ACTA FACULTATIS XYLOLOGIAE ZVOLEN, 59(2): 105−114, 2017
Zvolen, Technická univerzita vo Zvolene
DOI: 10.17423/afx.2017.59.2.10

DETERMINATION OF THE WOOD THERMODYNAMIC CHARACTERISTICS AT CONVECTION DRYING

Olena Pinchevska – Andriy Spirochkin – Rostislav Oliynyk – Ján Sedliačik

ABSTRACT

The article analyses the peculiarities of sawn timber convection drying. There is a possibility to represent it as a relaxation process. The thermodynamic coefficients characterizing the temperature dependence of the moisture removal rate from the wood in the drying process are determined to have inversely proportional value to the relaxation time. Relaxation parameters of the moisture removal from the wood process have been determined using empirical kinetic dependencies of convection drying, which allowed calculating the thermodynamic coefficient K_1 characterizing the process of moisture removal from the wood. There has been calculated the activation energy of the bound moisture removal from the wood process using the Arrhenius's method of the relaxation time τ_1 graphical and logarithmic dependencies on temperature. The calculations have showed that the moisture removal from all studied wood spices is characterized by the same energy, its value is $E_{a_1} = 4{,}806 \times 10^{-20} J = 0{,}30 eV$. The damping capacity temperature dependence of the "conventional" moisture source has been determined in the result of experimental studies of the convection drying kinetics in an industrial environment. This allowed us to detect the presence of the activation mechanism in its life cycle at the stage of the material initial heating in the chamber. The activation energy of the "conventional" moisture source has been determined from the relaxation time logarithmic dependence on the reciprocal temperature. The obtained results allowed us to determine the thermodynamic coefficient K_2 characterizing the kinetics of "conventional" moisture source in the equation of the sawn timber current moisture content.

Key words: convection sawn timber drying, activation energy, thermodynamic parameters, current moisture content forecast.

INTRODUCTION

The complex study of numerous elementary transport phenomena, forming the actual drying process is of paramount importance to understand and properly develop technologies and equipment for wood drying. Theoretical and experimental study of heat and mass transfer in the solid phase is closely connected with the problems of studying the regularities of the substance properties changing in the course of physical processes. The particular importance in modern engineering calculations of technological equipment is granted to the modelling of technological processes, moreover, nowadays it is a standard approach for a designer, a technologist, a specialist in instrumentation and automation of technological processes. The reliability of physical quantities determination affects the adequacy of mathematical models of technological processes. With the advent of new capabilities in measuring technology, there arise the new opportunities in mathematical modelling and optimization (SOKOLOWSKYI and SHYMANSKYI 2014).

Researches in the field of heat and mass transfer are still relevant in connection with the need to increase the efficiency of various industries (DZURENDA and DELIISKI 2012). The requirements for engineering calculations associated with the need for further accumulation and systematization of the reference data of material physical properties used in technological processes are increasing.

To determine the exposure of the sawn timber drying process accurately it is necessary to establish the interaction of moisture with wood thermal effects of different intensity (KLEMENT and VILKOVSKA 2016). In the process of convective drying at temperatures below 100 °C the moisture in the wood does not change its aggregate state, remaining liquid (SOKOLOVSKYY *et al.* 2016). The thermal motion in the liquid is basically reduced to the chaotic molecular vibrations near some equilibrium positions that are non-stationary and periodically change (DZURENDA 2016).

The Arrhenius's equation is used to determine the average relaxation time of molecules of different substances. It is usually applied to describe the temperature dependence of the chemical reaction rate coefficient. Now the use of this equation has considerably expanded, and now the so-called "Arrhenius kinetics" is used to explain a wide range of phenomena belonging to different kinetic processes: from stress relaxation in solids, to mass transfer in gas systems (SHTILLIER 2000). In modern interpretation this equation determines the temperature dependence of the various processes speed coefficient.

The Arrhenius's equation was widely used in the wood drying process, in particular, to determine the diffusion coefficient (HUNTER 1992, SHI 2007, HOSSEINABADI *et al.* 2012, MONKAM *et al.* 2013).

$$D = D_0 \exp(-E_a / RT) \tag{1}$$

where: D – diffusion coefficient, m^2s^{-1};
D_0 – constant Arrhenius's equation, m^2s^{-1};
R – gas constant, kJ mol^{-1} K^{-1}
T – temperature, K

MONKAM *et al.* (2013), SHI (2007), HUNTER (1992) indicate that equation (1) as extremely important for mathematical modelling of wood drying processes, and their results confirmed a significant effect of temperature on the kinetics of drying.

Another approach of the Arrhenius's equation applying for the modelling of drying processes was used by ARAPOV (2001, 2012), considering the processes of drying food products. He proposed to represent drying as a physical and chemical process, in which a moist material can be divided into vapour moisture and a dry residue under the influence of heat. Accordingly, the moisture transition into the vapour state is associated with the energy barrier overcoming, the presence of which is due to the connection of water with the dry part of the material and the vaporization heat. In this case, the drying process speed is represented as the equation:

$$\frac{\partial a}{\partial t} = f(a) C \exp(-E_a / RT) \tag{2}$$

where: a – degree of substance transformation,
C – coefficient, s^{-1},
$f(a)$ – function of the substance transformation,
E_a – energy of activation, kJ mol^{-1},
t – conversion time of substance, s.

Thus, the author shows the possibility of the Arrhenius's equation using to determine the moisture removal rate from materials in the drying process.

SRIVARO *et al*. (2008) have considered the possibility of the Arrhenius's equation using for the process modelling of convection drying of sawn timber made of the rubber tree. Conventionally, the drying process was divided into two periods: when moisture was above and below the fibre saturation point. In the first period, moisture from the lumber is removed due to capillary pressure and diffusion, as it is indicated by the previous studies (SKAAR 1972, SIMPSON 1991), and in the second period, the drying process is mainly determined by diffusion. But despite significant differences between these periods, in both cases the authors propose to describe the process by the Arrhenius's equation (SRIVARO *et al.* 2008):

$$k' = k'_0 \exp(-\frac{E_a}{RT}) \tag{3}$$

where: k' – drying speed, % s^{-1},
k'_0 – constant, which has a dimension similar to the drying speed, % s^{-1}.

As a result of the research, the authors have obtained two different values of the activation energy for each of the processes, thereby confirming the possibility of using the Arrhenius's equation to determine the thermodynamic parameters of various stages of the wood drying process.

The main purpose of the work is to determine the wood thermodynamic characteristics at convection drying using the Arrhenius's equation.

MATERIAL AND METHODS

Material

Studies were conducted for pine (*Pinus sylvestris* L.), alder (*Alnus glutinosa* L.) and oak (*Quercus petraea*). Samples of equal size were selected from different parts of the trunk. They had the same initial moisture content, determined by the gravimetric method and were equal to 25 ± 1% and dimensions: length of 103 ± 2 mm, width of 84 ± 2 mm and a thickness of 28–30 mm.

To determine the relaxation time the samples were dried at fixed temperatures of 40; 60; 80 and 100 °C in thermoelectric laboratory drying oven 2V–151 with automatic temperature regulation with an accuracy of ± 1 °C. The investigated batch for every temperature and wood species consisted of 9 samples. After a certain interval, the samples weight was determined with accuracy of 0.01 g in the process of drying.

Methods

Since relaxation processes represent a sequence of elementary processes due to local fluctuations of thermal energy, the activation energy magnitude controls the probability of these processes occurrence (SHTILLIER 2000).

In experiments on the kinetics of various processes, their characteristics are measured: speed, frequency, duration, concentration depending on the temperature. It is common to represent them in the form of the Arrhenius's equation (SHTILLIER 2000):

$$\Phi_i(T) = A_i \exp(\pm E_a / kT) \tag{4}$$

where: $\Phi_i(T)$ – the defined characteristics of the process,
A_i – constant that have a dimension similar to the characteristics being determined.

When using a narrow temperature interval and, accordingly, a relatively small measuring range $\Phi_i(T)$, the dependence $\ln \Phi_i(1/T)$ is close to linear. This indicates the possibility of using equation (4) for the experimental results analysis, meanwhile, determines the activation energy on the slope $\ln \Phi_i (1/T)$.

The rate of moisture removal from the wood is specified by a moisture transfer, which can occur under the moisture gradients, temperature and pressure (KLEMENT and VILKOVSKA 2015, SOKOLOVSKYY *et al.* 2016). The pressure gradient has a negligible value at convection drying of sawn timber in convection chambers and, therefore, it is neglected. The liquid motion under the action of a moisture gradient is characterized by the moisture conductivity coefficient, but under the action of moisture and temperature gradients, it is characterized by the coefficients of moisture conductivity and thermal conductivity. These coefficients are known to depend on temperature. This dependence has an exponential character for the moisture conductivity coefficient. As for the coefficient of thermal conductivity, the data for its determination are very limited, although exponential temperature dependence can also be observed.

The kinetic curves for sawn timber drying at a point wall are known to be exponential (PINCHEVSKA *et al.* 2016). Changes in the material moisture content during the drying process are directly related to the reduction of its mass (Fig. 1), which makes it possible to represent the kinetics of wood drying by the following regularity:

$$m_{cur} = m_{in} e^{-\frac{t_{int}}{\tau_1}} \tag{5}$$

where: m_{cur} – mass of a wet sample during the drying process after a time interval t_{int}, g,

m_{in} – mass of the sample at the beginning of the drying process, g,

τ_1 – relaxation time of the moisture removal from the wood process, hour.

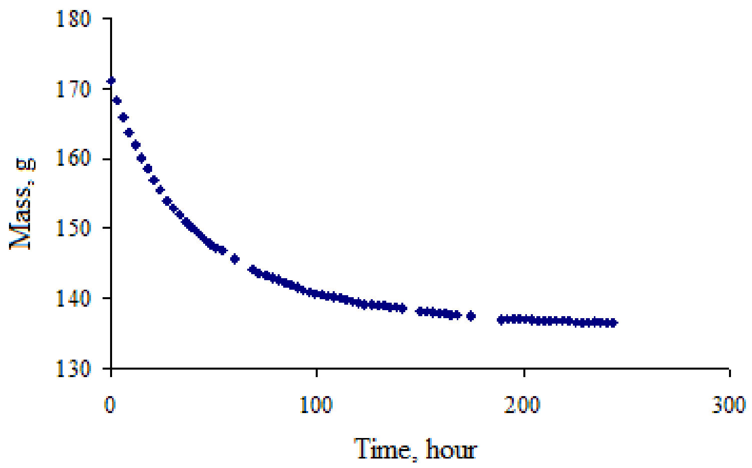

Fig. 1 The change curve in the mass of a pine wood sample when dried in a laboratory drying oven at a temperature of 40 °C.

If you build the graphical dependence $\ln(\frac{m_{in}}{m_{cur}})$ as a function of drying time at a fixed temperature, we get a certain piecewise-linear dependence, where the angular coefficients are proportional to the relaxation time. If necessary, their values at different drying times can be determined by the method of least squares.

Knowing τ_1, it is possible to determine the activation energy E_{a1} of water molecules in the studied wood sample:

$$\tau_1 = \tau_{0_1} e^{\frac{E_{a_1}}{kT}} \tag{6}$$

where: τ_0 – pre-exponential factor, which has a dimension similar to the relaxation time, hour,

k – the Boltzmann's constant, JK^{-1},

E_{a1} – activation energy, which characterizes the process of moisture removal from the wood during the drying process, J.

Knowing the activation energy values and pre-exponential factor we can calculate the relaxation time of water molecules for the drying at any temperature.

RESULTS AND DISCUSSION

Traditionally, the drying kinetics curves in the initial warm-up have the appearance of an exponent view. The drying process in this case has two periods: the first period is one of the constant drying rate, which corresponds to the removal of the free moisture main mass. The second one is a period of the falling process speed. The bound moisture and residuals are removed during it.

To simulate the convection drying processes, the most common is the heat and mass transfer theory by Lykov (1967), which is valid and gives reliable results for the second period of convection drying. Taking into account the features of the process in modern chambers the kinetics of convection drying is more fully represented in (PINCHEVSKA *et al.* 2016):

$$W_{cur}^{(n)} = \left(W_{cur}^{(n-1)} - W_{eq}^{n}\right)\left[D_1 e^{-K_1 t} - D_2 e^{-K_2 t}\right] + W_{eq}^{n} \tag{7}$$

where: n – mode stage index,

t – drying duration, hour,

$W_{cur}^{(n)}$ – average value of the current moisture at n - th mode stage, %,

$W_{cur}^{(n-1)}$ – values of the transfer moisture at the previous mode stage for the initial conditions: $W_{cur}^{(n-1)} = W_0$, %,

W_0 – initial moisture content of material, %,

$W_{eq}^{(n)}$ – equilibrium moisture at the n-th mode stage, %,

D_1, D_2 – coefficients depending on the material thickness, S ,mm,:

$$D_1 = 105{,}1 \times S^{-1} \tag{8}$$

K_1, K_2 – thermodynamic coefficients, $hour^{-1}$, characterizing the thermodynamic features of the convection drying process and can be determined through the relaxation time.

The coefficient K_1 directly characterizes the rate of moisture removal from the wood under the influence of temperature and can be determined by the formula:

$$K_1 = \frac{1}{\tau_1} \tag{9}$$

The second thermodynamic coefficient K_2 characterizes the power dependence of the "conditional" type of moisture source temperature. This source is manifested at the first stage of convection sawn timber drying with initial moisture that is above the fibre saturation point and characterizes the gradual heating of the material in the chamber with a gradual moisture removal. This is due to the availability of a temperature gradient directed towards a lower temperature – from the surface to the centre of the material. A negative temperature gradient prevents the wood moisture movement from the centre to the surface and its removal, resulting in a region with increased moisture content, which can be qualified as a "conditional" source of moisture. On the kinetic curve of convection drying, this stage is manifested by the presence of an additional section at the beginning of the process, which has the form of a convex exponent. A similar kind of curves for sawn timber kinetics drying is described by SHUBIN (1990). SAZHIN (1990), investigating the process of drying textile materials, pointed out that without the initial material heating at elevated temperatures, the kinetics curves have the $S-$ shaped form, that is, the form of a double exponent. This form is observed at relatively low coolant temperatures, when material heating occurs gradually with the simultaneous redistribution and moisture removal due to its gradient (SAZHIN 1984). This nature of the process suggests that, it can also be attributed to the relaxation processes. In this case the relaxation time will be determined by the equation:

$$\tau_2 = \tau_{0_2} e^{-\frac{E_{a2}}{kT}} \qquad (10)$$

where: τ_2 – relaxation time-power of the "conventional" moisture source, hour,

τ_{0_2} – pre-exponential factor – relaxation time-power of the "conventional" moisture source at temperature $T \to \infty$, hour,

E_{a2} – activation energy-power "conventional" moisture source, J.

The thermodynamic factor K_2 can be calculated by the equation:

$$K_2 = \frac{1}{\tau_2} \qquad (11)$$

When drying sawn timber from the initial moisture which is below the fibre saturation point, the kinetics curves have the form of a simple exponent without an additional section. In the mathematical description of such a process, only one thermodynamic coefficient will be used in equation (7) – K_1. Regarding that to calculate the coefficient K_1 you need to determine the activation energy of the process of moisture removal from the wood. Special experimental studies were carried out for drying samples of oak, alder and pine wood under laboratory conditions.

In the result of experimental studies there have been carried out the drying kinetics curves for each sample in the form of graphic dependences of the natural logarithm of the initial mass ratio m_{in} to the current mass m_{cur} as a time function. An example of a curve is shown in Fig. 2.

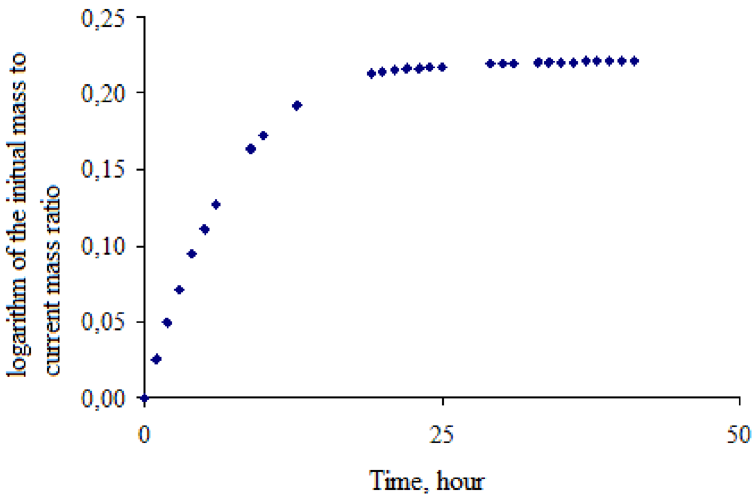

Fig. 2 The logarithmic kinetics curve of the sample initial mass to the current mass ratio in the process of drying a sample of a pine wood at a temperature of 100 °C.

The relaxation time value of the moisture removal from the wood process is obtained for each curve at the inflection point by the method of graphical differentiation. The averaged values of the relaxation time for every wood spices and temperature are shown in Tab. 1.

Tab. 1 Average relaxation time of moisture removal from the wood.

Average temperature T, °C	Relaxation time τ_1, hour		
	Oak	Pine	Alder
40	618	297	317
60	316	152	162
80	175	84	90
100	103	50	53

After that, the activation energy of the moisture removal from the wood process was found. For a narrow temperature range, that is typical for convection sawn timber drying, the dependence $ln\,\tau$ on *1/T* is close to linear. In this case, the activation energy is determined by the inclination angle of the straight line to the abscissa axis (Fig. 3).

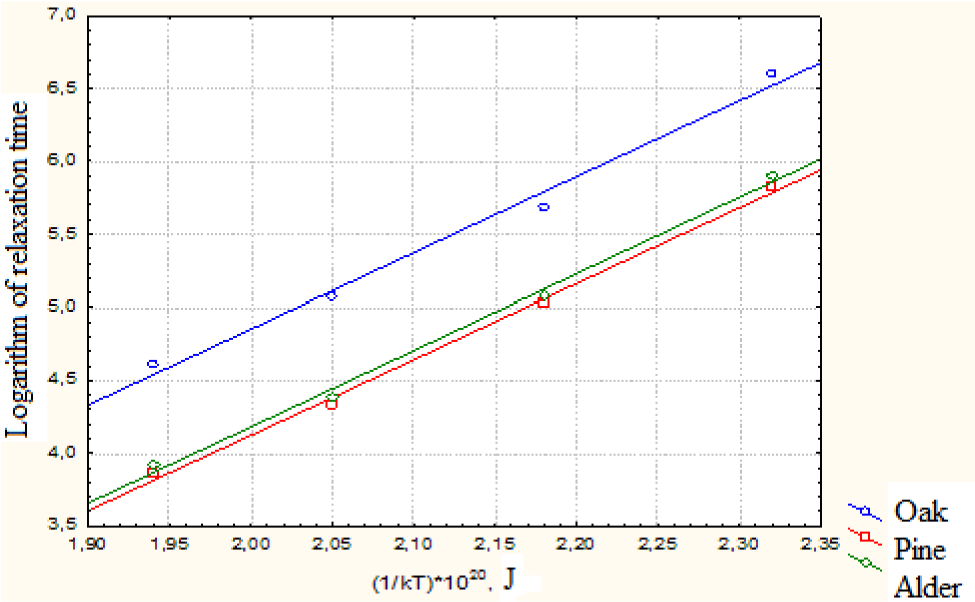

Fig. 3 The relaxation time logarithmic dependence on the inverse temperature.

Using the method of graphical differentiation, the activation energy of the moisture removal from the wood process for each wood species was obtained. The calculations have showed that the same energy is needed for moisture removal for all studied wood species: $E_{a_1} = 4{,}806 \times 10^{-20} J = 0{,}30 eV$.

The values of the pre-exponential factor τ_{0_1} for each species were determined by extrapolating the lines to the ordinate axis: for oak τ_{0_1} = 0,009026 hours, for pine τ_{0_1} = 0,004347 hours and for alder τ_{0_1} = 0,004627 hours. It can be seen that the values of the pre-exponential factor depend on the wood species, at what, they increase with increasing density, which may be associated with the peculiarities of the wood microstructure. Since the activation energy and the pre-exponential factor do not depend on the temperature, but are exclusively characteristics of the process, this makes it possible to calculate the relaxation times of moisture removal from the wood process and, consequently, determine the thermodynamic coefficient K_1 for the studied wood species at any temperature within the low temperature process.

The kinetics experimental studies of convection drying in industrial conditions for sawn timber from oak, alder and pine of a different thickness in modern chambers of foreign manufacture: "Nardi", "Copcal", "Termolegno", "Katres", "Luka-Alexis" have been carried out to determine the thermodynamic characteristics of the material initial heating.

As a result of the study, there have been obtained the values of the moisture changes during the drying process, on which the experimental curves of kinetics are constructed, as well as the values of the experimental mode parameters to construct calculated curves.

The drying kinetics curves have been calculated to analyse the power of the "conditional" moisture source, taking into account the only component of the thermodynamics process, which characterizes the bound moisture removal from the wood process. In this case, the thermodynamic coefficient characterizing the source of moisture will be zero $K_2 = 0$. Some calculations have been made at two temperatures: 50 °C and 80 °C to study the temperature dependence of the "conditional" moisture source. This allowed constructing a "conditional" moisture source profile. The obtained results have showed that the maximum power of the "conditional" moisture source increases with increasing temperature, and the time to reach this maximum remains constant for the investigated temperature range. The equations have been achieved for each tree spices and temperature describing the kinetics of a "conditional" moisture source that made it possible to determine the relaxation time of its power. After that, the activation energy values of the "conditional" moisture source E_{a2} and the pre-exponential factor τ_{0_2} have been determined. The calculation results are shown in Tab. 2.

Tab. 2 The values of the pre-exponential factor and the activation energy of the "conditional" moisture source at convection sawn timber drying of oak, alder and pine wood.

	Oak	**Pine**	**Alder**
τ_{0_2}, **hour**	4×10^{6}	3.4126×10^{4}	9.68×10^{11}
Ea_2, **J**	4.005×10^{-20}	2.083×10^{-20}	9.932×10^{-20}

Having the values of the pre-exponential factor and activation energy of the "conditional" moisture source, it is possible to calculate its relaxation time and, consequently, determine the thermodynamic coefficient K_2 for sawn timber drying in the temperature range from 50 °C to 80 °C.

CONCLUSIONS

The proposed approach to the description of the convection drying process and the results obtained to determine the activation energy, pre-exponential factors of the moisture removal from the wood process, kinetics of a "conditional" moisture source give the possibility to predict the values of the sawn timber current moisture from the wood of oak, alder and pine of the various thicknesses with convection drying.

Analysis of the results on determination of the thermodynamic characteristics of the bound moisture removal from the wood process has shown that the activation energy of this process does not depend on the wood species and has the same value for all investigated species. The pre-exponential factor is established to be the parameter characterizing the influence of the wood structure upon the moisture removal rate. The pre-exponential factor depends on the wood density, its value increases with increasing density. To determine the regularity between the pre-exponential factor and the wood density, it is necessary to carry out similar studies for other types of wood, it will allow us to predict the current moisture values for drying sawn timber of any species.

REFERENCES

ARAPOV V.M. 2001. Wet substances thermal separation processes calculation on the basis of chemical kinetics laws. News of universities. Food technology, 4: 72–76.
ARAPOV V.M. 2012. Information technology and mathematical modeling. Actual biotechnology, 4: 23–26.
DZURENDA L. 2016. Numeric model of the normative consumption of heat for the color homogenisation of wood in pressure autoclaves. Application of experimental and numerical methods in fluid mechanics and energy 2016: XX anniversary of international scientific conference V 1745, 7 pp.
DZURENDA L., DELIISKI N. 2012. Convective drying of beech lumber without color changes of wood. Drvna Industrija 63(2): 95–103.
HOSSEINABADI H.Z., DOOSTHOSEINI K., LAYEGHI M. 2012. Drying kinetics of poplar (*Populus Deltoides*) wood particles by a convective thin layer dryer. Drvna Industrija 63(3).
HUNTER A.J. 1992. On the activation energy of diffusion of water in wood. Wood Science and Technology, 26: 73–82.
KLEMENT I., VILKOVSKA T. 2015. The influence of drying characteristics and quality of spruce timber with content of reaction wood. Acta Facultatis Xylologiae Zvolen, 57(1): 75–82.
KLEMENT I., VILKOVSKA T. 2016. Determining the influence of sample thickness on the high-temperature drying of beech wood (*Fagus sylvatica* L.). Bioresources, 11(2): 5424–5434.
LYKOV A.V. 1967. The heat conduction theory. Moscow : Vysshaya Shkola, 599 pp.
MONKAM L., AYINA O.L.M., CHUGOUA N.A., MEKONGO A.F. 2013. Determination of the diffusion coefficient and the activation energy of water desorption in IROKO wood (*Chlorophora excelsa*), during a conductive drying. International Journal of Thermal Technologies, 3(3): 75–79.
PINCHEVSKA O., SPIROCHKIN A., SEDLIAČIK J., OLIYNYK R. 2016. Quality assessment of lumber after low temperature drying from the view of stochastic process characteristics. Wood Research, 61(6): 871–884.
SAZHYN B.S. 1984. Drying technique fundamentals. Chemistry, Moscow, Russia, 200 pp.
SAZHYN B.S., REUTSKYJ V.A. 1990. Drying and washing of textile materials: theory, processes calculation. Moscow, Russia, 224 pp.
SHI S.Q. 2007. Diffusion model based on Fick's second law for the moisture absorption process in wood fiber-based composites: is it suitable or not? Wood Sci Technol, 41: 645.
SHTILLIER V. 2000. Arrhenius equation and nonequilibrium kinetics, Moscow, Russia, 176 pp.
SHUBIN G.S. 1990. Wood drying and heat treatment. Forestry, Moscow, Russia, 336 pp.
Simpson W.T. 1991. Dry kiln operator's manual, Forest Products Laboratory Madison, Wisconsin. 274 pp.
SKAAR C. 1972. Water in wood. Syracuse : Syracuse University Press.
SOKOLOVSKYY YA., SHYMANSKYI V., LEVKOVYCH M. 2016. Mathematical modeling of non-isotermal moisture transfer and visco-elastic deformation in the materials with fractal structure. In: XI-th International scientific and technical conference: computer science and information technologies CSIT, Lviv, Ukraine: 91–95
SOKOLOVSKYY YA., SHYMANSKYI V., LEVKOVYCH M., YARKUN V. 2016. Mathematical modeling of heat and moisture transfer and reological behavior in materials with fractal structure using the parallelization of predictor-corrector numerical method. 1-st International Conference Data Stream Mining Processing DSMP, Lviv: 108–111
SOKOLOWSKYI YA., SHYMANSKYI V. 2014. Mathematical modelling of non-isothermal moisture transfer and rheological behavior in cappilary-porous materials with fractal structure during drying. Computer and Information Science. Canadian Center of Science and Education 7 (4): 111–122.

SRIVARO S., WONGPROT T., MATAN N., KYOKONG B. 2008. Accelerated conventional temperature drying of 30 mm thick rubberwood lumber. Songklanakarin Journal of Science and Technology, 30(4): 475–483.

ACKNOWLEDGEMENTS

This work was supported by the Ukrainian Ministry of Education and Science under Program No 2201040. "The research, scientific and technological development, works for the state target programs for public order, training of scientific personnel, financial support scientific infrastructure, scientific press, scientific objects, which are national treasures, support of the State Fund for Fundamental Research". The authors are grateful to Ministry of Education and Science of Ukrainian for financial support of this study.

This work was supported by the grant agency VEGA under the projects No. 1/0626/16 and 1/0010/17.

AUTHOR'S ADDRESS

Prof. Ing. Olena Pinchevska, DrSc.
Andriy Spirochkin
National University of Life and Environmental Sciences of Ukraine
Department of Wood Processing
vul. Geroiv Oborony 15
Kyiv 03041
Ukraine
OPinchewska@gmail.com
a.spirochkin@gmail.com

Rostislav Oliynyk, PhD.
Associate Professor of the Meteorology and Climatology Department
Kyiv National Taras Shevchenko University
Geography Faculty
Akademika Glushkova 2a
02000 Kyiv
Ukraine
rv_oliynyk@ukr.net

Prof. Ing. Ján Sedliačik, PhD.
Technical University in Zvolen
Department of Furniture and Wood Products
T.G. Masaryka 24
960 53 Zvolen
Slovakia
sedliacik@tuzvo.sk