

Computation of Temperature Conductivity of Frozen Wood during its Defrosting

Računanje toplinske vodljivosti smrznutog drva tijekom postupka odmrzavanja

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ABSTRACT • An approach for the computation of the temperature conductivity of frozen wood during its defrosting has been suggested. The approach takes into account the physics of the processes of melting of both the frozen bound and free water in the wood in respective temperature ranges. It reflects for the first time also the influence of the fiber saturation point and of the volume shrinkage of each wood species on its temperature conductivity coefficient in frozen state.

In the present paper, the suggested approach for the computation of the temperature conductivity of poplar, spruce, beech, oak, walnut and acacia in the temperature range between $-60\text{ }^{\circ}\text{C}$ and $-1\text{ }^{\circ}\text{C}$ is used. It is determined that the temperature conductivity of wood, during melting of frozen bound water in it, is up to some tens of times larger than the temperature conductivity of wood during melting of frozen free water in it.

The obtained results can be used both for technological and other engineering calculations and analysis of processes of thermal and hydrothermal treatment of wood materials, as well as in software of systems for model based automatic control of such treatment.

Key words: temperature conductivity, frozen wood, frozen bound water, frozen free water, computation

SAŽETAK • U radu se daje preporuka za izračunavanje toplinske vodljivosti smrznutog drva tijekom procesa odmrzavanja. U pristupu se uzima u obzir fizika procesa topljenja smrznute vezane i slobodne vode u drvu u odgovarajućim temperaturnim rasponima. Predloženim se pristupom po prvi put uzima u obzir utjecaj točke zasićenosti vlaknaca i volumnog utezanja svake vrste drva na njezin koeficijent vodljivosti topline u smrznutom stanju.

U radu se predlaže pristup za izračunavanje toplinske vodljivosti drva topole, smreke, bukve, hrasta, oraha i bagrema u temperaturnom rasponu između $-60\text{ }^{\circ}\text{C}$ i $-1\text{ }^{\circ}\text{C}$. Utvrđeno je da je toplinska vodljivost drva tijekom topljenja smrznute vezane vode u drvu do nekoliko desetaka puta veća od toplinske vodljivosti drva tijekom topljenja smrznute slobodne vode u njemu.

Dobiveni se rezultati mogu upotrijebiti za tehnološke i druge inženjerske proračune i analize procesa toplinske i hidrotermičke obrade drvnog materijala, kao i pri izradi softvera za sustave automatskog upravljanja tim procesima.

Ključne riječi: toplinska vodljivost, smrznuto drvo, smrznuta vezana voda, smrznuta slobodna voda, proračun

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1 INTRODUCTION

1. UVOD

For the technological and other engineering calculations of processes of thermal and hydrothermal treatment of wood materials, the wood temperature conductivity coefficient a is often used. It is known that it represents the relationship of the thermal conductivity coefficient λ to the multiplication of the specific heat capacity c and density ρ of the material. During calculations of heating or cooling of non-frozen wood, its temperature conductivity coefficient can be determined according to that relationship using the values of c , λ , and ρ of the wood for specific temperature and moisture content.

During the calculation of the freezing or defrosting processes of wood, however, it is necessary to take into account the impact both of the specific heat capacity of the wood itself, and of the heat of the phase transition of water in the wood from its liquid to hard aggregate condition and vice versa upon the wood temperature conductivity coefficient.

The heat of the water phase transition in the wood can be represented by the specific heat capacity of the frozen hygroscopically bound (c_{bw}) and the frozen free (c_{fw}) water in the wood. As a result of in-depth dissertation studies, Chudinov (1966) discovers that the melting of the frozen free water in the wood takes place at temperatures in the range between -2 °C and -1 °C. The author also discovers that the melting of the frozen hygroscopically bound water in the wood ends at -2 °C, and besides this, the quantity of this frozen water increases with the decrease in temperature, but even during extremely small climatic temperatures on earth, a definite part of it, u_{nfw} , remains in a non-frozen state.

Subsequently for the determination of a during the calculation of the wood defrosting processes, it makes sense to use the so called effective specific wood capacity c_e , which in the range -2 °C $< t \leq -1$ °C is equal to the sum of c and (c_{fw}), and when $t \leq -2$ °C and simultaneously $u_{nfw} < u \leq u_{fsp}$, then $c_e = c + c_{bw}$ (Chudinov, 1966; Deliiski, 2003b).

For a precise determination of the wood temperature conductivity coefficient, it is also necessary 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 (Perelygin, 1965; Nikolov and Videlov, 1987; Chudinov, 1966, 1968; Reginač *et al.*, 1990; Shubin, 1990; Požgaj *et al.*, 1997; Trebula and Klement, 2002; Pervan, 2009; Kurjatko *et al.*, 2010; Videlov, 2003; Deliiski, 2003b; Dzurenda and Deliiski, 2010).

The aim of the present work is to suggest an approach for the computation of the temperature conductivity of the wood during defrosting of the ice, which is created by both the hygroscopically bound and free water in the wood, using the mathematical descriptions of thermo-physical characteristics of frozen wood, made earlier by one of the authors.

2 MATERIAL AND METHODS

2. MATERIJAL I METODE

2.1 Computation of a at temperatures $T \leq 271.15$ K and wood moisture content $u \geq 0$ kg·kg⁻¹

2.1. Izračun koeficijenta toplinske vodljivosti pri temperaturi $T \leq 271.15$ K i sadržaju vode $u \geq 0$ kg·kg⁻¹

As described in the introduction, during the calculations of the wood defrosting processes at $T \leq 271.15$ K (i.e. at $t \leq -2$ °C) and $u_{fsp} \geq u > u_{nfw}$, the wood temperature conductivity must be determined according to the following equation (Deliiski, 2003b):

$$a(T, u, u_{fsp}) = \frac{\lambda(T, u, u_{fsp})}{[c(T, u, u_{fsp}) + c_{bw}(T, u, u_{fsp})] \cdot \rho(\rho_b, T, u, u_{fsp}, S_v)} \quad (1)$$

where a is temperature conductivity of the wood with frozen bound water in it (m²·s⁻¹), λ is thermal conductivity of the wood (W·m⁻¹·K⁻¹), c is specific heat capacity of the wood itself (J·kg⁻¹·K⁻¹), c_{bw} is specific heat capacity of the frozen bound water in the wood, (J·kg⁻¹·K⁻¹), ρ is wood density (kg·m⁻³), ρ_b is basic wood density equal to dry mass divided to green volume (kg·m⁻³), S_v is volume shrinkage of the wood (%), u is wood moisture content (kg·kg⁻¹), u_{fsp} is wood moisture content at fibre saturation point (kg·kg⁻¹), T is temperature (K).

The thermal conductivity λ and the own specific heat capacity c of the frozen wood during its defrosting is described mathematically using the data experimentally determined in the dissertations of Kanter (1955) and Chudinov (1966) for its change as a function of t and u . The same experimental data for λ and c , obtained by Kanter and Chudinov, are widely used in both the European literature (Sergovski, 1975; Shubin, 1990; Trebula, 1996; Trebula and Klement, 2002; Videlov, 2003) and the American specialized literature (Steinhagen, 1986, 1991; Khatabbi and Shteinhagen, 1992, 1993, 1995), when calculating various processes of thermal treatment of wood.

In the description of a apart from t and u , the independent parameter u_{fsp} has been input, which is different for the separate wood species and reflects the influence of the anatomic characteristics of the wood on λ and c_e (Deliiski 2003b; Deliiski and Dzurenda, 2010). The mathematical description of the wood density ρ , depending on the moisture content u , u_{fsp} , the basic density, ρ_b , and (only in the hygroscopic range) the volume shrinkage, S_v , which influence it, has been carried out using the experimental values set by (Sergovski, 1975) and shown in (Deliiski, 1977, 2003b, 2011).

The wood thermal conductivity λ in equation (1) can be calculated with the help of the equations (Deliiski, 1994, 2003b, 2013c):

$$\lambda = \lambda_0 \cdot \gamma \cdot [1 + \beta \cdot (T - 273.15)] \quad (2)$$

where

$$\lambda_0 = K_{ad} \cdot \nu \cdot [0.165 + (1.39 + 3.8 \cdot u) \cdot (3.3 \cdot 10^{-7} \cdot \rho_b^2 + 1.015 \cdot 10^{-3} \cdot \rho_b)] \quad (3)$$

$$v = 0.15 - 0.07 \cdot u \text{ @ } u \leq u_{fsp} + 0.1 \text{ kg} \cdot \text{kg}^{-1} \quad (4)$$

$$v = 0.1284 - 0.013 \cdot u \text{ @ } u > u_{fsp} + 0.1 \text{ kg} \cdot \text{kg}^{-1} \quad (5)$$

The equations, which have been suggested by Chudinov (1966, 1968) and shown in (Deliiski, 1977) can be used for the determination of the values of the coefficient K_{ad} in equation (3), which takes into account the influence on λ_0 of the heat flux towards the separate anatomic directions of the wood. Deliiski (2003b) determined more precise values of K_{ad} for ten wood species. For wood species discussed below in this paper, the following values of K_{ad} cross sectional to the fibers (i.e. of $K_{ad} = K_c$) have been determined: $K_c = 1.13$ for oak, $K_c = 1.15$ for acacia, $K_c = 1.24$ for walnut, $K_c = 1.28$ for beech, $K_c = 1.33$ for spruce, $K_c = 1.42$ for poplar wood.

The coefficients γ and β in equation (2) are calculated by the following equations:

- For non-frozen wood, i.e. when $T_{dfr} < T \leq 423.15 \text{ K}$ and simultaneously with this $u > u_{nfw}$ or when $u \leq u_{nfw}$ and simultaneously with this $213.15 \text{ K} \leq T \leq 423.15 \text{ K}$:

$$\gamma = 1.0 \quad (6)$$

$$\beta = (2.05 + 4 \cdot u) \cdot \left(\frac{579}{\rho_y} - 0.124 \right) \cdot 10^{-3} \quad (7)$$

$$\text{@ } u \leq u_{fsp} + 0.1 \text{ kg} \cdot \text{kg}^{-1}$$

$$\beta = 3.65 \cdot \left(\frac{579}{\rho_y} - 0.124 \right) \cdot 10^{-3} \quad (8)$$

$$\text{@ } u > u_{fsp} + 0.1 \text{ kg} \cdot \text{kg}^{-1}$$

$$u_{fsp} = u_{fsp}^{293.15} - 0.001 \cdot (T - 293.15) \quad (9)$$

- For frozen wood, i.e. when $213.15 \text{ K} \leq T \leq T_{dfr}$ and simultaneously with this $u > u_{nfw}$:

$$\gamma = 1 + 0.34 \cdot [1.15 \cdot (u - u_{fsp})] \quad (10)$$

$$\beta = 0.002 \cdot (u - u_{fsp}) - 0.0038 \cdot \left(\frac{579}{\rho_b} - 0.124 \right) \quad (11)$$

$$u_{nfw} = 0.12 + (u_{fsp} - 0.12) \exp[0.0567 \cdot (T - 271.15)]$$

$$\text{@ } 213.15 \text{ K} \leq T \leq 271.15 \text{ K} \quad (12)$$

$$T_{dfr} = 271.15 + \frac{\ln \frac{u_{nfw} - 0.12}{u_{fsp} - 0.12}}{0.0567} \quad (13)$$

$$\text{@ } 0.12 \text{ kg} \cdot \text{kg}^{-1} \leq u = u_{nfw} \leq u_{fsp}^{271.15}$$

$$T_{dfr} = 271.15 \text{ @ } u > u_{fsp}^{271.15} \quad (14)$$

$$u_{fsp} = u_{fsp}^{293.15} - 0.001 \cdot (T_{dfr} - 293.15) \text{ @ } T \leq T_{dfr} \quad (15)$$

In equations (12) and (13) u_{nfw} is the amount of the non-frozen bound water in the wood (in $\text{kg} \cdot \text{kg}^{-1}$) at given temperature $T \leq 271.15 \text{ K}$ and in equations (13), (14), and (15) T_{dfr} is the temperature (in K), at which the melting of the frozen bound water in wood with given u is completed. In equations (9) and (15) $u_{fsp}^{293.15}$ is the fiber saturation point of the wood at $T = 293.15 \text{ K}$, i.e. at $t = 20 \text{ }^\circ\text{C}$, and in equations (13) and (14) $u_{fsp}^{271.15}$ is the fiber saturation point of the wood at $T = 271.15 \text{ K}$, i.e. at $t = -2 \text{ }^\circ\text{C}$ (Stamm, 1964; Deliiski 2013b, 2013c).

The values for basic wood density ρ_b and for moisture content at fibre saturation point at $T = 293.15 \text{ K}$ of wood species discussed below in this paper are shown in Table 1.

The specific heat capacity of the frozen wood itself c in equation (1) can be calculated with the help of the following equations (Deliiski 1990, 2011; Deliiski and Dzurenda, 2010):

$$c = K_c \cdot \frac{526 + 2.95 \cdot T + 0.0022 \cdot T^2 + 2261 \cdot u + 1976 \cdot u_{nfw}}{1 + u} \quad (16)$$

$$K_c = 1.06 + 0.04 \cdot u + \frac{0,00075 \cdot (T - 271.15)}{u_{nfw}} \quad (17)$$

where u_{nfw} is determined according to equation (12).

For the calculation of the specific heat capacity of the frozen bound water in the wood, c_{bw} , the following equation (Deliiski, 2003b, 2004, 2011) has been obtained:

$$c_{bw} = 1.8938 \cdot 10^4 \cdot (u_{fsp} - 0.12) \frac{\exp[0.0567 \cdot (T - 271.15)]}{1 + u}$$

$$\text{@ } u_{fsp} \geq u > u_{nfw} \quad (18)$$

Table 1 Basic density, wood moisture content at fibre saturation point at 20 °C, and volume shrinkage of some wood species (acc. to Perelygin, 1965; Nikolov and Videlov, 1987; Reginač *et al.*, 1990; Požgaj *et al.*, 1997; Kurjatko *et al.*, 2010)

Tablica 1. Osnovna gustoća, sadržaj vode pri zasićenosti vlaknanaca pri 20 °C te volumno utezanje nekih vrsta drva (prema Perelygin, 1965.; Nikolov and Videlov, 1987.; Reginač *et al.*, 1990.; Požgaj *et al.*, 1997.; Kurjatko *et al.*, 2010.)

№ Red. br.	Wood species Vrsta drva	Basic density ρ_b Gustoća drva $\text{kg} \cdot \text{m}^{-3}$	Fiber saturation point $u_{fsp}^{293.15}$ Točka zasićenosti vlaknanaca $\text{kg} \cdot \text{kg}^{-1}$	Volume shrinkage Volumno utezanje $S_v, \%$
1.	Poplar / topola	355	0.35	13.3
2.	Spruce / smreka	380	0.26 – core; 0.32 – sapwood	11.4
3.	Walnut / orah	555	0.24 - core	12.9
4.	Beech / bukva	560	0.31	17.3
5.	Acacia / bagrem	660	0.20 – core; 0.30 – sapwood	11.2
6.	Oak / hrast	670	0.22 – core; 0.29 – sapwood	11.9

The density of the frozen wood, ρ , in equation (1) can be calculated with the help of the following equations (Deliiski, 2013b):

$$\rho = \rho_b \cdot \frac{1 + u}{1 - \frac{S_v}{100} \cdot [u_{fsp}^{293.15} - 0.001 \cdot (T_{dfr} - 293.15) - u]}$$

(19)

@ $u \leq u_{fsp}$ & $T \leq T_{dfr}$

$$\rho = \rho_b(1 + u) \quad @ \quad u > u_{fsp} \quad (20)$$

In equation (19) S_v is the volume shrinkage of the wood (in %), whose values are given in the last column of Table 1.

2.2. Computation of a at temperatures 271.15 K < $T \leq 272.15$ K and wood moisture content $u > u_{fsp}$

2.2. Izračun koeficijenta toplinske vodljivosti pri temperaturi 271.15 K < $T \leq 272.15$ K i sadržaju vode $u > u_{fsp}$

During the calculations of defrosting processes of wood, which contains free water, i.e. when the condition $271.15 < T \leq 272.15$ & $u > u_{fsp}$ holds, the wood temperature conductivity must be determined according to the following equation (Deliiski, 2003b):

$$a(T, u, u_{fsp}) = \frac{\lambda(T, u, u_{fsp})}{[c(T, u, u_{fsp}) + c_{fw}(T, u, u_{fsp})] \cdot \rho(\rho_b, T, u, u_{fsp})} \quad (21)$$

where a is temperature conductivity of wood with frozen free water in it ($m^2 \cdot s^{-1}$), λ is thermal conductivity of the frozen wood ($W \cdot m^{-1} \cdot K^{-1}$), c is specific heat capacity of wood with frozen free water in it ($J \cdot kg^{-1} \cdot K^{-1}$), c_{fw} is specific heat capacity of the frozen free water in the wood, ($J \cdot kg^{-1} \cdot K^{-1}$). The remaining variables in equation (21) are the same, as in the equation (1).

For the determination of a by equation (21) the values of λ and c must be calculated at

$T = \frac{271.15 + 272.15}{2} = 271.65$ K according to above given equations. The value of ρ in equations (1) and (21) must be determined by equations (19) and (20) correspondingly.

For calculation of c_{fw} in (21) the following equation (Deliiski 2003b, 2004, 2011) has been obtained:

$$c_{fw} = 3.34 \cdot 10^5 \cdot \frac{u - u_{fsp}}{1 + u} \quad (22)$$

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

For the computation of the wood temperature conductivity according to equations (1) and (21) a software program has been prepared in FORTRAN (Dorn and McCracken 1972), and it has been input in the calculation environment of Visual Fortran Professional developed by Microsoft.

With the help of the program, computations have been made for the determination of a in three cases: at $223.15 \text{ K} \leq T \leq 271.15 \text{ K}$ (i.e. $-60^\circ \text{C} \leq t \leq -2^\circ \text{C}$) & $0 \leq u \leq u_{fsp}$, at $-60^\circ \text{C} \leq t \leq -2^\circ \text{C}$ & $u_{fsp} \leq u \leq 1.2 \text{ kg} \cdot \text{kg}^{-1}$, and at $271.15 \text{ K} < T \leq 272.15 \text{ K}$ (i.e. $-2^\circ \text{C} < t \leq -1^\circ \text{C}$) & $u > u_{fsp}$. The temperature conductivity cross sectional to the fibers of beech (*Fagus Silvatica* L.), poplar (*Populus alba* L.), oak (*Quercus petraea* Liebl.), walnut (*Juglans regia* L.), acacia (*Robinia pseudoacacia* J.) and spruce (*Picea abies* L.) has been calculated.

3.1 Wood temperature conductivity cross sectional to the fibers at $-60^\circ \text{C} \leq t \leq -2^\circ \text{C}$ & $0 \leq u \leq u_{fsp}$

3.1. Toplinska vodljivost drva poprečno na vlakanca pri temperaturi $-60^\circ \text{C} \leq t \leq -2^\circ \text{C}$ i sadržaju vode $0 \leq u \leq u_{fsp}$

Fig. 1 and Fig. 2 show, according to equation (1), the calculated change in the temperature conductivity

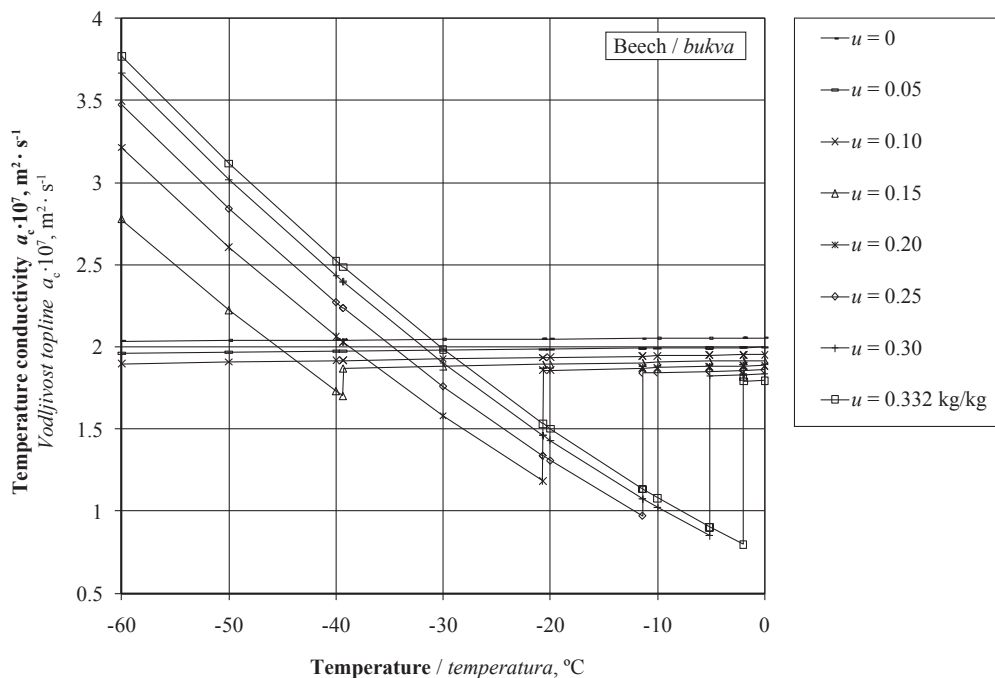


Figure 1 Change in the temperature conductivity of frozen beech wood with $\rho_b = 560 \text{ kg} \cdot \text{m}^{-3}$ and $u_{fsp}^{293.15} = 0.31 \text{ kg} \cdot \text{kg}^{-1}$ cross sectional to the fibres, depending on t and $u \leq u_{fsp}$
Slika 1. Promjena toplinske vodljivosti smrznute bukovine gustoće $\rho_b = 560 \text{ kg} \cdot \text{m}^{-3}$ i točke zasićenosti vlakanca $u_{fsp}^{293.15} = 0,31 \text{ kg} \cdot \text{kg}^{-1}$ poprečno na vlakanca u ovisnosti o temperaturi t i pri $u \leq u_{fsp}$

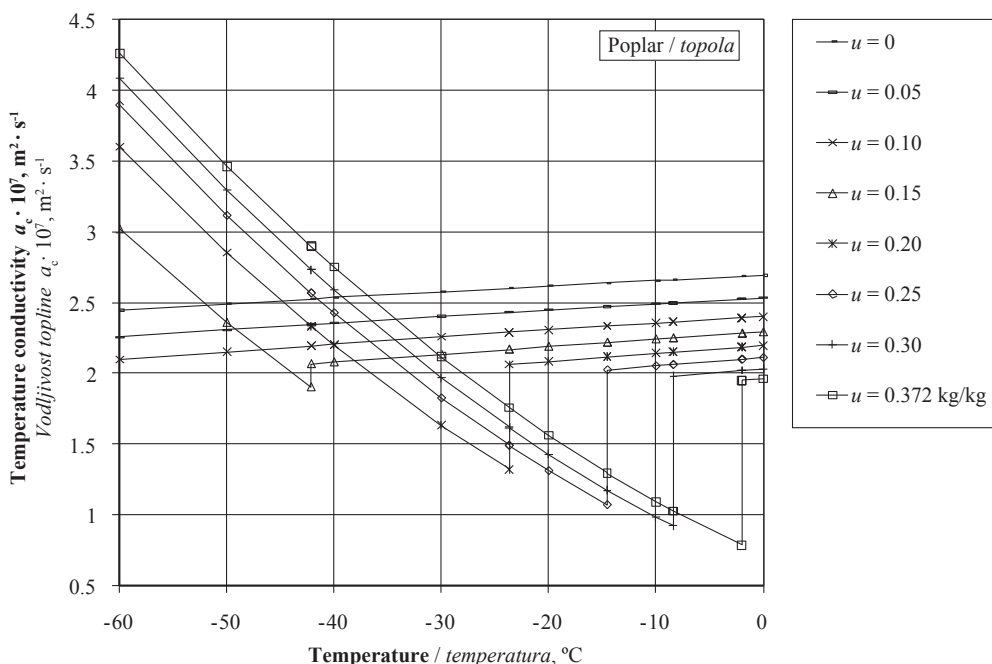


Figure 2 Change in the temperature conductivity of frozen poplar wood with $\rho_b = 355 \text{ kg}\cdot\text{m}^{-3}$ and $u_{\text{fsp}}^{293.15} = 0.35 \text{ kg}\cdot\text{kg}^{-1}$ cross sectional to the fibres, depending on t and $u \leq u_{\text{fsp}}$

Slika 2. Promjena toplinske vodljivosti smrznute topolovine gustoće $\rho_b = 355 \text{ kg}\cdot\text{m}^{-3}$ i točke zasićenosti vlaknaca $u_{\text{fsp}}^{293.15} = 0.35 \text{ kg}\cdot\text{kg}^{-1}$ poprečno na vlakanca u ovisnosti o temperaturi t i pri $u \leq u_{\text{fsp}}$

cross sectional to the fibers, a_c , of frozen beech and poplar wood, respectively, in the hygroscopic range, depending on t and u . During the computations, the values from Table 1 of ρ_b , $u_{\text{fsp}}^{293.15}$, and S_v have been used. The values of a_c for wood not containing ice, i.e. for $u = 0 \text{ kg}\cdot\text{kg}^{-1}$, $u = 0.05 \text{ kg}\cdot\text{kg}^{-1}$ and $u = 0.10 \text{ kg}\cdot\text{kg}^{-1}$, as well as for $t > t_{\text{dfr}} = T_{\text{dfr}} - 273.15$ at $u \geq 0.15 \text{ kg}\cdot\text{kg}^{-1}$ are calculated according to the equations for non-frozen wood, which are given in (Deliiski, 2003b, 2011; Dzurenda and Deliiski, 2010).

The obtained values of t_{dfr} according to equations (13) and (14) depending on u for the studied wood species during the calculation of a_c are given in Table 2. The value of u_{fsp} obtained according to equation (15) at $T_{\text{dfr}} = 271.15 \text{ K}$ (Chudinov, 1966), when the maximum possible amount of frozen bound water in the wood completely melts, for beech wood with $u_{\text{fsp}}^{293.15} = 0.31 \text{ kg}\cdot\text{kg}^{-1}$ is equal to $u_{\text{fsp}} = 0.332 \text{ kg}\cdot\text{kg}^{-1}$ and for poplar wood with $u_{\text{fsp}}^{293.15} = 0.35 \text{ kg}\cdot\text{kg}^{-1}$ is equal to $u_{\text{fsp}} = 0.372 \text{ kg}\cdot\text{kg}^{-1}$. This values of u_{fsp} are used as maximum values of $u = u_{\text{fsp}}$ during the computation of a_c .

The graphs in Fig. 1 and Fig. 2 show that an increase in t at a given value for u leads to a decrease in a for wood containing ice as a consequence of the increase in c_{bw} (refer to equation (18)) and to an in-

crease in a for wood, which does not contain ice. Also, the slope for the change in a of wood, which contains frozen bound water depending on t is much larger than the slope for the change in a of wood without ice. The change in a depending on t with sufficient precision for practical calculations can be taken as being linear.

From the analysis of Fig. 1 and Fig. 2, it can also be seen that at a given value of t , an increase in u for wood containing ice, formed in it from freezing of hygroscopically bound water, causes an increase in a . At temperatures, equal to t_{dfr} (see Table 2), a jump takes place in a . This jump in a is explained by the completing of the phase transition of the frozen bound water in the wood at these values for t and u , when the influence on λ and c of a significant difference in the specific heat capacity of the bound water in a liquid and hard aggregate condition is observed.

The presence of such a jump in a demonstrates the correct reflection in equation (1), and in the mathematical description of λ (Deliiski, 2013c) and c of the setting in the theory of wood thermal treatment (Chudinov, 1968), according to which exactly at temperature t_{dfr} for given value of u the melting of the frozen bound water in the wood is completed.

Table 2 Change in t_{dfr} (in °C) of frozen wood depending on wood moisture content and wood species

Tablica 2. Promjena temperature t_{dfr} (u °C) smrznutog drva u ovisnosti o sadržaju vode i vrsti drva

Wood species Vrsta drva	Wood moisture content u , $\text{kg}\cdot\text{kg}^{-1}$ / Sadržaj vode u drvu, $\text{kg}\cdot\text{kg}^{-1}$					
	0.15	0.20	0.25	0.30	0.332	0.372
Beech / bukva	-39.25	-20.68	-11.39	-5.15	-2.00	-2.00
Poplar / topola	-42.14	-23.69	-14.53	-8.37	-5.28	-2.00

3.2. Wood temperature conductivity cross sectional to the fibers at $-60\text{ }^{\circ}\text{C} \leq t \leq -2\text{ }^{\circ}\text{C}$ & $u_{\text{fsp}} \leq u \leq 1.2\text{ kg}\cdot\text{kg}^{-1}$

3.2. Toplinska vodljivost drva poprečno na vlakanca pri temperaturi $-60\text{ }^{\circ}\text{C} \leq t \leq -2\text{ }^{\circ}\text{C}$ i sadržaju vode $u_{\text{fsp}} \leq u \leq 1,2\text{ kg}\cdot\text{kg}^{-1}$

Fig. 3 shows, according to equation (1), the calculated change in the temperature conductivity cross sectional to the fibers, a_c , of frozen beech and poplar wood above the hygroscopic range, depending on t and u . During the computations, the values from Table 1 of ρ_b and $u_{\text{fsp}}^{293.15}$ for beech and poplar wood have been used. The values of a_c for wood not containing ice, i.e. for $t > t_{\text{dfr}} = -2\text{ }^{\circ}\text{C}$ (see equation (14)) at all studied values of u have been calculated according to the equations for non-frozen wood, which are given in (Deliiski, 2003b, 2011; Dzurenda and Deliiski, 2010).

The graphs in Fig. 3 show that an increase in t at a given value for u and an increase in u at a given value for t leads to the change in a both for wood not containing and containing ice from the free water, which is the same as the one shown above for wood, containing only frozen bound water.

The graphs in Fig. 3 also show that at $t = t_{\text{dfr}} = -2\text{ }^{\circ}\text{C}$ jumps take place in a for the wood with $u > u_{\text{fsp}}$. These jumps are explained by the phase transition into water of the whole amount of the ice, formed by the free water in the wood during defrosting above the hygroscopic range. Namely, at the value of $t = t_{\text{dfr}} = -2\text{ }^{\circ}\text{C}$, the influence on a of a significant difference in the temperature conductivity of the free water in a liquid and hard aggregate state occurs.

3.3. Wood temperature conductivity cross sectional to the fibers at $-2\text{ }^{\circ}\text{C} < t \leq -1\text{ }^{\circ}\text{C}$ & $u > u_{\text{fsp}}$

3.3. Toplinska vodljivost drva poprečno na vlakanca pri temperaturi $-2\text{ }^{\circ}\text{C} \leq t \leq -1\text{ }^{\circ}\text{C}$ i sadržaju vode $u > u_{\text{fsp}}$

Fig. 4 and Fig. 5 show, according to equation (21), the calculated change in the temperature conductivity of frozen wood from above mentioned six wood species, containing frozen free water, depending on $u >$

u_{fsp} in the temperature range $-2\text{ }^{\circ}\text{C} < t \leq -1\text{ }^{\circ}\text{C}$. During the computations, the values of ρ_b and $u_{\text{fsp}}^{293.15}$ from Table 1 have been used.

The values of a are determined for the entire possible range for the change in the free water in the wood, i.e. for $u_{\text{fsp}} < u \leq u_{\text{max}}$, where the maximum possible moisture content u_{max} depends on the density ρ of the respective wood specie. The results are shown separately in Fig. 2 and Fig. 3 for the moisture ranges $u_{\text{fsp}} < u \leq 0.4\text{ kg}\cdot\text{kg}^{-1}$ and $0.4\text{ kg}\cdot\text{kg}^{-1} < u \leq u_{\text{max}}$, due to the very big differences in the values of a in both ranges.

The results from the calculations show that for values of u , which are very close to u_{fsp} , but are slightly larger than u_{fsp} , the values of a in the temperature range $-2\text{ }^{\circ}\text{C} < t \leq -1\text{ }^{\circ}\text{C}$ are comparable with those that a has right after the melting of the frozen bound water in the wood. This fact fully corresponds to the physics of the wood defrosting process.

However, as u increases in relation to u_{fsp} , the values of a decrease significantly along a hyperbolic line: from 3.2 to 3.9 times at $u = 1.1u_{\text{fsp}}$, from 17 to 23 times at $u = 2u_{\text{fsp}}$, from 32 to 36 times at $u = 3u_{\text{fsp}}$, up to about 40 times at $u = 5u_{\text{fsp}}$ (when the density of the wood species allows to have such a high moisture content). A reason for this is the strong increasing quantity of the frozen free water in the wood with an increase of $u > u_{\text{fsp}}$ and the related increase in the specific heat capacity c_{fw} , which is a part of the denominator in equation (21).

The drastic decrease of the wood temperature conductivity in the range $-2\text{ }^{\circ}\text{C} < t \leq -1\text{ }^{\circ}\text{C}$ for all anatomic directions of wood, which contains frozen free water, causes a significant slowing down of the change in temperature in the frozen wood materials subjected to thermal treatment in this range up to the moment when this frozen water melts completely. This fact is illustrated by many graphs in the specialized literature (Deliiski, 2003b, 2004, 2009, 2013a; Dzurenda and Deliiski, 2010; Steinhagen, 1986, 1991; Khatabbi and Shteinhagen, 1992, 1993, 1995). It confirms the correct reflection in equation (21) of the physical laws that influence a in the shown temperature range.

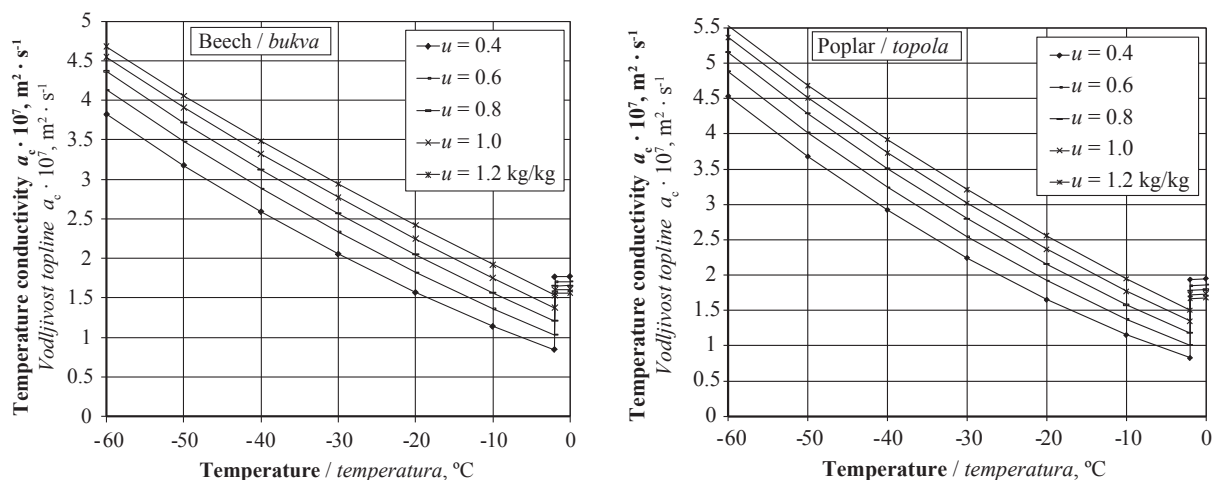


Figure 3 Change in the temperature conductivity of frozen beech (left) and poplar (right) wood cross sectional to the fibres, depending on t and $u > u_{\text{fsp}}$

Slika 3. Promjena toplinske vodljivosti smrznute bukovine (lijevo) i topolovine (desno) poprečno na vlakanca, u ovisnosti o temperaturi t i pri $u > u_{\text{fsp}}$

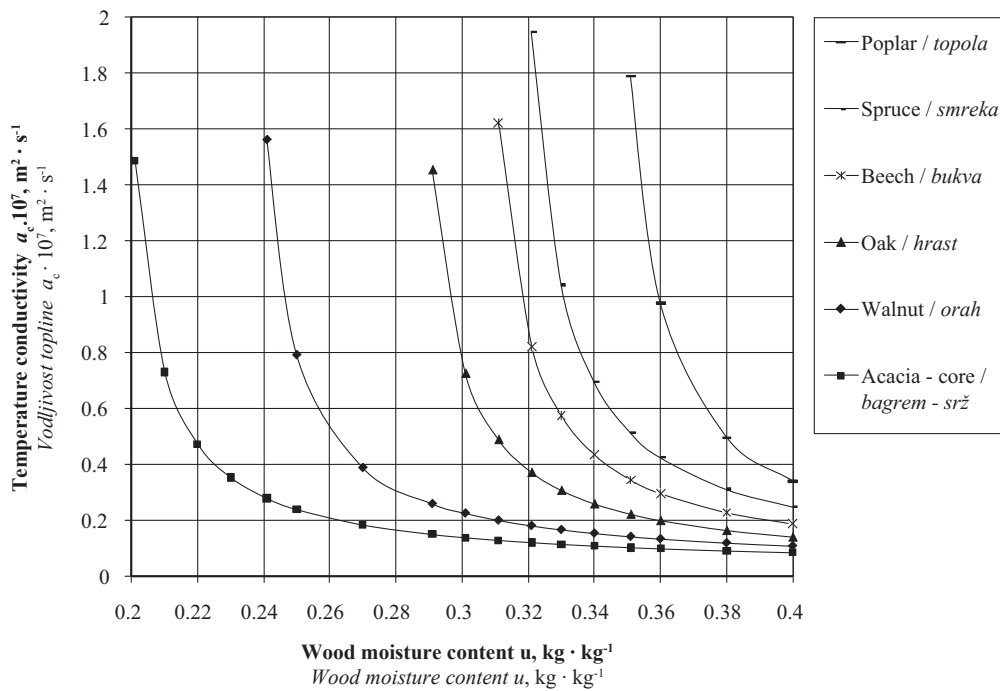


Figure 4 Change in the wood temperature conductivity of poplar, spruce, beech, oak, walnut and acacia cross sectional to the fiber depending on $u_{fsp} < u \leq 0.4 \text{ kg} \cdot \text{kg}^{-1}$ in the range $-2 \text{ }^\circ\text{C} \leq t < -1 \text{ }^\circ\text{C}$

Slika 4. Promjena toplinske vodljivosti topolovine, smrekovine, bukovine, hrastovine, orahovine i bagremovine poprečno na vlakanca, u ovisnosti sadržaju vode $u_{fsp} < u \leq 0.4 \text{ kg} \cdot \text{kg}^{-1}$ i pri temperaturi $-2 \text{ }^\circ\text{C} \leq t < -1 \text{ }^\circ\text{C}$

3.4 Computation of the 2D temperature distribution in frozen logs during their defrosting

$$\frac{\partial T}{\partial \tau} = a_r(T, u, u_{fsp}, \rho_b, S_v) \cdot \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial T}{\partial r} \right) \quad (23)$$

3.4. Proračun 2D raspodjele temperature u smrznutom trupcu tijekom odmrzavanja

$$+ a_p(T, u, u_{fsp}, \rho_b, S_v) \cdot \frac{\partial^2 T}{\partial z^2}$$

The above results have been used for the calculation of log defrosting according to the following mathematical model (Deliiski, 2003b):

with an initial condition

$$T(r, z, 0) = T_0 \quad (24)$$

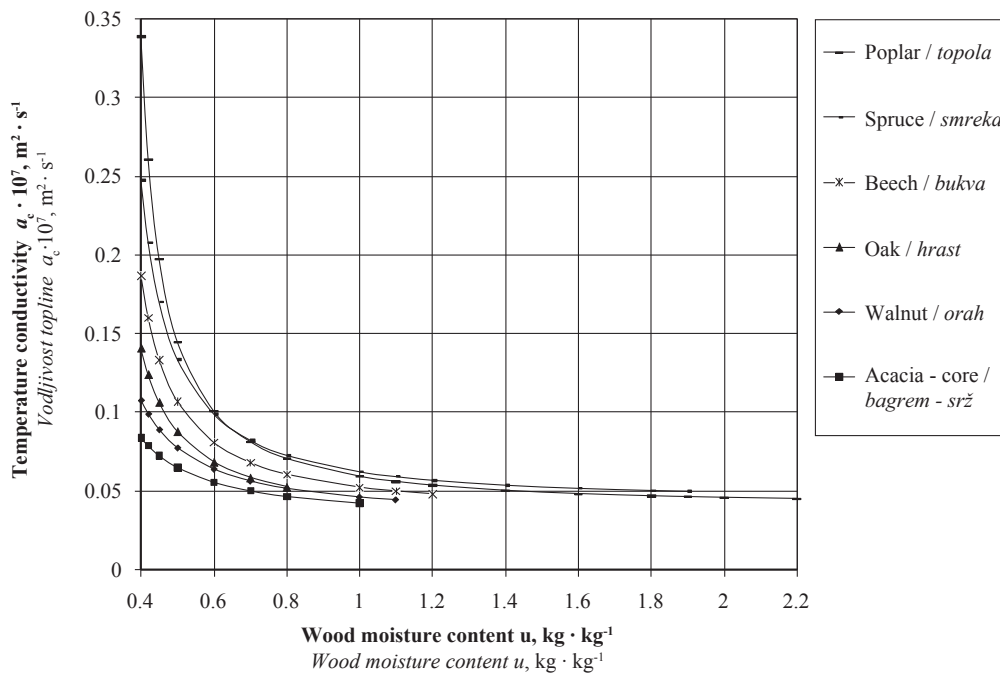


Figure 5 Change in the wood temperature conductivity of poplar, spruce, beech, oak, walnut and acacia cross sectional to the fiber depending on $0.4 \text{ kg} \cdot \text{kg}^{-1} < u \leq u_{max}$ in the range $-2 \text{ }^\circ\text{C} \leq t < -1 \text{ }^\circ\text{C}$

Slika 5. Promjena toplinske vodljivosti topolovine, smrekovine, bukovine, hrastovine, orahovine i bagremovine poprečno na vlakanca, u ovisnosti o sadržaju vode $0.4 \text{ kg} \cdot \text{kg}^{-1} < u \leq u_{max}$ i pri temperaturi $-2 \text{ }^\circ\text{C} \leq t < -1 \text{ }^\circ\text{C}$

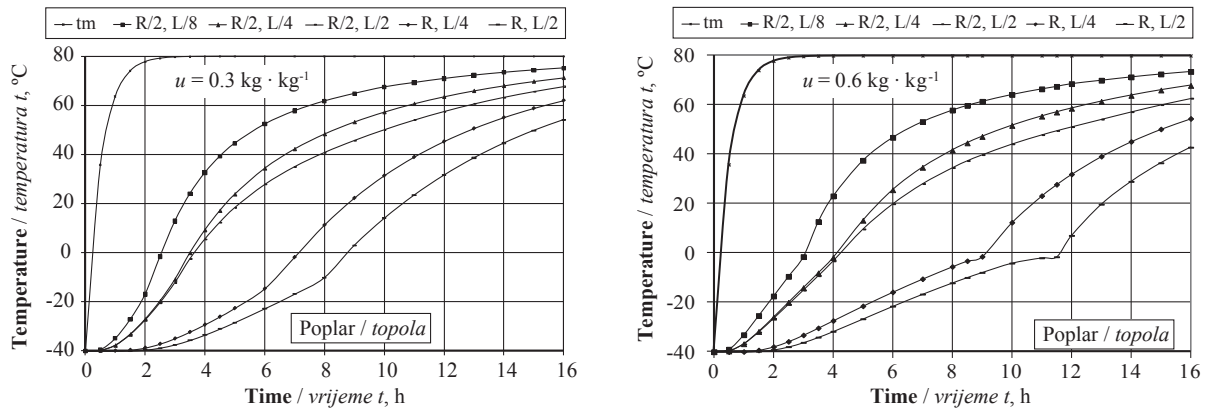


Figure 6 Change in t in the longitudinal section of poplar logs with $R = 0.2$ m, $L = 0.8$ m, $t_0 = -40$ °C, $u = 0.3$ kg·kg⁻¹ (left) and $u = 0.6$ kg·kg⁻¹ (right) during their defrosting at $t_m = 80$ °C

Slika 6. Promjena temperature u longitudinalnom presjeku topolova trupca promjera $R = 0,2$ m, duljine $L = 0,8$ m, temperature $t_0 = -40$ °C, sadržaja vode $u = 0,3$ kg·kg⁻¹ (lijevo) i sadržaja vode $u = 0,6$ kg·kg⁻¹ (desno) tijekom procesa odmrzavanja pri temperaturi $t_m = 80$ °C

and a boundary condition for thermal treatment of the logs in agitated hot water at their prescribed surface temperature:

$$T(0, z, \tau) = T_m(\tau), \quad (25)$$

where a_r and a_p are temperature conductivities of the wood in radial direction and parallel to the fiber, respectively (m²·s⁻¹), r is radial coordinate: $0 \leq r \leq R$, R is radius of the log (m), z is longitudinal coordinate: $0 \leq z \leq L/2$, L is length of the log (m), T is temperature (K), T_0 is initial temperature of the log subjected to defrosting (K), T_m is temperature of the processing (heating) medium (K), u is wood moisture content (kg·kg⁻¹), u_{fsp} is wood moisture content at fibre saturation point (kg·kg⁻¹), ρ_b is basic density of the wood (kg·m⁻³), S_v is volume shrinkage of the wood (%), τ is time (s).

For the numerical solution of the mathematical model, which is presented in common form by equations (23), (24), and (25), a software package has been prepared in the calculation environment of Visual Fortran Professional. With the help of the software package, computations have been made for the determination of the 2D non-stationary change in the temperature in frozen poplar logs subjected to defrosting with $R = 0.2$ m, $L = 0.8$ m, $t_0 = -40$ °C and two values of wood moisture content $u = 0.3$ kg·kg⁻¹ and $u = 0.6$ kg·kg⁻¹ during their 16 hours of heating in agitated hot water with $t_m = 80$ °C. The log with $u = 0.3$ kg·kg⁻¹ contains almost the maximum possible amount of frozen bound water in the wood and does not contain frozen free water. The log with $u = 0.6$ kg·kg⁻¹ contains not only frozen bound water but also contains a significant amount of frozen free water.

The increasing of the heating medium temperature, t_m , from the value of $t_{m0} = t_0$ to $t_m = 80$ °C = const grows exponentially with time constant, equal to 1800 s. This increasing of t_m at the beginning of log heating can be seen in the Fig. 6. The values of R , L , t_m , and u have been selected so as to correspond to cases common in practice. The duration of 16 h of log heating at

$t_m = 80$ °C has been proven as sufficient for complete melting of the ice in the studied logs.

During the computations, the values from Table 1 of ρ_b , $u_{fsp}^{293.15}$, and S_v for poplar wood have been used. The calculations have been done with values of $a_r = 1.04a_c$ and $a_p = 1.95a_r$ (Deliiski, 2003b), where a_c is the temperature conductivity of the poplar wood cross sectional to the fibers, whose values for $u = 0.3$ kg·kg⁻¹ and $u = 0.6$ kg·kg⁻¹ can be seen in Fig. 2, Fig. 3 (right), and Fig. 5.

Fig. 6 shows the computed change in the surface temperature of the logs, which is equal to t_m , and also in the temperature in 5 characteristic points in the 1/4 of the longitudinal section of logs (because of its symmetry to the remaining 3/4 of the section). The coordinates of the characteristic points are given in the legend of the graphs.

The curves of the log axe situated on characteristic points with coordinates (R, L/4) and (R, L/2) on the right part of Fig. 6 show the specific almost horizontal sections of retention of the temperature for a long period of time in the range from -2 °C to -1 °C, while in these points a complete melting of the frozen free water in the wood occurs. Such retention of the temperature in the range from -2 °C to -1 °C has been observed in wide experimental studies during the defrosting process of pine logs with frozen free water in them (Steinhagen, 1986; Khattabi and Steinhagen, 1992, 1993).

The reason for the temperature retention in the range from -2 °C to -1 °C is the very low value of the temperature conductivity coefficient a_c , which is equal to $0.1 \cdot 10^{-7}$ m²·s⁻¹ for the poplar wood with $u = 0.6$ kg·kg⁻¹ in this range (see Fig. 5). In the range -40 °C $\leq t \leq -2$ °C, the value of a_c of the same frozen poplar wood changes from $a_c = 3.24 \cdot 10^{-7}$ m²·s⁻¹ to $a_c = 1.01 \cdot 10^{-7}$ m²·s⁻¹ (see Fig. 3-right), i.e. it is from 32.4 to 10.1 times larger comparing with $a_c = 0.1 \cdot 10^{-7}$ m²·s⁻¹. Because of this, the temperature in the logs with frozen free water in them increases much faster in the range -40 °C $\leq t \leq -2$ °C than in the range -2 °C $< t \leq -1$ °C.

Analogically, the almost horizontal sections in the change of the wood temperature are absent during defrosting of the ice, formed only by bound water in the wood (see the left part of Fig. 6).

4 CONCLUSIONS

4. ZAKLJUČAK

The present paper describes the approach suggested by the authors for the computation of the temperature conductivity of frozen wood materials at temperatures below $-1\text{ }^{\circ}\text{C}$ during their defrosting. The approach takes into account to a maximum degree the physics of the processes of melting of the ice, formed by both the bound and the free water in the wood. It reflects the influence of the temperature, moisture content and density of the wood, and for the first time also the influence of the fiber saturation point of each wood species on its temperature conductivity in a frozen state.

The obtained results for poplar, spruce, beech, oak, walnut, and acacia show that, when all other conditions are equal, the wood temperature conductivity during melting of the frozen bound water is up to some tens of times larger than the wood temperature conductivity during melting of the frozen free water in the wood. This fact determined for the first time quantitatively for the studied wood species causes a significant slowing down of the change in temperature in the frozen wood materials subjected to thermal treatment up to the moment, when the frozen free water melts completely.

It has been determined that the change in a depending on t with sufficient precision of calculations can be taken as linear for practical reasons, when $t < -2\text{ }^{\circ}\text{C}$ for all $0 \leq u \leq u_{\text{fsp}}$ and hyperbolic when $-2\text{ }^{\circ}\text{C} < t \leq -1\text{ }^{\circ}\text{C}$ and simultaneously with this $u > u_{\text{fsp}}$.

The results of this work can be used for both technological and other engineering calculations and analysis of processes of thermal and hydrothermal treatment of wood materials, as well as in system software for model based automatic control (Hadjiski, 2003, 2013) of such treatment. The suggested methodology for the computation of the temperature conductivity of frozen wood during its defrosting can also be used for science based dimensioning of the mentioned processes with the help of all classical approaches, which are well known from the textbooks and other specialized literature.

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