2n}^{l(p)} + \Delta R_{3,2n}^{l(\tau)} + \Delta R_{2a,2n}^{l(p)} + \Delta R_{2a,2n}^{l(\tau)}. \tag{28}$$

Correlation for the structural parameters,

$$\alpha_1 + \alpha_2 + \alpha_3 = 1; \alpha_{2a} + \alpha_{2n} = 1; m_{2a} + m_{2n} = \alpha_2; m_{2a} = \alpha_{2a} \cdot \alpha_2; m_{2n} = \alpha_{2n} \cdot \alpha_2; \tag{29}$$

and also the equation of gas phase close the system of differential equations (23-28)

$$\rho_1 = \rho_1^0 T_1 B_1. \tag{30}$$

where T_1 – gas phase temperature, B_1 – individual gas constant.

System of initial conditions which corresponds to the rest state:

$$\vec{v}_1(0, x_3) = \vec{v}_{2n}(0, x_3) = 0, p_1(0, x_3) = p_{atm}, \alpha_2(0, x_3) = 0, m_{2m}(0, x_3) = 0. \tag{31}$$

The boundary conditions are set as follows:

1. At the end of a specimen which is in contact with plenum chamber when $x_3=0$:

$$m_{2n}(t, 0) = \alpha_2^k - m_{2eq}; \alpha_2(t, 0) = \alpha_2^k + 1/k_a \left. \frac{\partial \alpha_2}{\partial x} \right|_{x=0}; p_1|_{x_3=0} = p_1^k. \tag{32}$$

The values of the variables related to the chamber where the dispersed mixture is formed are marked with superscript k . It is assumed that the maximum possible number of particles, which is characterized by an equilibrium concentration value, precipitates almost instantaneously in the entrance section of the specimen m_{2eq} . The flow of the liquid phase in the inlet section of the work-piece satisfies the boundary condition of the third kind.

2. At the end of a specimen which is in contact with low-pressure chamber when $x_3=c$:

$$m_{2n}(t, c) = 0; \alpha_2(t, c) = 0; p_1|_{x_3=c} = p_1^v. \quad (33)$$

The values of variables related to the chamber of low pressure are marked with v subscript. The choice of the first two conditions in (33) implies that the process time is limited to the value that corresponds to the appearance of the first lubricant drops in the output section of the specimen.

Hydrodynamic equations (27-28) do not need boundary conditions after discarding convective and viscous terms in the motion equations of motion.

The formulated mathematical models of aerosol wood impregnation are based on the laws of conservation of mass and momentum of each of the phases of heterogeneous system. Analysis of constructed mathematical models enables to solve the problem of predicting the development of velocity field and phase concentration and developing the most effective technological modes for wood impregnation.

4 Results of numerical simulation and discussion

The mathematical model of the process of aerosol wood impregnation (28-46) represents a nonlinear initial boundary value problem. It has been analyzed using numerical methods and COMSOL Multiphysics 5.3a software package. The creation of computational model has been carried out using “General form PDE” toolkit, which is designed to solve arbitrary partial differential equations.

The calculations have been carried out with the following values of input parameters.

Length of the specimen - $c=0.7$ m. Gas pressure in the upper and lower cell of impregnation device has amounted to $p_1^k=0.8$ MPa and $p_1^v=0.08$ MPa respectively. Temperature of all the phases - $T=353$ K. Density of solid phase $\rho_3^0=1\ 500$ kg/m³, of liquid phase $\rho_2^0=1\ 000$ kg/m³. The density of gas component at the initial time $\rho_1^0=1$ kg/m³. Individual gas constant $B_1=286.7$ J/(kgK). Coefficient $k_a=40\ 000$ 1/m. Gas viscosity $21 \cdot 10^{-6}$ Pa·s, impregnation composition viscosity $25 \cdot 10^{-3}$ Pa·s. The permeability coefficients are $K_{1-2n}=10^{-10}$ m², $K_{1-2a}=10^{-12}$ m², $K_{1-3}=10^{-9}$ m², $K_{2a-2n}=10^{-13}$ m², $K_{3-2n}=4 \cdot 10^{-12}$ m². The concentration of the liquid phase in the plenum chamber (inlet) $\alpha_2^k=0.1$. Atmosphere pressure $p_{atm}=1.01 \cdot 10^5$. Mass coefficients are $\chi_{m_{ji}}=0$.

The “capture coefficient” of liquid inclusions by the porous system η , determining the kinetics of their precipitation, depends on the complex of textural parameters of this system, in particular, on the initial porosity of the sample $\varepsilon = \alpha_1 | t = 0$. The determination of η requires additional experiments. In this paper a linear dependence of the “capture coefficient” on porosity is accepted for hardwoods:

$$\eta = -5.19 + 0.13\varepsilon. \quad (34)$$

Porosity of wood is directly related to the density and depends on the type of wood. Aspen wood with porosity $\varepsilon = 69-74\%$, birch $\varepsilon = 62-63\%$, oak $\varepsilon = 50-53\%$ was used when conducting a full-scale and computational experiment.

Verification of the mathematical model of aerosol wood impregnation was carried out by comparing the results of calculations and data obtained in a full-scale experiment for wood of various species.

Figure 3 illustrates the satisfactory coincidence of these experiments and results of numerical studies for wood specimens with porosity values characteristic of deciduous ring-porous and diffuse-porous wood species (oak, birch, aspen). Specimens with larger initial porosity ε have a larger average volume concentration of impregnating composition at the end of the process in the selected mode of impregnation $m_{2a\text{ aver}}$. Volume concentration of oil in a material with a porosity of $\varepsilon = 74\%$ is two times higher than the value for a material with a porosity of $\varepsilon = 50\%$.

The formulated mathematical model of aerosol wood impregnation enables to investigate the development of volume content profiles of gas and liquid phases (precipitated and non-precipitated components) in time, speed, pressure in the phases. The results of a numerical study of mathematical model are presented in Figures 4-7.

The rate of impregnation increases with time (Figure 4). For specimens with a looser texture, the volume concentration of impregnating liquid, adsorbed by porous system, increases with time more intensively than those for harder species.

The dynamic change in the concentration distribution of the gas component along the sample, shown in Figure 5a, is explained by its extrusion from the wood porous system by impregnating fluid (Figure 5b).

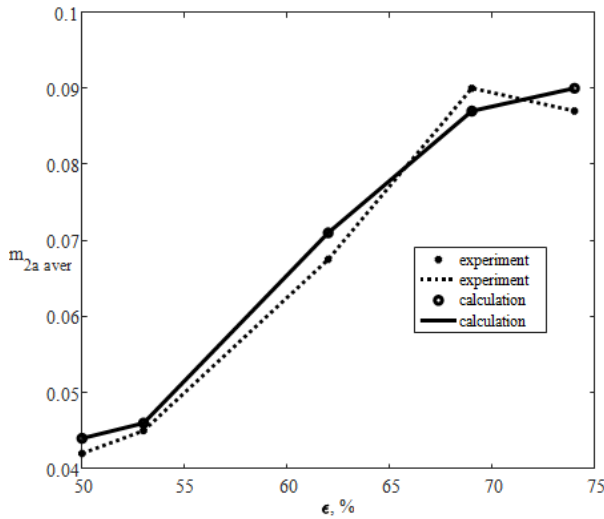


Fig. 3. Dependence $m_{2a\text{ aver}}$ - concentration of liquid inclusions, averaged over the volume of a wood specimen and precipitated in it, on the initial porosity of specimen ϵ , %.

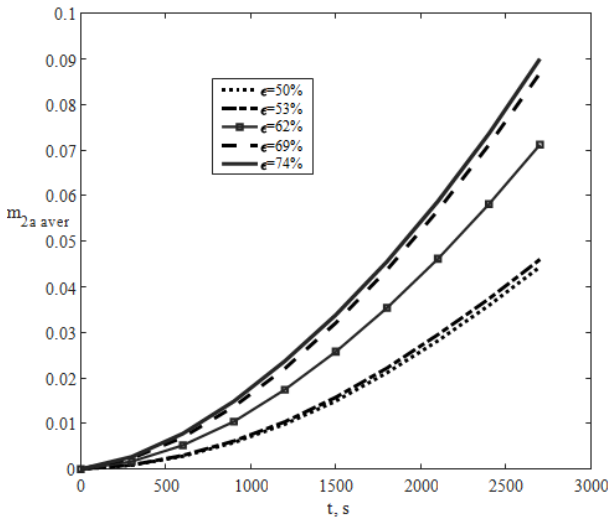


Fig. 4. The change (over time) of the average volume content of precipitated liquid phase inclusions $m_{2a\text{ aver}}$ for the systems with different initial porosities.

The range of velocity variation along the axis of specimen, both for liquid and gas component, is small, its boundaries differ little from some average velocity value for a given time point (Figure 6a-b). Under the considered conditions, average velocity of liquid phase v_2 is three orders of magnitude less than the velocity of gas phase, which is associated with a lower value of permeability coefficient for the liquid compared to gas.

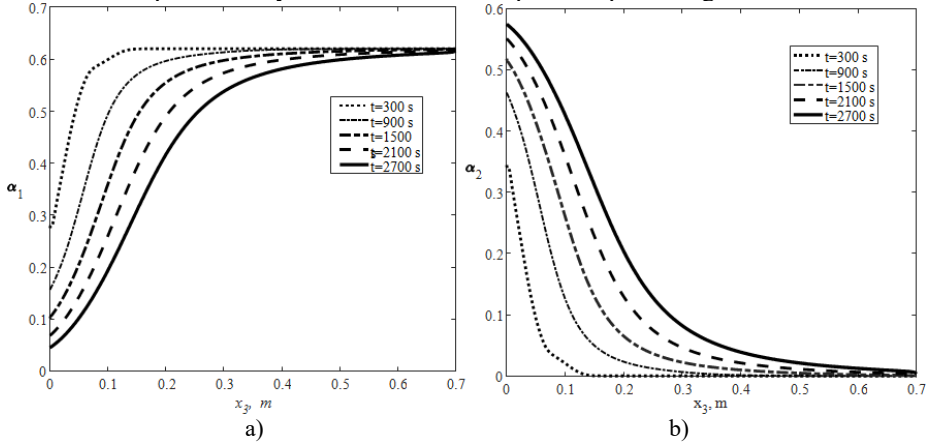


Fig. 5. The distribution of volume content of the gas phase (a) and impregnating liquid (b) in the porous wood system along the length of the specimen with the initial porosity value of $\varepsilon = 62\%$.

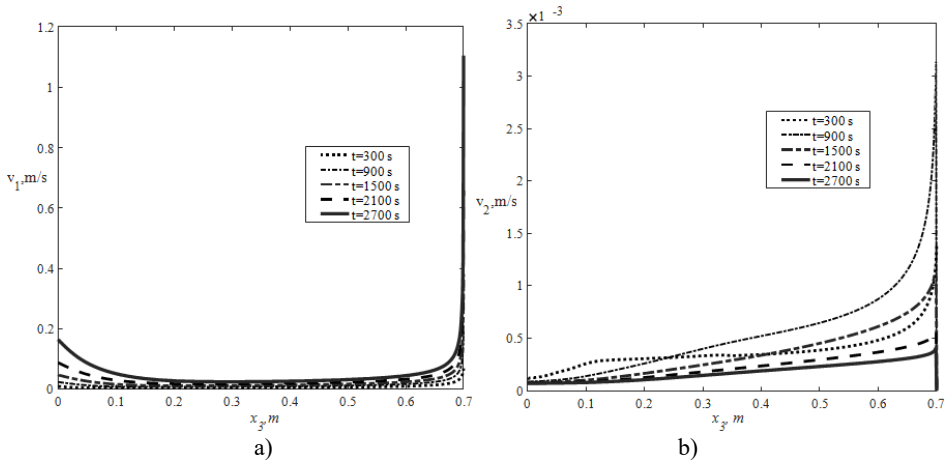


Fig. 6. The velocity distribution of gas (a) and treating solution (b) in the porous system of wood along the length of the specimen with a porosity value of $\varepsilon = 62\%$.

The flow rate of the liquid phase increases along the length of specimen (Figure 6b), which is caused by the interaction of liquid inclusions with a gas flow, which accelerates these inclusions. Resistance to the transfer by the liquid phase increases in time due to the reduction of free pore volume.

As the calculations show, the pressure in the gas phase increases with time in all the sections of the specimens, which is associated with an increase in resistance to vapor transport over the specimen (Figure 7). The pressure gradient of the gas phase, while remaining negative throughout the process, increases with time in modulus, which, in accordance with Darcy's law, leads to an increase in the gas phase velocity with time (Figure 6a).

Numerical analysis of the model enables to predict the distribution dynamics of structural, physical and mechanical parameters of the wood aerosol impregnation process, depending on the properties of wood and treating solution, as well as regime parameters of the process.

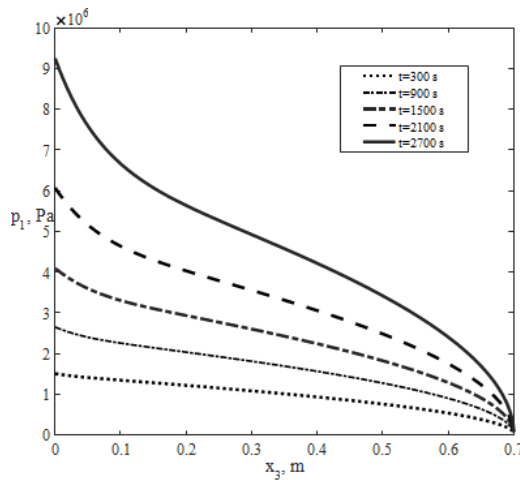


Fig. 7. The pressure distribution of the gas phase in the porous system of wood along the length of the specimen with an initial porosity value of $\varepsilon = 62\%$.

5 Conclusion

A mathematical model has been developed, describing the process of aerosol precipitation in a wood specimen.

The calculation results of the volume concentration of the averaged value of the precipitated liquid component for different values of initial wood porosity according to the proposed model are in satisfactory agreement with the data of the experiment, which has been carried out at the installation for aerosol impregnation of wood.

Numerical implementation of the model allows predicting the distribution dynamics (along the specimen length) of the structural parameters of wood aerosol impregnation process depending on the properties of wood and treating solution, as well as on the process parameters.

The mathematical model can be used to select the effective modes of aerosol impregnation of various wood species.

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