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Wood treatment with hydro impact: a theoretical and experimental study

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Abstract

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The article deals with mathematical models of the operation of installations for the impregnation of timber based on the effect of the piezo-periodic field, taking into account the difference in the parameters characterizing filtration in the capillaries and pores of the wood. Solutions of differential equations of motion of the front of impregnation are obtained taking into account the harmonic type of the pressure boosting function in the installation; taking into account the initial interval of impregnation, without neglecting the variable nature of the pressure of the impregnating fluid when choosing initial conditions for solving differential equations of motion of the impregnation front. To improve the efficiency of the wood impregnation process, an installation for impregnating wooden blanks using hydraulic shock, which has a simple structure, low energy consumption and the ability to mechanize the process of loading and unloading blanks, has been developed. The rate of impregnation in this way is higher than that of other known methods, since the work pieces are subjected to a double effect: a pulsed increase in pressure, which allows obtaining a periodic force field.

Keywords: wood; mathematical model; hydro impact; wood impregnation.

Introduction

A large number of works are devoted to the problem of modifying wood and obtaining new materials on its basis with specified properties (Kunitskaya, 2015; Grigoriev, 2016; Willems, 2016; Grigorev et al., 2014; Sandberg, Kutnar &Mantanis, 2017; Lin et al., 2017).

To improve the efficiency of the wood impregnation process, an installation for impregnating wooden blanks using hydraulic shock (Kunitskaya et al., 2018) has been developed, which has a simple structure, low energy consumption and the ability to mechanize the process of loading and unloading blanks. The rate of impregnation in this way is higher than that of other known methods, since the work pieces are subjected to a double effect: a pulsed increase in pressure, which allows obtaining a periodic force field.

It is well known autoclave method of impregnation of wood by the method of pressure – discharge – pressure. The second proposed impregnating device works according to this principle (Kunitskaya et al., 2018) – impregnated wooden products (product) are placed in the impregnating vessel. The size of the impregnation tank may be different, depending on the required production capacity of the installation. From the reserve topping tank the impregnating tank is filled completely. The hydraulic pump is turned on and the hydraulic cylinder moves the piston of the hydroaccumulator creating pressure in the impregnation tank. When the piston reaches the far right position, the hydraulic distributor switches and the pistons of the hydraulic cylinder and hydraulic accumulator move in the opposite direction, creating a vacuum in the impregnation tank. Then the valve switches the hydraulic cylinder to the over thrust, again creating pressure in the impregnation tank. The device provides an automated cyclic sequence of compression of the discharge, due to which it is possible to achieve a better (deep) impregnation of products.

Materials and Methods

The installation is shown in Figure 1. The workpiece 3 is placed in the dead end of the acceleration pipe 4 through the charging port 7. The pump 8 delivers the impregnating liquid 1 from the receiving tank 6 to the pressure tank. After the liquid in the pressure tank reaches the upper level sensor 2, the stop valve device 5 will open the path of the liquid to the drain, the level in the pressure tank will fall and at the moment of reaching the lower level sensor the locking device 5 closes abruptly. At the same time in the accelerating pipe will occur the phenomenon of water hammer? The shock wave will make damped oscillations in the accelerating tube from the locking device to the end of the workpiece. For example, at a flow rate of 1 m/s, the pressure in the pipe will increase from 1 to 1.5 MPa. At this time, the pump will fill the pressure tank to the level of the upper sensor and the process will repeat.

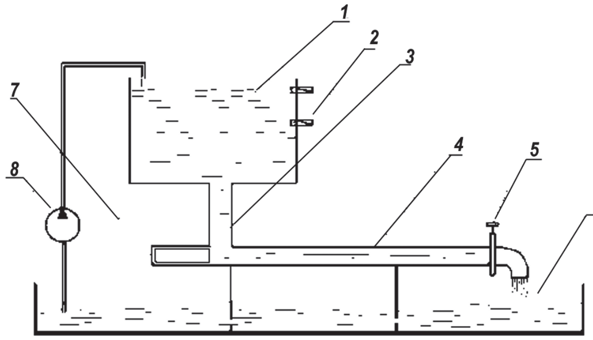

Fig. 1. Installation for wood impregnation using a water hammer: *1* – pressure tank; *2* – liquid level sensors; *3* – workpiece; *4* – accelerating tube; *5* – locking device; *6* – receiving tank; *7* – loading door; *8* – pump

Due to the complexity of the structure of the internal space of wood, when developing a model for impregnating wood with a hydraulic shock, the problem is considered as superpositional as a total picture of the impregnation of capillary and pore space (Venas and Morsing2014; Se Golpayegani et al., 2015; He et al., 2016).

Let us consider filling the capillaries of wood with an impregnating fluid. Let us take the connection of the velocity of the front of impregnation with the hydraulic pressure in the form of Darcy filtration law (Patyakin et al., 1990):

$$\frac{du_c}{dt} = \frac{k_c}{\mu}\Delta p_c, \qquad (1)$$

where k_c is the proportionality coefficient (filtration coefficient of the capillary structure), μ is the dynamic viscosity of the impregnating fluid, Δp_c is the gradient of the hydraulic head in the capillaries along the length of the impregnated part of the wood sample, u_c – the rate of propagation of the front of impregnation into the sample.

The gradient of the hydraulic head is determined by the formula (Patyakin et al., 1990):

$$\Delta p_c = \frac{p_c(t)}{L_c}, \qquad (1)$$

where $p_c(t)$ is the pressure of the impregnating fluid, L_c is the length of the impregnated area of the wood sample.

In the problem being solved, the pressure of the impregnating fluid is composed of a component caused by a hydraulic shock p and a component due to the pressure of the surface tension of the liquid inside the capillaries p_c.

$$p_c(t) = p + p_c, \qquad (3)$$

Let us take the following pattern of change in pressure increase during hydraulic shock:

$$p = p_0(1 + A\sin\omega t)\ , \qquad (4)$$

where p_0 is the average pressure of the liquid in the impregnation process, A is the pressure amplitude at the water hammer, ω is the disturbance frequency, t is the time.

The surface tension pressure is determined by the formula (Patyakin et al., 1990):

$$p_c = \frac{2\sigma}{r_c}, \qquad (5)$$

where σ is the coefficient of surface tension, r_c is the conditional capillary radius.

Then the gradient of the water hammer will find the formula:

$$\Delta p_c = \frac{p_0(1 + A\sin\omega t) + \frac{2\sigma}{r_c}.}{L_v}, \tag{6}$$

With (6), the equation (1) will be written as:

$$\frac{du_c}{dt} = \frac{k_c}{\mu}\,\frac{p_0(1 + A\sin\omega t) + \frac{2\sigma}{r_c}.}{L_c}, \tag{7}$$

The length of the impregnated area L_c is determined taking into account the speed of the impregnation front $\frac{du_k}{dt}$, and the speed is variable in time. Then, assuming that the length of the region L_c is equal to the path traveled by the front of impregnation at time *t*, can be written:

$$L_c = \int_0^t \frac{du_c}{dt}\,dt. \tag{8}$$

Let us differentiate equation (8) with respect to time t:

$$\frac{dL_c}{dt} = \frac{du_c}{dt}. \tag{9}$$

Taking into account equality (9) and with respect to $L_{c,,}$ equation (7) can be written as:

$$L_c\frac{dL_c}{dt} = \frac{k_c}{\mu}\left\{p_0(1 + A\sin\omega t) + \frac{2\sigma}{r_c}\right\}. \tag{10}$$

Let us solve the differential equation (10) with respect to L_c with the initial condition Lк (0) = 0, then:

$$L_c = \sqrt{\frac{2k_c}{\mu r_c\omega}}\,\sqrt{p_0 r_c(\omega t + A - A\cos\omega t) + 2\sigma\omega t}. \tag{11}$$

Let us express the speed $\frac{dL_k}{dt}$

$$\frac{dL_c}{dt} = \sqrt{\frac{k_c r_c\omega}{2\mu}}\,\frac{\left\{p_0(1 + A\sin\omega t) + \frac{2\sigma}{r_c}\right\}}{\sqrt{p_0 r_c(\omega t + A - A\cos\omega t) + 2\sigma\omega t}}. \tag{12}$$

The amount of fluid passing through the capillaries per unit of time can be calculated by multiplying the speed by the formula (12) on the cross-sectional area of the sample *S* and the proportion of capillaries from the sample volume η_c:

$$\frac{dQ_c}{dt} = S\eta_k\sqrt{\frac{k_c r_c\omega}{2\mu}}\,\frac{\left\{p_0(1 + A\sin\omega t) + \frac{2\sigma}{r_c}\right\}}{\sqrt{p_0 r_c(\omega t + A - A\cos\omega t) + 2\sigma\omega t}}. \tag{13}$$

Next, let us consider filling the pore space of wood with an impregnating fluid and take the connection of the speed of the front of impregnation with a hydraulic pressure in accordance with the recommendations (Patyakin et al., 1990) in the form of the equation:

$$\frac{du_p}{dt} = \frac{k_p}{\gamma}\Delta p_p, \tag{14}$$

where k_p is the proportionality coefficient (filtration coefficient of the porous structure), γ is the specific gravity of the impregnating fluid.

The hydraulic head Δp_p will be determined by analogy with equation (2) (Patyakin et al., 1990):

$$\Delta p_p = \frac{p_p(t)}{L_p}, \tag{15}$$

where the pressure again consists of two components:

$$p_c(t) = p + p_p, \tag{16}$$

and the pressure of the surface tension in the pores will be determined by the formula:

$$p_p = \frac{2\sigma}{r_p}, \tag{17}$$

where r_p is the conditional pore radius.

As a result, for the impregnation front velocity in the pores, an equation similar in structure to equation (7) can be obtained:

$$\frac{du_p}{dt} = \frac{k_p}{\gamma}\,\frac{p_0(1 + A\sin\omega t) + \frac{2\sigma}{r_p}.}{L_p}, \tag{18}$$

where the length L_p is also related to the derivative $\frac{du_p}{dt}$:

$$L_p = \int_0^t \frac{du_p}{dt}\,dt. \tag{19}$$

$$\frac{dL_p}{dt} = \frac{du_p}{dt}. \tag{20}$$

Then, taking into account the relation (20), the equation for the impregnation front velocity in the pores by equation (18) can be written as:

$$L_p\frac{dL_p}{dt} = \frac{k_p}{\gamma}\left\{p_0(1 + A\sin\omega t) + \frac{2\sigma}{r_p}\right\}. \tag{21}$$

The solution of the differential equation (21) with respect to L_p with the initial condition L_p (0) = 0 has the form:

$$L_p = \sqrt{\frac{2k_p}{\gamma r_p\omega}}\,\sqrt{p_0 r_p(\omega t + A - A\cos\omega t) + 2\sigma\omega t}, \tag{22}$$

while speed $\frac{dL_p}{dt}$:

$$\frac{dL_p}{dt} = \sqrt{\frac{k_p r_p \omega}{2\gamma}}\,\frac{\left\{p_0(1 + A\sin\omega t) + \frac{2\sigma}{r_p}\right\}}{\sqrt{p_0 r_p(\omega t + A - A\cos\omega t) + 2\sigma\omega t}}. \qquad (23)$$

The amount of fluid passing through the pores per unit of time can be calculated by multiplying the speed by the formula (23) by the cross-sectional area of the sample *S* and the proportion of pores in the sample volume η_n:

$$\frac{dQ_p}{dt} = S\eta_n\sqrt{\frac{k_p r_p \omega}{2\gamma}}\,\frac{\left\{p_0(1 + A\sin\omega t) + \frac{2\sigma}{r_p}\right\}}{\sqrt{p_0 r_p(\omega t + A - A\cos\omega t) + 2\sigma\omega t}}. \qquad (24)$$

The total filtration rate of the fluid through the capillary and pore space of the sample is defined as the sum of the capillary and porous components:

$$\frac{dQ}{dt} = \frac{dQ_c}{dt} + \frac{dQ_p}{dt}. \qquad (25)$$

The mass of the impregnating fluid absorbed by the sample at time point t is determined by the formula:

$$\Delta M = \frac{\gamma}{g}\int_0^t \frac{dQ}{dt}\,dt. \qquad (26)$$

Formulas (11), (13), (22), (24), (25) form the basis of a mathematical model for impregnating wood in a piezo-periodic field. For given pressure function parameters over time p_0, *A*, ω, properties of the impregnating fluid and wood sample μ, γ, σ, k_p, k_c, r_p, r_c, η_p, η_c, *S*, the model allows to calculate the main indicators of the impregnation process – mass and depth penetration of the impregnate into the workpiece.

Results and Discussion

Let us take the parameters of the function (4) $p_0 = 0.85$ MPa, $A = 1$, $\omega = 2\pi N/T$ (*N* is the number of pressure increase cycles, *T* is the total impregnation time), $N = 25$, $T = 60$ s.

The calculation will be carried out on the example of an impregnating liquid, which is similar in properties to water: $\gamma = 10$ kN/m^3, $\mu = 0.002$ Pa·s, $\sigma = 0.0727$ Pa·m.

The filtration coefficients were previously determined in centrifugal impregnation experiments, but without separation into capillary and pore filtration. At the present stage of the study let us take it approximately $k_p \approx k_c$ for the wood of aspen, birch and alder, respectively, $1.3 \cdot 10^{-13}$, $1.6 \cdot 10^{-13}$, $1.25 \cdot 10^{-13}$ m^2. The dimensional characteristics of pores and capillaries, as well as their volume fractions will be taken according to (Patyakin et al., 1990) ($\eta_p = 0.5$, $\eta_c = 0.2$, $r_p = 250$ μm, $r_c = 2.45$ μm). The sample section is rectangular, with an area of 25 cm^2.

All values are substituted into the calculated dependences in SI units.

An example of the calculation results is shown in Figure 2.

The results show that the contributions of pore and capillary filtration are comparable, while the filtration in the pores is somewhat slower than in the capillaries. In this regard, it is believed that the promising areas for further research are the experiments aimed at obtaining additional information on the permeability of wood, separately for pores and capillaries.

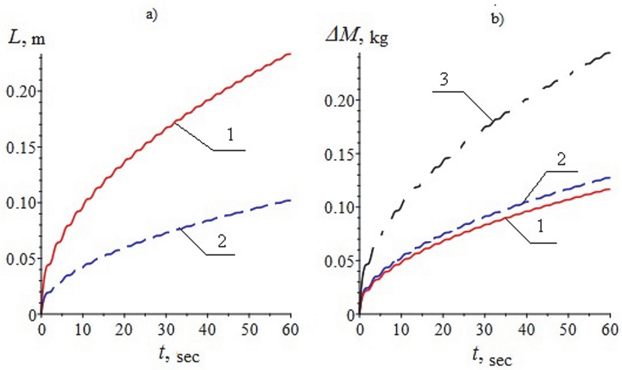

Fig. 2. Impregnation of a birch sample:
***a*) depth of impregnation; *b*) weight gain:**
***1* – capillary component, *2* – pore, *3* – total value**

Figure 2 shows that when organizing a study, one should proceed from the plans of a multifactorial experiment, which implies the possibility of obtaining the response surface of the studied quantity (depth of impregnation or mass of absorbed impregnate) in the form of second-order polynomials. How this was done in the study of changes in the filtration capacity of forest soils (Lisov & Grigorev, 2013).

Calculations show that over 25 cycles of pressure increase, the sample is impregnated by 25–30 cm depending on the wood type, which, taking into account the cycle time, which is 60 seconds, proves that the proposed design of wood impregnation plants using a hydraulic shock exceeds their potential properties known installation for the impregnation of wood (Venasand Morsing, 2014; Willems, 2016).

Preliminary studies have shown that it is also effective to impregnate wood in a piezo-periodic field in the "vacuum-pressure-vacuum-pressure" mode. The capillary-porous system of water conducting paths of wood can be considered as a bi-hydraulic structure, in which the hydraulic resistance of the porous structure substantially exceeds the hydraulic resistance of the capillary.

To develop a mathematical model of the wood impregnation process in the proposed device, let us consider filling the longitudinal capillary-porous structure (Patyakin et al., 1990):

$$\frac{du_c}{dt} = \frac{\left[p + \frac{2\sigma}{r_c} + p_0 \frac{l_h}{(l_h - L)}\right]}{L}, \tag{27}$$

Here l_h is half the length of the impregnated product, p_0 is the initial pressure in the impregnation chamber, p is the generated overpressure.

Taking into account (5), the following equation is obtained:

$$L\frac{dL}{dt} = \frac{k_c}{\mu}\left[p + \frac{2\sigma}{r_c} + p_0 \frac{l_h}{(l_h - L)}\right] \tag{28}$$

In the initial vacuum in the chamber, the equation becomes simpler and takes the form:

$$L\frac{dL}{dt} = \frac{k_c}{\mu}\left[p + \frac{2\sigma}{r_c}\right] \tag{29}$$

The solution of equation (20) with the initial condition L (0) = 0 has the form:

$$L = \sqrt{\frac{2k_c(pr_c + 2\sigma)}{\mu r_c}}\,t^{½}, \tag{30}$$

where the order of time of exposure of the product under pressure:

$$t_1 = \frac{L^2 \mu r_c}{2k_c(pr_c + 2\sigma)}. \tag{31}$$

After the pressure is followed by a vacuum, in which the rate of discharge of compressed air through the porous structure of wood can be estimated by the equation (Patyakin et al., 1990):

$$\frac{du}{dt} = \frac{k_p}{\gamma_v l_h} p. \tag{32}$$

and the exposure time under vacuum (Vasco et al., 2018):

$$t_2 = \frac{l_h^2 \gamma_v}{k_p} p. \tag{33}$$

This is followed by a pressure operation, which results in the filling of the pore space of wood in accordance with equation (Patyakin et al., 1990):

$$L^2 = \frac{2k}{\gamma_v} pt, \tag{34}$$

and the exposure time for this operation:

$$t_3 = \frac{L^2 \gamma_v}{2k_p} \frac{1}{p}. \tag{35}$$

The total impregnation cycle time is:

$$\mathrm{T} = t_1 + t_2 + t_3. \tag{36}$$

To conduct experimental studies of the impregnation of wood with a liquid due to the overpressure arising from a water hammer, an experimental facility was created on the territory of Listvin LLC. The task included checking the adequacy of the mathematical model developed in (Kunitskaya et al., 2018).

It is known that the velocity of propagation of a water hammer wave is found by the formula:

$$a = \frac{a_v}{\sqrt{1 + \frac{d}{\delta} \cdot \frac{K}{E}}}, \tag{37}$$

where a is the velocity of impact propagation, [m/s], a_v is the velocity of propagation of sound waves in an unlimited liquid medium, [m/s], d is the internal diameter of the pipeline, [m], δ is the thickness of the walls of the pipeline, [m], K is the modulus of elasticity of the liquid, [Pa], E is the modulus of elasticity of the material of the pipeline walls, [Pa].

The increase in pressure when the hammer is according to the formula:

$$\Delta P = a\rho\Delta v, \tag{38}$$

where ΔP is the pressure increase, [Pa]; ρ is the fluid density, [kg/m^3]; Δv is the decrease in the velocity of the fluid in the pipeline, causing a water hammer, [m/s].

To determine the speed in the pipeline, depending on the time, use the following relationship:

$$v = \tanh\left(\frac{t_1}{\tau}\right).\sqrt{\frac{2gH}{1 + \zeta_r}}, \tag{39}$$

where t_1 is the time elapsed from the beginning of the valve opening, [s]; τ is the time over which the fluid flow rate is established, [c]; g — gravitational acceleration, [m/s^2]; H – liquid head, [m]; ζ_r – dimensionless coefficient taking into account the pipe roughness (drag coefficient).

To determine the time τ, the following formula is known:

$$\tau = \frac{l}{\sqrt{2gH(1 + \zeta_r)}} \tag{40}$$

where l is the length of the pipeline, [m].

The change in the rate of fluid flow is determined by the formula:

$$\Delta v = \frac{v}{T}, \tag{41}$$

where T is the time of complete valve closure, [c].

Then, after substituting formulas (37), (41) with regard to formulas (39), (40) in the expression for increasing pressure (38), the result is:

$$\Delta P = \frac{\rho .\, a_v}{T} \tanh\left(\frac{t_1\sqrt{2gH(1+\zeta_r)}}{l}\right) \cdot \sqrt{\frac{2gH\delta E}{(1+\zeta_r)(\delta E + d.K)}} . \tag{42}$$

The installation characteristics required for calculations using formula (42) are as follows: $\rho = 1000$ kg/m^3, $a_v = 1425$ m/s, $g = 9.81$ m/s^2, $\zeta_C = 0.01$, $l = 2$ m, $\delta = 0.005$ m, $d = 0.05$ m, $E = 2{\cdot}10^8$ Pa, $K = 2.1{\cdot}10^7$ Pa, $T = 0.5$ s, $t_1 = 5.5$ s.

Samples for the experiments were made from small-scale assortments of birch, aspen and alder. The cross section of the samples was square, 25×25 mm, the length of the samples was 300 mm.

The samples were impregnated with an aqueous solution of catechol violet (dye); the solution temperature was 20°C.

The main controllable factors in the experiments were: the number of pressures increase cycles K, the increase in pressure of the impregnating fluid during hydraulic shock P [MPa], the moisture content of experimental wood samples W [%].

The main intervals and levels of variation of the experimental factors are presented in Table 1.

Table 1. The main levels and intervals of variation of factors in conducting research on the impregnation of birch wood, aspen and alder water hammer

Factor	Value at the appropriate level of variation			Variation interval
	Lower -1	Main 0	Upper +1	
K	5	15	25	5
P	1	1.5	2	0.5
W	10	40	70	30

The target function was the depth of impregnation L, equal to the distance from the end of the experimental sample to the front of impregnation. The depth of impregnation was determined after splitting the samples using a ruler.

Before the experiments, plans were drawn up for a full factorial experiment on impregnating birch, aspen and alder wood with a hydraulic shock.

Statistical processing of the results of the full factorial experiment was carried out on the basis of the methodology described in (Vasco et al., 2018).

Table 2. The results of experiments on the impregnation of birch wood due to water hammer

№	N	P, MPa	W, %	L, mm	
				Average	S^2
1	25	2	10	134.2	175.7
2	5	1	10	46.8	27.2
3	5	1	70	50.6	50.3
4	5	2	70	45.4	6.8
5	5	1.5	10	54.8	42.7
6	25	2	70	196.0	347.5
7	25	1.5	40	194.6	368.3
8	15	1	70	57.6	61.3
9	15	1	10	31.2	31.2
10	25	2	40	206.6	331.3
11	25	1.5	70	191.0	74.0
12	5	1	40	46.6	40.3
13	5	1.5	40	102.4	156.8
14	25	1	40	128.4	418.3
15	15	1.5	40	183.6	41.8
16	25	1	70	120.4	267.3
17	5	2	40	83.0	81.5
18	15	1	40	79.4	130.8
19	15	2	70	103.0	96.5
20	25	1	10	72.6	80.3
21	15	1.5	70	131.4	119.8
22	15	1.5	10	102.8	48.7
23	15	2	10	92.6	24.8
24	5	2	10	39.8	35.2
25	15	2	40	147.4	109.3
26	5	1,5	70	67.6	74.3
27	25	1.5	10	150.4	88.8

The results of the full factorial experiments are presented in Tables 2–4.

Table 5 presents the results of calculating the statistics needed to verify the reproducibility of the experiments.

Tabular data indicate reproducible experiments. The calculated value of the Cochran's criterion in the impregnation of birch wood $G_{\text{calc}} = 0.1256$, aspen wood $G_{\text{calc}} = 0.1370$, alder wood $G_{\text{calc}} = 0.1283$. In all experiments, the calculated values of the criterion are less than the critical $G_{\text{crit}} = 0.1503$ at a significance level of $q = 0.05$.

The regression equations relating the depth of impregnation of birch, aspen and alder wood with the number of cycles of pressure increase, pressure increase during hydraulic impact and humidity of the blanks are as follows:

Table 3. Results of experiments on the impregnation of aspen wood due to hydraulic shock

№	N	P, MPa	W, %	L, mm	
				Average	S^2
1	15	2	40	167.4	932.3
2	25	2	40	231.8	458.2
3	25	1	10	88.8	174.2
4	25	2	70	216.8	1002.7
5	5	1	10	49.6	27.8
6	15	1	70	63.0	34.5
7	5	1.5	40	118.8	346.7
8	15	1.5	10	118.8	263.2
9	25	2	10	170.8	185.7
10	25	1.5	40	251.4	527.3
11	15	1	10	37.6	23.3
12	25	1	40	160.4	454.8
13	15	1	40	100.6	161.3
14	5	2	10	48.4	8.3
15	5	2	70	53.2	40.7
16	15	1.5	40	202.6	391.3
17	25	1.5	10	180.8	573.7
18	15	2	10	97.8	175.2
19	5	1,5	70	74.4	71.3
20	25	1.5	70	214.8	520.7
21	5	1	40	45.2	11.2
22	15	1.5	70	163.8	407.2
23	15	2	70	145.0	263,5
24	25	1	70	128.8	216.7
25	5	2	40	114.2	8.7
26	5	1.5	10	69.8	7.2
27	5	1	70	47.8	30.7

$$L = -334 + 460P + 3.229W + 2.432NP + \\ + 0.02996NW - 150.1P^2 - 0.04048W^2 \quad (43)$$

$$L = -412.3 + 563.1P + 3.996W + 2.924NP + \\ + 0.03211NW - 182.9P^2 - 0.0503W^2 \quad (44)$$

$$L = -499.1 + 690.1P + 3.908W + 4.294NP + \\ - 233.2P^2 - 0.04405W^2 \quad (45)$$

The results of the comparison of the calculated and experimental values of the depth of impregnation are presented in Figures 3–5, respectively.

The statistics needed to verify the adequacy of the regression models obtained are presented in Table 5.

Table 4. The results of experiments on the impregnation of alder wood due to water hammer

№	N	P, MPa	W, %	L, mm	
				Average	S^2
1	25	1.5	40	282.4	443.3
2	25	1	10	93.4	293.3
3	5	2	70	52.4	12.8
4	25	1	70	145.4	392.3
5	15	1	40	90.4	96.3
6	15	2	40	179.0	634.0
7	5	2	40	91.6	139.8
8	25	1.5	10	219.4	282.8
9	15	1.5	70	179.6	310.3
10	25	1.5	70	244.8	547.7
11	25	2	10	186.8	110.2
12	15	2	70	134.6	489.3
13	5	2	10	42.2	24.7
14	15	1.5	10	126.0	256.0
15	5	1	40	51.0	29.5
16	5	1.5	70	80.0	168.5
17	15	1	10	36.2	10.2
18	15	1	70	68.6	47.3
19	25	2	40	228.4	839.8
20	15	2	10	107.6	212.8
21	25	2	70	203.8	343.2
22	5	1	10	48.4	39.8
23	5	1.5	40	111.8	111.7
24	5	1	70	30.4	28.3
25	5	1.5	10	72.4	53.8
26	15	1.5	40	188.4	493.3
27	25	1	40	169.8	133.2

Table 5. Testing the reproducibility of experiments on the impregnation of hardwood using water hammer

Statistics	Wood species		
	Birch	Aspen	Alder
$S^2_{\max}$	418.3	1002.7	839.8
ΣS^2	3330.8	7318.4	6544.2
G_{calc}	0.1256	0.137	0.1283
G_{crit}	0.1503	0.1503	0.1503

The data in Table 6 show that equations (43)–(45) are adequate: for a birch wood impregnation equation, the calculated value of the Fisher criterion $F_{calc} = 1.5369$, which is less than the critical value $F_{crit} = 1.6685$ at a significance level $q = 0.05$; for the equation of impregnation of aspen wood, $F_{calc} = 0.7522$, which is less than $F_{crit} = 1.6685$; for the equation of wood alder impregnation $F_{calc} = 1.3821$, which is less than $F_{crit} = 1.6546$. The high values of the coefficients of determination of the constructed equations show a good convergence of the experimental and calcu-

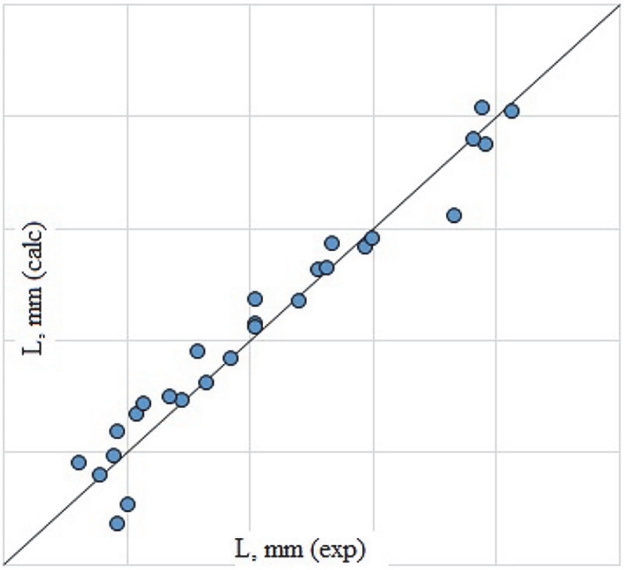

Fig. 3. Comparison of calculated and experimental values of the depth of impregnation of birch wood due to water hammer

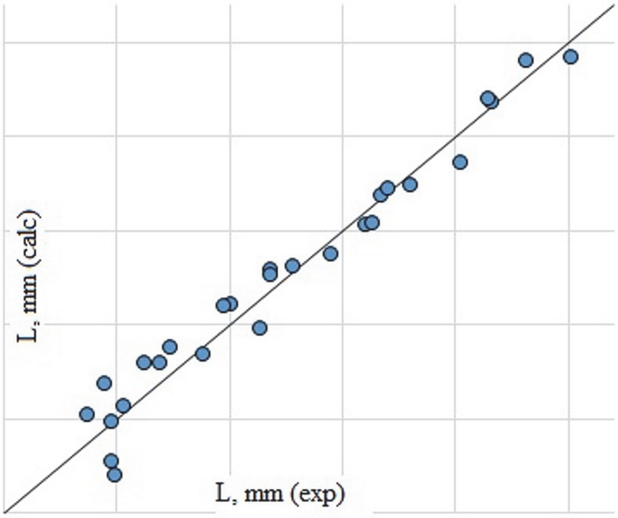

Fig. 4. Comparison of calculated and experimental values of the depth of impregnation of aspen wood due to hydraulic shock

lated values of the depth of impregnation of hardwood.

Let us set the optimal modes of impregnation blanks.

Using the Lagrange method, the catch point of the functions of the impregnation depth according to equations (43) – (45) with the constraints $N = 1 \div 25$, $P = 1 \div 2$ MPa, $W = 10 \div 70\%$ can be calculated. The results of the calculations are presented in Table 7.

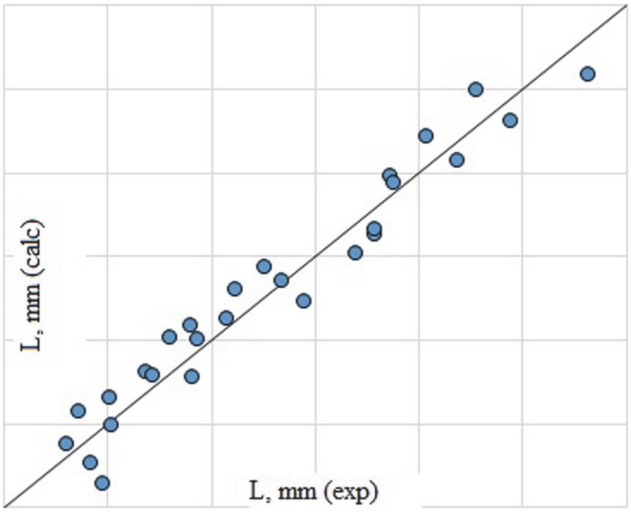

Fig. 5. Comparison of calculated and experimental values of the depth of impregnation of alder wood due to hydraulic shock

Table 6. Checking the adequacy of regression models of hardwood impregnation

Statistics	Wood species		
	Birch	Aspen	Alder
S^2_{adeq}	189.59	203.88	334.99
F_{adeq}	20	20	21
S^2_{repro}	123.36	271.05	242.38
F_{repro}	108	108	108
F_{calc}	1.5368	0.7522	1.3821
F_{crit}	1.6685	1.6685	1.6546
R^2	0.9513	0.9626	0.9471

Table 7. Optimum modes of wood impregnation with water hammer

Wood species	L, mm	N	P, MPa	W, %
Birch	215	25	1.73	49.1
Aspen	255	25	1.74	47.7
Alder	269	25	1.71	44.4

Conclusions

The calculation of the parameters of the wood impregnation process using a water hammer should be considered superpositionally as the sum of the pore and capillary components. The proposed mathematical model is based on dependencies (11), (13), (22), (24), (25), which take into account the parameters of water hammer (increase in pressure, amplitude and frequency), impregnating fluid and wood (viscosity and specific gravity of impregnate, surface tension, filtration coefficients of the capillary and pore space, the radii of the pores and capillaries, as well as the fraction of the sample volume falling on the pores and capillaries). With the given parameters, the model allows to calculate the main indicators of the impregnation process – the mass and depth of penetration of the impregnate into the workpiece.

The results of the model implementation show that the contributions of pore and capillary filtration are comparable, while the filtration in the pores is somewhat slower than in the capillaries. Experiments aimed at obtaining additional information on the permeability of wood separately for pores and capillaries can be considered a promising direction for further research. New experimental data will solve the problem of optimizing the parameters of the impregnation process in order to obtain uniformly impregnated workpieces in the shortest processing time. It was found that the best impregnation rates are achieved with an increase in pressure of 1.71–1.74 MPa with an initial moisture content of the blanks of 44.4–49.1% with the number of cycles 25 equal to the upper boundary of the search for the optimum point.

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