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MULTI-FACTOR MODELING OF DYNAMICS OF HARDWOOD DENSITY IN THE PROCESS OF THERMOMODIFICATION

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ABSTRACT

The results of experiments and statistical modeling of changes in the density of hardwood over the cross section of the samples in the process of vacuum-contact heat treatment are given in the paper. The study of the layer-by-layer density of the samples was performed using a laboratory X-ray Density profile Analyzer - DPX300. In each series of experiments, the change in the density of wood samples was recorded at the different values of temperature and time of heat treatment, sample thickness and layer depth. Modeling the process by the identification method made it possible to obtain one-factor regularities, ranked according to an increase in the correlation coefficient. It was found that the main influence on the density change is exerted by such factors as processing time and temperature. Subsequent modeling made it possible to create a four-factor model of the dynamics of the density of samples during the heat treatment, which allows the prediction of the density profile of the material depending on the thickness of the material and the operating parameters of the process. The proposed model can be further used in the development of new operating parameters of the process of vacuum-conductive thermal modification of hardwoods in order to achieve a uniform degree of processing over the entire section of lumber.

Key words: thermal modification, hard wood, density, correlation coefficient.

INTRODUCTION

The process of heat treatment of wood is being currently discussed and developed in Russia and abroad. It is of intense interest to many researchers, since this issue has a huge variety of development courses and a good prospect for in-depth study and the use in the future. Thermally treated wood surpasses untreated one in a number of indicators: it has improved performance characteristics (for example, such as biological stability, size and shape stability), has a decent appearance from light brown to dark aristocratic hues.

Heat treatment is gradually introduced into many wood processing technologies, such as production of massive thermally modified wood, composite materials and solid biofuels (BEHR *et al.* 2018, GALYAVETDINOV *et al.* 2016, SAFIN *et al.* 2015a, KHASANSHIN *et al.* 2016, SAFIN *et al.* 2015b). Chemical compositions are not used in the process of heat treatment; therefore, when the European Commission banned the use of chemically treated wood (2004), this type of modification of plant raw materials has become primary, both for producers and consumers of these products. The East European Plain ecosystem is represented by taiga-broadleaved forests with spruce, pine, aspen, mountain ash, birch, oak, and other tree species. Hardwood species are of great interest, and their thermal modification allows the improved performance and improved decorative properties of wood.

Thermal modification is carried out at the processing temperatures from 180 to 240^{0}C, while the wood undergoes thermochemical transformations causing a change in its physical properties. The feature of the thermal modification process is the change in properties throughout the volume of the material. The number of researchers claim (MÖTTÖNEN 2006, SALIN 2010, ESPINOZA *et al.* 2016, SANDOVAL-TORRES 2012, OUERTANI 2015) that the most suitable method for assessing the degree of heat treatment is the value describing the change in wood density. Still there are no theoretical and experimental data characterizing the change in the density of wood by layers in the process of thermal modification. However, the process of monitoring the changes in the density of the material by layers will ensure the uniformity of thermal modification of wood throughout the section of the workpiece, and, thereby, prevent possible negative phenomena in service. Thus the authors set the following objectives:

- to investigate the change in the wood density of the main hardwood (aspen, birch and oak) over the cross section of the samples in the process of thermal modification;
- to identify single-factor patterns and, according to an increase in the correlation coefficient, to identify the factors of the greatest influence on the change in the wood density in the process of heat treatment;
- to conduct multi-factor process modeling with the use of an identification method to further control the process and ensure smooth heat treatment.

MATERIALS AND METHODS

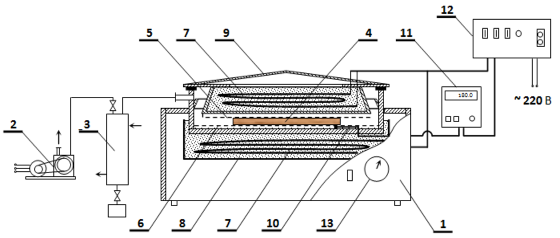
To research the process of thermal modification, the samples of aspen, birch and oak wood without wood defects with a cross section of 20 × 50 mm and the length of 250 mm were prepared. The samples of each tree species were taken from one radial sawing board, that helped ensure the same structure of growth rings along the tangential sections of the sample.

The bars underwent vacuum drying at 60 ºC for 5 days, which ensured a smooth moisture distribution over the cross section of the samples in the range between 5–6%.

All samples were weighed in order to determine the average density for the entire batch prior to the beginning of the experiment. The samples with a deviation of their density from the average value throughout the batch of not more than 1% were accepted for further experiments. The initial temperature of the samples was taken to 20 ^{0}C during their room storage.

48 samples of each tree species were selected to carry out the studies on the change in the density of wood during thermal modification. A number of experiments with varied parameters such as sample thickness, temperature and processing time were carried out using experimental equipment with diagram given in Fig. 1.

The equipment for the heat treatment of wood contains a chamber 1, which is connected to a vacuum line consisting of a vacuum pump 2 and a condenser 3. The supply of thermal energy to the treated timber 4 is carried out by means of a contact method using heat-supplying surfaces 5 and 6. They are perforated metal plates heated by filaments 7. The plates are thermally insulated from the side opposite to the material processed with porous moisture-proof and breathable material 8. While conducting the experiment, the chamber is sealed with a cover 9. As a result of close contact of sample 4 with heating surfaces 5 and 6, heating of the sample can be observed. The heating temperature is controlled by a thermocouple 10 installed in the plate, a control electronic device 11 and a control panel 12. The pressure in the chamber is recorded by a pressure gauge 13.



1 - chamber, 2 - vacuum pump, 3 - condenser,
4 - treated timber, 5,6 - heat-supplying
surfaces, 7 - filaments, 8- porous heat
insulator,
9 - camera cover, 10 - thermocouple,
11- control electronic device,
12 - control panel, 13 - pressure gauge.

Fig. 1 Experimental equipment of vacuum-contact heat treatment of wood.

In each series of experiments, four samples of a certain thickness (4, 12, or 20 mm) were simultaneously loaded into a chamber preheated to the required temperature, which were then subjected to the thermal modification under the same conditions, but at different temperatures (180, 200, 220, and 240 ºC). After a specified time interval (2, 3, 4, and 5 hours), one sample was taken out of the chamber and immediately placed in a desiccator for cooling without moisture gain.

The change in density over the thickness of the obtained samples was assessed with the X-RAY Density Profile Analyzer - DPX300 (Fig. 2), which contains a radiation source (X-ray tube), a detector, and a data acquisition and processing unit.

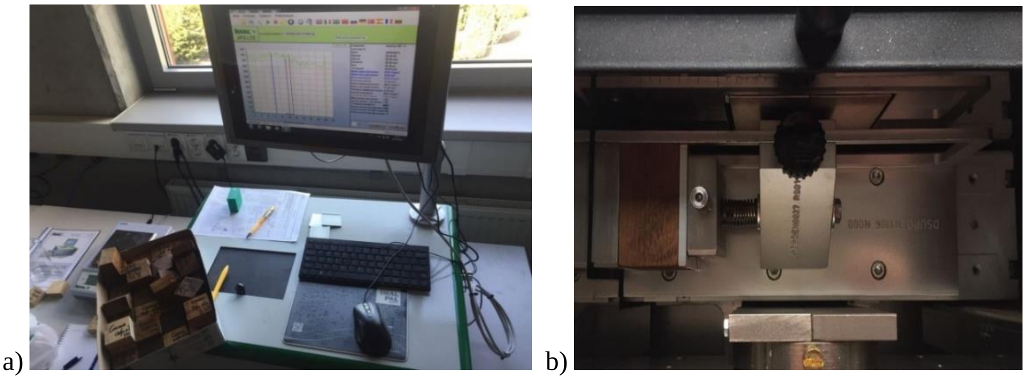


Fig. 2. Measurement of sample density:
a - appearance of the X-RAY Density Profile Analyzer - DPX300, b - sample in the equipment.

The non-contact technology allows scanning the samples under study by irradiation with primary X-ray radiation and, based on the response X-rays, registering the change in density over the cross section of the material with a step of 1 mm with a detector. The high sensitivity of the analyzer ensured small measurement errors, and the compatibility with Windows made it possible to obtain graphs of the density change during the measurement procedure.

RESULTS AND MODELLING

An array of data was obtained as a result of the experiments carried out for each type of wood, which makes it possible to study the dynamics of wood density through multivariate modeling by the identification method (AHMED *et al.* 2008, WIECZOREK 2017, SERGIENKO 2014, ROFFEL *et al.* 2004).

The process of multi-factor modeling on the example of aspen is described in detail. To do so, the data obtained within each series of experiments is combined in Table 1.

Tab. 1 Initial data for multi-factor modeling of the process of changing the density of the aspen samples in the process of thermal modification.

Item number	Sample thickness s, (mm)	Processing temperature t, (°C)	Processing time τ, (h)	i-th depth of layer x, (mm)	Wood density ρ, (kg/m^3)	Absolute err. ε, (kg/m^3)	Relative err. Δ, (%)
1	4	180	2	1	535	-3.51117	-0.66
2	4	180	2	2	536	-3.32837	-0.62
3	4	180	3	1	533	-3.59447	-0.67
4	4	180	3	2	535	-2.41177	-0.45
5	4	200	2	1	528	-4.80906	-0.91
6	4	200	2	2	529	-4.62631	-0.87
…	…	…	…	…	…	…	…
11	4	220	3	1	516	-2.19333	-0.43
12	4	220	3	2	517	-2.01053	-0.39
…	…	…	…	…	…	…	…
15	4	240	2	1	493	-4.63393	-0.94
16	4	240	2	2	495	-3.45113	-0.70
…	…	…	…	…		…	…
24	12	180	3	2	536	-1.02577	-0.19
25	12	180	3	4	538	-0.226268	-0.04
…	…	…					
55	12	200	4	4	519	0.247113	0.05
56	12	200	4	6	521	0.959613	0.18
…	…	…	…	…		…	…
143	20	200	5	1	526	-2.58409	-0.49
144	20	200	5	2	528	-1.40135	-0.27
…	…	…	…	…	…	…	…
169	20	220	4	4	520	1.42682	0.27
170	20	220	4	6	522	2.13934	0.41
…	…	…	…	…		…	…
207	20	240	5	8	499	0.789271	0.16
208	20	240	5	10	500	0.0647711	0.01

Similar tables of initial data for subsequent mathematical modeling of the process were obtained for the samples of birch and oak wood.

The experimental data were processed in the CurveExpert-1.40 software environment, which made it possible to obtain graphs based on the existing array of points and select the optimal dependences. The analysis of deviations of the obtained experimental data from the obtained model was carried out along with the selection. Further, the obtained regularities were ranked according to the increasing correlation coefficient.

One-factor patterns were identified at the first stage of modeling. The factors according to the growth of their influence on wood density according to the increase in the correlation coefficient were arranged.

In Figure 3, in the upper right corner are located: s – dispersion; r – correlation coefficient characterizing the levels of adequacy of the laws: above 0.7 – a strong relation between the factors; 0.5-0.7 – medium relation; 0.3-0.5 – weak relation (WIECZOREK 2017).

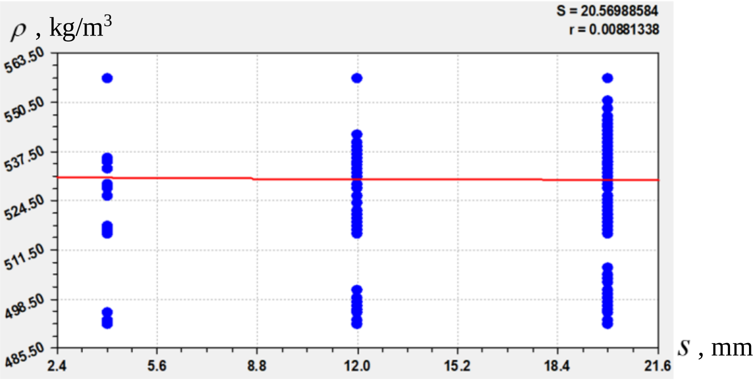


Fig. 3 The effect of thickness on the density of aspen samples.

The one-factor function of the effect of sample thickness on density with a correlation coefficient of 0.0088 is determined by the formula:

$$\rho(s) = 686.52127\exp(-0.25658 s^{0.0025686}) . \tag{1}$$

Thus, the aspen density decreases exponentially with average calculations with increasing sample thickness.

The data of graph 4 shows that when the correlation coefficient is 0.0969 (less than 0.3), the effect of the layer depth on the density of the samples becomes more obvious according to the law of exponential growth:

$$\rho(x) = 527.80274\exp(0.00079932 x^{1.18730}) . \tag{2}$$

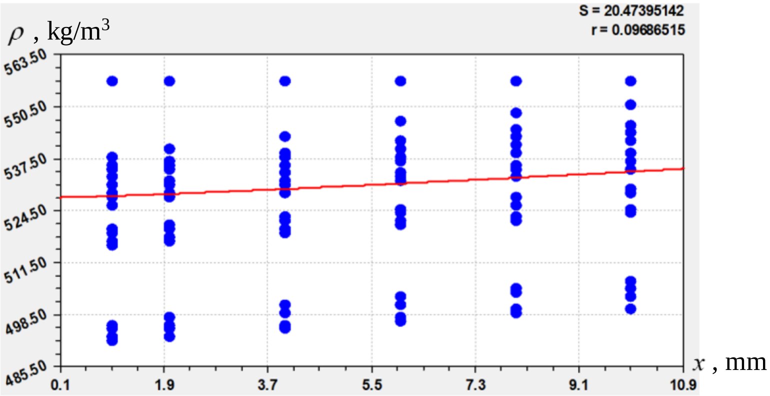


Fig. 4 The effect of layer depth on the density of aspen samples.

An increase in the density of the wood of the studied samples with an increase in the depth of the layer is observed.

The processing time is the next factor with an adequacy of 0.7199:

$$\begin{gathered}\rho(\tau) = 557.00000\exp(-0.14383\tau^{0.43969}) + \\ + 60.86110\tau^{0.55309}\exp(-0.28278\tau^{0.12405})\end{gathered} . \tag{3}$$

The indicated regularity includes two components. The first was the law of exponential death, and the second was the biotechnical law. The graph 5 shows that the impact of the first component was significant.

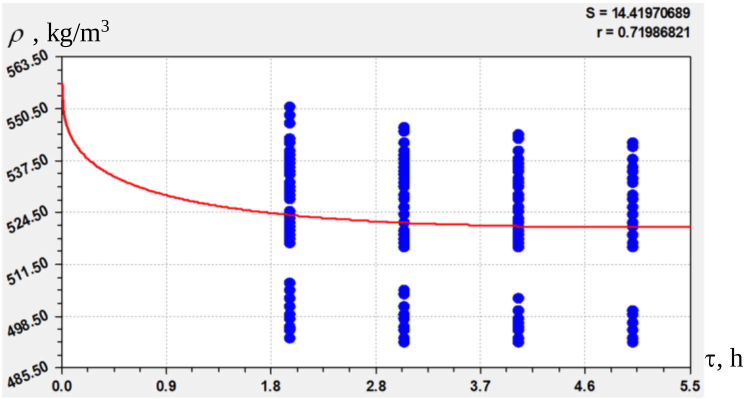


Fig. 5 The effect of the time of processing on the density of aspen samples.

And, finally, the highest correlation coefficient of 0.9836 has a factor in the influence of temperature on the change in density of wood samples (Fig. 6) according to the inverse Weibull law:

$$\rho(t) = 557.15069 - 0.37191\exp(0.021100t)\,. \tag{4}$$

According to this formula, the exponential law of growth is subtracted from the initial density at growth rate 1.

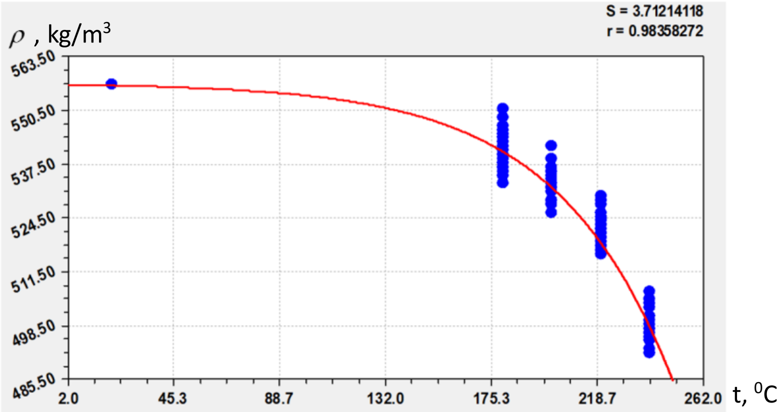


Fig. 6 The effect of temperature on the density of aspen samples.

Thus, single-factor patterns were determined, which were further ranked according to an increase in the correlation coefficient as a result of the modeling:

1) the function of the effect of sample thickness on density with a correlation coefficient of 0.0088;
2) the function of the effect of layer depth on density with a correlation coefficient of 0.0969;
3) the function of the effect of processing time on the density with a correlation coefficient of 0.7199;
4) the function of the effect of processing temperature on the density with a correlation coefficient of 0.9836.

Later we match the obtained data to get a multifactor model of the dynamics of the density of the hardwood sample in the process of heat treatment. Therefore, we take the absolute errors from model (1) and find their dependence on the next most important factor - the depth of the x layer. The values of the absolute errors ε are given in Table 1.

$$\varepsilon_s(x) = -557.55228\exp(-5.49169x^{0.076154}) + 0.098879x^{1.71497}\,. \tag{5}$$

There was a slight increase in the correlation coefficient from 0.0969 (Fig. 4) to 0.1009. The modeling results are given in Figure 7.

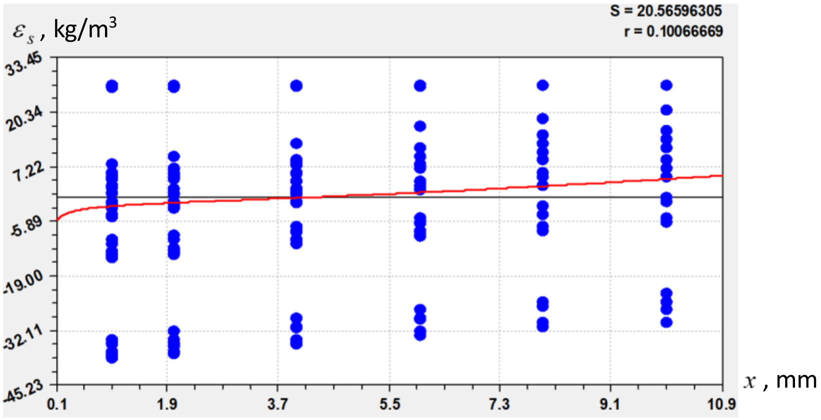


Fig. 7 The dependence of the absolute error of the thickness of the work material on the depth of the layer of the studied samples of aspen.

Then we find the dependence of the total absolute errors of the work material thickness and the layer depth on the next most important factor - the processing time τ (Fig. 8).

$$\varepsilon_{s,x}(\tau) = 26.90364\exp(-0.016314\tau^{1.76265}) - 1.30535\,\tau^{0.28704}\exp(-0.089971\tau^{1.06196}) \quad (6)$$

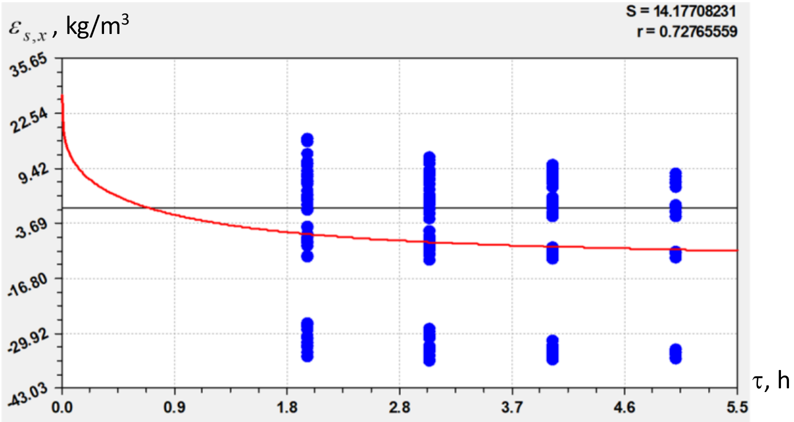


Fig. 8 The dependence of the absolute error of the thickness and depth of the layer of the work material on the processing time.

Compared with Fig. 5, the correlation coefficient became 0.7277 instead of 0.7199 (in single-factor modeling).

Next, the dependence of absolute errors on the last factor-the processing temperature t is determined:

$$\varepsilon_{s,x,\tau}(t) = 2.86459\cdot10^{-7}\exp(8.41213t^{0.15959}) - 2.15207\cdot10^{-9}\,t^{4.59846} \quad (7)$$

Figure 9 shows the result of modeling this dependency.

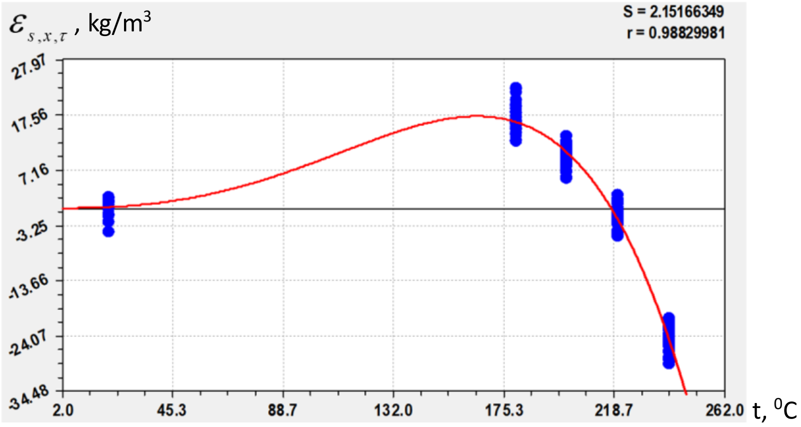


Fig. 9 The dependence of the absolute error of the thickness, the depth of the layer and the processing time on the processing temperature.

According to calculations, a correlation coefficient of 0.9883 was obtained, which is slightly higher than the value in the single-factor model of 0.9836 (Fig. 6).

A four-factor model of the density dynamics of wood samples during thermo modification is presented in the form of a formula:

$$\rho(s,x,\tau,t)=\rho(S)+\varepsilon_s(x)+\varepsilon_{s,x}(\tau)+\varepsilon_{s,x,\tau}(t)\,, \tag{8}$$

where:

$\rho(s)$ - function of the influence of the sample thickness on the density according to the equation (1);

$\varepsilon_s(x)$ - absolute accuracy of the sample thickness versus the layer depth of the samples under study according to the equation (5);

$\varepsilon_{s,x}(\tau)$ - absolute accuracy of the sample thickness and layer depth versus processing time according to the equation (6);

$\varepsilon_{s,x,\tau}(t)$ - absolute accuracy of the sample thickness, layer depth and processing time versus sample processing temperature according to the equation (7).

The relative error of the model at each point is determined by the formula:

$$\Delta=100\varepsilon/\rho_\phi\,, \tag{9}$$

where ρ_ϕ - the actual values of the density of aspen according to Table 1. The maximum relative error of the four-factor model for aspen wood was 1.18%.

Figures 7-9 show small fluctuations confirming the vibrational nature of the process of thermal modification of wood (Zhou *et al*. 2019, Defo *et al*. 2004). Fluctuations occur due to frequent removal of the samples and rapid cooling to register the density profile.

Similarly, the dynamics of the density of birch and oak in the process of thermal modification were simulated.

When modeling the dynamics of the density of birch, we found that, unlike aspen and oak, the first factor with the lowest correlation coefficient is the depth of the layer, and the thickness of the work material goes second in terms of the adequacy rating of single-factor models. The highest correlation coefficient of 0.8845 has an effect of temperature on the change in density of hardwood samples.

The four-factor model for birch wood is given as a formula:

$$\rho(x,s,\tau,t)=\rho(x)+\varepsilon_x(s)+\varepsilon_{x,s}(\tau)+\varepsilon_{x,s,\tau}(t)\,, \tag{10}$$

where:

$$\rho(x) = 533.53307\exp(0.00058880x), \tag{11}$$

$$\varepsilon_x(s) = 75.90639 - 38.36827S^{0.25332}, \tag{12}$$

$$\varepsilon_{x,s}(\tau) = 63.32358\exp(6.6978\tau^{0.013788}) - 51277.8183\tau^{0.093219}, \tag{13}$$

$$\varepsilon_{x,s,\tau}(t) = 9.07283\cdot 10^{-6}\exp(6.75709t^{0.19455}) - 1.97986\cdot 10^{-6}t^{3.86043}. \tag{14}$$

a correlation coefficient of 0.6771 was obtained for the average constraint force between all factors, which is significantly less than the calculated above indicator. The maximum relative error of the four-factor model for birch was 13.39%.

The four-factor model for oak is presented as a formula:

$$\rho(s, x, \tau, t) = \rho(S) + \varepsilon_s(x) + \varepsilon_{s,x}(\tau) + \varepsilon_{s,x,\tau}(t), \tag{15}$$

where:

$$\rho(s) = 2026.66952\exp(-0.99239s^{0.0050216}), \tag{16}$$

$$\varepsilon_s(x) = -281.48238\exp(-1.88476\cdot 10^{-5}x^{3.02178}) + 276.03376x^{0.013825}, \tag{17}$$

$$\varepsilon_{s,x}(\tau) = 93.28925\exp(0.27708\tau^{1.01788}) + 84.02560\tau, \tag{18}$$

$$\varepsilon_{s,x,\tau}(t) = 2.37693\exp(0.0014055t^{1.61074}) - 1.24980\cdot 10^{-30}t^{14.05239}. \tag{19}$$

As a result of the simulation, a correlation coefficient of 0.7017 of a strong relation between all factors was obtined. The maximum relative error of the four-factor model for oak was 14.57%.

CONCLUSION

The processes of thermal modification of wood are currently under study and of great interest both to manufacturers and to many researchers whose aim is to study and improve technologies. One of the important parameters for assessing the quality and degree of heat treatment of wood is the change in density over the cross section of the material. In this regard, monitoring the density drop of the material by layers will ensure the uniformity of thermal modification of wood throughout the entire section of the sample, thereby prevent possible negative phenomena in operation.

Numerous experimental studies of hardwood samples (aspen, birch and oak) of various thicknesses at different temperatures and processing times were carried out in order to study the dynamics of changes in wood density during heat treatment.

Multi-factor modeling of the process was carried out by the method of identification based on the results of the experimental studies. The obtained experimental data were processed in the CurveExpert-1.40 software environment, as a result of which the authors built graphical dependencies, performed regression analysis, and identified one-factor patterns, which were further ranked according to an increase in the correlation coefficient.

According to the rating of the adequacy of one-factor models for the considered tree species, strong factor relations with a correlation coefficient of not less than 0.7 were found under the influence of time and temperature of processing on the density of the samples under study.

The four-factor models of the dynamics of the density of aspen, birch and oak wood in the process of heat treatment were obtained based on the results of one-factor modeling by the method of identification. Those models allow the prediction of the change in density depending on the thickness of the material and the parameters of the technological process. The calculated correlation coefficients indicate a strong relation between all factors, while the greatest influence on the change in wood density is exerted by such factors as processing time and temperature. The maximum relative error of the presented models does not exceed 15%, which proves that they could be used in modeling the processes of vacuum-conductive thermal modification in order to optimize the operating parameters and ensure a uniform degree of processing over the entire section of lumber.

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