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USING CELLULAR AUTOMATA TO SIMULATE EXTERNAL HEAT AND MASS TRANSFER IN THE WOOD DRYING PROCESS

This work involves modeling the external heat and mass transfer in the wood drying chamber. One of the remarkable features of this research is to use cellular automata with variable cell sizes closely related to the geometric parameters of the considered wood materials. This approach allows for modeling and analyzing the changes in the characteristics of wood materials during the hydrothermal treatment process, taking into account their unique geometry. Such modeling provides valuable information about how different shapes and sizes of wood react to various drying conditions. This research has significant implications for industries dependent on wood drying, such as construction and furniture production, as it offers an individual approach to upgrading the drying processes of wood materials with different geometries. The modeling in this work is carried out using wood materials, primarily pine, with a standardized thickness of 25 mm and an initial moisture content of 30 %. The modeling is conducted under conditions of moderate drying, accurately mirroring real-world scenarios. Using pine as the researched material aimed to represent a widely used wood species in the industry, thereby increasing the relevance of the results. The work also explores the influence of various parameters of the wood drying agent. To achieve this, three key factors are systematically varied: temperature, relative humidity, and drying agent velocity. Temperature fluctuations are carried out within a range of ±10 °C. Similarly, relative humidity is adjusted within ±10 % of standard technological parameters. Finally, the drying agent velocity was increased to a maximum of 6 m/s. Thus, the impact of these changes on the moisture content in wood materials is investigated. The results obtained can be applied in an industrial setting. The knowledge gained from the experiments can play a crucial role in improving the wood drying process. In summary, the work investigates the hydrothermal treatment of wood materials, shedding light on the critical role of wood drying agent parameters in controlling moisture content in wood materials. The potential advantages in terms of product quality and overall production efficiency cannot be overstated, and it is expected that this work will be a valuable resource for industries dependent on wood processing.

Keywords: external heat and mass exchange; environment temperature; relative humidity; speed of movement of wood drying agent; rules of transitions.

Introduction / Вступ

Setting the research task. The problem of drying lumber has always been an urgent task in the forest and woodworking industry. All lumber manufacturers to ensure product stability and quality use appropriate wood drying methods and technologies. Now, there are various effective and scientifically based methods for modeling the wood drying process, but their effectiveness can be improved by using more accurate but not more complex models, such as cellular automata model.

Characterization of the research problem in the global scientific literature. In the worldwide scientific literature, the matter of heat and mass transfer in wood drying chamber has garnered the interest of esteemed experts in the field. Distinguished researchers like L. M. Hirnyk, Ya. I. Sokolovskyy, S. Kadem, Z. Jingyao, A. J. Ghiaus, M. A. Istrate and numerous others have substantially advanced the comprehension of this issue and have either innovated or enhanced fundamental techniques for simulating heat and mass transfer in wood drying chambers.

The relevance of the research. Notwithstanding the progress made so far, the challenge of simulating process of heat and mass transfer remains intricate and inadequately explored. In order to upgrade this process, it is imperative to innovate and refine existing modeling techniques. This research underscores the importance of further investigation in this field. In essence, this study is focused on updating the existing transition rules for the cellular automata model, by using mathematical models of external heat and mass transfer in wood drying chambers. This study takes a significant step forward by proposing a novel approach to expand the existing cellular automaton model. There are also introduce new transition rules that dynamically alter the key parameters of the drying agent, thereby offering a more nuanced understanding of the drying process.

Object of research – the process of drying wood in drying chambers.

Subject of research – the influence of various parameters of the drying agent (temperature, relative humidity,

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speed) on the moisture content of lumber.

The purpose of the work – elucidate the multifaceted influence of temperature, relative humidity, and the velocity of the drying agent on the moisture content of lumber during the drying process in order to enhance the efficiency of lumber drying techniques.

To achieve this purpose, the following *main research objectives are identified*:

1. Overview of the process of external heat and mass transfer and input data.
2. Development and implementation of updated rules of transition to the cellular automata model for more accurate modeling of drying processes.
3. Study of the influence of various key parameters of the wood drying agent (temperature, humidity, speed) on the drying process and moisture content of lumber.
4. Analysis of simulation results when using parameters that differ from the parameters of the technological process.

Analysis of recent research and publications. Currently, there is a large amount of literature that gives us an idea about external heat and mass transfer. In particular, in [19] describes the processes of drying solid materials, including wood, and also describes the process of external heat and mass transfer during these processes. It also contains information on modeling these processes. In [8], a model of heat and mass transfer in a coniferous lumber was developed. The model includes fluid transport by capillary action as well as diffusion. This model is unique in that the transport properties, which in some cases are not available in the literature and are difficult to measure, are developed based on knowledge of the wood structure. Computed results are compared with experimental ones, which are the first of their kind since moisture profiles are measured during the drying process using gamma attenuation. In turn, work [20] developed a three-dimensional mathematical model of heat and mass transfer for drying wood in drying chambers, taking into account the influence of the surrounding fluid flow (drying agent). The model describes the characteristics of wood and fluid movement, and the simulation results were confirmed by experimental data. The study also revealed uneven movement of the drying agent and a temporary accumulation of moisture around the lumber in the chamber.

Work [16] also describes methods of studying heat transfer in the process of drying wood. To conduct these studies, it is proposed to use the cellular automata. For this, a three-dimensional mathematical model is proposed, which is described by an interconnected system of partial differential equations in terms of time derivatives and spatial coordinates. The work also describes the developed software and its functionality. To verify the mathematical model, a number of experiments were conducted using the developed software. In paper [6], a macroscopic model was developed that takes into account the nonlinear processes of heat-moisture transfer and ventilation in the wood materials and simultaneously includes the influence of thermal diffusion and infiltration phenomena. The parameters of the model were experimentally determined according to recognized standards of material characterization. In addition, numerous calculations of hygrothermal processes in one-dimensional and two-dimensional cases were carried out to assess the dimensionless influence on such wood material. In addition, the sensitivity of the model to changes in the connection between potentials and changes in the parameters of the drying agent was studied, and it was found that the connection in the model has a significant effect on the kinetics of changes in temperature and humidity in the material.

Also, in [17], the aerodynamics of a wood drying chamber is investigated. In particular, the parameters of the drying agent are investigated, especially in the gaps between the horizontal rows of wood in stacks. The results of the study show that the studied wood drying chamber does not work in the optimal aerodynamic mode, and to improve the efficiency of the drying process, it is recommended to reduce the speed of the drying agent. In [14], the parameters of the drying agent were calculated, including the speed of air circulation, its temperature and humidity. The result of the calculation is the creation of a radial-based artificial neural network that allows you to determine any parameter of the drying agent at any point in the drying chambers. Also, this paper gives the calculation of extrapolation of the existing parameters of the drying agent for their forecast. In work [9], a mathematical model was developed to predict the process of heat and moisture transfer in porous materials, which can be wood. The model takes into account the internal release of heat and moisture by these materials, as well as the effect of changes in temperature and humidity of the environment on the storage and drying processes. Using numerical calculations, the researchers found that the heat and moisture transfer occurs in the upper layers of the material, and the inner layers heat up and increase humidity due to their dependence on the humidity of the environment. These literatures cover the fundamental and practical aspects of external heat and mass transfer during drying of solid materials such as wood. They help to understand and apply this knowledge in practical research, in particular in the development of transition rules for cellular automata.

Research results and their discussion / Результати дослідження та їх обговорення

Overview of the process of external heat and mass transfer and input data. The process of heat and moisture transfer between drying timber and the drying agent is a crucial component for improving the wood drying technology. The behavior of moisture in timber is determined by thermodynamic processes on its surface and the interaction of surface forces in an equilibrium system. In this context, there is always a hydrodynamic boundary layer between the surface of the timber and the drying agent. Its thickness is conditional and depends on the conditions of interaction between the drying agent and the surface of the wood. The relationship between these parameters [12] in external heat and mass transfer, considering the stress-strain state of the timber, has the following form:

$$T_c = \frac{0.13(238+T_p)\ln B}{1+\left(\dfrac{238+T_p}{1785}\right)\ln B} \quad \ln B = \frac{20m\rho_0(1+\beta_0 W_0)\sigma_в}{E_m K Nu_q D_p \rho_{nc}}; \qquad (1)$$

$$\phi = \frac{(1+\beta_0 W_0) l \rho_0 (2\sigma_в + E_\varepsilon)}{2E_m \beta (0.33 - X^2) Nu_m \rho_{nc}} + \exp\left(-\frac{\tau-\tau'}{\tau_{rel}} + \frac{\pi^2 Bi Fo}{4Bi+\pi^2}\right) d\tau', \quad (2)$$

where: T_c is the temperature of the drying agent, T_p is the temperature on the surface of the lumber, m is the mass of the lumber, ρ_0 is the initial density of the lumber, β_0, β are the moisture exchange coefficients, W_0 is the initial moisture content of the lumber, σ_B is the moisture stress, E_m is the instantaneous modulus of elasticity, W is moisture content of lumber, T is temperature of lumber, $K = Bu / Ko$ is similarity criterion, Nu_q, Nu_m are heat and mass transfer Nusselt number, D_p is molecular diffusion coefficient, ρ_{nc} is saturated vapor density, l is characteristic length, E is Young's modulus, ε is deformations, τ, τ' are simulation time, τ_{rel} is relaxation time, Bi is Bio criterion, Fo is Fourier criterion, Bu is Bulyhim criterion, Ko is Kosovich criterion.

At the same time, the values of E_m, τ_{rel}, ε, $\sigma_в$ can be calculated as follows:

$$E_m = (304.55 + 759.7\ \exp(-17.88W))\ \exp(-0.02T)\ ; \quad (3)$$

$$\tau_{rel} = 147\ \exp(-0.073W)\ ; \quad (4)$$

$$\varepsilon = \frac{1}{E}(\sigma_в - \nu\sigma_в) + \beta(W - W_0)\ ; \quad (5)$$

$$\sigma_в = \frac{E\beta}{1-\nu}(\overline{W} - W)\ , \quad (6)$$

where: ν is Poisson's ratio, is average value of moisture concentration by thickness.

In general, deformation values are determined according to Hooke's Law, and they are also provided in [11]. The value of the Poisson's ratio in this case can be taken as 0.5 if the calculation is conducted in a one-dimensional case and along the fibers and 0.02 if the calculation is performed transversely to the fibers. Furthermore, the Young's modulus depends on the wood species, for example: pine (~8 GPa), oak (~12 GPa), spruce (~9 GPa), birch (~10 GPa), beech (~11 GPa).

For the period of constant velocity of convective wood drying, was find the following relationships for the Nusselt heat transfer [10] and mass transfer criteria:

$$Nu_q = 0.0641 Re^{0.8} Gu^2 Pr^{1/3}\ ; \quad (7)$$

$$Nu_m = 2.5 Re^{0.6} Gu^{0.135} Pr^{1/3}\ ; \quad (8)$$

$$Re = \frac{Vl}{v \cdot Gu} = -\frac{T_c}{T \cdot Pr} = \frac{v}{a}\ , \quad (9)$$

where: Re is the Reynolds number, Gu is the Huhman criterion, Pr is the Prandtl number, λ is the thermal conductivity coefficient of the drying agent; V is the speed of movement of the drying agent; ν is the coefficient of kinematic viscosity; a is the coefficient of thermal diffusion.

The criterion equations (7)–(9) are used to assess heat and mass transfer during the drying process, helping to determine their optimal and safe parameters. This is especially relevant in the context of raising the temperature of the environment under constant wet-bulb temperature conditions. It is evident that with such an increase in temperature, the heat transfer coefficient during the constant-rate drying process will increase. However, an increase in the kinematic viscosity of the medium at the same time will contribute to a decrease in the Reynolds number, which will directly affect the scale of convective phenomena.

To carry out calculations, it is suggested to use the results from the previous work [7]. In this work describes in detail the rules of transitions for modeling the non-stationary process of moisture transfer during wood drying at the stage of removing bound moisture by the method of cellular automata.

Description of the algorithm for applying cellular automata. The algorithm for applying cellular automata have five stages:

Stage 1. Creation of the cellular automaton grid. The primary task is to divide the surface of the investigated timber into cells using its geometric dimensions, for example, 50×25 cm. This allows discretizing the study space for further modeling. As a result of this stage, a cellular automata grid consists of a certain number of cells of the same size.

Stage 2. Setting initial conditions. At this stage, it is necessary to specify the initial values of temperature and humidity for each cell, as well as other parameters, including coefficients and parameters of the drying agent. Some of these values will be calculated at the beginning of the modeling, while the rest will be obtained from reference sources [4].

Stage 3. Initialization. At this stage, data arrays are created to store the parameter values of all cells. There are mainly nine of them: T[i][j] is wet bulb temperature in the specified cell(i, j); T_p[i][j] is the temperature on the surface of the lumber in the specified cell(i, j); W[i][j] is moisture content in the specified cell(i, j); T_c[i][j] is temperature of the drying agent in the specified cell(i, j); ϕ[i][j] is relative humidity in the specified cell(i, j); E_m[i][j] is instantaneous elasticity model in the specified cell(i, j); $\sigma_в$[i][j] is moisture stress in the specified cell(i, j); ε[i][j] is deformation in the specified cell(i, j); Nu_q[i][j] is Nusselt heat transfer criterion value in the specified cell(i, j) and Nu_m[i][j] is Nusselt mass transfer criterion value in the specified cell(i, j).

Stage 4. Calculation using transition rules. At this stage, calculations are initially carried out for the starting iteration at τ = 0 s. For each cell(i, j), new values of T_c and ϕ need to be computed based on the developed transition rules, which are based on the equations from the previous section. At the same time, there is a nonlinearity in equation 1. To calculate T_c, it is necessary to know the value of Nu_q. In turn, to find Nu_q, it is necessary to know Gu, which is calculated by T_c. To solve this problem, was used the Newton–Raphson method, which is based on the idea of linearization of a nonlinear function by using its local tangent or linear approximation. The main goal is to find such a value at which the function is zero. This method involves several basic steps, including choosing a starting point, evaluating the local derivative (tangent) of the function at a given point, calculating the value of the new point using linear approximation, and repeating the previous steps until a satisfactory approximation to the root is obtained.

In this case, it is necessary to perform the following steps:

1. Select the initial value of $Gu^{(0)}$ and $_{error}$;
2. Calculate $Nu_q(Gu^{(0)})$ and $T_c^{(0)}$ according to equations (7) and (1);
3. Save the new value of $Gu^{(1)}$, as follows: $Gu^{(1)} = Gu^{(0)} + _{error}$;
4. Calculate $Nu_q(Gu^{(1)})$ and $T_c^{(1)}$ using the same equations (7) and (1);
5. Calculate the derivative $\partial T_c/\partial Gu = (T_c^{(1)} - T_c^{(0)})/(Gu^{(1)} - Gu^{(0)}) = (T_c^{(1)} - T_c^{(0)})/_{error;}$
6. Calculate the new value $Gu^{(new)}$ as follows: $Gu^{(new)} = Gu^{(0)} - (T_c^{(0)}/(\partial T_c/\partial Gu))$.

Then the following transition rule can be used:

IF $(Gu^{(0)} + _{error}) < Gu^{(new)} < (Gu^{(0)} - _{error})$ **THEN** $Gu^{(0)} = Gu^{(new)}$ **AND** repeat steps 2-6 **ELSE** complete this iteration (τ += Δτ)

To continue performing calculations by using cellular automata, it is also worth applying the following rules of transitions:

IF $E_m[i][j]$ **THEN**

$$E_m[i][j]^{(next)} = (304.55 + 759.7\exp(-17.88W[i][j]^{(next)})) \cdot \cdot \exp(-0.02T_p[i][j]^{(next)})$$

IF $\sigma_в[i][j]$ **THEN**

$$\sigma_в[i][j]^{(next)} = \frac{E\beta}{1-\nu}\left(\Delta W[i][j]^{(next)} - W[i][j]^{(next)}\right)$$

IF $Nu_q(Gu^{(0)})$ **OR** $Nu_q(Gu^{(1)})$ **THEN**

$$Nu_q[i][j]^{(old)} = 0.0641\left(\frac{Vl}{\nu}\right)^{0.8}(Gu^{(0)}\ \mathbf{OR}\ Gu^{(1)})^2\left(\frac{\nu}{a}\right)^{0.333}$$

IF Nu_m **THEN**

$$Nu_m[i][j]^{(next)} = 2.5\left(\frac{Vl}{\nu}\right)^{0.6}\left(-\frac{T_c[i][j]^{(next)}}{T[i][j]^{(next)}}\right)^{0.135}\left(\frac{\nu}{a}\right)^{0.333}$$

IF T_c **THEN**

$$T_c[i][j]^{(next)} = 0.13(238 + T_p[i][j]^{(next)})\cdot$$
$$\cdot\frac{20m\rho_0(1+\beta_0 W_0)\sigma_в[i][j]^{(next)}}{E_m[i][j]^{(next)}KNu_q[i][j]^{(next)}D_p\rho_{nc}} +$$
$$+\frac{1+(238+T_p[i][j]^{(next)}}{1785(20m\rho_0(1+\beta_0 W_0)\sigma_в[i][j]^{(next)})} +$$
$$+(E_m[i][j]^{(next)}KNu_q[i][j]^{(next)}D_p\rho_{nc})$$

IF .. **THEN**

$$\varepsilon[i][j]^{(next)} = \frac{1}{E}(\sigma_в[i][j]^{(next)} - \nu\sigma_в[i][j]^{(next)}) +$$
$$+\beta(W[i][j]^{(next)} - W_0)$$

IF $\phi[i][j]$ **THEN**

$$\phi[i][j]^{(next)} = (1+\beta_0 W_0)l\rho_0\cdot$$
$$\cdot\frac{2\sigma_в[i][j]^{(next)} + E\varepsilon[i][j]^{(next)}}{2E_m[i][j]^{(next)}\beta(0.33-x^2)Nu_m[i][j]^{(next)}\rho_{nc}} +$$
$$+\exp\left(-\frac{\tau}{147\exp(-0.073W[i][j]^{(next)})}\right) + \frac{\pi^2 BiFo}{4Bi+\pi^2}$$

Where: $^{(old)}$ is value at a previous moment in time; $^{(next)}$ is value at the current time; E ≈ 8 GPa (pine), 9 GPa (spruce), 10 GPa (birch), 11 GPa (beech), 12 GPa (oak); ν ≈ 0.5 (along the fibers), 0.02 (across the fibers).

Stage 5. Iterative cycle and completion check. At this stage, calculations are made according to the iteration cycle. At the same time, the conditions for stopping execution are checked, such us:

IF $\phi[i][j]^{(next)} \neq \phi[i][j]^{(old)}$ **THEN** τ += $\Delta\tau$ **ELSE** Stop calculations **AND** give a message about reaching the stability state for the relative humidity values of the drying agent. Waiting for continuation.

IF W[i][j] > W_p **THEN** Perform calculations according to stage 4 **ELSE** Stop execution **AND** give a message that the condition has been met for the specified parameters of the technological process. Saving the results.

IF $\tau_{max} < \tau$ **THEN** Perform calculations according to stage 4 **ELSE** Stop execution **AND** give a message that the maximum allotted time has been reached. Saving the results.

Where: W_p is the equilibrium humidity, τ_{max} is the final specified simulation time.

To carry out modeling, it is first necessary to create [5] a cellular automata field (Fig. 1). Since the geometric parameters for all lumber are the same, then the shape of the cellular automatic field will not change.

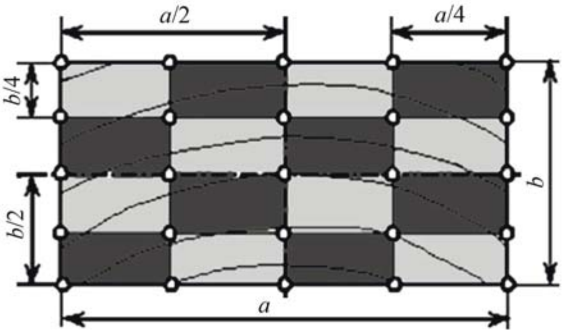

Fig. 1. View of the cellular automatic field in the cross-section of material $a\times b$ / Вид поля клітинного автомата в поперечному перерізі пиломатеріалу $a\times b$

Assuming that the wood is a solid anisotropic hygroscopic material, where the coefficients of moisture conductivity and exchange are constants but different for various axes of anisotropy, the following input data can be considered for the dynamic moisture distribution in pine lumber:

- Cross-section dimensions of the lumber $a = 2\ b = 50$ mm;
- Initial moisture content of the material $W_0 = 35$ %;
- Drying agent parameters for the given drying mode obtained from [3]. The following initial conditions can be used for the selected technological mode, such us: $T_c^{(0)} = 75$ °C, $T_0 = 24$ °C, $\varphi_0 = 0.6$, $W_0 = 0.35$, $v = 2$ m/s;
- the equilibrium humidity W_p, as well as the coefficients of moisture exchange β and moisture conductivity α are set constant and determined according to [4];
- duration of the technological process $\tau_{max} = 10$ h. with the steep of $\Delta\tau = 0.1$ h.

To compare the moisture content in lumber of different wood species with the same geometry, some input data can be modified, specifically: equilibrium moisture content $W_p = 7$ %, moisture conductivity coefficient $\alpha = 2\cdot10^{-9}$ m/s, and moisture exchange coefficient $\beta = 4\cdot10^{-6}$ м^2/c. The rest of the parameters remain unchanged. Next, the parameters for low-temperature drying modes for different wood species can be specified, according to [1]. It is known that moisture removal from the surface layers is uniform for all wood species, yet the values vary due to the distinct drying modes associated with each wood species, thereby determining W_p.

Analysis of the obtained results. To conduct further calculations, was focused on wood of pine. To determine the influence of the temperature of the wood drying agent on the moisture content in lumber, it is necessary to first conduct research based on the use of the drying agent temperature under constant technological conditions. Then, these values are changed by 10°C in both directions. If these data are substituted into the input parameters of the cellular automata model, the following graphical dependence (Fig. 2) of the moisture content in pine lumber on its surface is obtained.

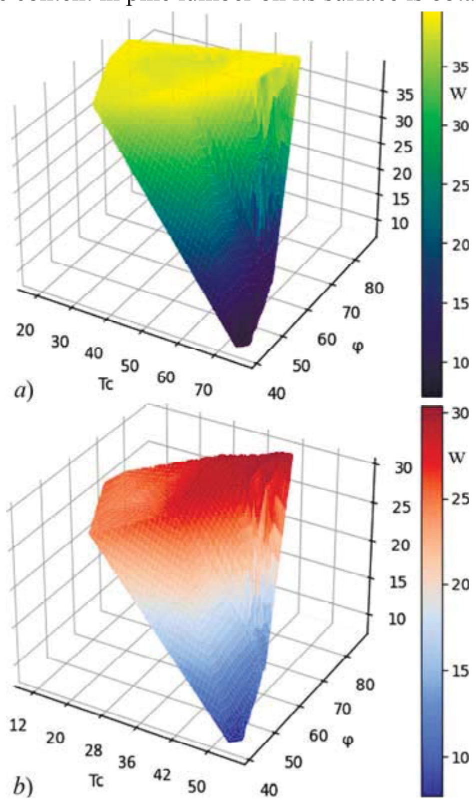

Fig. 2. The influence of the temperature of the drying agent on the dynamics of moisture on the surface of 25×50 mm pine lumber,

where initial temperature value (T_c^0): left figure – increased by 10 °C; right figure – decreased by 10 °C / Вплив температури агента сушіння на динаміку вологи на поверхні соснового бруса 25×50 мм, де значення (T_c^0): рисунок зліва – збільшено на 10 °C; рисунок справа – зменшено на 10 °C

In a detailed analysis, it was noticed that at the beginning of the drying process, the temperature change of the drying agent on the surface differs by an amount proportional to the change in the equilibrium moisture content. Over time, as a result of changes in the coefficients of moisture conductivity and moisture release at different temperature modes, an acceleration of moisture removal is observed. At higher temperatures, moisture removal occurs much faster, accordingly, the moisture content of the material quickly reaches 20 %, which means the transition to the next stage of the technological process.

To determine the influence of the relative humidity of the wood drying agent on the moisture content in lumber, it is also worth conducting research based on the use of relative humidity values under constant technological conditions. Then, the results should be determined when changing the relative humidity values of the drying agent by 10 % in both directions. By substituting these changes into the input parameters of the cellular automaton model, the following graphical dependence (Fig. 3) of the moisture level in lumber on its surface is obtained.

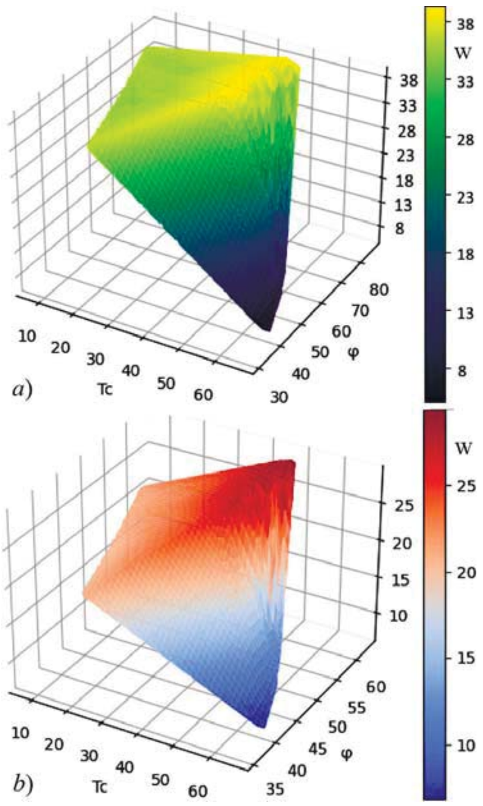

Fig. 3. The influence of the relative humidity of the drying agent on the dynamics of moisture on the surface of lumber 25×50 mm in size pines, where the initial value of relative humidity (φ_0): left figure – increased by 10 %; right figure – reduced by 10 % / Вплив відносної вологості сушильного агента на динаміку вологи на поверхні соснового бруса 25×50 мм, де значення відносної вологості (φ_0): рисунок зліва – збільшено на 10 %; рисунок справа – зменшено на 10 %

Upon detailed analysis, it was observed that at the beginning of the drying process, the change in the relative humidity of the drying agent differs on the surface by an amount equal to the change in equilibrium moisture content. Over time, the moisture content on the lumber's surface evens out to equilibrium. At lower relative humidity of the drying agent, the transition to the next stage of the technological process will occur more quickly, as compared to other values of the transition criterion – moisture content of the material at 20 %. According to the results, it is evident that changes in the relative humidity of the drying agent lead to a greater change in equilibrium moisture content and moisture exchange coefficients compared to changes in temperature. The obtained dependencies also indicate that decreasing the relative humidity of the drying agent results in faster moisture removal, leading to a transition to the next stage of the technological process, while increasing it delays the transition.

The velocity of the drying agent (V) affects the moisture exchange coefficients. Therefore, moisture removal is faster on the surface of lumber with increased circulation compared to its inside, where moisture transfer coefficients don't depend on the velocity of the drying agent. Thus, increasing the velocity of the drying agent reduces the duration of the technological process (Fig. 4).

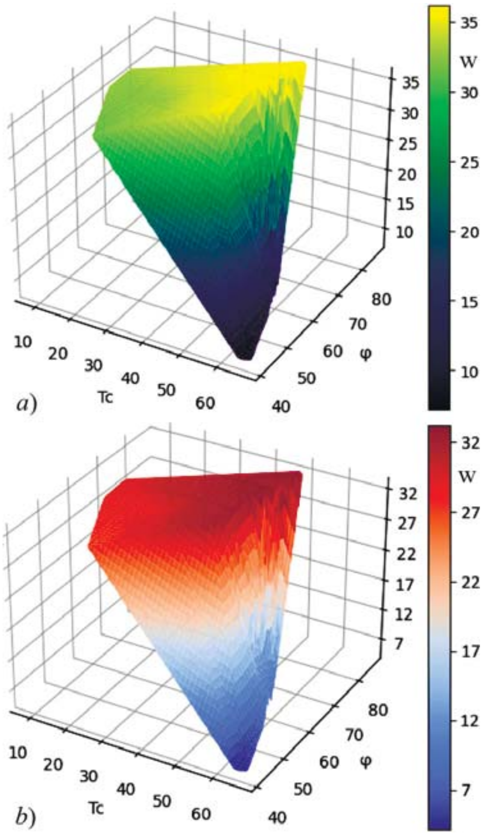

Fig. 4. Influence of the speed of movement of the drying agent on the dynamics of moisture on the surface of 25×50 mm pine lumber, where the speed of movement: left figure – corresponds to stable technological conditions; right figure – increased to 6 m/s / Вплив швидкості руху агента сушіння на динаміку вологи на поверхні соснового бруса 25×50 мм, де швидкість руху: рисунок зліва – відповідає стабільним технологічним умовам; рисунок справа – збільшено до 6 м/с

From the obtained graphical dependencies, it is evident that controlling the velocity of the drying agent is a key factor affecting the efficiency and quality of the drying process. Properly adjusting the drying agent velocity within technological limits, helps distribute heat and moisture evenly across the surface of the lumber, facilitating accelerated moisture evaporation and preventing negative effects such as uneven deformation or cracks.

The geometry of lumber, including its dimensions, shape, and structure, plays a significant role in determining moisture content [13]. Geometry influences the interaction between the lumber surface and the drying agent, affecting how quickly the material absorbs or releases moisture, as well as the uniformity of these processes. For example, the surface area of the lumber promotes increased external contact with the drying agent, allowing more water vapor to escape from the lumber. However, a substantial volume of lumber can retain moisture inside, leading to a slower drying process. Additionally, the thickness of the lumber regulates the rate of moisture release, as thicker lumber requires moisture to travel a longer distance before being released. Therefore, changes in the geometric parameters of lumber can also be applied in the developed cellular automaton model [18], provided that the cellular automaton field created earlier is modified accordingly [2].

Discussion of research results. The findings from this study offer valuable insights into the mathematical modelling of external heat and mass transfer during lumber drying. When compared to similar research in this area [9, 14, 15], it becomes clear that cellular automata present a novel and promising method for this type of simulating. Unlike traditional methods employed in earlier studies, cellular automata prove to be more efficient, delivering faster results at lower computational expenses. This research highlights the potential of this approach, paving the way for future investigations and innovations in the field, which could ultimately lead to more effective models for wood drying processes.

So, based on the results of the work performed, it is possible to formulate the following scientific novelty and practical significance of the research results.

Scientific novelty of the obtained research results – development of a cellular automata model for simulating external heat and mass transfer in wood drying chamber, taking into account the parameters of wood drying agent.

Practical significance of the research results – a novel approach has been devised, providing a more efficient and cost-effective method for modelling and analysing the lumber drying process.

Conclusions / Висновки

As a result of this study, a multifaceted impact of temperature, relative humidity, and the drying agent's velocity on the moisture content of wood materials during the drying process was investigated.

The study built upon previous work using cellular automata for moisture level measurement under constant conditions. Was introduced new transition rules to the cellular automata model for modifying the drying agent's parameters, offering a more dynamic and adaptable modeling approach. The cellular automata utilized in this research featured varying cell sizes, tailored to the geometric characteristics of the wood materials being modeled. This approach enabled the analysis of timber behavior based on its unique geometry, promising potential enhancements in the wood drying process.

Modeling was conducted using 25 mm thick lumber, primarily pine, with an initial moisture content of 30 %. The research findings hold practical significance for the industrial wood drying process. Enhanced wood drying models can lead to more effective drying processes, ultimately improving the stability and quality of wood products in the competitive market.

In summary, this study explores the interaction of external heat and mass transfer during wood drying and proposes a more adaptive and precise modeling approach. The insights gained from this research can be applied in industrial settings, paving the way for improved wood drying processes and higher-quality lumber production.

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ЗАСТОСУВАННЯ КЛІТИННИХ АВТОМАТІВ ДЛЯ МОДЕЛЮВАННЯ ЗОВНІШНЬОГО ТЕПЛОМАСООБМІНУ У ПРОЦЕСІ СУШІННЯ ДЕРЕВИНИ

Проведено моделювання зовнішнього тепломасообміну в камері сушіння деревини. Однією з особливостей цього дослідження є використання клітинних автоматів зі змінними розмірами клітинок, які тісно пов'язані з геометричними параметрами розглядуваних пиломатеріалів. Завдяки цьому підходу можна змоделювати та проаналізувати зміни характеристик пиломатеріалів під час процесу гідротермічного оброблення з урахуванням їх унікальної геометрії. Таке моделювання дає цінну інформацію про те, як різні форми та розміри деревини реагують на різні умови сушіння. Це дослідження має значущі наслідки для галузей, які залежать від сушіння пиломатеріалів, таких як будівництво та виробництво меблів, оскільки пропонує індивідуальний підхід до модернізації процесів сушіння пиломатеріалів різної геометрії. Проведено моделювання, в якому застосовують пиломатеріали, переважно із сосни, стандартизованої товщини 25 мм і з початковим вмістом вологості 30 %. Моделювання виконано за умов помірного сушіння, максимально точно відтворюючи сценарії реального світу. Як досліджуваний матеріал використано сосну, щоб підвищити релевантність результатів. Досліджено вплив різних параметрів агента сушіння деревини. Щоб досягти цього, систематично змінювали три ключові чинники: температуру, відносну вологість та швидкість агента сушіння. Коливання температури становило в діапазоні ±10 °C. Так само відносну вологість регулювали в межах ±10 % від стандартних технологічних параметрів. Нарешті було збільшено швидкість агента сушіння до максимум 6 м/с. У такий спосіб досліджено вплив цих змін на вміст вологи в пиломатеріалах. Отримані результати можна застосувати в промисловому середовищі, зокрема для покращення процесу сушіння деревини. Унаслідок гідротермічного оброблення пиломатеріалів підтверджено важливе значення параметрів агента сушіння деревини в контролі вмісту вологи в пиломатеріалах. Потенційні переваги щодо якості продукції та загальної ефективності виробництва неможливо переоцінити, сподіваємося, що ця робота стане цінним ресурсом для галузей, які залежать від переробляння деревини.

Ключові слова: зовнішній тепломасообмін; температура навколишнього середовища; відносна вологість; швидкість руху агента сушіння деревини; правила переходів.