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Pulse drying of red oak wood workpieces

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Abstract. The reasons for reducing the cost of lamella made of oak wood – the front covering of floorboards – are determined. It is established that when drying oak wood at low temperatures, moisture accumulates in the area near the surface – the so-called conditional source of moisture. This leads to the development of light spots inside the lumber, which were stored for a long time in conditions of increased air humidity and had a low rate of moisture removal. It is proposed to intensify the drying process by using pulse modes, which consist of periods of heating and cooling of wood to avoid this defect. During the heating period, the temperature of the material gradually increases, the wood receives a thermal shock and accumulates heat, and drying occurs only due to the humidity gradient. During cooling, the temperature of the medium decreases, the degree of saturation increases and, accordingly, the equilibrium humidity increases. As a result, the surface layers of the material are moistened, moisture is levelled along the thickness of the wood, and drying stresses are relaxed. Experimental studies of pulse drying of workpieces made of red oak wood with a thickness of 30 mm and 50 mm were conducted in laboratory conditions. The amplitude of the temperature fluctuation – 30°C and the expediency of cyclic heating are determined only until the average humidity of the material reaches 20%, after which the wood must be dried to the required final humidity at a constant heating temperature. A method for calculating the duration of pulse drying is proposed, which considers the kinetics of heating and cooling periods of red oak lumber products with a thickness of 30 mm and 50 mm. It is recommended to consider the process of temperature change kinetics as the sum of the processes of cyclic heating, which occurs according to the polynomial dependence, and cyclic cooling, which occurs according to the exponential dependence. It is determined that the ratio of the duration of cyclic heating to the duration of cyclic cooling is 1/3. Using heat and mass transfer criteria and the experimentally determined moisture conductivity coefficient of red oak wood, an adequate model for calculating wood temperature and relative humidity during wood heating and cooling cycles was developed. Based on the results of theoretical and experimental studies, pulsed drying modes of red oak workpieces of various thicknesses are proposed, which prevent the development of white spots inside the material. There was a reduction in the process duration by 1.5-2.4 times and a reduction in energy consumption by 1.53 times. The indicators of residual stresses, the values of the stress difference in the workpieces after drying, and the values of the static flexural strength determined experimentally showed that their drying quality corresponds to the first quality category according to DSTU 4921:2008. Comparison of the obtained values with the maximum permissible values of the tensile strength across the fibres in the tangential direction σ_m = 6.5 MPa showed a safety margin of 25%, which indicates the possibility of using pulse drying modes for high-quality drying of workpieces made of red oak wood

Keywords: Red Oak (Quercus rubra), coefficient of moisture conductivity, pulse modes, drying quality, drying time

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Introduction

Among manufacturers of floor coverings, the fast-growing introduction of red oak *(Quercus rubra)* is gaining popularity today. Red oak covers an area of 2251 hectares in the forests of the State Forestry fund of Kyiv Polesia (Poliakova, 1999).

Parquet billet, made of solid wood and coatings in the form of parquet boards, consisting of several layers and having a front coating in the form of slats made of solid hardwood are considered floor coverings. In the technology of manufacturing lamella, the following methods are used: pre-cutting of lumber to slats and its subsequent drying, accompanied by substantial labour costs for the formation of drying sets, and pre-drying of lumber with subsequent production of lamella.

Today, convection chambers heated with hot water are used for drying lumber. When drying oak wood at low temperatures, moisture accumulates in the area near the surface – the so-called conditional source of moisture (Pinchevska, Spirochkin, Sedliacik & Oliynyk, 2016). This leads to the development of light spots inside the lumber, which were stored for a long time in conditions of increased air humidity and had a low rate of moisture removal. The development of stains reduces the cost of the lamella. It is possible to get rid of this defect by intensifying the drying process by increasing the temperature of the drying agent. However, prolonged exposure to high temperatures t_{heat} >60°C for wood with a humidity greater than W>30% contributes to a sharp decrease in its strength. Because of this, it became necessary to develop rational modes for the drying process of lumber made from red oak wood.

The removal of moisture from hard hardwoods is characterised by certain features: a substantial duration of the process; fastidiousness to the drying regime parameters due to temperature and humidity limits; the risk of defects or discolouration during the drying process, etc. (Pinchevska, Koval & Marchenko, 2012; Wegener & Fengel, 1987). This is primarily due to the anatomical structure of wood – substances that form the microstructure of these species (Vintoniv & Uholiev, 2007).

One of the ways to intensify the drying process of lumber is the use of pulse modes, the essence of which is to alternate periods of heating and cooling (Miliü & Kolin, 2008; Remond & Perre, 2008). During pulsed drying, the heating and cooling cycles play different roles in heat and mass transfer processes (Lykov, 1956). During the heating period, the temperature of the material gradually increases, the wood receives a thermal shock and accumulates heat, and drying occurs only due to the humidity gradient. During cooling, the temperature of the medium decreases, the degree of saturation increases and, accordingly, the equilibrium humidity increases. The temperature inside the wood exceeds the temperature of the surface layers. Due to this difference, a positive temperature gradient occurs in the wood, which leads to the migration of moisture from more heated layers to less heated ones. As a result, the surface layers of the material are moistened, moisture is levelled along the thickness of the wood, and drying stresses are relaxed (Pleschberger, Hansmann, Mueller & Teischinger, 2013). Since no energy is consumed during the cooling period of wood, this leads to a substantial reduction in its usage (Kosarin, 2012; Miliü & Kolin, 2008) and a 24% reduction in the prime cost of the process (Kosarin, 2012). Mixed opinions are expressed about the effect of periodic heating on the drying time, in particular, the reduction of the process duration by 1.5-2 times for beech and oak wood is indicated in (Lubovitsly, 1986), the opposite opinion is highlighted in the papers (Bond & Espinoza, 2016; Salin, 2003). However, all researchers note an improvement in the quality of drying.

It is necessary to consider the temperature and humidity of the drying agent during heating, determine the safe amplitude of temperature fluctuations for the drying quality, and the influence of the heating temperature level on the mechanical properties of the material to determine the quantitative values of the parameters of pulsed drying modes of lumber. The frequency of heating-cooling cycles during drying should be conducted only during the period when the wood contains Free Moisture. Further application of such cycles does not affect the rate of removal of bound moisture (Pleschberger, Hansmann, Mueller & Teischinger, 2013; Miliü & Kolin, 2008). After the wood reaches humidity W = 20% the temperature of the drying agent should be maintained at a constant level until the lumber reaches the specified final humidity (Welling, Riehl & Zerhau, 2004; Folvik & Magnar, 2004).

The creation of pulsed modes is based on the principle of intermittent processes observed during atmospheric drying or drying using solar energy in solar dryers (Tepnadse, 1986; Hasan & Langrish, 2016), when the wood is heated during the day and cooled at night. The use of pulse modes, in contrast to drying in solar dryers, allows adjusting the parameters of the drying agent depending on the characteristics of the dried material. The difficulty lies in determining rational modes since the known analytically calculated parameters differ both in the level of temperature and the amplitude of its fluctuations, the level of relative humidity, the duration of the "heating – cooling" cycles, even for lumber of the same species and thickness (Kosarin, 2012; Shyshkina, 2006). Thus, today, there are no theoretically confirmed and experimentally verified modes of intensive drying of red oak wood that would not cause the formation of a so-called conditional source of moisture, which causes the appearance of light spots in the inner layers of lumber.

The purpose of the study is to determine the parameters of a rational drying mode for lumber made of red oak wood in the process of pulse drying, which will ensure high-quality drying of wood with the preservation of mechanical properties.

Materials and Methods

Red oak workpieces without visible defects with a thickness of 30 mm and 50 mm were selected, which corresponds to the thickness of industrial lumber, which is most often used in lamella manufacturing technology to analyse the main operating parameters. The width of the experimental samples was 85-90 mm, and the average initial humidity ranged between 45-50%. The samples were dried to a humidity of 7-8%. Drying was conducted in a laboratory drying device with a loading volume of 0.12 m^3 of dense material equipped with an automatic process control system that maintains the drying agent circulation rate at 1.2 m/s. The temperature inside the samples was measured using thermocouples. Saturated steam was supplied to the chamber to avoid rapid removal of moisture and, accordingly, cracking of the material during heating.

The DSTU 4921:2008 and ENV 14464:2002 methods were used to calculate the internal stress index of dried workpieces based on the relative deformation of the teeth of power sections. The values of the elastic modulus and elastic deformations were determined according to the method presented in a paper (Uholiev, 2007).

Determination of the mechanical properties of dried wood (tensile strength and elastic modulus under static bending) was performed in accordance with the instructions of the standard method (EN 408:2010) using the P-5 testing machine. The tests were conducted indoors at an air humidity of 65±5% and an environment temperature of 20±2°C.

The hypothesis of oscillatory drying kinetics is proposed to calculate the rational parameters of the drying mode, which consists in representing the temperature change of the material according to the sinusoidal law:

$$t_{surf} = t_{mid} + A_t \cdot \sin\left(\frac{2\pi}{\tau_{per}} \cdot \tau_{dr}\right) + \frac{1}{2}(t_a - t_{in}) Ki \cdot \varepsilon \cdot Ko \cdot Ly, \quad (1)$$

where t_{surf} – wood surface temperature, °C; t_{mid} – arithmetic mean of the heating and cooling temperature values,°C; A_t – oscillation amplitude,°C; τ_{per}– duration of one cycle (heating–cooling), h; τ_{dr} – duration of the drying process, h; t_a– environment temperature,°C; t_{in} – initial wood temperature,°C; *Ki* – Kirpichev criterion (Lykov, 1956); ε – coefficient of phase transformation of moisture (Horokhovsky, 2008); *Ko* – the Kosovich criterion (Lykov, 1956); *Ly* – Lykov criterion (Lykov, 1956).

It is necessary to have quantitative values of the moisture conductivity coefficients of oak wood, which are determined experimentally to determine the quantitative values of the Lykov criterion *Ly* and the Kirpichev criterion *Ki*. The contact humidification method was used (Serhovsky & Rasev, 1987; Alpatkina, 1970) to determine the coefficients of moisture conductivity. For this purpose, samples of red oak wood originating from the Polesia zone – the largest area of oak forests in Ukraine were selected. The total number of experiments considering the obtained (Alpatkina, 1970) coefficient of variation $V_{a'}$ = 7.7% was 32 pcs. Other components of the above-mentioned criteria and the coefficient of phase transformation of moisture were determined by known dependencies (Vintoniv, Sopushynsky & Teischinger, 2007; Horokhovsky, 2008; Kosarin, 2012; Shubin,1990; Ozarkiv & Kopynets, 2006).

Results and Discussion

The parameters of the pulse drying mode were determined empirically. The parameters of the drying agent during heating were as follows: temperature t = 100°C, relative humidity – φ = 90-100%. The heating duration is determined by reaching the temperature of the centre of the workpieces t_{cen} = 85°C. A study of the duration of the process was conducted in the case of reaching different cooling temperature levels (t_{cool1}= 25°C, t_{cool2}= 55°C, and t_{cool3}= 70°C) to determine the rational amplitude of temperature fluctuations. It is determined that the highest rate of moisture removal from samples is characteristic of the amplitude of fluctuations in the sample temperature period equal to 30°C, similar to the results obtained in the studies (Zakharzhevsky, 1948; Minhazov & Kachalin, 1976).

The hypothesis of temperature change according to the sinusoidal law does not correspond to experimental data, while the duration of heating the material is almost 3 times shorter during cooling (Fig. 1).

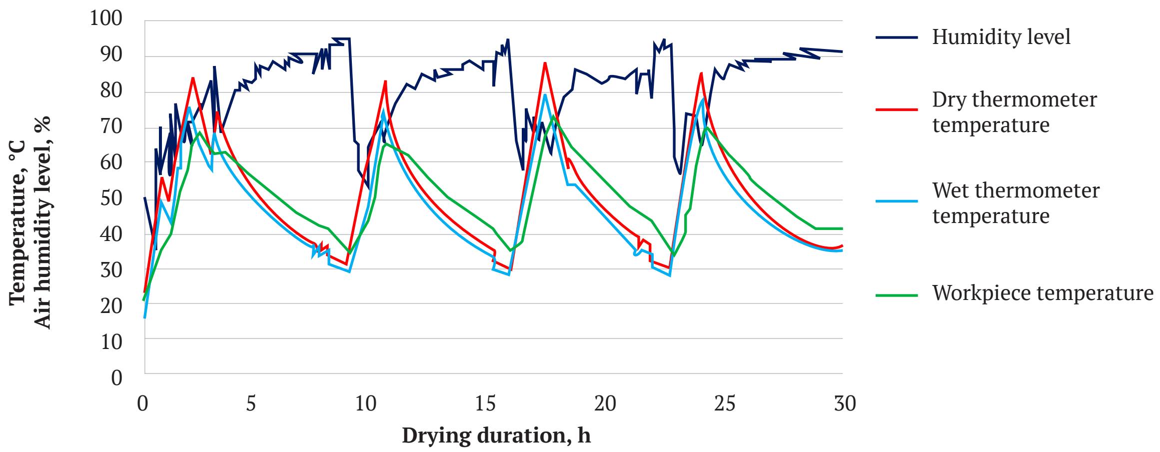


Figure 1. Factual values of the parameters of the drying mode of red oak with a thickness of 50 mm at the initial stage

Experimental data on the kinetics of temperature changes (Fig. 2) showed that the heating period is polynomial dependent, and the cooling period is exponential. According to the differences in the kinetics of changes in the surface temperature of samples corresponding to the temperature of a wet piece during the heating period $t_{sur.\ heat}$, h, and cooling $t_{sur.\ cool}$, h, the hypothesis of the sinusoidal law of its change was adjusted. It is proposed to consider separate periods of heating and cooling:

$$\begin{cases} t_{surf.heat} = t_{cen.heat} + \frac{1}{2} \cdot (t_c - t_{cen.cool}) \cdot Ki_m \varepsilon KoLu, \\ t_{surf.cool} = t_{cen.cool} + \frac{1}{2} \cdot (t_c - t_{cen.heat}) \cdot Ki_m \varepsilon KoLu, \end{cases} \quad (2)$$

where $t_{cen.\ heat}$, $t_{cen.\ cool}$ – temperature of the central part of the workpieces during the heating and cooling period, respectively, °C.

Total drying time τ_{dry}, h, according to the proposed mode, is advisable to be determined by the total number of cycles consisting of the sum of heating periods τ_{heat}, h, cooling τ_{cool}, h, and continuous heating period τ_{cont}, h (from humidity W = 20% to final humidity W_f = 6-10 %):

$$\tau_{суш} = n \cdot (\tau_{heat} + \tau_{cool}) + \tau_{cont}, \quad (3)$$

where n – number of cycles of the oscillating drying process, pcs.; τ_{heat} – heating duration, h; τ_{cool} – duration of the cooling process, h; τ_{cont} – duration of drying with continuous heating to the operational humidity of the material from humidity W = 20%, h.

The following equation was used (Serhovsky & Rasev, 1987) to determine the last drying period at constant temperature:

$$\tau_{cont} = \frac{3600 \cdot S^2}{\pi^2 \cdot a'} ln\left(\frac{W_{in} - W_{eq}}{W_к - W_{eq}}\right), \quad (4)$$

where a' – coefficient of moisture conductivity, cm²/s; W_{in}, W_f, W_{eq} – initial, final, and equilibrium humidity, respectively, %; S – material thickness, cm.

An empirical equation is proposed to determine the number of heating-cooling cycles depending on the thickness of the material and the initial humidity:

$$n = (14 \cdot W_{in} - 85) \cdot S + 0{,}033 \cdot W_{in} - 5{,}623. \quad (5)$$

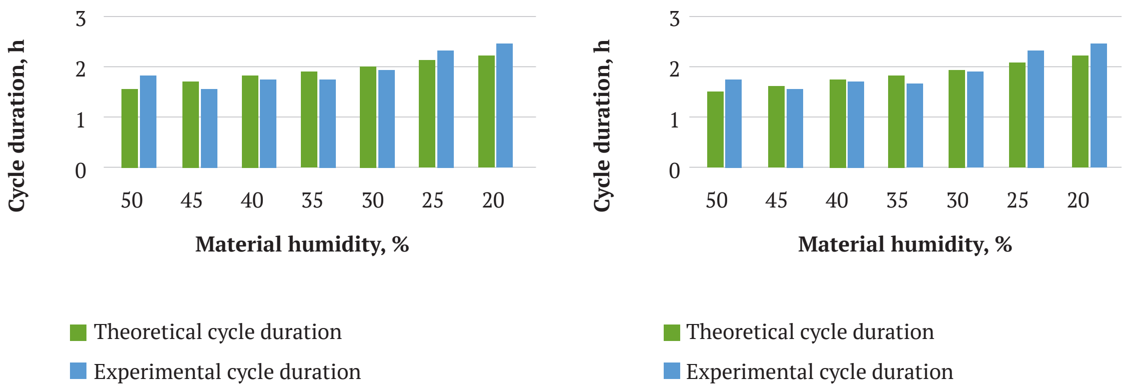
Checking the obtained equation for the substantiality level of 5% confirmed the adequacy of the model (according to the Student's criterion $t_{calc} = 0.01 < t_{table} = 2.05$; according to the Fischer criterion $F_{calc} = 1.10 < F_{table} = 2.98$).

Considering the specific features of the kinetics of heating and cooling cycles, the regression equation of the drying duration of the material during pulsed heating is presented as:

$$\begin{cases}\tau_{heat} = ((0{,}005 \cdot S - 0{,}0012) \cdot W_к + 0{,}65 \cdot S + 0{,}05) \cdot t_{heat} + \\ +(0{,}14 - 2{,}00 \cdot S) \cdot W_к + 75{,}05 \cdot S - 6{,}54; \\ \tau_{cool} = ((1{,}65 \cdot S - 0{,}069) \cdot ln(W_к) - 10{,}17 \cdot S + 0{,}264) \cdot t_{cool} + \\ +(4{,}08 - 86{,}48 \cdot S) \cdot ln(W_к) + 474{,}92 \cdot S - 10{,}09,\end{cases} \quad (6)$$

where W_f – final moisture content of the material, %; t_{heat}, t_{cool} – heating and cooling temperatures, respectively (according to Table 1), °C.

Verification of theoretical equations for the duration of heating and cooling cycles (Fig. 2) confirmed the adequacy of the models (Table 1).



a) b)

Figure 2. Comparison of experimental and calculated duration of drying cycles of 50 mm thick red oak workpieces: *a* – heating; *b* – cooling

Table 1. Results of checking the adequacy of models for duration values for different drying periods

Species	Drying period	Student's *t*-criterion		*F*- Fischer criterion	
		t_{calc}	t_{crit}	F_{calc}	F_{table}
Red oak heating	cooling	0.41	2.07	1.31	2.82
	heating	0.41	2.07	1.31	2.82

The following equation of the treatment in different periods of pulsed drying to determine the degree of saturation φ agent is proposed:

$$\begin{cases} \phi_{heat} = 100^{1-(0,006+10^{-5}(120-t_c)^{1,46})\cdot(t_c-n\cdot t_{cen_{heat.}}+\frac{1}{2}\cdot(t_c-t_0)\cdot Ki_m \varepsilon Ko Lu)^{1,074+10^{-17}(146-t_c)^{7,77}}} \\ \phi_{cool} = 100^{1-(0,006+10^{-5}(120-t_c)^{1,46})\cdot(t_c-n\cdot t_{cen_{cool.}}+\frac{1}{2}\cdot(t_c-t_0)\cdot Ki_m \varepsilon Ko Lu)^{1,074+10^{-17}(146-t_c)^{7,77}}} \end{cases}, \quad (7)$$

where t_{env} – environment temperature of the drying chamber, °C.

The values of medium base density of red oak wood – ρ_B = 570 kg/m³, and also dependences of moisture conductivity coefficients on the temperature in the tangential and radial directions obtained experimentally are used to calculate the corresponding criteria in equations (2) and (7):

- for the radial direction:

$$a' = (0,1491 \cdot t - 3,4210) \cdot 10^{-6}, \quad (8)$$

- for the tangent direction:

$$a' = (0,1203 \cdot t - 2,9170) \cdot 10^{-6}. \quad (9)$$

In accordance with the obtained results of theoretical and experimental studies, pulsed drying modes of workpieces made of red oak wood are proposed (Table 2).

Table 2. Recommended pulse drying modes for red oak wood

Average humidity, %	**Mode parameters**	**Lumber thickness, mm**	
		30	50
1%	Environment temperature t_{env}, °C	100	80
	Workpiece temperature t_{heat}, °C	85	65
	Cooling temperature t_{cool}, °C	55	35
	Degree of air humidity φ, %	95	95
30-25	Environment temperature t_{env}, °C	100	80
	Workpiece temperature t_{heat}, °C	85	65
	Cooling temperature t_{cool}, °C	55	35
	Degree of air humidity φ, %	50	79

Table 2. Continued

Average humidity, %	Mode parameters	Lumber thickness, mm	
		30	50
25-20	Environment temperature t_{env}, °C	100	80
	Workpiece temperature t_{heat}, °C	85	65
	Cooling temperature t_{cool}, °C	55	35
	Degree of air humidity φ, %	38	55
20-15	Environment temperature t_{env}, °C	100	80
	Degree of air humidity φ, %	35	40
<15	Environment temperature t_{env}, °C	100	80
	Degree of air humidity φ, %	35	38

According to the results of drying by the proposed modes, it was identified that no unacceptable defects were observed in the workpieces of thicknesses, the wood colour became darker, and the texture was more clearly manifested. After cutting the lumber, no white spots were identified on the lamella (Fig. 3).

a) b)

Figure 3. The surface of lamella made of oak wood, dried in various modes:
a) low-temperature with the presence of white spots; b) cyclic – with a uniform colour

Comparison of the obtained results of the drying duration according to the proposed pulse modes with the calculated values of the drying duration according to conventional continuous modes (Serhovsky & Rasev, 1987) showed a reduction in the process duration by 1.5-2.4 times, depending on the thickness of the workpieces.

According to the relative deformation of the power sections, it was determined that dried workpieces correspond to the first category of drying quality according to DSTU 4921: 2008 in terms of the assessment of internal stresses. The stress plots were visualised (Fig. 4) and the values of the voltage drop after drying are determined by the mode given in Table 2 to quantify the stress state of red oak samples with a thickness of 50 mm. Comparison of the obtained values with the maximum permissible values of the tensile strength across the fibres in the tangential direction σ_m = 6.5 MPa showed a safety margin of 25%, that is, dried workpieces should not deform during further processing.

Figure 4. Diagram of residual stresses of sample No.2

When testing dried workpieces for static bending, it was identified that after reaching the maximum load, the samples retained their shape for a certain time before final destruction. The maximum fracture load at the factual humidity of the sample dried in the classical continuous mode and the developed pulse mode was 3.1 kH and 3.8 kH, respectively. Consequently, short-term exposure to elevated temperatures of the drying agent did not affect the mechanical properties of 50 mm thick red oak samples.

Conclusions

Based on the conducted theoretical and experimental studies of pulse drying of workpieces made of red oak wood, rational modes are proposed that allow for avoiding the appearance of white spots inside the workpieces. It is determined that the values of the ultimate strength for static bending of dried workpieces made of red oak wood are 15.0% higher than the values of the ultimate strength for wood that was dried according to the classical low-temperature regime.

It is advisable to implement the developed oscillatory modes in non-heater drying units, the advantage of which is low inertia in temperature, that is, the dryer heats up and cools down quickly. The use of the developed modes of oscillatory drying in such chambers, tested in industrial conditions, provides economic efficiency by reducing the drying time and reducing energy costs by up to 40%.

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Імпульсне сушіння заготовок із деревини дуба червоного

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Анотація. Визначено причини здешевлення виготовленої з деревини дуба ламелі – лицьового покриття дошок для підлоги. Встановлено, що під час сушіння деревини дуба за низьких температур виникає накопичення вологи у зоні біля поверхні – так зване умовне джерело вологи. Це призводить до утворення світлих плям усередині пиломатеріалів, які довгий час зберігались в умовах підвищеного ступеня насичення повітря та мали низьку швидкість видалення вологи. Для уникнення цього дефекту запропоновано інтенсифікувати процес сушіння шляхом використання імпульсних режимів, які складаються з періодів нагрівання та охолодження деревини. У період нагрівання температура матеріалу поступово підвищується, деревина отримує тепловий удар і накопичує тепло, сушіння відбувається лише за рахунок градієнта вологості. Під час охолодження температура середовища знижується, ступінь насичення зростає і, відповідно, підвищується рівноважна вологість. У результаті поверхневі шари матеріалу зволожуються, волога по товщині деревини вирівнюється, відбувається релаксація сушильних напружень. У лабораторних умовах проведено експериментальні дослідження імпульсного сушіння заготовок із деревини дуба червоного товщиною 30 мм і 50 мм. Визначено амплітуду коливання температури – 30 °С та доцільність проведення циклічного нагрівання лише до досягнення середньої вологості матеріалу 20 %, після чого деревину потрібно висушувати до необхідної кінцевої вологості за сталої температури нагрівання. Запропоновано метод розрахунку тривалості імпульсного сушіння, який враховує особливості кінетики періодів нагрівання і охолодження пилопродукції з деревини дуба червоного товщиною 30 мм і 50 мм. Рекомендовано розглядати процес кінетики зміни температури як суму процесів циклічного нагрівання, що відбувається за поліноміальною залежністю, та циклічного охолодження, що відбувається за експоненціальною залежністю. Визначено, що співвідношення тривалості циклічного нагрівання до тривалості циклічного охолодження становить 1/3. З використанням тепломасообмінних критеріїв та визначеного експериментальним шляхом коефіцієнта вологопровідності деревини дуба червоного розроблено адекватну модель розрахунку температури деревини та відносної вологості повітря протягом циклів нагрівання та охолодження деревини. На основі отриманих результатів теоретичних і експериментальних досліджень запропоновано імпульсні режими сушіння заготовок дуба червоного різної товщини, які запобігають утворенню білих плям усередині матеріалу. Зауважено скорочення процесу у 1,5-2,4 разу та зменшення енерговитрат у 1,53 разу. Визначені експериментальним шляхом показники залишкових напружень, величини перепаду напружень у заготовках після сушіння та величини межі міцності на статичний згин показали, що якість сушіння їх відповідає І категорії якості згідно з ДСТУ 4921:2008. Порівняння отриманих значень із максимально допустимими значеннями межі міцності на розтяг поперек волокон у тангенціальному напрямку $\sigma_м$ = 6,5 МПа показало запас міцності 25 %, що свідчить про можливість застосування імпульсних режимів сушіння для якісного сушіння заготовок із деревини дуба червоного

Ключові слова: дуб червоний (*Quercus rubra*), коефіцієнт вологопровідності, імпульсні режими, якість сушіння, термін сушіння