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Use of a polymer shell of thermally modified wood to establish moisture diffusion patterns

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Abstract. This study analyses the process of thermal modification of wood, obtained by a controlled heating process. The unique technological properties (durability, low hygroscopicity, and dimensional stability) of thermally modified wood allow using it in various fields. Due to the effect of temperature, some chemical changes occur in the structures of the cell wall components (lignin, cellulose, and hemicellulose) of wood. This leads to an increase in density, hardness, hydrophobicity (water repulsion), thereby reducing the ability of wood to absorb moisture and swell. Products absorb moisture gradually, are less prone to swelling and drying out, but still need elastic coatings. It was proved that heat-treated wood eventually turns grey when exposed to sunlight, and therefore added surface treatment with a coating is necessary. Added application of protective substances on the surface of products made of thermally modified wood contributes to dimensional stability and protects against rapid weathering of the surface in open air conditions. Clear coatings and oils do not protect surfaces from discolouration during weathering. They are recommended for products made of thermally modified wood, which are used away from direct sunlight and rain. The parameters of moisture penetration into wood are mathematically modelled based on the quasi-stationary equation of moisture diffusion through a polymer film on the surface of a flat sample. The dynamics of changes in the moisture content in thermally modified wood were experimentally investigated under different regime parameters. Mathematical relations obtained from experimental studies allow calculating the moisture diffusion coefficient in thermally modified wood in the presence of a polymer shell. It was established that the application of a wax coating on the surface of the product reduces the moisture diffusion by more than 10 times for surfaces already treated at 160°C for one hour, which allows using it on objects with increased humidity

Keywords: wood, thermal modification efficiency, moisture absorption, water diffusion, decomposition, wood stability

Introduction

The unique technological properties (durability, low hygroscopicity, and dimensional stability) of thermally modified wood allow using it in various fields.

Designers often used this material for interior decoration due to the colour it acquires under high temperature. Due to the stability of geometric

dimensions and resistance to the external environment, thermally modified is used in the production of furniture, window frames, doors, parquet boards. Jirouš-Rajković & Miklečić (2021) claim that this material can be used as an external facade cladding, in the form of decking and garden paths. The material

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is well suited for covering saunas and baths. Specific features of inhibiting the moisture advancement in thermally modified wood are that water-resistant components are formed, as well as capillary-porous elements, due to which a waterproof layer forms on the wood surface (Tsapko et al., 2021).

The resistance of thermally modified wood to weather conditions (UV rays, wetting) is slightly better compared to untreated wood, but added surface treatment with coatings is required. The market offers many substances for external treatment of wood. For horizontal surfaces (decks, decking, garden paths), Miklečić (2010) recommends penetrating treatment with oils. There are many oils on the market that retain the “natural” appearance of wood and resist weathering.

It is known that thermally modified wood turns grey over time. As reported by Schaller & Rogez (2007), clear coatings and oils do not protect surfaces from discolouration during weathering. Such surface treatment is recommended for products made of thermally modified wood, which are used away from direct sunlight and rain. Recently, increasingly more attention has been paid to the effect of sunlight on the surface of thermally modified wood. A novel approach has been developed to stabilize the dark colour of thermally modified wood by combining visible light screens with organic UV light absorbers (Slabjová et al., 2019).

Processing of thermally modified wood is similar to processing of dried wood, but it is necessary to consider the change in some of its properties. Akyildiz & Kesik (2014) found that thermally modified wood becomes more hydrophobic; absorbs moisture gradually; is less prone to swelling and drying, but still needs elastic coatings; has a darker colour that can fade due to light exposure.

Vernois (2001) noted that cracking of thermally modified wood occurs considerably less compared to natural wood due to improved dimensional stability. Cracking spruce and pine wood after thermal modification when exposed to external conditions without a protective coating was equivalent to cracking untreated wood with unpigmented coatings. Jëamsëa et al. (2000) found that oil application did not prevent cracking of thermally modified wood after natural exposure. However, Miklečić (2010) managed to reduce cracking of samples of thermally modified wood with oil treatment. The results of the study indicate that during accelerated weathering, samples without a protective surface coating had fewer surface cracks than thermally modified samples without a coating.

Pavlič et al. (2021) investigated the compatibili-

ty of nine different coatings with thermally modified Scots pine wood. Coatings applied to thermally modified wood showed better performance than coatings on unmodified wood. The authors attributed this phenomenon to altered characteristics of thermally modified wood, such as lower equilibrium moisture content, lower water permeability, increased dimensional stability, better resistance to UV radiation, and resistance to blue spot fungi compared to unmodified wood. Better penetration of the coating into modified wood and better wetting with protective substances were also demonstrated. Furthermore, solvent-based paint and varnish materials showed better results after one year of external weathering compared to water-based coatings.

Drying oils provide the best protection for wood products, but their use is limited to long-term polymerization. Armingier et al. (2020) investigated the drying behaviour of linseed oil, tung oil, and their 1:1 mixture. Repeated measurements of the water contact angle of coatings applied to beech and oak wood showed clear differences in wetting. Tung oil provided hydrophobicity to all wood samples shortly after application, even when used without a dryer. Linseed oil required a longer drying time and was more susceptible to the effects of the substrate, but eventually reached the highest contact angles after forced drying.

Thus, the literature sources indicated that thermal modification of wood improves the resistance to temperature and humidity factors. Added surface treatment with protective substances contributes to the stability of the product dimensions and protects against rapid weathering of the surface in open air conditions. New products are constantly appearing on the market, which are designed to protect the colour of wood in the interior and to prevent the product from dimensional changes in natural conditions. This indicates the relevance of this study to establish the effectiveness of protection of wood products with paint and varnish materials, which will contribute to the extension of the period of use of building structures in environmental conditions.

The purpose of this study was to estimate the effectiveness of surface treatment with oil-wax based on the determined diffusion coefficient on the resistance of products made of thermally modified wood to the temperature and humidity conditions of the environment.

Materials and Methods

To establish moisture absorption, the authors of this study used randomly selected 90 samples of horn-

beam wood of radial cross-section, previously dried. The samples had dimensions of 20×10×10 mm. Next, the samples underwent thermal modification at 160°C, 190°C, and 220°C, exposure in the chamber for 1, 10, 20 hours. According to the regime parameters of thermal modification, all samples were divided into nine groups and a group of control samples (unmodified wood) (Fig. 1).

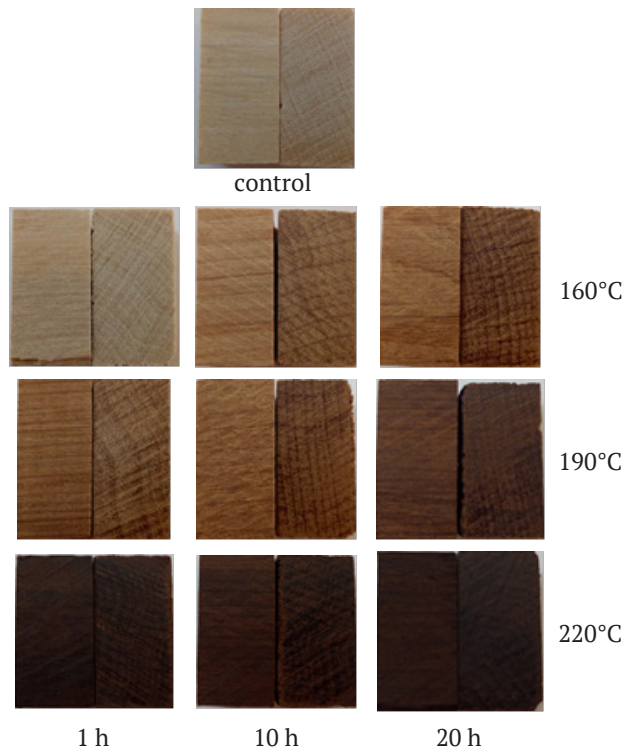


Figure 1. Prototypes of untreated (control) and thermally modified wood

Then the samples were treated with oil-wax by immersion with repeated treatment after the first layer dried in 24 hours. After drying, the samples were placed in a desiccator for 1 day. Subsequently, the dimensions and weight of each sample were recorded. The procedure was repeated on Days 2, 3, 6, 9, 13, 20, and 30.

Results and Discussion

The parameters of moisture diffusion into wood were modelled. The quasi-stationary equation of moisture diffusion through a polymer film on the surface of a flat wood sample is as follows:

$$\frac{d^2 C_w}{dx^2} = 0, \quad (1)$$

where C_w is the moisture concentration at a distance x from the middle of the wood sample (by thickness).

The double integral of Equation (1) is calculated according to the following formula:

$$C_w = Ax + B, \quad (2)$$

where A and B are constants found from the boundary conditions:

for $x=H$

$$C_w = C_0, \quad (3)$$

for $z=H+\delta$

$$C_w = C_1, \quad (4)$$

where H is half the thickness of the sample, δ is the thickness of the polymer shell, C_0 , C_1 is the moisture concentration inside the sample and in the external environment, respectively.

Through mathematical transformations, the solution (2) can be presented as follows:

$$C_x = \delta^{-1}(C_0(H+\delta) - C_1 H - (C_0 - C_1)x). \quad (5)$$

Since the diffusion flow of moisture through the wood surface covered with a shell is:

$$j = -S \cdot D \frac{dC_x}{dx}, \quad (6)$$

where S is the sample surface area, then, after substituting (5) into (6) and integrating, one obtains the expression for the diffusion flow of moisture:

$$j = \frac{S \cdot D(C_0 - C_1)}{\delta}. \quad (7)$$

Then the equation of the mass transfer process through the shell will have the following form:

$$\frac{S \cdot D(C_0 - C_1)}{\delta} = V_1 \frac{dC_1}{d\tau}, \quad (8)$$

where τ is the time; V_1 is the volume of the external environment.

Using the material balance equation, one finds the unknown values of equation (8) C_0 and C_1 :

$$V_0 C_0 + V_1 C_1 = m, \quad (9)$$

where V_0 is the volume of wood, m is the mass of moisture in the sample before the experiment.

From equation (9), one finds the value:

$$C_0 = C_0^* - \gamma C_1, \quad (10)$$

where $C_0^* = \frac{m}{V_0}$ is the initial moisture concentration

in the sample; $\gamma = \frac{V_1}{V_0}$ – the ratio of the volume of the external environment and the sample.

Substituting (10) into (8), one gets the equation for determining C_1 :

$$\frac{dC_1}{d\tau} = \frac{S \cdot D}{\delta \cdot V_1} (C_0^* - (1 + \gamma) C_1). \quad (11)$$

The integral of equation (11) under condition $C_1|_{\tau=0}=0$ gives the following expression:

$$\ln\left(\frac{C_0^* - (1 + \gamma) C_1}{C_0^*}\right) = -\frac{D \cdot (1 + \gamma)}{\delta^2 \cdot \gamma} \tau. \quad (12)$$

It follows from equation (12) that the moisture concentration in the sample changes, considering $\gamma \gg 1$ as a function of:

$$C_1 = \frac{C_0^*}{\gamma} \left(1 - e^{-\frac{D}{\delta^2} \tau}\right). \quad (13)$$

Having performed mathematical transformations, equation (12) can be presented as follows:

$$\ln\left(\frac{C_0^*}{C_0^* - \gamma C_1}\right) = \frac{D}{\delta^2} \tau. \quad (14)$$

The thickness of the polymer shell corresponded to a value of about 10 μm , the humidity in the desiccator was 100%, and the volume ratio of the external environment to the sample was 5. Table 1 presents the weight gain of samples when exposed to a humid environment.

Table 1. Results of experimental determination of sample mass gain

Thermal modification mode		Change in the mass of samples during exposure in a humid environment, g								
		Exposure time in desiccators, days								
T, °C	τ , h	0	1	2	3	6	9	10	20	30
control		1.82	1.86	1.88	1.91	1.94	1.99	2.00	2.03	2.03
	1	1.87	1.89	1.91	1.94	1.98	2.02	2.03	2.07	2.08
	10	1.87	1.88	1.90	1.92	1.97	2.00	2.01	2.03	2.05
	20	1.85	1.86	1.87	1.90	1.95	1.97	1.98	2.00	2.02
160	1	1.85	1.86	1.87	1.90	1.95	1.97	1.98	2.00	2.02
	10	1.85	1.86	1.87	1.90	1.95	1.97	1.98	2.00	2.02
	20	1.85	1.86	1.87	1.90	1.95	1.97	1.98	2.00	2.02
190	1	1.95	1.95	1.97	2.00	2.05	2.09	2.08	2.12	2.13
	10	1.86	1.86	1.87	1.90	1.93	1.95	1.96	1.99	2.00
	20	1.82	1.82	1.83	1.84	1.86	1.88	1.89	1.91	1.92
220	1	1.84	1.84	1.85	1.88	1.91	1.93	1.94	1.97	1.99
	10	1.77	1.77	1.77	1.78	1.79	1.81	1.80	1.83	1.84
	20	1.84	1.84	1.84	1.85	1.86	1.88	1.88	1.91	1.92

Figure 2 shows the dependence (14) on time τ for the control sample, Figure 3 – for processing mode 160/1, Figure 4 – for processing mode 190/1, Figure 5 – for processing mode 220/1. The tangent of the angle of inclination ($\text{tg}\alpha$) of this straight line gives the coefficient for τ , i.e.:

$$(\text{tg}\alpha) = \frac{D}{\delta^2}. \quad (15)$$

The moisture diffusion coefficients were calculated based on dependence (15), presented in Table 2.

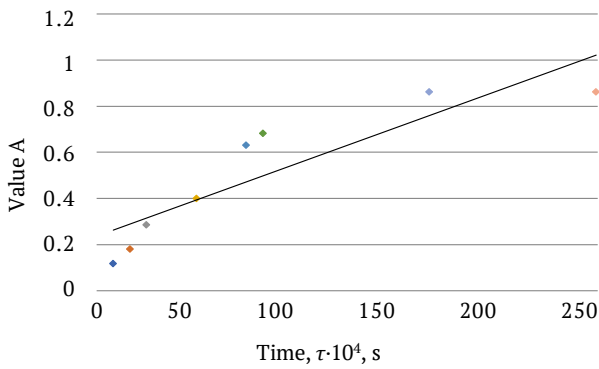


Figure 2. The dynamics of changes in the percentage of moisture in wood for the control sample

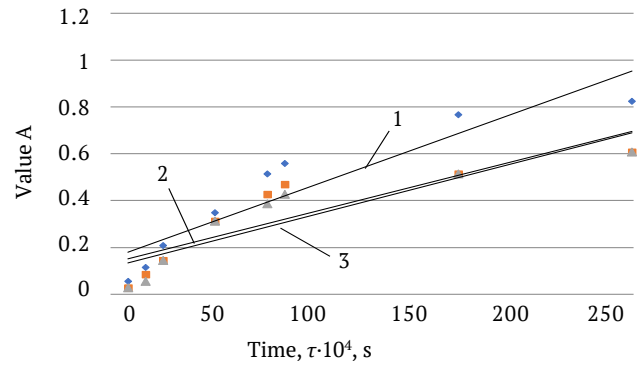


Figure 3. The dynamics of changes in the moisture content in wood thermally modified at 160°C for: 1 – 1 hour, 2 – 10 hours, 3 – 20 hours

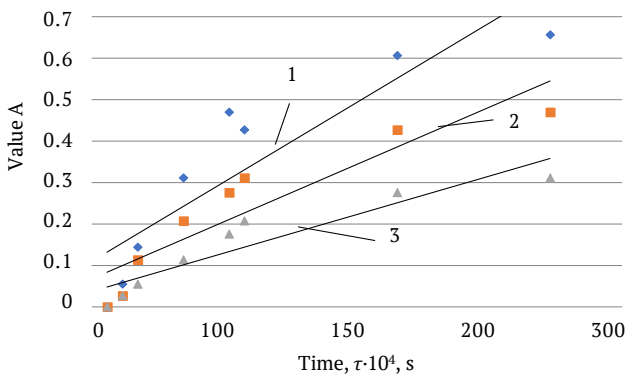


Figure 4. The dynamics of changes in the moisture content in wood thermally modified at 190°C for: 1 – 1 hour, 2 – 10 hours, 3 – 20 hours

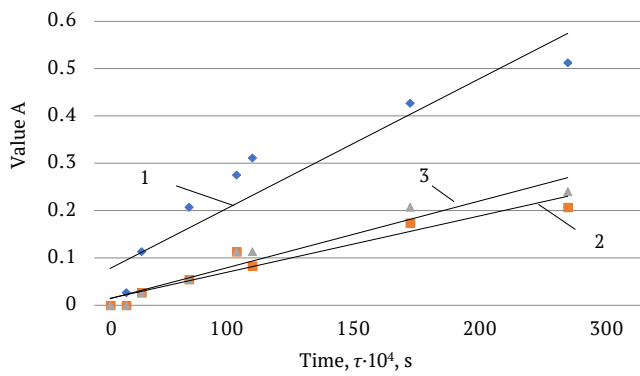


Figure 5. The dynamics of changes in the moisture content in wood thermally modified at 220°C for: 1 – 1 hour, 2 – 10 hours, 3 – 20 hours

Table 2. Diffusion coefficient value for moisture absorption of thermally modified wood, 10, 20 hours

Indicator	control sample	Modification mode parameters								
		Processing temperature, °C								
		160			190			220		
		Processing time, h								
		1	10	20	1	10	20	1	10	20
Moisture diffusion coefficient, $\cdot 10^{-8} \text{ m}^2/\text{s}$	0.753	0.077	0.0062	0.0047	0.0031	0.0028	0.0015	0.00127	0.000088	0.000177

Conclusions

Mathematical relations obtained from experimental studies allow calculating the moisture diffusion coefficient in thermally modified wood in the presence of a polymer shell. It was established that the application of a wax coating on the surface of the product reduces the moisture diffusion by more than 10 times for surfaces already treated at 160°C for one

hour. This coating considerably increases the service life of wood and allows it to be used on objects with increased humidity.

The research results will also help purposefully solve further tasks related to the creation of new means and methods of wood protection according to the conditions of wood operation at various facilities.

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**Встановлення закономірностей дифузії вологи
через полімерну оболонку термічно модифікованої деревини**

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Анотація. Проведено аналіз процесу термічного модифікування деревини, яку було отримано шляхом контрольованого процесу нагрівання. Унікальні технологічні властивості (довговічність, низька гігроскопічність і розмірна стабільність) термомодифікованої деревини роблять можливим її застосування у різних сферах. Унаслідок впливу температури виникають деякі хімічні зміни у структурах компонентів клітинної стінки (лігнін, целюлоза та геміцелюлоза) деревини. Це призводить до збільшення щільності, твердості, підвищується гідрофобність (відштовхування води), тим самим зменшується здатність деревини вбирати вологу і набрякати. Вироби поглинають вологу поступово, менш схильні до набрякання та всихання, але все-таки потребують еластичних покриттів. Доведено, що термооброблена деревина з часом набуває сірого кольору під впливом сонячних променів, а тому необхідне додаткове оброблення поверхні покриттям. Додаткове нанесення захисних речовин на поверхні виробів із термомодифікованої деревини сприяє стабільності розмірів і захищає від швидкого вивітрювання поверхні за умов відкритого повітря. Прозорі покриття та масла не захищають поверхні від знебарвлення під час вивітрювання. Їх рекомендують для виробів із термічно модифікованої деревини, які експлуатуються подалі від прямих сонячних променів та дощу. Математично змодельовано параметри проникнення вологи у деревину на основі квазістаціонарного рівняння дифузії вологи через полімерну плівку на поверхні плоского зразка. Експериментально досліджено динаміку зміни частки вологи в термічно модифікованій деревині за різних режимних параметрів. Отримані математичні співвідношення на основі результатів експериментальних досліджень дають можливість здійснювати розрахунки коефіцієнта дифузії вологи у термічно модифікованій деревині за наявності полімерної оболонки. Встановлено, що застосування воскового покриття на поверхні виробу зменшує процес дифузії вологи у понад 10 разів для поверхонь, оброблених уже за температури 160 °C упродовж однієї години, що дає змогу використовувати її на об'єктах із підвищеною вологою

Ключові слова: деревина, ефективність термічної модифікації, вологопоглинання, дифузія води, розклад, стійкість деревини