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Key words: *wood modification, impregnation, coniferous wood, raw materials, rotational speed*
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IMPROVING IMPREGNATION TECHNIQUES FOR FINE CONIFEROUS AND NON-CONIFEROUS WOOD

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Wood modification with the improvement of its physical and mechanical properties is a promising way to increase the commercial quality of the material and enhance its sustainable use. This article presents the results on developing a model for impregnation with water of fine coniferous and non-coniferous wood by centrifugal processing techniques. The mathematical modeling is based on Darcy's law. According to the model representation, the impregnation rate of the wood specimenis proportional to the pressure ratio of the impregnation liquid. The proportionality factor is a constant value that depends on the. Performed comparative analysis revealed the perfect consistency of calculations made using the formula of a centrifugal model with the experimental data. According to the analysis of impregnation rate time dependencies, the main saturation of the treated sample with liquid (70%) occurs in 1/3 of the complete cycle time. Besides, the established model allows determining with high accuracy the impregnation time as a function of atmospheric pressure, rotational speed, and the ratio of woodsample length to centrifuge platform radius for different wood species. Further studies are planned on evaluating the effect of different liquids viscosity on the kinetics of wood impregnation as well as determining the applicability of the proposed model.

Key words: wood modification, impregnation, coniferous wood, raw materials, rotational speed

INTRODUCTION

Over the past decades, increasing demand in wood products specified a shortage in quality of wood raw materials for woodworking factories in Russia and elsewhere in the world despite the broad forest areas [1] This is mainly due to the depletion of the old-growth and overmature commercial forest reserves near the handling centers, which leads to the need in building new haul roads and the increase in wood transportation distances [2]. The remaining areas are located remotely and territorially dispersed, which makes their logging with the help of modern high-performance forest machinery economically inefficient [3]. Also, inadequate legislative base and economic disadvantages result in a significant reduction of forest trees areas and the absence of large-scale practices on post-cutting cleaning, especially on frozen soils [4]. As a result of extensive felling in past years, forest areas are covered with low-quality non-coniferous trees, which grow rapidly but are very often rotten by the age of maturity. This significantly reduces the efficiency of its processing along with showing worse physical and mechanical properties compared to conifers [5,6]. Besides, the cost of harvesting and transporting low-quality wood may exceed the selling cost [7,8].

Low-quality wood includes fine coniferous and non-coniferous trees [9]. Modification of wood with improving its physical and mechanical properties can enhance its performance and application [10].

One of the most common ways to modify fine coniferous and non-coniferous wood for improvement of its exploration properties, such as bio- and fire resistance, is to impregnate wood with aqueous solutions of different salts and supercritical carbon [11]. Wood impregnation constitutes a complex diffusion process, and resulting material properties will be dependent on the level of solution penetration and distribution in the porous structure of the wood. The degree of the latter depends on the wood speciesand the viscosity of the liquid [12]. To date, the use of synthetic and natural polymers in wood impregnation is being actively researched [13,14].

The wood can be impregnated in several ways differing in the efficiency level in relation to the material requirements. Soaking of wood and impregnation in vacuum chambers refers to techniques, at which the movement of liquid occurs due to the level of the capillary pressure in the pores [15].

Dynamic methods with emerging pressure gradients include wood impregnation in a periodic modes under the vacuum-pressure-vacuum-pressure mode [12,16] and autoclave wood impregnation method under the pressure-release-pressure mode [17]. Newer and less studied techniques involve the plasma impregnation method

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[18]. However, despite modern technological solutions and approaches, these methods are multistage, technologically complicated, and, therefore, energy-intensive making its application in softwood and fine coniferous trees modification ineffective.

The centrifugal impregnation method refers to dynamic methods of wood processing and is quite well known, demonstrating very good results for further exploitation. [19,20]. This method is characterized by a high ability to provide a uniform complete impregnation, which allows for further mechanical processing of impregnated wood. However, the process of centrifugal wood impregnation has not been yet sufficiently studied. Thus, the existing kinetic model of centrifugal impregnation [20] lacks essential examination and does not offer relatively simple dependencies for determining efficient wood treatment techniques with centrifugal facilities. Also, no technique is proposed for establishing reasonable modes of centrifuges operation for wood impregnation by varying the length and type of treated samples. Therefore, further study of impregnating fine coniferous and non-coniferous wood in the field of centrifugal forces, as well as further improvement of impregnation techniques, is a highly relevant practical task.

The purpose of the work was to develop an improved model of centrifugal impregnation. Mathematical modelling of wood impregnation was carried out by employing the proportional relation-ships of Darcy's law. The following tasks are set to implement the developed theoretical foundations:

1. to determine the degree of filling the wood inner space with impregnating liquid;
2. to calculate the filtration coefficient of the tested wood species;
3. to evaluate the effect of equipment operating modes on centrifugal impregnation rate.

THEORY AND EXPERIMENTAL

Mathematical modeling of the impregnation process

The permeability of the impregnation liquid is generally determined based on the Darcy's law [21]. A process calculation scheme is shown in Fig. 1. The sample to be impregnated is placed into a cylinder filled with liquid and rotated together with the cylinder around the axis at an angular speed ω; the height of the liquid column within the cylinder is Δ.

The liquid and the sample itself are incompressible, and the longitudinal filtration of the liquid in the sample is subjected to Darcy's law:

$$v(x,t) = K\frac{dH}{dx} \tag{1}$$

where v is the rate of impregnation liquid advancement in the direction x (impregnation area rate), K is the longitudinal filtration coefficient, $H(x,t)$ is the hydraulic head, and x is the longitudinal coordinate. At that, the beginning of the x-axis coincides with the end face of the sample submerged in the liquid. The hydraulic head is determined by the formula:

$$H(x,t) = u(x,t) - \frac{\rho_l \omega^2 (\Delta - x)(2R - \Delta - x)}{2} \tag{2}$$

where $u(x,t)$ is pressure in the sample, ρ_l is the density of impregnation liquid, and R is the distance from the beginning of the x-axis to the rotation axis. Filtration coefficient K is estimated experimentally and individually for each wood species.

The pressure at the end face of the sample at $x=0$ amounts to:

$$u(0,t) = \frac{1}{2}\rho_l \omega^2 \Delta (R2 - \Delta) \tag{3}$$

At filling a particular area $x \in (0, l)$ with liquid (Fig.1), the sidewalls of the sample are impermeable to liquid, which is expressed by the differential equation:

$$\frac{\partial^2 H(x,t)}{\partial x^2} = 0 \tag{4}$$

Taking into consideration the force of the surface tension, the initial and boundary conditions for equation (4) can be expressed as:

$$H(0) = \frac{1}{2}\rho_l \omega^2 (l - \Delta)(2R - l - \Delta) \tag{5}$$

$$H(l) = P_a$$

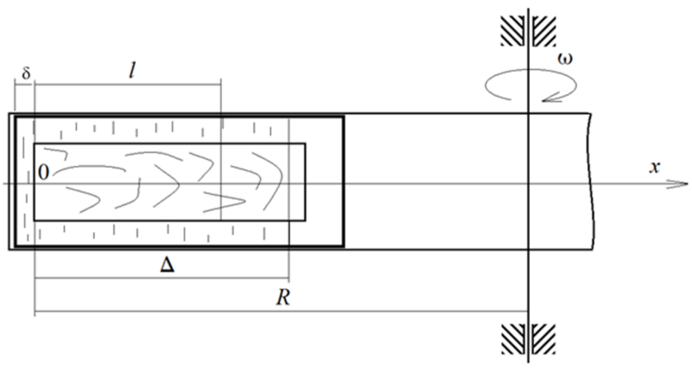

Figure 1: Scheme of oncoming-impregnation of the sample in the centrifugal force field

where P_a is the pressure caused by the action of surface tension forces, the value and sign of which depends on the wettability parameters of the system "wood - impregnating liquid" and the interaction force of molecules of this system.

In case when the sidewalls of the sample are permeable, the flow of liquid through the sidewall of the sample will be determined as:

$$Q(x,t) = -\alpha^2\left[u(x,t) - \frac{\rho_l \omega^2(\Delta - x)(2R - \Delta - x)}{2}\right] \quad (6)$$

where α^2 is the lateral filtration coefficient.

Consequently, the pressure of the pores area will be subjected to the following differential equation:

$$\frac{\partial^2 H(x,t)}{\partial x^2} - \alpha H(x,t) - q = 0 \quad (7)$$

$$q = \frac{1}{2}\alpha\rho_l\omega^2(l - \Delta)(2R - l - \Delta) \quad (8)$$

The solution of differential equation (7) considering formula (8) and boundary conditions (5) is as follows:

$$x = \frac{1}{2}\frac{e^{-al}(2P_a + \rho\omega^2 l^2 + 2\rho\omega^2\Delta^2 - 2\rho\omega^2 lR}{e^{-al} - e^{al}} - \\ - \frac{1}{2}\frac{e^{ax}(2P_a + \rho\omega^2 l^2 + 2\rho\omega^2\Delta^2 - 2\rho\omega^2 lR}{e^{-al} - e^{al}} + \\ +(l - \Delta)\left(-\frac{1}{2}l + R - \frac{1}{2}\Delta\right)\omega^2\rho \quad (9)$$

After differentiating (9) by x, the expression of impregnation rate is as follows:

$$v = aK\left[\left(-\frac{1}{2}l + R - \frac{1}{2}\Delta\right)\omega^2(l - \Delta)\rho - P_a\right]\frac{e^{-al} - e^{al}}{e^{-ax} + e^{axl}} \quad (10)$$

Then, for the impregnation time the equation is:

$$t = \int_0^{\Delta}\frac{1}{v}dl \quad (11)$$

Experimental section

To examine the process of centrifugal wood impregnation, an experimental plant provided by the Department of Forest Harvesting Technology with additional equipment designed by the author was employed [20]. The scheme of the plant is shown in Fig. 2.

Fig.1 shows that the sample length L is placed into a glass with impregnating liquid, and the glass is connected to a carousel 3 rotating at an angular speed ω. The distance from the edge of the platform to the axis of its rotationis marked with R (0.55 m), and δ is the distance from the lower end of the sample submerged into liquid to the edge of the platform amounting to 0.05 m.

The samples of four wood specieswere impregnated, namely, pine, spruce, aspen, and birch with the length L = 0.32 m and rectangular cross-section b = 25 mm, h = 50 mm. The initial absolute humidity was Wa = 10-12%. Since the features like density and viscosity of poorly concentrated solutions of inorganic antiseptics and antipyrenes are close to those of water, catechol-painted violet water was employed as impregnation liquid.

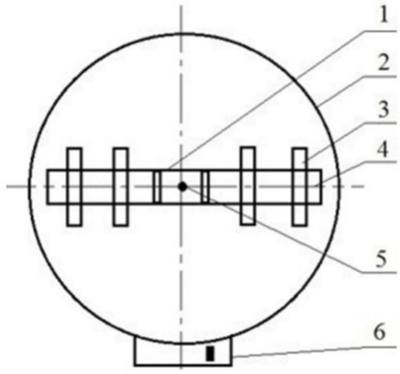

Figure 2. Scheme of the experimental plant: 1 – carousel; 2 – body; 3 – fastening half-rings; 4 – glass; 5 – axis of rotation; 6 – control panel

The variables are presented in Table 1.

Table 1 .Coefficients variability levels

Coef-ficient	Units of measure	Variaton levels			Interval
		Lower	Primary	Upprer	
Δ	m	0.1	0.2	0.3	0.1
n	rpm	450	900	1350	450

During experiments, the mass of liquid Δm absorbed by the sample was measured, and its value was determined by weighing samples every 30 seconds until the mass growth ceased. Empirical dependencies were obtained by the method of least squares. The following type of dependence was chosen as the approximation function for the mass growth:

$$\Delta m = At + B\ln(t + C) \quad (12)$$

The ratio of absorbed liquid volume to pore space volume of samples was determined by the following formula:

$$k = \frac{\Delta m_{max}}{\rho_L bhL\left(1 - \frac{\rho_{sam}}{1540}\right)} \quad (13)$$

where Δm_{max} is the maximum total mass growth of the sample, and ρ_{sam} is the average density of the sample before impregnation.

The following designation was introduced:

$$S = \rho_l bh\left(1 - \frac{\rho_{sam}}{1540}\right) \quad (14)$$

Assuming that the impregnation area is uniform, its position will be then determined as follows:

$$x(t) = \frac{\Delta m(t)}{kS} \quad (15)$$

At that, the rate of the impregnation area is:

$$v_x(x) = \frac{dx(t)}{dt} = \frac{d\Delta m(t)}{kSdx} \quad (16)$$

Accepting that at the use of liquids similar to water by its properties for centrifugal impregnation, the impregnation rate of the sampleis proportional to the ratio of impregnation liquid pressure at the level of the lower end face of the sample to the mass of the absorbed liquid. Therefore, the impregnation area rate can be expressed as:

$$v_x(x) = f\frac{P_{max}^2}{x(t)P(x)} \quad (17)$$

where f is a constant value specific for each wood species.

To verify this hypothesis, the value of the following function was calculated based on the results of each experiment:

$$K = \frac{P_{max}^2}{v_x(x)x(t)P(x)} \quad (18)$$

This value assumes the filtration coefficient when the wood is impregnated. By solving Eq. (18), the expression of time τ, when the impregnation reaches a certain position x, can be defined by:

$$\tau = \frac{2K\left[\frac{1}{4}x^4 + \frac{1}{3}x^3(2R - 2\delta - 2\Delta)\right]}{\rho_l\omega^2\Delta^2(2R - 2\delta - \Delta)^2} \quad (19)$$

Afterward, by applying the obtained expressions for the mass of absorbed liquid according to Eq. (18), the instant value of the function *K(t)* for each experiment was calculated. When determining the average (used in further calculations) value for *K*, a known formula for the function average value was used:

$$K = \int_{0.1T}^{T} K(t)dt \quad (20)$$

where *T* is the total impregnation time.

The choice of integration interval is explained by the fact that *K(0)* → ∞ due to the function type *Δm*, which makes integration impossible. After calculating *K* by Eq. (20) using the formula, it follows:

$$T_{calc} = \frac{2K\left[\frac{1}{4}x^4 + \frac{1}{3}x^3(2R - 2\delta - 2\Delta)\right]}{\rho_l\omega^2\Delta^2(2R - 2\delta - \Delta)^2} \quad (21)$$

assuming that $x = \Delta$, impregnation time T_{calc1} was estimated. The second value of calculated time T_{calc2} was similar to that of T_{calc1} with the only difference that instead of *K*, the average value K_{av} was applied:

$$K_{av} = \frac{\sum_{i=1}^{n} K_i}{n} \quad (22)$$

where *n* is the number of experiments.

Values *Δ1* and *Δ2* were determined by formulas:

$$\Delta_1 = \frac{T_{exp} - T_{calc1}}{T_{exp}} \cdot 100\,\%\,; \quad \Delta_2 = \frac{T_{exp} - T_{calc2}}{T_{exp}} \cdot 100\% \quad (23)$$

where the T_{exp} is an experimentally determined time of sample saturation with liquid.

Results and Discussion

In order to estimate the influence of parameters on the impregnation time of the sample, the integral is calculated by Eq. (11) numerically. Since *K* is a constant value for a certain speciesof wood, the results of estimations will be presented in the form of relations shown in graphics of Fig. 3-6.

Fig. 3 shows the relation of the whole impregnation cycle time *T(ω)*, i.e., the time for which the impregnation area reaches the value *Δ*, for angular speed 50–150 rad/s to process parameters at *ω* = 25 rad/s - *T(25)*. As the angular speed increases, the time for which the impregnation area reaches the liquid level in volume *Δ* decreases. At that, the dependence is nonlinear (Fig. 3) and can be expressed by the following equation:

$$T(\omega)/T(25) = 0.00008\omega^2 - 0.0198\omega + 1.385 \quad (24)$$

Performed calculations showed that varying the lateral filtration coefficient *α* has no significant effect on the time of impregnation (Fig. 4). Thus, when changing *α* from 0 (the side surface is impermeable) to 1 (the side surface is as permeable as the end face submerged into liquid), the impregnation time is reduced by only 7.5 %.

The results of calculations at variable surface tension of liquid showed its significant influence on impregnation time (Fig. 5), i.e., with the growth of *Pa* from 1000 to 5000 *Pa*, the impregnation time decreases by about 60%. Besides, capillary forces are necessary to be considered when describing centrifugal impregnation. The difference in capillary size that affects the value *Pa* in different wood speciesspecifies the need for separate experimental research on each wood species studied.

Calculations at variable value *R* demonstrated that the dependence of impregnation time, in this case, is close

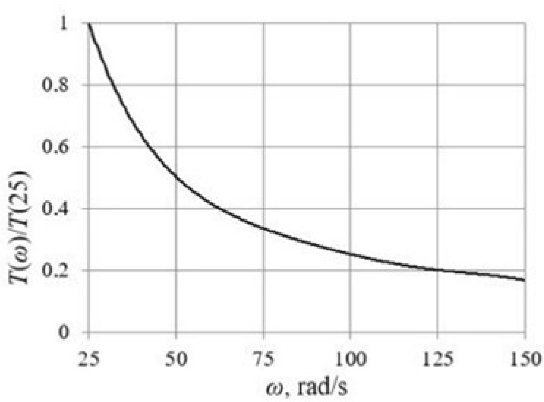

Figure 3: Ratio T(ω)/T(25)

to linear (Fig. 6), so the length of impregnation does not influence the speed of impregnation area advancement.

The mass of absorbed liquid was measured in samples for each wood species, and, based on these measurements, the graphics of mass growth for each experiment were drawn. An example of spruce mass growth is shown in Fig. 7.

As seen from the Fig., the main volume of absorbed liquid (75-80 %) occurs in the first-third of the treatment cycle. The expression (12) establishes the relationship between the mass of the liquid absorbed by the treated sampleand the treatment time (12).

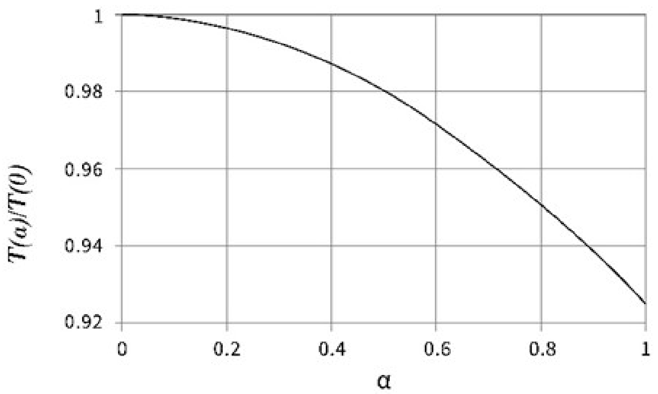

Figure 4: Ratio T(ω)/T(0)

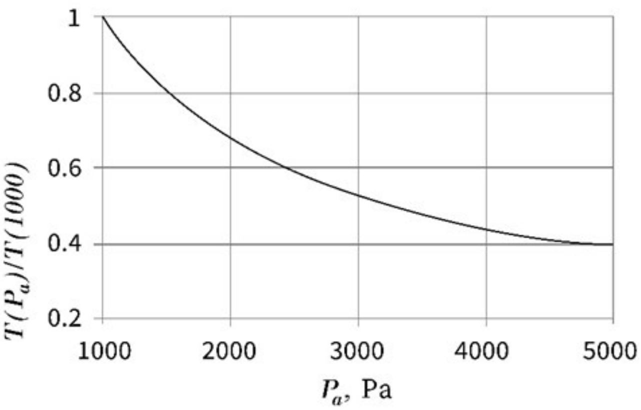

Figure 5: Ratio T(Pa)/T(1000)

The calculations result of the instant function *K(t)* by the formula (18) and K_{av} by the formula (20) for each experiment are presented in Table 2.

According to the data in Table 2, experimental measurements of impregnation time and common parameters

Table 2: Value of function K(t)-1010 for different wood species

No p/p	Spruce	Pine	Aspen	Birch
1	1.606	1.856	1.344	1.494
2	1.917	1.974	1.301	1.547
3	2.250	2.262	1.498	2.303
4	1.602	1.778	1.309	1.514
5	1.585	1.881	1.396	1.530
6	1.650	1.982	1.360	1.682
7	1.618	1.728	1.269	1.380
8	1.725	1.590	1.321	1.501
9	1.813	2.031	1.409	1.648
Average value, K_{av}	1.752	1.928	1.356	1.622

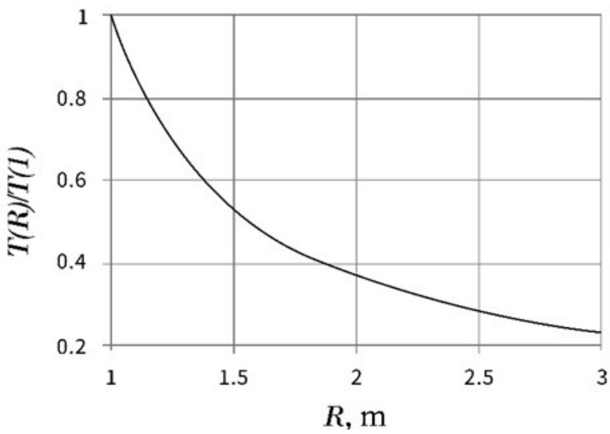

Figure 6: Ratio T(R)/T(1)

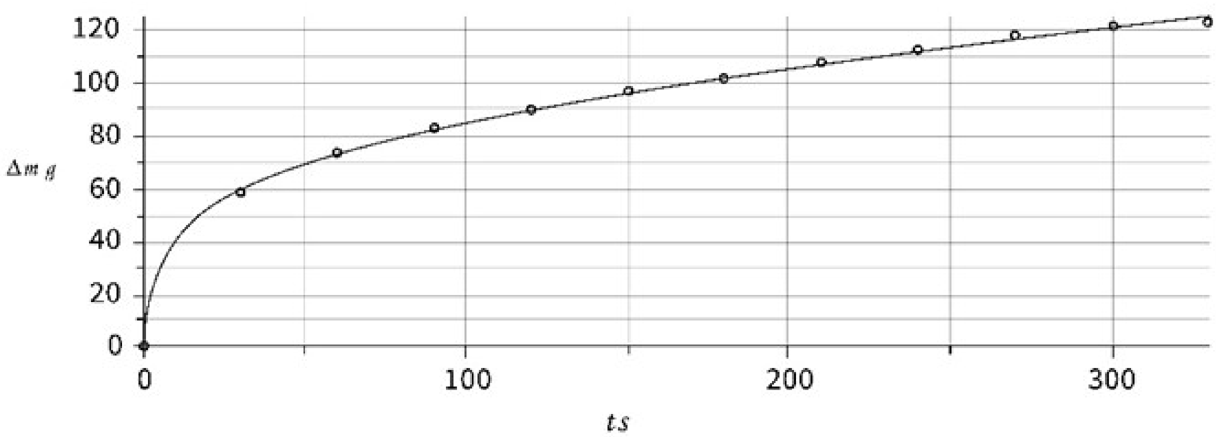

Figure 7: Change in the mass of spruce samples during impregnation (n = 900 rpm, Δ = 0.2 m)

were used to calculate impregnation time values by formulas (21) - (23) for each wood species. The results on the example of spruce are presented in Table 3.

Table 3. Calculated and experimental values of impregnation time (for spruce)

№ p/p	T_{exp}, s	T_{calc1}, s	T_{calc2}, s	Δ_1, %	Δ_2, %
1	630	584	637	7	1
2	180	174	169	3	6
3	90	91	86	1	4
4	1320	1276	1395	3	6
5	330	316	349	4	6
6	150	146	155	3	3
7	2160	2125	2301	2	7
8	570	566	575	1	1
9	270	265	256	2	5

The data in Table 3 show that the impregnation time determined by (21) and value Kav is close to the experimentally determined one, i.e., the deviation does not exceed 7%. The same maximum deviation is observed when comparing the calculation results with the experimental data by impregnation of other studied species of wood.

The graphic in Fig. 8 illustrates the dependence of impregnation rate on time, where a solid line is a graph

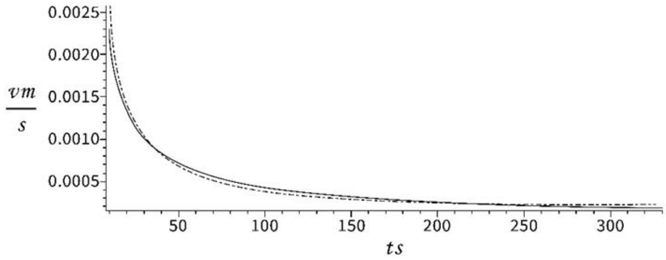

Figure 8: Impregnation rate for spruce samples (n = 900 rpm, Δ = 0.2 m)

drawn on experimental data basis by formula (16), and the dashed line is calculated data by equation (18) at *K = Kav*. The impregnation time is determined from expression (21) using the data in Table 2.

As seen from the charts in Fig. 8, both curves almost completely merge, which indicates a qualitative convergence of both methods. Thus, the proposed method for calculating the impregnation time and certain values of the filtration coefficient *K* is suitable for practical application. Besides, the graphs of dependence show that the basic saturation of the processed sample with liquid (70 %) occurs for the time making 1/3 of the whole treatment cycle.

The impact of rotational speed and the ratio of the sample length to the centrifuge platform radius *a = R/L* can be tracked by the graphics in Figs. 9-12.

The figures show that the impregnation time at a given ratio of the centrifuge platform radius to the sample length depends on the wood species to be impregnated

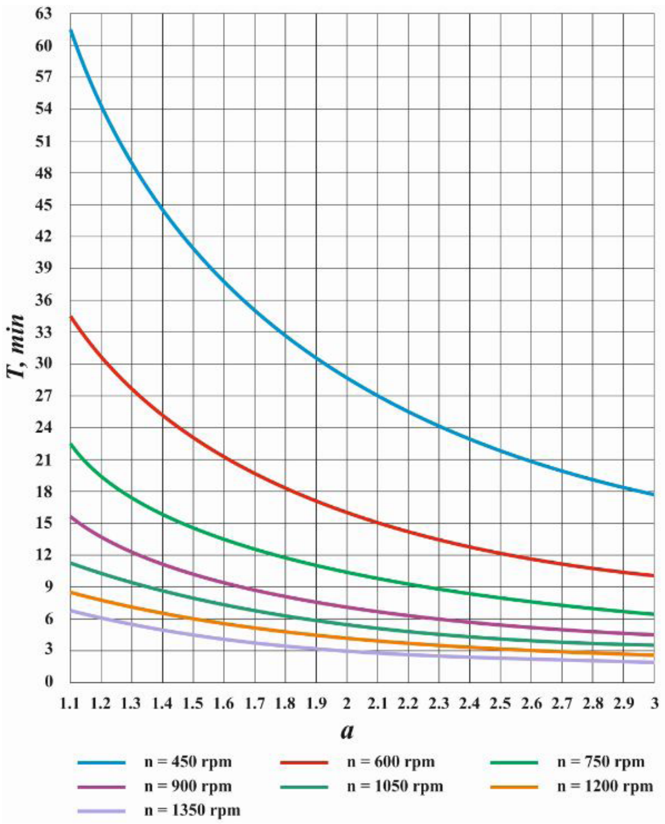

Figure 9: Impregnation time depending on a (spruce)

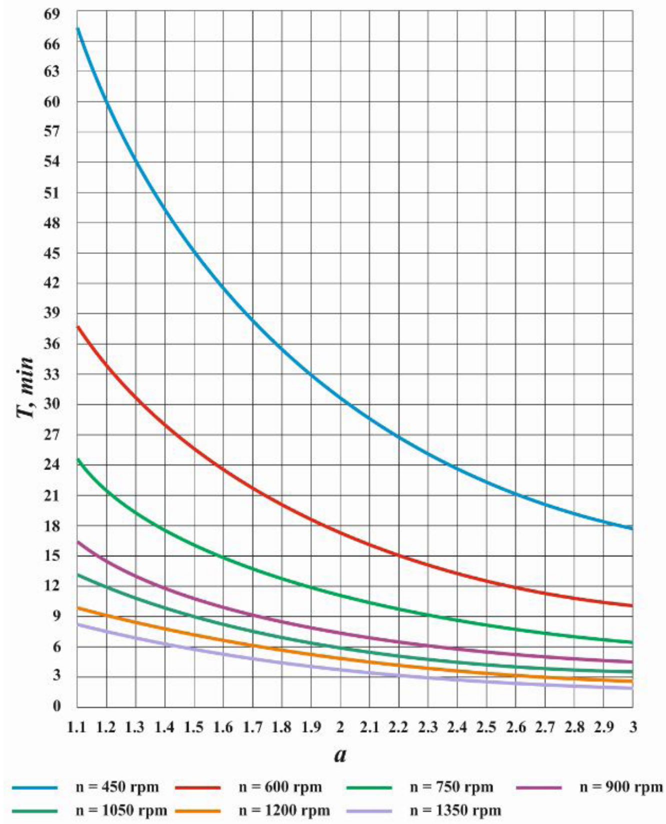

Figure 10: Impregnation time depending on a (pine)

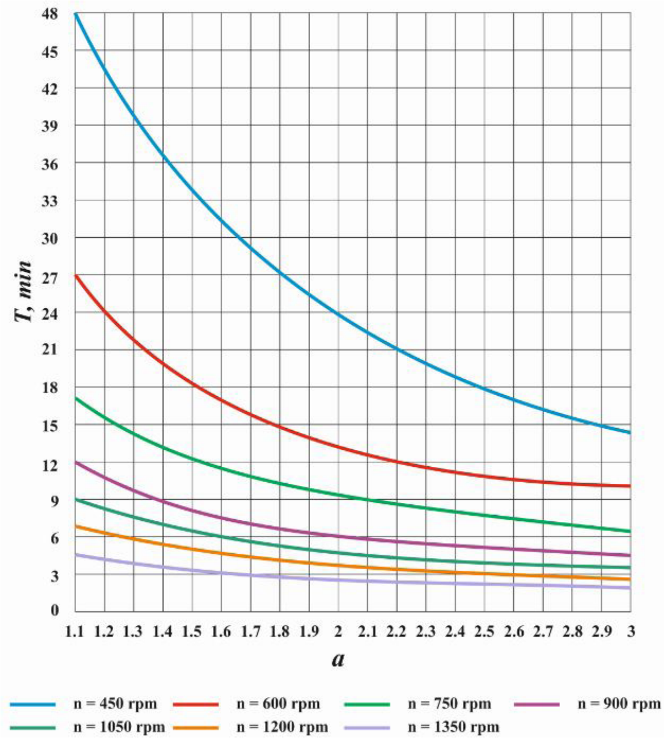

Figure 11: Impregnation time depending on a (aspen)

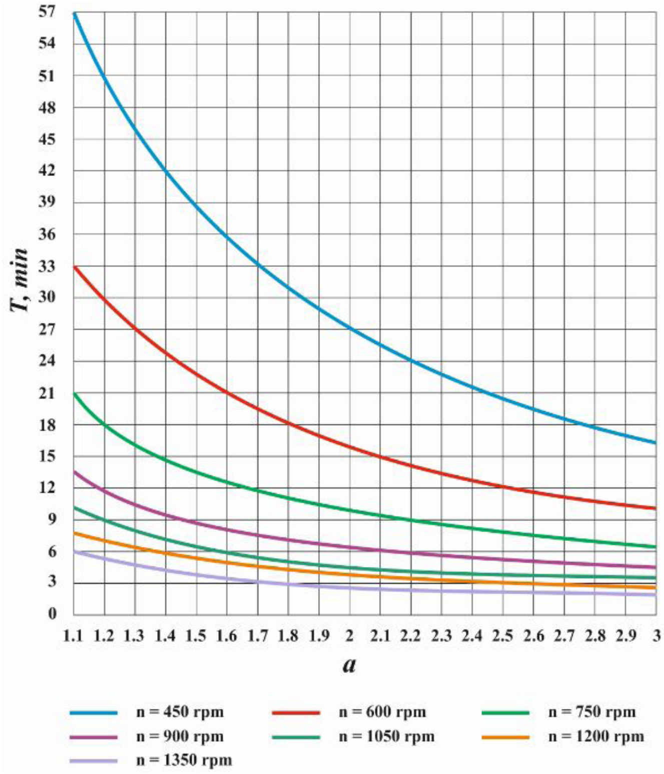

Figure 12: Impregnation time depending on a (birch)

and the centrifuge speed. At a minimum rotational speed of 450 rpm, the greatest impregnation time is observed for spruce and pine and decreases exponentially with increasing value a. At higher frequencies (more than 900 rpm), impregnation time decreases by 2-3 times and slightly depends on the value of a. Thus, the rotational speed of the centrifuge platform can be determined experimentally through graphics in Fig. 9-12, or applying the obtained expression (21) and filtration coefficient values (Table 2).

A comparative analysis of available literature revealed that depending on the chosen impregnation technique, the development of similar kinetic mathematical models demolishes its high efficiency in calculations in comparison with experimental measurements. In the paper [22], the results of testing a computational model based on a viscous liquid flow of super-critical carbon dioxide in wood materials showed that the model calculations are relatively accurate under subcritical pressure conditions. Besides, it was concluded that the theoretical basis of Darcy's Law can be applied to various wood species. In another paper [17], the presented model of wood permeability was reported to allow determining the boundary conditions of pressure dropping and release of supercritical liquid to prevent the destruction of the internal wood structure at the autoclave treatment method. Also, such mathematical modeling allows for qualitatively and quantitatively estimation of the temperature and pressure inside the board during regular impregnation. Similar results have been obtained in numerous studies for various wood species[23-25]. The aforementioned results and the conclusions of other studies are in good agreement with the results of present research on the versatility of model application.

Apart from Darcy's law, other approaches and theoretical foundations are used in the development of the impregnation model as well. The application of the parallel exponential kinetics model demonstrates excellent compliance with experimental data for the modification of palm oil in non-coniferous trees [26] considering the degree of oil absorption relative to the moisture content of the wood. In case of impregnation with different salt solutions, the electrostatic interaction forces of ions in the kinetic impregnation model [27-29] are used to describe the diffusion processes, which explains the reasons for swelling of the wood sample walls and other effects caused by the salt solutions.

In the paper [30] was reported that this approach can also be based on Darcy's law when taking into account the dynamic nature of the longitudinal filtration coefficient. The analysis of other studies revealed great potential for further investigations on improving the presented model for liquids with different physical and chemical properties. Expanding knowledge and incorporating various factors and aspects into a mathematical filtration model not only greatly contributes to scientific knowledge, but also enlarges the scope of its application to boost the efficiency of forest resources application and preservation.

CONCLUSIONS

According to the theoretical and experimental studies performed, the following conclusions can be drawn. The results of experimental measurements at centrifugal impregnation of fine coniferous and non-coniferous wood qualitatively and quantitatively confirm the calculation results of the developed mathematical model for impregnation technique based on Darcy's Law. The mathematical formulation is based on the statement that the rate of impregnation of the wood sampleis proportional to the ratio of impregnation liquid pressure at the level of the lower end face of the sample to the mass of the absorbed liquid, where the proportionality factor is a constant value depending on the wood species. It has also been determined that the lateral filtration factor is not significantly influenced by the impregnation time but depends on the atmospheric pressure and the speciesof wood. Besides, the impregnation time is inversely dependent on the rotational speed and the ratio of the samplelength to the centrifuge platform radius. Based on a comparative analysis of experimental and calculated data, it is shown that the model presented is perfectly consistent with the experiment. Obtained results of both approaches allow stating that the main saturation of the processed sample with liquid (70%) occurs during 1/3 of the whole processing cycle. Thus, the investigation of wood impregnation with liquids different in properties (viscosity and density) from water, as well as the study of Darcy's linear filtration law applicability, constitute the perspective for further research.

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