ISSN 2707-1898 (print)
Український журнал інформаційних технологій
Ukrainian Journal of Information Technology
http://science.lpnu.ua/uk/ujit
https://doi.org/10.23939/ujit2021.02.039
Article received 16.10.2021 р.
Article accepted 23.11.2021 р.
UDK 004.94:536.2

Correspondence author
Ya. I. Sokolovskyy
yaroslav.i.sokolovskyi@lpnu.ua

***Ya. I. Sokolovskyy*[1]*, O. V. Sinkevych*[2]**

[1] *Lviv Polytechnic National University, Lviv, Ukraine*
[2] *National Forestry University of Ukraine, Lviv, Ukraine*

THE USE OF CELLULAR AUTOMATA IN MODELING THE PROCESSES OF WOOD DRYING IN A STACK

In this work, we investigated the possibilities of using a model of cellular automata in solving the problem of heat and moisture transfer in a periodic wood drying chamber. Thus, in this work are investigating the processes of heat and moisture transfer between the wood and its drying agent. Studies are carried out by using CAD model of stack of dried wood. To use cellular automata, it is proposed to present the CAD model as an array of cubes, each of which has six faces (cells). In this work also proposes to use the different research zones, each of which allows us to calculate the values of temperature and moisture content in different places of the CAD model. In particular, these zones can be placed inside the wood, on its boundary or in the agent of its drying. The proposed cell-automata model contains local relationships between cells that describe their general behavior. In addition to describing the general behavior of cells, the model provides the possibility of setting the physical characteristics of the material. This allows us to approximate processes and determine new values of the physical characteristics of the material, including temperature and moisture content. The proposed algorithm for the use of cellular automata makes it possible to obtain a reliable result unnecessarily to conduct complex and expensive practical experiments. To speed up the calculation process, propose to use multilayered, which consists in obtaining numerical values of the physical characteristics of the material from several adjacent cells, which are located in the same direction of interaction. The work also provides graphs of changes in temperature and relative humidity of the wood drying agent. In this work is also given graphs of changes in temperature and moisture content of wood inside and on its boundary. To check the adequacy and reliability, all results are compared with the results of another experiment. To check the adequacy and reliability, we compared the obtained results with the results of another experiment. For this comparison in work it is calculated the relative error between the temperature and moisture content values of both experiments. The value of this relative error makes it possible to determine the prospects for the use of cellular automata in the simulation of heat and moisture transfer processes in wood drying chambers.

Keywords: cellular automata; CAD model; algorithm of work; transition rules; wood drying chamber.

Introduction

Justification for a research study. To modeling the processes of heat and moisture transfer in the wood drying chamber (WDC), we selected the methods of cellular automata (CA) [13]. They are flexible simulation models, which provide the ability to set rules of conduct for each of its elements [1]. Unlike differential equations on which classical models of physical processes are based, CA can be used in more complex cases, without serious limitations or assumptions [9].

Relevance of research. Increase the efficiency of the process of choosing the optimal drying parameters in periodic WDC.

Object of research – the processes of temperature and moisture transfer between the WDA and the surface of the dried wood, which is located in the stack and vice versa.

Subject of research – the CA model of temperature and moisture transfer between the surface of the wood and its wood drying agent (DWA).

The purpose of the research – to use a CA model to solve the problem by using new algorithms and software tools.

To achieve this *purpose*, the following main *research objectives* are identified: develop a model of CA, which will be able to modelling the processes of heat and moisture transfer in WDC and determine changes in their numerical values of temperature and moisture content over time.

Scientific novelty of the obtained research results – for the first time develop and use the CA methods in solving the problem of heat and moisture transfer in WDC. The proposed CA model, in combination with the developed algorithm for it uses, gives the opportunity to use them to determine changes in temperature and moisture content in wood, on its surface and in WDA. In this work we also propose to work with multilayered, in which we can use the numerical values of temperature and moisture content from several neighboring cells simultaneously, which in turn speeds up the process of calculating.

The practical significance of the research results – speed up the process of calculating and reducing the number of computer system resources that are necessary for their implementation. This was achieved through by using different zones, each of which has its own characteristics and principles of calculation.

Materials and methods of research. In this work we used methods of CA and computer modeling.

Analysis of recent research and publications. Many researchers have tried to use CA in solving various kinds of problems. For example, in [7] the authors managed to build a CA model for the thermal conductivity process, taking into account the phenomenon of segregation. In [2] CA is used in the modeling of probasical, evolutionary and hydro gas dynamic processes. In turn, in [14] the authors managed to use CA in the construction of a series of endless Petri networks. CA are also used in simulating the grain formation process in small volumes with uniform cooling, which was demonstrated in [8].

Most of these authors managed to develop working CA models and apply them in solving various problems. To solve the problems, the developed models were able to improve the main characteristics of the study. For example, in [5] due to the use of CA model, the authors managed to significantly speed up the process of calculations when modeling static recrystallization in non-thermal burn. In [4] the authors determined the mechanical characteristics of composite materials based on microlevel cell structures. Also, in [3] achieved good indicators of computational acceleration when using CA for modern hardware and general-purpose GPUs.

All these works once again demonstrate the prospects of using CA methods, and the number of researchers that using them is growing steadily every year. Despite this, we first proposed to use the CA methods in the study of heat and moisture transfer in periodic WDC [11].

The results of the study and their discussion

Description of the studied CAD model. The studied CAD model consists of a stack of wood that needs to be dried. The stack contains 20 lumbers which are arranged in rows. Each of lumbers has the following dimensions: height 0.075 m., length 4 m., width 0.25 m. Each row contains 4 lumbers and arranged on gaskets, the height of which is 0.05 m. To visualize the studied CAD model, it was designed in SolidWorks (Fig. 1).

Fig. 1. View of the studied CAD model in SolidWorks

Unfortunately, in this form of the CAD model, we wont be able to use cellular automata. To use them, it is necessary to make another representation of this CAD model. We propose to divide the CAD model into 5 different zones (Fig. 2), each of which will have its own characteristics and principles of calculation.

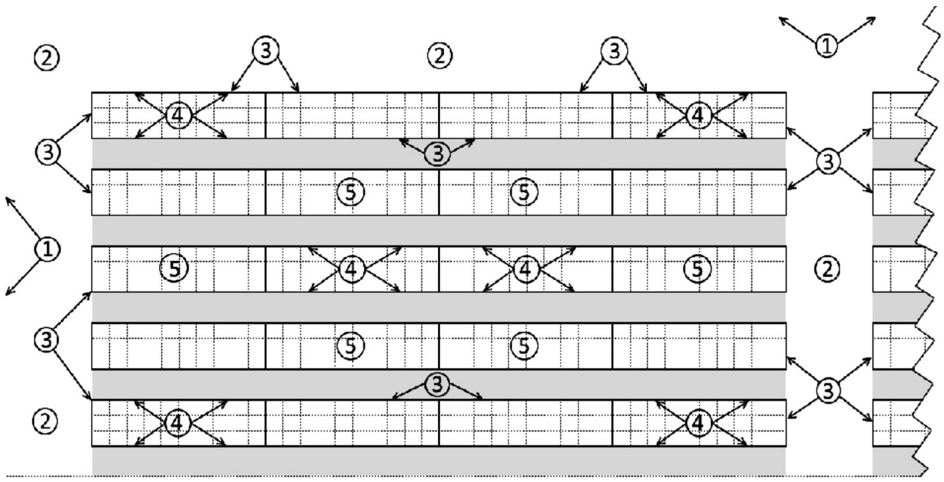

Fig. 2. View of the locations of the zones in and around the stack

In zone "1" we have the value of parameters of WDA at the entrance, supported at a sustainable level. In zone "2" we can change the parameters of the WDA in time and space. Zone "3" is the contact of the WDA with the surface of dried wood. Zone "4" is the contact with the surface of dried wood with the WDA. In the zone "5" we can change the temperature and moisture content in the wood.

Description of the possibilities for using zones. The first zone allows us to use input parameters for WDA, which in periodic WDC are always maintained at the same level. These parameters include: T_c, v, φ, c_c, P_s, α. We can describe it as follows:

$$\begin{matrix} T_c^k = T_c^0 = const & v^k = v^o = const & \phi^k = \phi^0 = const \\ c_c^k = c_c^0 = const & P_s^k = P_s^0 = const & \alpha^k = \alpha^0 = const \end{matrix}, \qquad (1)$$

where: T_c is the temperature of WDA (°C), v is a WDA movement speed (m/c), ϕ is a relative humidity of WDA, c_c is specific heat capacity of WDA ($J/kg\,°C$), $P_s = f(T_c)$ is a pressure of saturated vapor (kPa), $\alpha = f(T_c, v)$ is a heat exchange coefficient ($W/m^2°C$), k, 0 are time iteration number, which corresponds to the current modeling time t and changes according to the time step Δt.

The second zone allows us to change the parameters of the WDA. This zone applies when studied CAD model have more than one stack. Since our CAD model has only one stack, we dont apply to use the first two zones.

The third zone also allows us to change the parameters of the WDA, but already taking into account the parameters of the dried material. In this zone, there is an intensive change the values of T_c and φ due to the heating and the evaporation of moisture on the surface of the wood. In this regard, the mathematical model of heat and moisture transfer can be written as follows:

$$\begin{cases} \dfrac{\partial T_c}{\partial z} = \dfrac{\alpha(T_b - T_c)}{0.5 h_g v \rho_c c_c} \\ \dfrac{\partial \phi}{\partial z} = \dfrac{a\rho_0(U_b - U_p)}{0.5 h_g v \rho_s} - \dfrac{\phi}{0.5 h_g}\left(\dfrac{T_c\left(\dfrac{\partial P_s}{\partial z}\right) - P_s\left(\dfrac{\partial T_c}{\partial z}\right)}{T_c^2}\right)\dfrac{1}{\rho_s} \end{cases}, \qquad (2)$$

where: $T_c=f(t, z)$ is the temperature of WDA (°C), $\varphi=f(t,z)$ is a relative humidity of WDA, T_b is wood surface temperature (°C), ρ_c is the density of WDA (kg/m^3), h_g is gasket height (m), ρ_0 is basic wood density (kg/m^3), $U_p=f(T_c, \varphi)$ is equilibrium humidity, $a=f(U_b, Tb)$ is the coefficient of moisture conductivity (m^2/s), $\rho_s=f(Tc)$ is saturated vapor density (kg/m^3), U_b is wood surface moisture content.

The fifth zone allows us to change the temperature and moisture content in the wood with time, taking into account the values on its boundary. To do this, we can use the following mathematical model:

$$\begin{cases} c_m\rho_m \dfrac{\partial T_m}{\partial t} = \sum\limits_{j=1}^{3} \lambda_j \dfrac{\partial^2 T_m}{\partial x_j^2} + \varepsilon\rho_0 r \dfrac{\partial U_m}{\partial t} \\ \dfrac{\partial U_m}{\partial t} = \sum\limits_{j=1}^{3} a_j \dfrac{\partial^2 U_m}{\partial {x_j}^2} + \delta \sum\limits_{j=1}^{3} a_j \dfrac{\partial^2 T_m}{\partial {x_j}^2} \end{cases}, \quad (3)$$

where: c_m is specific heat capacity of wood ($J/(kg\ °C)$), $\lambda_j = f(U_m, T_m)$ are thermal conductivity coefficients ($W/m^2 °C$), $T_m=f(t, x_j)$ is wood temperature (°C), ρ_m is wood density (kg/m^3), t is current modeling time (s), r is specific heat of vapor formation (kJ/kg), $a_j = f(U_m, T_m)$ are coefficients of moisture conductivity (m^2/s), $U_m=f(t, x_j)$ is moisture content of wood, $\varepsilon=f(\rho_0)$ is coefficient of phase transition, $\delta=f(U_m, T_m)$ is thermo gradient coefficient, j is responsible for the coordinate at which the calculation is performed and can take the value of $x(j=1)$, $y(j=2)$ or $z(j=3)$.

The fourth zone allows us to change the temperature and humidity content on the surface of the wood, taking into account the parameters of the WDA. In fact, in this zone there is an intensive exchange of heat and moisture content between the surface of the wood and WDA. The mathematical model can be written as follows:

$$\begin{cases} \sum\limits_{j=1}^{3} \lambda_j \dfrac{T_b - T_m}{h_j} + \rho_0(1-\varepsilon)\beta(U_b - U_p) = \alpha(T_b - T_c) \\ \sum\limits_{j=1}^{3} a_j \delta \dfrac{T_b - T_m}{h_j} + \sum\limits_{j=1}^{3} a_j \dfrac{U_b - U_m}{h_j} = \beta(U_p - U_b) \end{cases}, \quad (4)$$

where: h_j is a displacement step at a given coordinate x, y or $z(m)$, $a = f(U_m, T_m)$ is a moisture conductivity coefficient (m^2/s), $\beta = f(v, T_c, \varphi)$ is moisture exchange coefficient (m^2/s).

Algorithm for using CA model. To use CA model, we must have a set of cells. In this work, we propose to divide the CAD model into a certain number of cubes, each of them has 6 cells [10]. In order for all cubes have the same size, we can set the density of the partition, for example d = 0.025 m. Next, it is necessary to indicate the type of cell (wood or WDA) and the zone number to which it belongs.

In general, we have developed an algorithm for the use of CA, which involves the following steps:

- We select the R_i point of a certain cell according to a discrete uniform distribution. The index i can take different values, for example: a is a point belonging to the WDA, b is a point that located on the boundary of wood, m is a point belonging to wood and tmp is a point to preserve temporary values;
- We select direction of interaction W according to the x, y or z coordinate;
- We select points R_i^+, R_i^- from adjacent cells, according to the direction of interaction W;
- We define some constants C_1, C_2,..., C_N, which will be necessary for calculations. They will be calculated depending on the zones of cells involved in the interaction. In general, there are possible seven types of interactions in zones, namely: [2]-[1], [2]-[2], [2]-[3], [3]-[4], [4]-[3], [5]-[4], [5]-[5]. Since there is only one stack in the CAD model, then we dont use first and second zones, as well as interactions [2]-[1], [2]-[2] and [2]-[3];
- We determine new values of temperature and humidity content for point P_i;
- We check the obtained numeric values;
- We save new numeric values for the point R_i.

According to this algorithm, we see that in the process of calculating we have an interaction between the points of two adjacent cells. This is enough for calculations, but to speed up the calculation process, we offer the use of multilayered. It involves the use of temperature and moisture content of points for two, four or six adjacent cells at the same time (Fig. 3). However, we need some conditions for this:

- All cells belong to the same type (wood or WDA);
- The direction of interaction between these cells is the same and equal to W;
- The distance to cells of another type is least 3 cells.

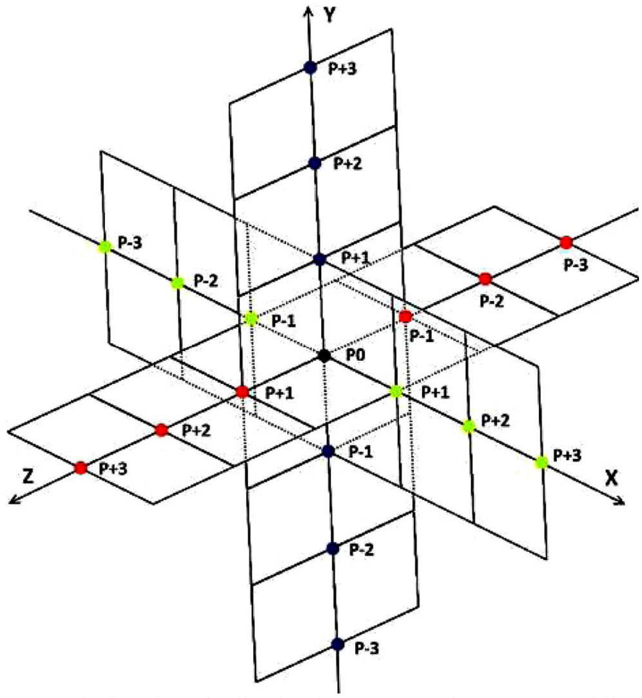

Fig. 3. The location of cell points in 3D space when we use multilayered

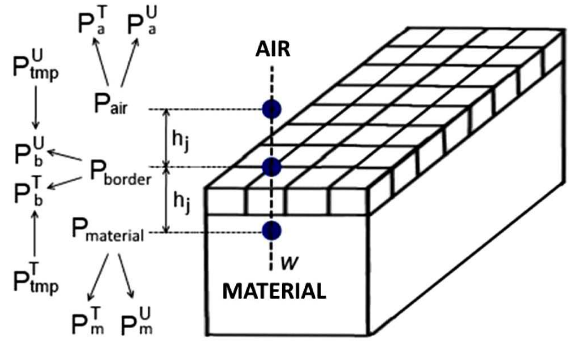

Fig. 4. Scheme of using CA on the material surface

Practical implementation of the proposed algorithm. The most difficult task is to calculate the change in temperature and humidity content on the surface of the wood. It is difficult because wood in the drying process emits part of its moisture, which absorbs by WDA. It happens because the WDA gives part of its heat to the wood, thereby heating it [6].

To implement these dependencies, when we use CA model, we can use the scheme (Fig. 4). This scheme shows the relationship between WDA, the wood surface, and its internal values according to the chosen direction of interaction W. Since all cubes have the same size of faces (cells), then the distance between the points of its adjacent cells h_j will also be the same.

When we use this scheme, the upper point-marking indexes (P^T , P^U) are responsible for numerical temperature and humidity values at this point. In addition, the new values $P_b{}^U$ and $P_b{}^T$ we save only after checking the intermediate values $P_{tmp}{}^U$ and $P_{tmp}{}^T$, which are defined as follows:

$$\begin{cases} P_{tmp}{}^T = \dfrac{P_a{}^T(C_3 - C_2 - C_1\delta) + P_m{}^T(C_5 - C_4) - C_1(P_m{}^U - P_a{}^U)}{C_3 + C_5 - C_2 - C_4 - C_1\delta}; \\ P_{tmp}{}^U = \dfrac{C_6(P_m{}^T - P_{tmp}{}^T) + a_j P_m{}^U + C_7 P_a{}^U}{a_j + C_7}. \end{cases} \quad (5)$$

The coefficients C_1–C_7 are defined as follows:

$$C_1 = a_j\rho_0(1-\varepsilon)\beta \quad C_3 = \beta\lambda_j \quad C_5 = \alpha\beta h_j \quad C_2 = (a_j\lambda_j)/h_j \quad C_4 = \alpha a_j \quad C_6 = a_j\delta \quad C_7 = \beta h_j . \quad (6)$$

If we use multilayered (Fig. 3), to determine the internal numeric values of T_m, U_m in wood, we can determine intermediate values $P_{tmp}{}^U$ and $P_{tmp}{}^T$ as follows:

$$\begin{cases} P_{tmp}^U = P_m^U - C_1\left(\Sigma P_m^U + \delta\left(\Sigma P_m^T\right)\right); \\ P_{tmp}^T = P_m^T + C_2\left(\Sigma P_m^U\right) + C_3\left(P_{tmp}^U - P_m^U\right), \end{cases} \quad (7)$$

where:

$$\Sigma P_m^U = \frac{1}{6}P_{m+3}^U + \frac{1}{3}P_{m+2}^U + \frac{1}{2}P_{m+1}^U - 2P_m^U + \frac{1}{2}P_{m-1}^U + \frac{1}{3}P_{m-2}^U + \frac{1}{6}P_{m-3}^U;$$

$$\Sigma P_m^T = \frac{1}{6}P_{m+3}^T + \frac{1}{3}P_{m+2}^T + \frac{1}{2}P_{m+1}^T - 2P_m^T + \frac{1}{2}P_{m-1}^T + \frac{1}{3}P_{m-2}^T + \frac{1}{6}P_{m-3}^T.$$

The coefficients C_1–C_3 are defined as follows:

$$C_1 = \frac{a_j\Delta t}{h_j{}^2} \quad C_2 = \frac{\lambda_j\Delta t}{c_m\rho_m h_j{}^2} \quad C_3 = \frac{\varepsilon\rho_0 r}{c_m\rho_m}. \quad (8)$$

To determine the numeric values T_c and φ, when we use CA, it is also necessary to determine the intermediate values $P_{tmp}{}^T$ and $P_{tmp}{}^U$. These values can be defined as follows:

$$\begin{cases} P_{tmp}{}^T = P_a{}^T + \dfrac{C_1(P_b{}^T - P_a{}^T)}{C_2}; \\ P_{tmp}{}^U = P_a{}^U + \dfrac{C_3(P_b{}^U - U_p)}{C_4} - \dfrac{P_a{}^U(P_n - P_s)}{C_5 P_a{}^T} + \dfrac{P_a{}^U P_s P_{tmp}{}^T}{C_5(P_a{}^T)^2} - \dfrac{P_a{}^U P_s}{C_5 P_a{}^T}, \end{cases} \quad (9)$$

where: $P_n = f\left(P_{tmp}{}^T\right)$ is the new value of $P_s(kPa)$. In this case, the coefficients C_1–C_5 are defined as follows:

$$C_1 = \alpha h_j \quad C_3 = a_j\rho_0 h_j \quad C_2 = \nu c_c\rho_c h_g \quad C_4 = \nu\rho_s h_g \quad C_5 = h_g\rho_s . \quad (10)$$

When we use CA, between adjacent cells, there is an interaction, which can be described by the following transition rules:

IF we choose P_b , $P_a{}^+$, $P_m{}^-$ THEN $P_{tmp}{}^T$ and $P_{tmp}{}^U$ calculate according to Eq. 5

IF we choose P_m , $P_m{}^+$, $P_m{}^-$ THEN $P_{tmp}{}^T$ and $P_{tmp}{}^U$ calculate according to Eq.7

IF we choose P_a , $P_a{}^+$, $P_b{}^-$ THEN $P_{tmp}{}^T$ and $P_{tmp}{}^U$ calculate according to Eq. 9

IF $P_{tmp}{}^T > T_c{}^0$ THEN $P_{tmp}{}^T = T_c{}^0$

IF $P_{tmp}{}^T < T_m{}^0$ THEN $P_{tmp}{}^T = T_m{}^0$

IF $P_{tmp}{}^U < U_p$ THEN $P_{tmp}{}^U = U_p$

Analysis of the obtained results. To check the performance of the proposed algorithm, we conducted an experiment in the developed software application [11]. The input data for the experiment we took from the work [12]. As a result, we received graphs of changes the temperature and the moisture content of the material (Fig. 5), as well as temperature and relative humidity of the WDA (Fig. 6). In addition, we created a graph that reflects changes in temperature and humidity values on the material surface (Fig. 7).

To verify the adequacy of the results, we determined the relative error between the obtained results and the results that given in the work [12]. As a result, the relative error doesn't exceed 6.9 % for T_m and 4.5 % for U_m. At the same time, their greatest values were recorded at the beginning of the experiment, which we can see on the graph (Fig. 8). These results can be justified by increasing the number of cells whose values are calculated. This number increases over time modeling. It happens because calculations start from zone 3 and 4 and gradually continue in zone 5.

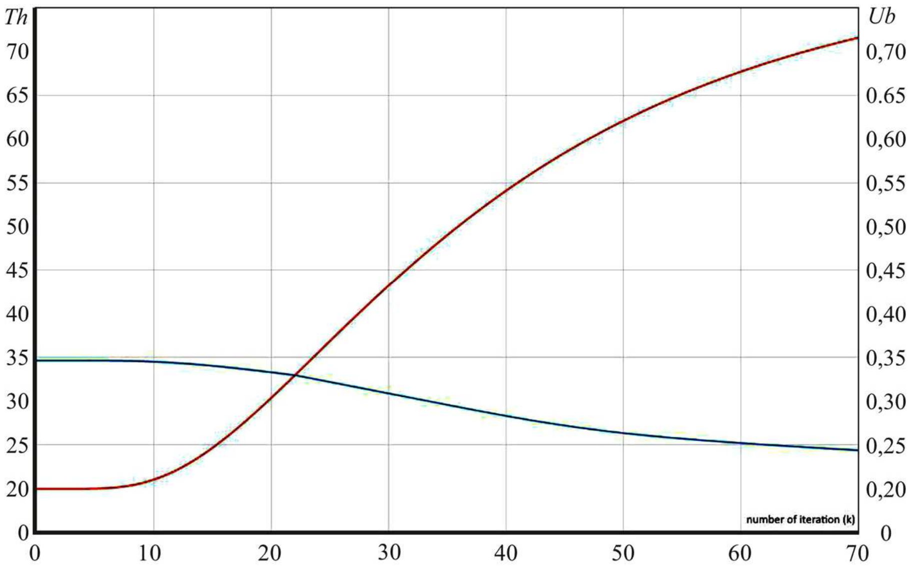

Fig. 5. Graph of changes the temperature and the moisture content of the material in time

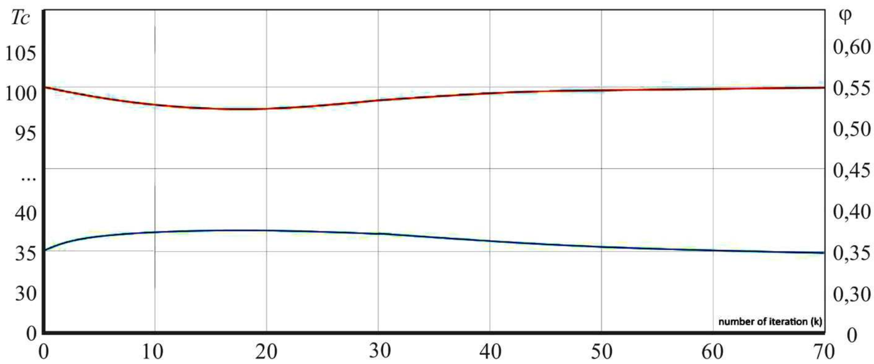

Fig. 6. Graph of changes temperature and relative humidity of the WDA in time

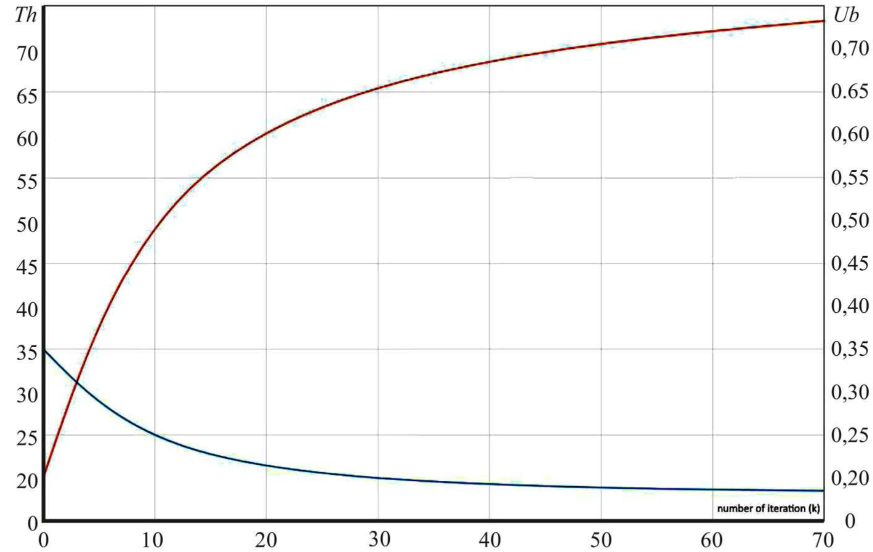

Fig. 7. Graph of changes temperature and humidity on the material surface in time

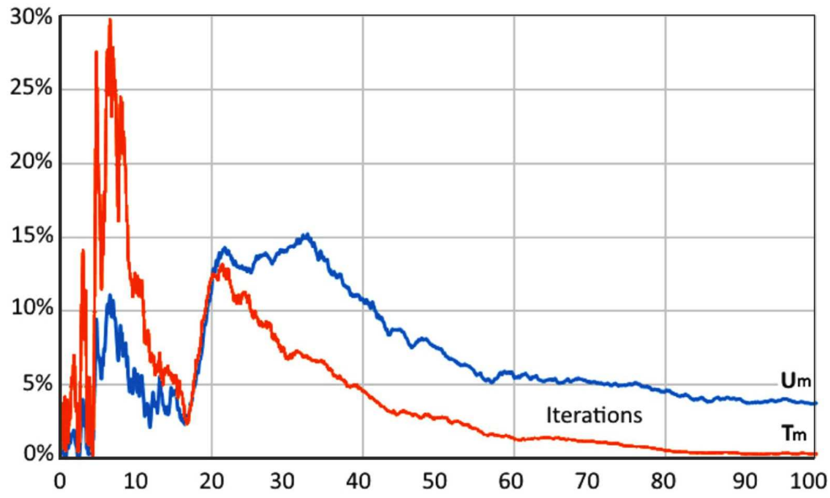

Fig. 8. Graphical representation of the relative error for T_m and U_m

Conclusions

As a result of the work, we obtained graphs of changes in temperature and humidity of wood in stack. In addition, we obtained the graph for changing the parameters of the WDA. Despite the fact that the numerical values of the WDA parameters in the periodic WDC action are always supported at the same level, we see some deviations from these values on the obtained graph. This indicates the release of moisture from wood surface during the drying process. As the modeling time increases and the rate of moisture removal from the wood decreases, the values of WDA returns to the initially specified level.

As a result of comparison of the obtained results with the results of existing experiments, we received low values of the relative error for T_m and U_m. This indicates that the proposed algorithm for use the CA really allows us to solve problems of heat and moisture transfer in periodic WDC.

In addition, divide the cad model into 5 zones, combined with proposed algorithm, allows us to determine changes in the temperature and moisture content of wood in the stack. In general, this work fully confirms the possibility of using a CA model to solve this kind of problems. In this case, CA allow us to find the result faster, and the resulting error isnt significant and is usually present at the beginning of modeling.

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Я. І. Соколовський[1], О. В. Сінкевич[2]

[1] *Національний університет "Львівська політехніка", м. Львів, Україна*
[2] *Національний лісотехнічний університет України, м. Львів, Україна*

ВИКОРИСТАННЯ КЛІТИННИХ АВТОМАТІВ ПІД ЧАС МОДЕЛЮВАНЯІ ПРОЦЕСІВ СУШІННЯ ДЕРЕВИНИ У ШТАБЕЛІ

Досліджено можливості використання моделі клітинних автоматів при вирішені завдання тепло- і вологоперенесення в камері сушіння деревини періодичної дії. Також досліджено процеси тепло- і вологообміну між деревиною та її агентом сушіння. Дослідження проведено з використанням CAD-моделі штабеля висушуваної деревини. Для використання клітинних автоматів запропоновано подання досліджуваної CAD-моделі у вигляді масиву кубів, кожен з яких має шість граней (клітин). Також в роботі запропоновано використання різних зон дослідження, кожна з яких дає змогу обчислювати значення температури та вологовмісту в різних місцях досліджуваної CAD-моделі, зокрема всередині деревини, на її межі чи в агенті її сушіння. Запропонована клітинно-автоматна модель містить локальні взаємозв'язки між клітинами, які описують їх загальну поведінку. Окрім опису загальної поведінки клітин, в моделі передбачена можливість задавання фізичних характеристик матеріалу. Це дає змогу апроксимувати процеси та визначити нові значення фізичних характеристик матеріалу, у т. ч. температуру та вологовміст. Запропонований алгоритм використання клітинних автоматів дає можливість отримувати достовірний результат без потреби проводити складні та дороговартісні практичні експерименти. Для пришвидшення процесу розрахунку використовується багатошаровість, яка полягає в отриманні числових значень фізичних характеристик матеріалу в декількох сусідніх клітинах, які розташовані на одному напрямку взаємодії. В роботі також наведено графіки зміни температури та відносної вологості агенту сушіння деревини. Окрім цього, наведено графіки зміни температури та вологовмісту деревини всередині та на її межі. Для перевірки адекватності та достовірності, проводиться порівняння отриманих результатів із результатами іншого експерименту. Для цього порівняння обчислюється середня абсолютна похибка між значеннями температури та вологості обох експериментів. Значення цієї похибки дають можливість визначити перспективи використання клітинних автоматів під час моделюваняі процесів тепло- і вологоперенесення в камерах сушіння деревини.

Ключові слова: клітинні автомати; CAD-модель; алгоритм роботи; правила переходів; камера сушіння деревини.

Інформація про авторів:

Соколовський Ярослав Іванович, д-р техн. наук, професор, кафедра систем автоматизованого проектування. **Email:** yaroslav.i.sokolovskyi@lpnu.ua; https://orcid.org/0000-0003-4866-2575

Сінкевич Олексій Вячеславович, аспірант, асистент, кафедра інформаційних технологій. **Email:** oleksiy1694@gmail.com; https://orcid.org/0000-0001-6651-5494

Цитування за ДСТУ: Соколовський Я. І., Сінкевич О. В. Використання клітинних автоматів під час моделюваняі процесів сушіння деревини у штабелі. *Український журнал інформаційних технологій.* 2021, т. 3, № 2. С. 39–44.

Citation APA: Sokolovskyy, Ya. I., & Sinkevych, O. V. (2021). The use of cellular automata in modeling the processes of wood drying in a stack. *Ukrainian Journal of Information Technology, 3*(2), 39–44. https://doi.org/10.23939/ujit2021.02.039