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COMPUTATION OF THE CHANGE IN THERMAL CONDUCTIVITIES OF POPLAR LOGS DURING THEIR FREEZING

Nencho Deliiski, Natalia Tumbarkova
University of Forestry, Sofia, Bulgaria
e-mail: deliiski@netbg.com; nataliq_manolova@abv.bg

ABSTRACT

A mathematical description of the thermal conductivities λ of frozen and non-frozen wood has been introduced in an own non-linear mathematical model of the logs' freezing process. For the numerical solution of the model a software program has been prepared in the calculation environment of Visual Fortran Professional. With the help of the program, the 2D non-stationary distribution of the temperature and the change of λ in the longitudinal section of poplar logs with diameter of 240 mm and length of 480 mm during their 50 h freezing in a freezer at about –30 °C have been calculated. The change of λ in the radial and longitudinal directions of the wood on both surfaces and in the center of the subjected to freezing logs during the freezing process has been calculated, visualized and analyzed.

Key words: poplar logs, freezing, radial thermal conductivity, longitudinal thermal conductivity, Visual Fortran.

INTRODUCTION

It is known that the wood thermal conductivity λ characterizes the intensity of the heat distribution in the wood materials. Because of this, for the calculation of the freezing process in wood materials at given initial and boundary conditions, the knowledge of λ of non-frozen and frozen wood is needed.

From the view point of the theory of heat conduction, the moist wood represents a 3-component dispersion capillary porous material, which includes wood substance, water, and air. The thermal conductivity of each of the three components, as well as of the water and the ice, is different. The thermal conductivity of the water at $t = 0$ °C is equal to 0.551 $W \cdot m^{-1} \cdot K^{-1}$, and of the ice at the same temperature it is 1.047 $W \cdot m^{-1} \cdot K^{-1}$, i.e. almost twice as large and it increases to 2.780 $W \cdot m^{-1} \cdot K^{-1}$ at $t = -50$ °C (Chudinov 1968). That is why the moisture content u is one of the most important factors, which influences the wood thermal conductivity. The replacement of the air in the wood pores by water causes a significant increase in λ according to a complex dependency. The wood thermal conductivity increases if the water in the wood is in a frozen state and decreases after the melting of the ice in the wood (Videlov 2003).

According to the theory of wood thermal treatment, the impact of the temperature t on the thermal conductivity of the wood, which contains ice, is different in comparison to the wood, which does not contain ice. If t decreases, the thermal conductivity of the wood, which contains ice, increases (Kanter 1955, Chudinov 1968, Shteinhagen 1986, 1991, Trebula and Klement 2002). A reason for this on one hand is the decrease with decreasing of t of the quantity of non-frozen hygroscopically bounded water in the wood, which has a significantly smaller λ according to that of the ice, and on another hand – the increase of λ of the ice in the wood when t decreases. The increase of t in the wood, which does not contain ice, causes an increase of its λ (Kollmann 1951, Kanter 1955, Chudinov 1968, Požgaj et al. 1997).

The wood density, which indirectly reflects its porosity, also has a significant impact on λ. The change of the wood density causes the change of the partial participation of the separate components of the wood, for which the thermal conductivity is different. With the increase of the density, i.e. with the decrease of the porosity, λ increases (Vorreiter 1958, Chudinov 1968, 1968, Deliiski 2003, 2011, 2013b). Not only the porosity, but also the form, dimensions, and position of the pores influence λ. Since the dimensions of the pores are different for the separate anatomical directions of the wood, this causes anisotropy of λ.

Besides this the precise determination of the wood thermal conductivity needs to take into account the impact of the fiber saturation point of the wood u_{fsp}, which for the various wood species changes in a large range between 0.2 kg.kg^{-1} and 0.4 kg.kg^{-1} (Požgaj et al. 1997, Videlov 2003, Deliiski and Dzurenda 2010).

The aim of the present work is to study the change in the thermal conductivities in the radial and longitudinal directions of poplar logs with an initial temperature of about 20 $^{\mathrm{o}}$C and different moisture content u during their freezing in a freezer at about –30 $^{\mathrm{o}}$C.

MATHEMATICAL DESCRIPTION OF Λ DURING THE FREEZING OF LOGS

A mathematical description of the thermal conductivity λ of non-frozen and frozen wood has been suggested by the first co-author earlier (Deliiski 2013a) using the experimentally determined in the dissertations by Kanter (1955) and Chudinov (1966) data for its change as a function of t and u. This data for $\lambda(t,u)$ finds a wide use in both the European (Shubin 1990, Požgaj et al. 1997, Trebula and Klement 2002, Videlov 2003) and the American specialized literature (Steinhagen 1986, 1991, Khattaby and Steinhagen 1992, 1993, 1995) when calculating various processes of the wood thermal treatment. According to the suggested in Deliiski (2013a) mathematical description, the wood thermal conductivity during freezing of the logs can be calculated with the help of the following equations for $\lambda(T,u,\rho_{\mathrm{b}},u_{\mathrm{fsp}})$ above the hygroscopic range:

$$\lambda = \lambda_0 \cdot \gamma\left[1+\beta(T-273.15)\right] \ @ \ u > u_{\mathrm{fsp}}^{272.15} \ \& \ 213.15 \ \mathrm{K} \le T \le 423.15 \ \mathrm{K}, \quad \textbf{(1)}$$

$$\lambda_0 = K_{\mathrm{ad}} \cdot v[0.165+(1.39+3.8u)\cdot(3.3.10^{-7}\rho_{\mathrm{b}}^2+1.015.10^{-3}\rho_{\mathrm{b}})], \quad \textbf{(2)}$$

$$v = 0.1284-0.013u. \quad \textbf{(3)}$$

In Deliiski (2003, 2013b) and Deliiski and Dzurenda (2010) precise values of K_{ad} in eq. (2) for different wood species have been determined. For the discussed in this paper poplar wood the following values of K_{ad} have been determined: $K_{\mathrm{r}} = 1.48$ and $K_{\mathrm{p}} = 2.88$, i.e $K_{\mathrm{p}}/K_{\mathrm{r}} \approx 1.95$.

The coefficients γ and β in equation (1) are calculated using the following equations:

- For non-frozen wood when $u > u_{\mathrm{fsp}}^{272.15}$ and at the same time $272.15 \ \mathrm{K} < T \le 423.15 \ \mathrm{K}$:

$$\gamma = 1.0, \quad \textbf{(4)}$$

$$\beta = 3.65\left(\frac{579}{\rho_{\mathrm{b}}}-0.124\right)\cdot 10^{-3}. \quad \textbf{(5)}$$

• For frozen wood when $u > u_{\text{fsp}}^{272.15}$ and at the same time $213.15\ \text{K} \le T \le 272.15\ \text{K}$:

$$\gamma = 1 + 0.34[1.15(u - u_{\text{fsp}})], \quad \textbf{(6)}$$

$$\beta = 0.002(u - u_{\text{fsp}}) - 0.0038\left(\frac{579}{\rho_{\text{b}}} - 0.124\right), \quad \textbf{(7)}$$

where the fiber saturation point of the wood specie u_{fsp} is calculated according to the equation

$$u_{\text{fsp}} = u_{\text{fsp}}^{293.15} - 0.001(T - 293.15), \quad \textbf{(8)}$$

and $u_{\text{fsp}}^{272.15}$ is the fiber saturation point at T = 272.15 K (i.e. at t = –1 °C). At this temperature the freezing of the bound water in the wood starts, kg·kg^{-1} (Deliiski and Tumbarkova 2016);

$u_{\text{fsp}}^{293.15}$ – standardized value of u_{fsp} at T = 293.15 K (i.e. at t = 20 °C), kg·kg^{-1};

ρ_{b} – basic density of the wood specie equal to dry mass divided by green volume, kg·m^{-3}.

EXPERIMENTAL RESEARCH OF THE FREEZING PROCESS OF POPLAR LOGS

The logs subjected to experimental research were with a diameter D = 240 mm, length L = 480 mm, and moisture content above the hygroscopic range. They were produced from the sap-wood of freshly felled poplar trunk (*Populus nigra* L.). Before the experiments, 4 holes with diameters of 6 mm and different lengths were drilled in each log. Sensors with long metal casing were positioned in these 4 holes for the measurement of the wood temperature during the experiments. One of the sensors was positioned in the center of the logs.

The coordinates of the points of the logs are, as follows: Point 1: along the radius r =30 mm and along the length z =120 mm; Point 2: with r = 60 mm and z =120 mm; Point 3: with r =90 mm and z = 180 mm, and Point 4: with r = 120 mm and z = 240 mm. These coordinates of the points allow to cover the impact of the heat fluxes simultaneously in radial and longitudinal directions on the temperature distribution in logs during their freezing. For the freezing of the logs according to the suggested by the authors methodology (Deliiski and Tumbarkova 2016), a horizontal freezer was used with adjustable temperature range from –1 °C to –30 °C.

The automatic measurement and record of the temperature and humidity of the air processing medium in the freezer and also of the temperature in the 4 points in logs during the experiments was carried out with the help of Data Logger type HygroLog NT3 produced by the Swiss firm ROTRONIC AG (http:/www.rotronic.com).

On Fig. 1 the change in the temperature of the processing air medium, t_{m} and in its humidity, φ_{m}, and also in the temperature in 4 characteristic points of poplar log named below as P1 with u =1.44 kg·kg^{-1} and ρ_{b} = 359 kg·m^{-3} (left) and poplar log named as P2 with u = 1.78 kg·kg^{-1} and ρ_{b} = 364 kg·m^{-3} (right) during their separate 50 h freezing is presented.

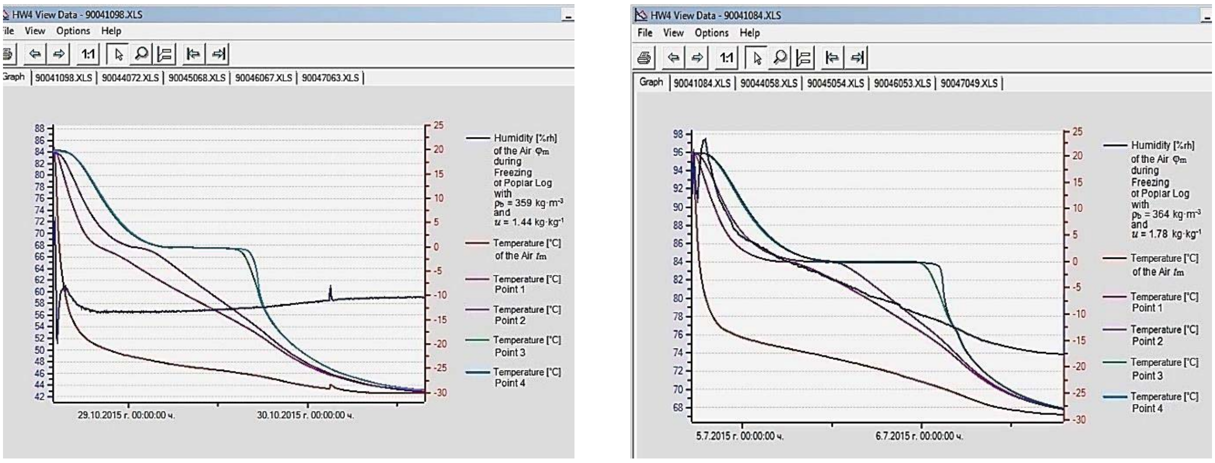

Figure 1: Experimentally determined change in t_m, φ_m, and t in 4 points of the studied poplar logs P1 (left) and P2 (right) with D = 0.24 m and L = 0.48 m during their 50 h freezing

RESULTS AND DISCUSSION

The above presented mathematical descriptions of the thermal conductivity of non-frozen and frozen wood is introduced in the mathematical model of the logs' freezing process, which has been suggested by us earlier (Tumbarkova and Deliiski 2017). This model has been solved with the help of explicit schemes of the finite difference method in a way, analogous to the one used and described in (Deliiski 2003, 2009, 2011, 2013b, Deliiski and Dzurenda 2010) for the solution of models of the heating process of prismatic and cylindrical wood materials.

For the numerical solution of our mathematical model, a software program was prepared in FORTRAN in the calculation environment of Visual Fortran Professional. With the help of the program computations were made for the determination of the 2D non-stationary change of t in ¼ of the longitudinal section of the poplar logs, whose experimentally determined temperature distribution is shown on Fig. 1. The model was solved using a step of 6 mm along the coordinates r and z and with the same initial and boundary conditions, as they were during the experimental research.

The comparison to each other of the analogous curves on Fig. 1 and these from the model solutions show good qualitative and quantitative conformity between the calculated and experimentally determined changes in the very complicated temperature field of the logs during their freezing. It was calculated that the root square mean error (*RSME)* for all studied 4 points in the log P1 is σ_{avg} = 1.73 °C and in the log P2 is σ_{avg} = 2.14 °C. These values of *RSME* do not exceed 5% of the ranges between the initial and the end temperatures of the logs subjected to freezing.

Simultaneously with the computation of the temperature distribution in the logs, a calculation of the change in the radial λ_r and longitudinal λ_p temperature conductivities in the following points during the freezing has been carried out: a. in the central points of the cylindrical and the frontal surfaces of the logs, λ_{rsc} and λ_{psc}; b. in the central points of the logs, λ_{rc} and λ_{pc}.

Figure 2 presents the calculated change of all these thermal conductivities during the freezing.

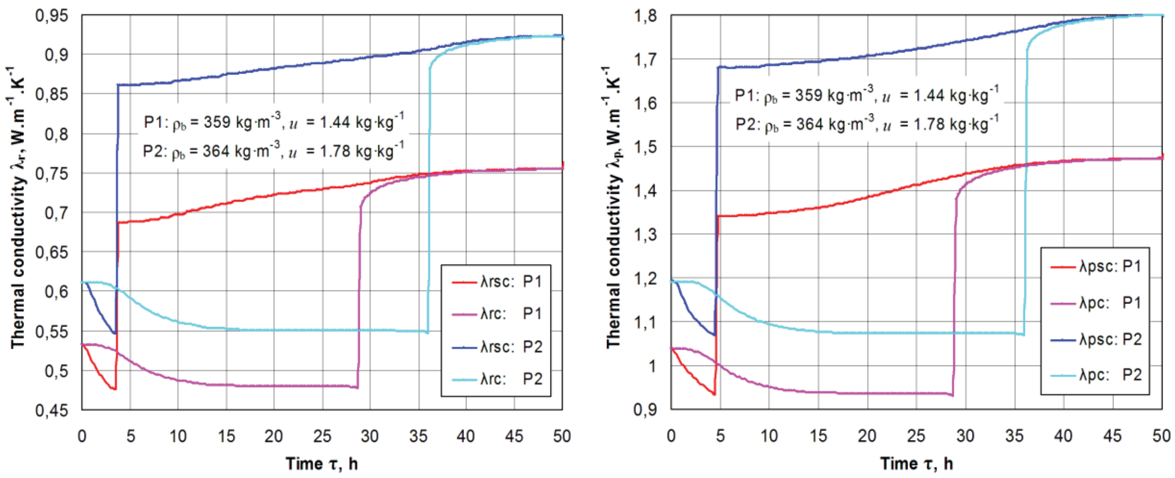

Figure 2: Change in λ_r (left) and λ_p (right) of the surfaces and in the centers of the logs P1 and P2 during their 50 h freezing in the freezer at approximately –30 ºC

The analysis of the obtained results leads to the following conclusions:

1. In the beginning of the freezing process the logs P1 and P2 have an initial temperature of 19.8 ºC and of 20.5 ºC respectively. At these temperatures the whole amount of the water in the logs is in a liquid state and their thermal conductivities are equal to the following:

- for P1: $\lambda_{rsc} = \lambda_{rc} = 0.532$ W·m^{-1}·K^{-1} and $\lambda_{psc} = \lambda_{pc} = 1.037$ W·m^{-1}· K^{-1};
- for P2: $\lambda_{rsc} = \lambda_{rc} = 0.611$ W·m^{-1}·K^{-1} and $\lambda_{psc} = \lambda_{pc} = 1.192$ W·m^{-1}·K^{-1}.

2. During the first 3.50 h and 4.50 h of the cooling of the logs the water on their cylindrical and frontal surfaces respectively remains in a liquid state. This causes a decrease of the conductivities λ_{rsc} and λ_{psc} which reach the following values: $\lambda_{rsc} = 0.477$ W·m^{-1}·K^{-1}, $\lambda_{psc} = 0.933$ W·m^{-1}·K^{-1} for P1 and $\lambda_{rsc} = 0.548$ W·m^{-1}·K^{-1}, $\lambda_{psc} = 1.069$ W·m^{-1}·K^{-1} for P2.

The difference between 3.50 h and 4.50 h is caused by the larger heat transfer coefficient of the cylindrical log's surface in comparison with that one of the frontal surface.

3. When the mentioned 3.50 h and 4.50 h of the cooling of the logs are reached, a freezing of the free water in their surface layers is fully completed and a freezing of the bound water there starts. This causes jumps in the change of λ_{rsc} and λ_{psc} as follows:

- for P1: from $\lambda_{rsc} = 0.477$ to 0.687 W·m^{-1}·K^{-1} and from $\lambda_{psc} = 0.933$ to 1.340 W·m^{-1}·K^{-1};
- for P2: from $\lambda_{rsc} = 0.548$ to 0.861 W·m^{-1}·K^{-1} and from $\lambda_{psc} = 1.069$ to 1.679 W·m^{-1}·K^{-1}.

4. The further decreasing of the temperature in the freezer causes a gradual freezing of the bound water in the logs. Because of that, after their jumps, the conductivities λ_{rsc} and λ_{psc} increase slowly and at the end of 50 h freezing reach the following values: for P1: $\lambda_{rsc} = 0.755$ W·m^{-1}·K^{-1}, $\lambda_{psc} = 1.473$ W·m^{-1}·K^{-1}; for P2: $\lambda_{rsc} = 0.924$ W·m^{-1}·K^{-1}, $\lambda_{psc} = 1.801$ W·m^{-1}·K^{-1}. Then the calculated temperatures on the logs' surfaces are equal to –29.66 ºC for P1 and –28.07 ºC for P2.

5. During the first 28.75 h for P1 and 36.00 h for P2 of the cooling of the logs the water on their centers remains in a liquid state and this causes gradual decrease of the conductivities λ_{rc} and λ_{pc} until reaching of the following values: $\lambda_{rc} = 0.477$ W·m^{-1}·K^{-1}, $\lambda_{pc} = 0.933$ W·m^{-1}·K^{-1} for P1 and λ_{rc} =

0.548 $W \cdot m^{-1} \cdot K^{-1}$, λ_{pc} = 1.069 $W \cdot m^{-1} \cdot K^{-1}$ for P2.

6. When the mentioned 28.75 h and 36.00 h of the cooling of the logs are reached, a freezing the free water in their centers is fully completed and a freezing of the bound water there starts. This causes jumps in the change of λ_{rc} and λ_{pc} as follows:

- for P1: from λ_{rc} = 0.477 to 0.706 $W \cdot m^{-1} \cdot K^{-1}$ and from λ_{pc} = 0.933 to 1.378 $W \cdot m^{-1} \cdot K^{-1}$;
- for P2: from λ_{rc} = 0.548 to 0.882 $W \cdot m^{-1} \cdot K^{-1}$ and from λ_{pc} = 1.069 to 1.720 $W \cdot m^{-1} \cdot K^{-1}$.

7. The further decreasing of the temperature in the freezer causes a gradual freezing of the bound water in the logs' centers. Because of that, after the jumps, the conductivities λ_{rc} and λ_{pc} increase slowly and at the end of 50 freezing reach the following values: for P1: λ_{rc} = 0.755 $W \cdot m^{-1} \cdot K^{-1}$, λ_{pc} = 1.472 $W \cdot m^{-1} \cdot K^{-1}$; for P2: λ_{rc} = 0.923 $W \cdot m^{-1} \cdot K^{-1}$, λ_{pc}=1.800 $W \cdot m^{-1} \cdot K^{-1}$. Then the temperatures in the logs' centers are equal to –29.57 °C for P1 and –27.84 °C for P2.

Our comprehensive experimental research showed that the jump in the thermal conductivities in separate points of logs occurs at –1 °C when the freezing of the free water in the wood is completed and the freezing of the bound water starts (Deliiski and Tumbarkova 2016).

CONCLUSIONS

The present paper describes the applying of the suggested by the first co-author earlier mathematical description of the wood thermal conductivities of non-frozen and frozen wood for computation by an own non-linear 2D model of the temperature distribution in subjected to freezing logs. The description takes into account to a maximum degree the physics of the processes of freezing of both the free and the bound water in the wood. It reflects the influence of the temperature, wood moisture content, wood density, and fiber saturation point of each wood specie on the thermal conductivities in logs' radial and longitudinal directions during freezing and also the influence of the temperature on the fiber saturation point.

For the solution of the mathematical model of the logs' freezing process and computation of the logs' temperature conductivities according to the applied mathematical description a software program has been prepared in FORTRAN, which has been input in the calculation environment of Visual Fortran Professional developed by Microsoft.

With the help of the program computations have been carried out for determination of the radial and longitudinal thermal conductivities on the frontal and cylindrical surfaces and also in the centers of two poplar logs during their 50 h freezing in a freezer at about –30 °C. The logs have a diameter of 0.24 m, length of 0.48 m, initial temperatures of 19.8 °C and 20.5 °C, basic densities of 359 $kg \cdot m^{-3}$ and 364 $kg \cdot m^{-3}$, and moisture contents of 1.44 $kg \cdot kg^{-1}$ and 1.78 $kg \cdot kg^{-1}$. It was determined, that the longitudinal thermal conductivities of poplar logs are about 1.95 times larger than their radial thermal conductivities.

The obtained computed results show that a decrease in t at a given value for u leads to a decrease in λ for wood, which does not contain ice and to an increase in λ for wood containing ice as a consequence of the increase in the ice quantity with decreasing of t. The results show also that at a given value of t an increase in u for non-frozen wood and for wood containing ice, formed in it from the freezing of both the free and bound water, causes a non-linear increase in λ. When the decreasing temperature in subjected to cooling logs reaches –1 °C, a jump take place in λ. This jump is explained by the phase transition into ice of the whole amount of free water in the logs at –1 ºC during their freezing. Our wide experimental research proved this fact (Deliiski and Tumbarkova 2016). The validated high precision of the mathematical description of λ and the other thermo-physical characteristics of wood and also of our models of non-stationary freezing and defrosting processes of wood materials make them user friendly for contemporary systems for model-based automatic control (Hadjiski and Deliiski 2015, 2016) of different processes of thermal and hydrothermal treatment.

REFERENCES

CHUDINOV, B. S. 1968. Theory of thermal treatment of wood. Publishing Company "Nauka", Moscow, USSR (in Russian).

DELIISKI, N. 2003. Modelling and technologies for steaming wood materials in autoclaves. Dissertation for Dr.Sc., University of Forestry, Sofia (in Bulgarian).

DELIISKI, N. 2009. Computation of the 2-dimensional transient temperature distribution and heat energy consumption of frozen and non-frozen logs. Wood Research 54(3): 67−78.

DELIISKI, N. 2011. Transient heat conduction in capillary porous bodies. In: Convection and Conduction Heat Transfer. In Tech Publishing House, Rieka, 149−176 p. http://dx.doi.org/10.5772/21424.

DELIISKI, N. 2013a. Computation of the Wood Thermal Conductivity during Defrosting of the Wood. Wood research, 58 (4): 637−650.

DELIISKI, N. 2013b. Modelling of the Energy Needed for Heating of Capillary Porous Bodies in Frozen and Non-frozen States. Lambert Academic Publishing, Scholars' Press, Saarbrücken, Germany, 116 p. http://www. scholars-press.com//system/covergenerator/ build/1060.

DELIISKI, N., DZURENDA, L. 2010. Modelling of the thermal processes in the technologies for wood thermal treatment. TU Zvolen, Slovakia, 224 p. (in Russian).

DELIISKI, N., TUMBARKOVA, N. 2016. A Methodology for Experimental Research of the Freezing Process of Logs. Acta Silvatica et Lignaria Hungarica, Vol. 12, № 2: 145−156, DOI: 10.1515/aslh-2016-0013, http://www. journals4free.com.

HADJISKI, M., DELIISKI, N. 2015. Cost Oriented Suboptimal Control of the Thermal Treatment of Wood Materials. IFAC-PapersOnLine 48−24 (2015): 54−59, www.sciencedirect.com.

HADJISKI, M., DELIISKI, N. 2016. Advanced Control of the Wood Thermal Treatment Processing. Cybernetics and Information Technologies, Bulgarian Academy of Sciences, 16 (2): 179−197.

KANTER, K. R. 1955. Investigation of the thermal properties of wood. Dissertation, MLTI, Moscow, USSR (in Russian).

KHATTABI, A., STEINHAGEN, H. P. 1992. Numerical solution to two-dimensional heating of logs. Holz als Roh- und Werkstoff, 50, 308−312. http://dx.doi.org/ 10.1007/BF02615359.

KHATTABI, A., STEINHAGEN, H. P. 1993. Analysis of transient nonlinear heat conduction in wood using finite-difference solutions. Holz als Roh- und Werkstoff, 51, 272−278. http://dx.doi.org/10.1007/BF02629373.

KHATTABI, A., STEINHAGEN, H. P. 1995. Update of "Numerical solution to two-dimensional heating of logs". Holz als Roh- und Werkstoff, 53, 93−94, http://dx.doi.org/10.1007/ BF02716399.

KOLLMANN, F. 1951. Technologie des Holzes and Holzwerkstoffe. I. Bd., 2 Auflage, Springer, Berlin/Göttingen, Heidelberg, 2233 p.

POŽGAJ, A., CHOVANEC, D., KURJATKO, S., BABIAK, M. 1997. Structure and Properties of Wood. 2nd edition, Priroda a.s., Bratislava, 485 p. (in Slovak).

SHUBIN, G. S. 1990. Drying and Thermal Treatment of Wood. Lesnaya Promyshlennost, Moscow, URSS, 337 p. (in Russian).

STEINHAGEN, H. P. 1986. Computerized Finite-difference Method to Calculate Transient Heat Conduction with Thawing. Wood Fiber Science, 18(3): 460−467.

STEINHAGEN, H. P. 1991. Heat Transfer Computation for a Long, Frozen Log Heated in Agitated Water or Steam – A Practical Recipe. Holz als Roh- und Werkstoff, 49(7−8): 287−290. http://dx.doi.org/10.1007/BF02663790

TREBULA, P., KLEMENT., I. 2002. Drying and hydrothermal treatment of wood. Technical University in Zvolen, Slovakia, 449 p. (in Slovak).

TUMBARKOVA, N., DELIISKI, N. 2017. Applying of the software package Table Curve 2D for computation of processing air medium temperature during freezing in a freezer and defrosting of logs.

Innovations in woodworking industry and engeneering design. Volume VI, № 1: 69−76.
VIDELOV, H. 2003. Drying and thermal treatment of wood, University of Forestry, Sofia, 335 p. (in Bulgarian).
VORREITER, L. 1949. Holztechnologisches Handbuch, Fromm, Vien, 2080 p.

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