Nencho Deliiski[1]

3D Modeling and Visualization of Non-Stationary Temperature Distribution during Heating of Frozen Wood

3D modeliranje i vizualizacija nestacionarne distribucije temperature tijekom zagrijavanja smrznutog drva

Original scientific paper • Izvorni znanstveni rad
Received – prispjelo: 27. 1. 2013.
Accepted – prihvaćeno: 6. 11. 2013.
*UDK: 630*812.141; 630*847*
doi:10.5552/drind.2013.1306

ABSTRACT • *A 3-dimensional mathematical model has been developed, solved, and verified for the transient non-linear heat conduction in frozen and non-frozen wood with prismatic shape at arbitrary initial and boundary conditions encountered in practice. The model takes into account for the first time the fiber saturation point of each wood species, u_{fsp}, and the impact of the temperature on u_{fsp} of frozen and non-frozen wood, which are then used to compute the current values of the thermal and physical characteristics in each separate volume point of the material subjected to defrosting.*
This paper presents solutions of the model with the explicit form of the finite-difference method. Results of simulation investigation of the impact of frozen bound water, as well as of bound and free water, on 3D temperature distribution in the volume of beech and oak prisms with dimensions 0.4 x 0.4 x 0.8 m during their defrosting at the temperature of the processing medium of 80 °C are presented, analyzed and visualized through color contour plots.

Keywords: *3D mathematical model, frozen wood, finite difference method, temperature distribution, contour plots*

SAŽETAK • *Kreiran je i riješen 3D matematički model te provjeren za nelinearno provođenje topline u smrznutome i nesmrznutom drvu prizmatičnog oblika pri proizvoljnim početnim i rubnim uvjetima koji se susreću u praksi. Prvi put model uzima u obzir točku zasićenosti vlakanaca za svaku vrstu drva (u_{fsp}) i utjecaj temperature na u_{fsp} smrznutoga i nesmrznutog drva, koji se primjenjuju pri izračunavanju trenutačne vrijednosti termo-fizikalnih svojstava u svakoj posebno definiranoj točki volumena materijala koji se odmrzava.*
Rad prikazuje rješenja modela s eksplicitnim oblikom metode konačnih razlika. Rezultati simulacijskih istraživanja o utjecaju zamrznute vezane vode te vezane i slobodne vode na 3D raspodjelu temperature u volumenu bukovih i hrastovih prizmi dimenzija 0,4 x 0,4 x 0,8 m tijekom odmrzavanja pri temperaturi procesnog medija od 80 °C prezentirani su i analizirani te vizualizirani crtežima u boji.

Ključne riječi *: 3D matematički model, smrznuto drvo, metoda konačnih razlika, raspodjela temperature , konturni crteži*

[1]Author is professor at Faculty of Forest Industry, University of Forestry, Sofia, Bulgaria.
[1]Autor je profesor Fakulteta šumske industrije Šumarskog sveučilišta, Sofija, Bugarska.

1 INTRODUCTION
1. UVOD

For the optimization of the control of the heating process of wood in veneer and plywood mills, it is necessary to know the temperature distribution at every moment of the process (Shubin, 1990; Trebula and Klement, 2003; Pervan, 2009). Considerable contribution was made to the calculation of non-stationary distribution of temperature in frozen and non-frozen logs, and to the duration of their heating (Steinhagen, 1986, 1991). Later on, 1-dimensional and 2-dimensional models were developed and solved (Steinhagen *et al*., 1987; Steinhagen and Lee, 1988; Khattabi and Steinhagen, 1992, 1993, 1995), whose applications are limited only to wood with moisture content above fiber saturation point.

The heat energy, required for melting the ice, formed from bound water in the wood, has not been taken into account in these models. The models assume that the fiber saturation point is identical for all wood species (i.e. $u_{\mathrm{fsp}} = 0.3$ kg·kg^{-1} = const) and that the melting of the ice, formed from free water in the wood, occurs at 0 ºC.

However, it is known that there are significant differences between the fiber saturation point of different wood species (Požgai *et. al*., 1997; Videlov, 2003) and that, depending on this point, the quantity of the ice formed from free water in the wood melts at a temperature in the range between -2 ºC and -1 ºC (Chudinov, 1968, 1984). The complications and deficiencies indicated in these models have been overcome by a 2-dimensional mathematical model of the transient non-linear heat conduction in frozen and non-frozen logs suggested by Deliiski (2004, 2011).

This paper presents the development, verification and solutions of an analog 3-dimensional mathematical model of the transient non-linear heat conduction in frozen and non-frozen wood with prismatic shape at arbitrary initial and boundary conditions encountered in practice. The model takes into account for the first time the fiber saturation point of each wood species, u_{fsp}, and the impact of the temperature on u_{fsp} of frozen and non-frozen wood, which are then used to compute the current values of the thermal and physical characteristics in each separate volume point of the material subjected to defrosting.

This paper also presents the results of simulation investigation of the impact of the frozen bound water and free water on 3D temperature distribution in the volume of beech and oak prisms with dimensions 0.4 x 0.4 x 0.8 m during their defrosting at the temperature of the processing medium of 80 °C.

2 MATHERIAL AND METHODS
2. MATERIJAL I METODE

2.1. 3D mathematical model of the defrosting process of prismatic wood materials
2.1. 3D matematički model procesa odmrzavanja prizmatičnoga drvnog materijala

The defrosting process of prismatic wood materials during their thermal treatment can be described by a non-linear differential equation of the thermal-conductivity, using the Cartesian coordinates (Deliiski, 2003a):

$$c_{\mathrm{e}}(T,u)\rho(T,u)\frac{\partial T(x,y,z,\tau)}{\partial\tau} = \frac{\partial}{\partial x}\left[\lambda_{\mathrm{r}}(T,u)\frac{\partial T(x,y,z,\tau)}{\partial x}\right] + \frac{\partial}{\partial y}\left[\lambda_{\mathrm{t}}(T,u)\frac{\partial T(x,y,z,\tau)}{\partial y}\right] + \frac{\partial}{\partial z}\left[\lambda_{\mathrm{p}}(T,u)\frac{\partial T(x,y,z,\tau)}{\partial z}\right] \quad (1)$$

After the differentiation of the right side of equation (1) on the spatial coordinates *x, y,* and *z*, excluding the arguments in the brackets for shortening of the record, the following mathematical model is obtained of the non-stationary defrosting of wood materials with prismatic shape subjected to heating:

$$c_{\mathrm{e}}\rho\frac{\partial T}{\partial\tau} = \lambda_{\mathrm{r}}\frac{\partial^2 T}{\partial x^2} + \frac{\partial\lambda_{\mathrm{r}}}{\partial T}\left(\frac{\partial T}{\partial x}\right)^2 + \lambda_{\mathrm{t}}\frac{\partial^2 T}{\partial y^2} + \frac{\partial\lambda_{\mathrm{t}}}{\partial T}\left(\frac{\partial T}{\partial y}\right)^2 + \lambda_{\mathrm{p}}\frac{\partial^2 T}{\partial z^2} + \frac{\partial\lambda_{\mathrm{p}}}{\partial T}\left(\frac{\partial T}{\partial z}\right)^2 \quad (2)$$

with an initial condition

$$T(x,y,z,0) = T_0\,, \quad (3)$$

and a boundary condition

$$T(0,y,z,\tau) = T(x,0,z,\tau) = T(x,y,0,\tau) = T_{\mathrm{m}}(\tau). \quad (4)$$

For the solution of the system of equations (2) to (4), it is necessary to make a mathematical description of thermal and physical characteristics of the wood, c_{e}, λ_{r}, λ_{t}, λ_{p}, and of its density, ρ. Equations in (Deliiski, 2003a, 2011) and (Deliiski and Dzurenda, 2010) present a mathematical description of the effective specific heat capacity coefficient, c_{e}, of the frozen wood as a sum of the capacities of the wood itself, *c*, and the ice produced by freezing of the free water, c_{fw}, and of the hygroscopically bound water, c_{bw}. Other equations quoted by the above authors present mathematical descriptions of wood density, *ρ*, and of its thermal conductivity, λ, in different anatomical directions.

The given mathematical descriptions of c_{e}, λ_{r}, λ_{t}, and λ_{p} (Deliiski, 2011), which are part of the model (2) to (4), have now been updated by taking into account, for the first time, the influence of the fiber saturation point of wood species on the values of thermal and physical characteristics during wood defrosting, and the influence of the temperature on fiber saturation point of frozen and non-frozen wood. This has been done using the method presented by Deliiski (2013) during the update of the mathematical description of λ.

2.2. Transformation of 3D model to a form suitable for programming
2.2. Transformacija 3D modela u odgovarajući oblik za programiranje

The following system of equations (Equation 5) has been derived by passing to final increases in equation (2) with the usage of the same, as well as by the explicit form of the finite-difference method described by Deliiski (2003a, 2011) and taking into account the mathematical description of the thermal conductivity, λ, in different anatomical directions.

Since in practice prismatic materials subjected to thermal treatment usually do not have a clear radial or clear tangential orientation, and are partially radially or partially tangentially oriented, then in equation (5) instead of the coefficients λ_0 in the observed two anatomical directions, their average arithmetic value can be used, as it determines the thermal conductivity at 0 °C perpendicular to the wood fibers (Equation 6):

$$T_{i,j,k}^{n+1} = T_{i,j,k}^{n} + \\ + \frac{\gamma\Delta\tau}{c_{\mathrm{e}}\rho}\left\{\begin{array}{l} \frac{\lambda_{0\mathrm{r}}}{\Delta x^2}\left[\begin{array}{l}\left[1+\beta\left(T_{i,j,k}^{n}-273{,}15\right)\right] \\ \left(T_{i+1,j,k}^{n}+T_{i-1,j,k}^{n}-2T_{i,j,k}^{n}\right)+\beta\left(T_{i,j,k}^{n}-T_{i-1,j,k}^{n}\right)^2\end{array}\right]+ \\ \frac{\lambda_{0\mathrm{t}}}{\Delta y^2}\left[\begin{array}{l}\left[1+\beta\left(T_{i,j,k}^{n}-273{,}15\right)\right] \\ \left(T_{i,j+1,k}^{n}+T_{i,j-1,k}^{n}-2T_{i,j,k}^{n}\right)+\beta\left(T_{i,j,k}^{n}-T_{i,j-1,k}^{n}\right)^2\end{array}\right]+ \\ \frac{\lambda_{0\mathrm{p}}}{\Delta z^2}\left[\left[1+\beta\left(T_{i,j,k}^{n}-273{,}15\right)\right]\left(T_{i,j,k+1}^{n}+T_{i,j,k-1}^{n}-2T_{i,j,k}^{n}\right)+\beta\left(T_{i,j,k}^{n}-T_{i,j,k-1}^{n}\right)^2\right] \end{array}\right\} \tag{5}$$

$$\lambda_{0\mathrm{cr}} = \frac{\lambda_{0\mathrm{r}}+\lambda_{0\mathrm{t}}}{2} \tag{6}$$

Also, the thermal conductivity at 0 °C in the direction parallel to the fibers $\lambda_{0\mathrm{p}}$ can be expressed through $\lambda_{0\mathrm{cr}}$ using the equation

$$\lambda_{0\mathrm{p}} = K_{\mathrm{p/cr}}\lambda_{0\mathrm{cr}}\,, \tag{7}$$

where the coefficient $K_{\mathrm{p/cr}} = \frac{\lambda_{0\mathrm{p}}}{\lambda_{0\mathrm{cr}}}$ depends on the wood species (Deliiski, 2003a).

For uniformity of the calculations, it is reasonable to use one step of the calculation mesh along the spatial coordinates $\Delta x = \Delta y = \Delta z$ (see Fig. 1). Taking into consideration this condition and equations (6) and (7), the system of equations (5) becomes equation (8).

The initial condition (3) in the model is presented using the following finite differences equation:

$$T_{i,j,k}^{0} = T_0\,. \tag{9}$$

$$T_{i,j,k}^{n+1} = T_{i,j,k}^{n} + \\ + \frac{\lambda_{0\mathrm{cr}}\gamma\Delta\tau}{c_{\mathrm{e}}\rho\Delta x^2}\left\{\begin{array}{l} \left[1+\beta(T_{i,j,k}^{n}-273{,}15)\right] \\ \left[\begin{array}{l}T_{i+1,j,k}^{n}+T_{i-1,j,k}^{n}+T_{i,j+1,k}^{n}+T_{i,j-1,k}^{n}+ \\ K_{\mathrm{p/cr}}(T_{i,j,k+1}^{n}+T_{i,j,k-1}^{n})-(4+2K_{\mathrm{p/cr}})T_{i,j,k}^{n}\end{array}\right]+ \\ +\beta\left[\begin{array}{l}(T_{i,j,k}^{n}-T_{i-1,j,k}^{n})^2+(T_{i,j,k}^{n}-T_{i,j-1,k}^{n})^2+ \\ K_{\mathrm{p/cr}}(T_{i,j,k}^{n}-T_{i,j,k-1}^{n})^2\end{array}\right]\end{array}\right\}. \tag{8}$$

The boundary conditions (4) acquire the following form suitatable for programming:

$$T_{1,j,k}^{n+1} = T_{i,1,k}^{n+1} = T_{i,j,1}^{n+1} = T_{\mathrm{m}}^{n+1}\,. \tag{10}$$

The presentation of a non-linear differential equation (2) from the mathematical model through its discrete analogue (8) corresponds to the setting of the coordinate system and positioning of the nodes in the mesh shown in Fig. 1, in which a non-stationary 3D temperature distribution in prismatic wood materials during their defrosting is calculated. The calculation mesh for the solution of the model through the finite-difference method is built on a 1/8 part of the prism volume, because of its mirror symmetry with the remaining 7/8 parts of the prism volume.

The setting of the coordinate system, shown in Fig. 1 allows, with the help of only one system of equations (8), to calculate the change in the temperature in any mesh node of the volume of the prism subjected to defrosting at the moment $(n + 1)\Delta\tau$ using the already calculated values of T at the preceding moment $n\Delta\tau$.

Wide experimental studies have been performed for the determination of a 1-, 2- and 3-dimensional temperature distribution in the volume of frozen and non-frozen oak, beech, poplar and pine

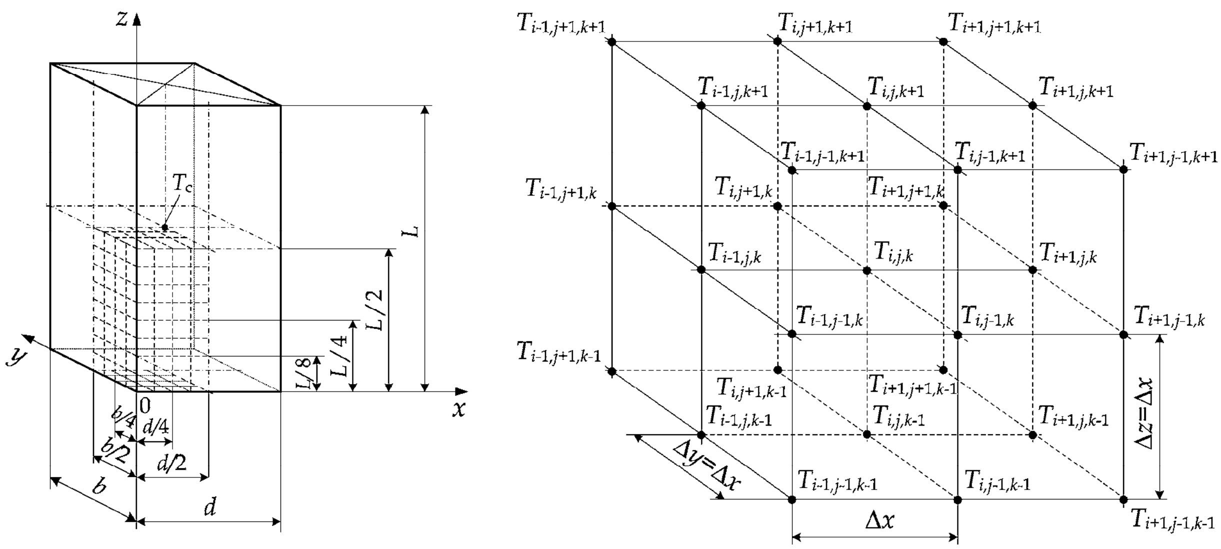

Figure 1 Positioning of nodes in a 3D calculation mesh of a discretized wooden prism
Slika 1. Pozicioniranje čvorova u 3D računskoj mreži u diskretiziranoj drvenoj prizmi

prismatic materials during their thermal treatment. The values of the coefficient $K_{p/cr} = \dfrac{\lambda_{0p}}{\lambda_{0cr}}$ in equation (8) have been determined through the solution of the model with the same initial and boundary conditions in order to achieve maximum conformity between the calculated and experimental results.

It has been determined that the coefficient $K_{p/cr}$ has the following values: for oak $K_{p/cr}$=1.76, for beech $K_{p/cr}$=1.88, for poplar $K_{p/cr}$=2.03, and for pine $K_{p/cr}$=2.26 (Deliiski, 2003a, 2011).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1. Computation of 3D temperature distribution in frozen wood during its defrosting
3.1. Izračun 3D raspodjele temperature u smrznutome drvnom materijalu tijekom njegova odmrzavanja

For the numerical solution of the above presented mathematical model, a software package has been developed in FORTRAN and integrated in the calculation environment of Visual Fortran Professional developed by Microsoft, as a part of the Windows Office software (Deliiski, 2011).

With the help of this software package, 3D temperature changes of beechwood (*Fagus Silvatica* L.) and oakwood (*Quercus petraea* Liebl.) prisms with dimensions d = 0.4 m, b = 0.4 m, L = 0.8 m, initial temperature of t_0 = -40 °C and two values of wood moisture content u = 0.3 kg·kg^{-1} and u = 0.6 kg·kg^{-1} have been studied during their 20 h heating with the intermediate stage of melting at the heating temperature of t_m = 80 °C. The prisms with u = 0.3 kg·kg^{-1} contain the maximum possible quantity of frozen bound water in beech and oak wood and contain no ice in the cell lumens (i.e. contain no ice from free water). The prisms with u = 0.6 kg·kg^{-1} not only contain frozen bound water but also contain a significant quantity of frozen free water.

The heating medium temperature, t_m, increases exponentially from $t_{m0} = t_0$ to t_m = 80 °C = const with the time constant of 1800 s. This increasing of t_m at the beginning of the heating process of prisms can be seen in Fig. 4 and 5. The values of d, b, L, t_m, and u have been selected so as to correspond to cases often encountered in practice.

The duration of 20 h of the prism heating at t_m = 80 °C has been proven suitable for complete melting of the ice in the studied prisms. The calculations have been done with average values of ρ_b = 560 kg·m^{-3} and u_{fsp}^{20} = 0.31 kg·kg^{-1} of the beech wood and of ρ_b = 670 kg·m^{-3} and u_{fsp}^{20} = 0.29 kg·kg^{-1} of the oak wood (Videlov, 2003; Deliiski and Dzurenda, 2010).

The computations have been carried out in a step on the spatial coordinates Δx = 0.001 m = 10 mm, i.e. with the nodes M = 1 + [d/(2 Δx)] = 21 and N = 1 + [b/(2 Δx)] = 21 along the x and y coordinates, respectively, and KD = 1 + [L/(2 Δx)] = 41 along the z coordinate. This means that the calculation meshes in the volume of the prisms consist of 21 x 21 x 41 = 18 081 nodes in total.

The step on time coordinate, $\Delta\tau$, which is determined by the software package that keeps the stability condition (Deliiski, 2011) of 3D solution of the explicit form of the finite-difference method and takes into account the maximum values of λ and c_e during wood defrosting process, is as follows:

- for beech wood: $\Delta\tau$ = 30 at u = 0.3 kg·kg^{-1} and $\Delta\tau$ = 25 at u = 0.6 kg·kg^{-1};
- for oak wood: $\Delta\tau$ = 40 at u = 0.3 kg·kg^{-1} and $\Delta\tau$ = 30 at u = 0.6 kg·kg^{-1}.

It takes 30 to 45 s to compute the temperature distribution in the volume of each of the studied prisms during a 20 h thermal treatment using the above values for $\Delta\tau$ with the help of Intel Pentium (4) CPU 3.0 GHz processor. Using the input data for solving the model, the value for the interval (INT) is given in seconds. After completing each INT from the beginning of the process, the calculated temperature distribution in the prism volume is recorded on computer hard-drive. The records can be consequently seen on a monitor, graphically processed, and/or printed. Besides taking into account the stability condition for solving the 3D model, the value of the step $\Delta\tau$ is calculated so as to be divisible by the input value of INT, using the software package.

Fig. 2 and 3 show the tables with the computed temperature distribution in 121 nodes of the calculation mesh in the central cross-section of the beech prisms at every 5 h of the defrosting process.

Fig. 4 and 5 shows the temperature change of the surface of beech and oak prisms subjected to defrosting, which is equal to t_m, as well as of t in 6 characteristic points of their volume.

The first three characteristic points with coordinates (d/4, b/8, L/8), (d/4, b/4, L/4), and (d/4, b/4, L/2) allow for the tracking of the influence on the defrosting process of the gap from the prisms base (see Fig. 1 –

```
                          I N P U T   D A T A
                      3D DEFROSTING OF BEECH PRISM
Kq=11 M= 21 N= 21 KD= 41 ROb=560. Kwc=1.28 Kwpc=1.88 U=0.30 Ufsp=0.31 Da=2.4 La= 9.0
two= -40. to=-40. t1= 80.0 t2= 80.0 t3= 80.0 tes= 80.0  dtm=.010  tk=20.0 dTAU=   30
T1=1800. T2=  10. T3=  10. dT3=  0. dtm3= 0. T4=  10. T5= 600.  TAUk=     0 INT=18000
ds=.008  Si=.10  ROi=120. Ai=.00000022 dFa=0.05 Kk=.2  tcs= 47.0 dtwc= 0.0  Ts=     0
Pw=.30 Vw=14.39 Va=47.95 tbi= 0. Sim=0.200 Xp=1.00  Lw=0.80 bw=.40 dw=.40  dx=.01000
                              R E S U L T S
***********************************************************************************
```

Time TAU, h / Coordinates z, mm y, mm	tm 0 oC	20 oC	40 oC	60 oC	80 oC	100 oC	120 oC	140 oC	160 oC	180 oC	200 oC
		Coordinate x of the characteristic points, mm									
TAU = 0.0 h											
z=400 mm y= 0 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
z=400 mm y= 20 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
z=400 mm y= 40 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
z=400 mm y= 60 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
z=400 mm y= 80 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
z=400 mm y=100 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
z=400 mm y=120 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
z=400 mm y=140 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
z=400 mm y=160 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
z=400 mm y=180 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
z=400 mm y=200 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
TAU = 5.0 h											
z=400 mm y= 0 mm	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0
z=400 mm y= 20 mm	80.0	75.3	70.8	66.9	63.7	61.2	59.4	58.3	57.7	57.4	57.3
z=400 mm y= 40 mm	80.0	70.8	62.1	54.2	47.7	42.6	39.1	36.8	35.5	34.9	34.7
z=400 mm y= 60 mm	80.0	66.9	54.2	42.7	33.0	25.4	20.0	16.7	14.8	13.9	13.6
z=400 mm y= 80 mm	80.0	63.7	47.7	33.0	20.4	10.4	3.3	-1.0	-3.7	-4.6	-4.9
z=400 mm y=100 mm	80.0	61.2	42.6	25.4	10.4	-1.7	-9.8	-13.9	-16.1	-17.2	-17.5
z=400 mm y=120 mm	80.0	59.4	39.1	20.0	3.3	-9.8	-17.3	-21.6	-23.9	-25.1	-25.5
z=400 mm y=140 mm	80.0	58.3	36.8	16.7	-1.0	-13.9	-21.6	-26.1	-28.7	-30.0	-30.4
z=400 mm y=160 mm	80.0	57.7	35.5	14.8	-3.7	-16.1	-23.9	-28.7	-31.5	-32.9	-33.4
z=400 mm y=180 mm	80.0	57.4	34.9	13.9	-4.6	-17.2	-25.1	-30.0	-32.9	-34.4	-34.9
z=400 mm y=200 mm	80.0	57.3	34.7	13.6	-4.9	-17.5	-25.5	-30.4	-33.4	-34.9	-35.4
TAU = 10.0 h											
z=400 mm y= 0 mm	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0
z=400 mm y= 20 mm	80.0	77.8	75.7	73.7	71.9	70.3	68.9	67.8	67.1	66.6	66.5
z=400 mm y= 40 mm	80.0	75.7	71.5	67.5	63.8	60.6	57.8	55.7	54.1	53.1	52.8
z=400 mm y= 60 mm	80.0	73.7	67.5	61.6	56.1	51.2	47.1	43.8	41.4	39.9	39.4
z=400 mm y= 80 mm	80.0	71.9	63.8	56.1	48.9	42.5	36.9	32.5	29.3	27.3	26.6
z=400 mm y=100 mm	80.0	70.3	60.6	51.2	42.5	34.6	27.7	22.2	18.1	15.6	14.7
z=400 mm y=120 mm	80.0	68.9	57.8	47.1	36.9	27.7	19.7	13.1	8.1	5.0	4.0
z=400 mm y=140 mm	80.0	67.8	55.7	43.8	32.5	22.2	13.1	5.4	-0.6	-4.4	-5.5
z=400 mm y=160 mm	80.0	67.1	54.1	41.4	29.3	18.1	8.1	-0.6	-7.0	-10.3	-11.3
z=400 mm y=180 mm	80.0	66.6	53.1	39.9	27.3	15.6	5.0	-4.4	-10.3	-13.4	-14.3
z=400 mm y=200 mm	80.0	66.5	52.8	39.4	26.6	14.7	4.0	-5.5	-11.3	-14.3	-15.3
TAU = 15.0 h											
z=400 mm y= 0 mm	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0
z=400 mm y= 20 mm	80.0	78.7	77.4	76.2	75.1	74.1	73.2	72.5	72.0	71.7	71.6
z=400 mm y= 40 mm	80.0	77.4	74.9	72.5	70.2	68.2	66.5	65.0	64.0	63.4	63.1
z=400 mm y= 60 mm	80.0	76.2	72.5	68.9	65.6	62.5	59.9	57.8	56.2	55.2	54.9
z=400 mm y= 80 mm	80.0	75.1	70.2	65.6	61.2	57.2	53.7	50.9	48.8	47.5	47.1
z=400 mm y=100 mm	80.0	74.1	68.2	62.5	57.2	52.3	48.1	44.6	42.0	40.4	39.9
z=400 mm y=120 mm	80.0	73.2	66.5	59.9	53.7	48.1	43.1	39.1	36.0	34.2	33.5
z=400 mm y=140 mm	80.0	72.5	65.0	57.8	50.9	44.6	39.1	34.5	31.1	29.0	28.3
z=400 mm y=160 mm	80.0	72.0	64.0	56.2	48.8	42.0	36.0	31.1	27.4	25.1	24.3
z=400 mm y=180 mm	80.0	71.7	63.4	55.2	47.5	40.4	34.2	29.0	25.1	22.7	21.9
z=400 mm y=200 mm	80.0	71.6	63.1	54.9	47.1	39.9	33.5	28.3	24.3	21.9	21.1
TAU = 20.0 h											
z=400 mm y= 0 mm	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0
z=400 mm y= 20 mm	80.0	79.2	78.4	77.7	77.0	76.4	75.9	75.5	75.2	75.0	74.9
z=400 mm y= 40 mm	80.0	78.4	76.9	75.5	74.1	72.9	71.9	71.0	70.4	70.1	69.9
z=400 mm y= 60 mm	80.0	77.7	75.5	73.3	71.3	69.6	68.0	66.8	65.8	65.3	65.1
z=400 mm y= 80 mm	80.0	77.0	74.1	71.3	68.7	66.4	64.4	62.8	61.6	60.8	60.6
z=400 mm y=100 mm	80.0	76.4	72.9	69.6	66.4	63.6	61.1	59.1	57.7	56.8	56.5
z=400 mm y=120 mm	80.0	75.9	71.9	68.0	64.4	61.1	58.3	56.0	54.3	53.3	52.9
z=400 mm y=140 mm	80.0	75.5	71.0	66.8	62.8	59.1	56.0	53.5	51.6	50.4	50.0
z=400 mm y=160 mm	80.0	75.2	70.4	65.8	61.6	57.7	54.3	51.6	49.6	48.3	47.9
z=400 mm y=180 mm	80.0	75.0	70.1	65.3	60.8	56.8	53.3	50.4	48.3	47.0	46.6
z=400 mm y=200 mm	80.0	74.9	69.9	65.1	60.6	56.5	52.9	50.0	47.9	46.6	46.1

Figure 2 Change in t in the nodes of the calculation mesh, situated in the central cross section of a beech prism with dimensions 0.4 x 0.4 x 0.8 m and u = 0.3 kg·kg^{-1} during every 5 h of defrosting at t_m = 80°C

Slika 2. Promjene temperature u čvorovima računske mreže smještenima na središnjemu poprečnom presjeku bukove prizme dimenzija 0,4 x 0,4 x 0,8 m i u = 0,3 kg·kg^{-1} tijekom svakih 5 h odmrzavanja pri temperaturi t_m = 80°C left side) to the points, which are equally distanced (at $d/4$ = 100 mm and $b/4$ = 100 mm) from both surfaces, shaping the cross sections of the prisms.

The first characteristic point is at $L/8$ = 100 mm from the prism base, the second one at $L/4$ = 200 mm, and the third one at $L/2$ = 400 mm. Fig. 4 and 5 shows that there is an almost identical non-linear character of the temperature change in these points, defined mainly by the heat transfer perpendicular to the wood fibers. The defrosting process in the wood slows down almost proportionally to the distance of the characteristic points from the prism base.

The fourth characteristic point with coordinates ($d/4$, $b/2$, $L/2$) is located at $d/4$ =100 mm and $b/2$ = 200 mm from the surfaces, forming the cross section of the prisms and at $L/2$ = 400 mm from the base and the top side of the prisms. The complex non-symmetrical heat transfer in both longitudinal and perpendicular directions to the wood fibers causes at that point an almost linear change in t during the defrosting process.

```
                           I N P U T   D A T A
                       3D DEFROSTING OF BEECH PRISM
Kq=11 M= 21 N= 21 KD= 41 ROb=560. Kwc=1.28 Kwpc=1.88 U=0.60 Ufsp=0.31 Da=2.4 La= 9.0
two= -40. to=-40. t1= 80.0 t2= 80.0 t3= 80.0 tes= 80.0  dtm=.010  tk=20.0 dTAU=   25
T1=1800. T2=  10. T3=  10. dT3=  0. dtm3= 0. T4=  10. T5= 600.  TAUk=     0 INT=18000
ds=.008  Si=.10  ROi=120. Ai=.00000022 dFa=0.05 Kk=.2  tcs= 32.0 dtwc= 0.0  Ts=     0
Pw=.30 Vw=14.39 Va=47.95 tbi= 0. Sim=0.200 Xp=1.00  Lw=0.80 bw=.40 dw=.40  dx=.01000
                                 R E S U L T S
*************************************************************************************
```

Time TAU, h / Coordinates z, mm	y, mm	tm 0 oC	20 oC	40 oC	60 oC	80 oC	100 oC	120 oC	140 oC	160 oC	180 oC	200 oC
TAU = 0.0 h												
z=400 mm	y= 0 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
z=400 mm	y= 20 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
z=400 mm	y= 40 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
z=400 mm	y= 60 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
z=400 mm	y= 80 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
z=400 mm	y=100 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
z=400 mm	y=120 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
z=400 mm	y=140 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
z=400 mm	y=160 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
z=400 mm	y=180 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
z=400 mm	y=200 mm	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0	-40.0
TAU = 5.0 h												
z=400 mm	y= 0 mm	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0
z=400 mm	y= 20 mm	80.0	74.7	69.7	65.3	61.8	59.2	57.5	56.6	56.1	55.9	55.8
z=400 mm	y= 40 mm	80.0	69.7	59.8	51.0	43.7	38.4	35.0	33.2	32.4	32.0	31.9
z=400 mm	y= 60 mm	80.0	65.3	51.0	37.8	26.9	18.7	13.5	10.3	9.7	9.4	9.3
z=400 mm	y= 80 mm	80.0	61.8	43.7	26.9	12.2	-1.1	-3.2	-6.1	-6.9	-7.3	-7.4
z=400 mm	y=100 mm	80.0	59.2	38.4	18.7	-1.1	-7.3	-11.8	-14.6	-16.1	-16.9	-17.2
z=400 mm	y=120 mm	80.0	57.5	35.0	13.5	-3.2	-11.8	-17.2	-20.6	-22.7	-23.7	-24.1
z=400 mm	y=140 mm	80.0	56.6	33.2	10.3	-6.1	-14.6	-20.6	-24.5	-27.0	-28.2	-28.6
z=400 mm	y=160 mm	80.0	56.1	32.4	9.7	-6.9	-16.1	-22.7	-27.0	-29.6	-31.0	-31.5
z=400 mm	y=180 mm	80.0	55.9	32.0	9.4	-7.3	-16.9	-23.7	-28.2	-31.0	-32.6	-33.0
z=400 mm	y=200 mm	80.0	55.8	31.9	9.3	-7.4	-17.2	-24.1	-28.6	-31.5	-33.0	-33.5
TAU = 10.0 h												
z=400 mm	y= 0 mm	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0
z=400 mm	y= 20 mm	80.0	77.5	75.1	72.8	70.8	69.0	67.5	66.3	65.5	65.0	64.9
z=400 mm	y= 40 mm	80.0	75.1	70.3	65.7	61.6	57.9	54.8	52.5	50.8	49.8	49.5
z=400 mm	y= 60 mm	80.0	72.8	65.7	59.0	52.7	47.1	42.4	38.8	36.3	34.8	34.3
z=400 mm	y= 80 mm	80.0	70.8	61.6	52.7	44.4	36.9	30.6	25.7	22.2	20.2	19.7
z=400 mm	y=100 mm	80.0	69.0	57.9	47.1	36.9	27.7	19.6	13.3	8.8	6.1	5.6
z=400 mm	y=120 mm	80.0	67.5	54.8	42.4	30.6	19.6	9.8	2.2	-2.0	-3.7	-4.1
z=400 mm	y=140 mm	80.0	66.3	52.5	38.8	25.7	13.3	2.2	-3.8	-6.6	-8.1	-8.6
z=400 mm	y=160 mm	80.0	65.5	50.8	36.3	22.2	8.8	-2.0	-6.6	-9.5	-11.2	-11.7
z=400 mm	y=180 mm	80.0	65.0	49.8	34.8	20.2	6.1	-3.7	-8.1	-11.2	-12.9	-13.5
z=400 mm	y=200 mm	80.0	64.9	49.5	34.3	19.7	5.6	-4.1	-8.6	-11.7	-13.5	-14.1
TAU = 15.0 h												
z=400 mm	y= 0 mm	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0
z=400 mm	y= 20 mm	80.0	78.5	76.9	75.5	74.1	72.9	71.9	71.0	70.4	70.0	69.8
z=400 mm	y= 40 mm	80.0	76.9	73.9	71.0	68.3	65.8	63.7	61.9	60.6	59.8	59.5
z=400 mm	y= 60 mm	80.0	75.5	71.0	66.7	62.6	58.9	55.6	52.9	50.9	49.6	49.2
z=400 mm	y= 80 mm	80.0	74.1	68.3	62.6	57.2	52.3	47.8	44.2	41.4	39.6	39.0
z=400 mm	y=100 mm	80.0	72.9	65.8	58.9	52.3	46.1	40.5	35.8	32.2	29.8	29.0
z=400 mm	y=120 mm	80.0	71.9	63.7	55.6	47.8	40.5	33.8	28.0	23.4	20.4	19.4
z=400 mm	y=140 mm	80.0	71.0	61.9	52.9	44.2	35.8	28.0	21.1	15.3	11.3	9.7
z=400 mm	y=160 mm	80.0	70.4	60.6	50.9	41.4	32.2	23.4	15.3	8.1	2.6	-1.1
z=400 mm	y=180 mm	80.0	70.0	59.8	49.6	39.6	29.8	20.4	11.3	2.6	-2.0	-2.1
z=400 mm	y=200 mm	80.0	69.8	59.5	49.2	39.0	29.0	19.4	9.7	-1.1	-2.1	-2.3
TAU = 20.0 h												
z=400 mm	y= 0 mm	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0
z=400 mm	y= 20 mm	80.0	79.0	78.0	77.0	76.2	75.3	74.6	74.1	73.6	73.4	73.3
z=400 mm	y= 40 mm	80.0	78.0	76.0	74.1	72.3	70.7	69.3	68.2	67.3	66.8	66.6
z=400 mm	y= 60 mm	80.0	77.0	74.1	71.3	68.7	66.2	64.1	62.4	61.1	60.3	60.0
z=400 mm	y= 80 mm	80.0	76.2	72.3	68.7	65.2	62.0	59.2	56.8	55.1	54.0	53.6
z=400 mm	y=100 mm	80.0	75.3	70.7	66.2	62.0	58.0	54.6	51.7	49.5	48.2	47.7
z=400 mm	y=120 mm	80.0	74.6	69.3	64.1	59.2	54.6	50.5	47.1	44.6	43.0	42.4
z=400 mm	y=140 mm	80.0	74.1	68.2	62.4	56.8	51.7	47.1	43.3	40.4	38.6	38.0
z=400 mm	y=160 mm	80.0	73.6	67.3	61.1	55.1	49.5	44.6	40.4	37.3	35.3	34.6
z=400 mm	y=180 mm	80.0	73.4	66.8	60.3	54.0	48.2	43.0	38.6	35.3	33.2	32.5
z=400 mm	y=200 mm	80.0	73.3	66.6	60.0	53.6	47.7	42.4	38.0	34.6	32.5	31.8

Figure 3 Change in t in the nodes of the calculation mesh, situated in the central cross section of a beech prism with dimensions 0.4 x 0.4 x 0.8 m and u = 0.6 kg.kg^{-1} during every 5 h of defrosting at t_m = 80°C
Slika 3. Promjene temperature u čvorovima računske mreže smještenima na središnjemu poprečnom presjeku bukove prizme dimenzija 0,4 x 0,4 x 0,8 m i u = 0,6 kg·kg^{-1} tijekom svakih 5 h odmrzavanja pri temperaturi t_m = 80°C

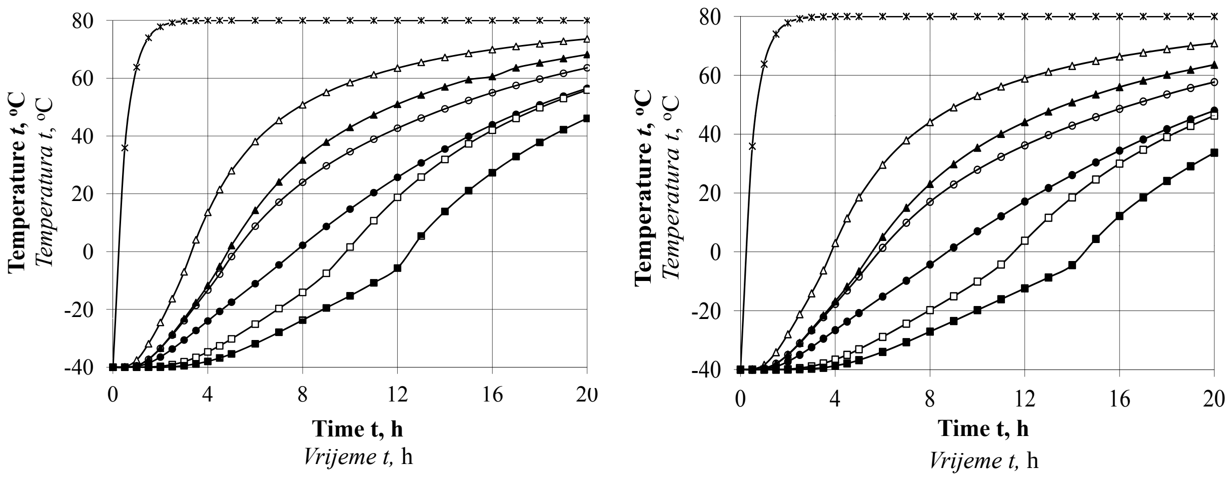

Figure 4 3D change in *t* of frozen beech (left) and oak (right) prism with dimensions 0.4 x 0.4 x 0.8 m, t_0 = -40°C, and $u = 0.3$ kg·kg^{-1} during their defrosting at t_m = 80°C, depending on τ
Slika 4. 3D promjene temperature smrznutih bukovih (lijevo) i hrastovih (desno) prizmi dimenzija 0,4 x 0,4 x 0,8 m, t_0 = -40°C, i $u = 0{,}3$ kg·kg^{-1} tijekom njihova odmrzavanja pri temperaturi t_m = 80°C, u ovisnosti o τ

The fifth and sixth characteristic points with coordinates (*d*/2, *b*/2, *L*/4) and (*d*/2, *b*/2, *L*/2) are located along the prism longitudinal axis. They are equally distanced (at *d*/2 = 200 mm and *b*/2 = 200 mm) from the surfaces forming the cross sections of the prisms. The sixth point with temperature T_C (see Fig. 1 – left side) is located in the centre of the prisms at a double distance (*L*/2 = 400 mm) from the prism base compared to the fifth point with *L*/4 = 200 mm.

The complex non-linear change in temperature in the fifth and sixth characteristic points is almost identical, but it differs from the change in the first three points. This is a result of not only the heat transfer perpendicular to the fibers, but is also caused, to a significant degree, by the heat transfer longitudinal to the fibers. Of course, the double distance of the sixth point from the base of the prism causes a significantly slower

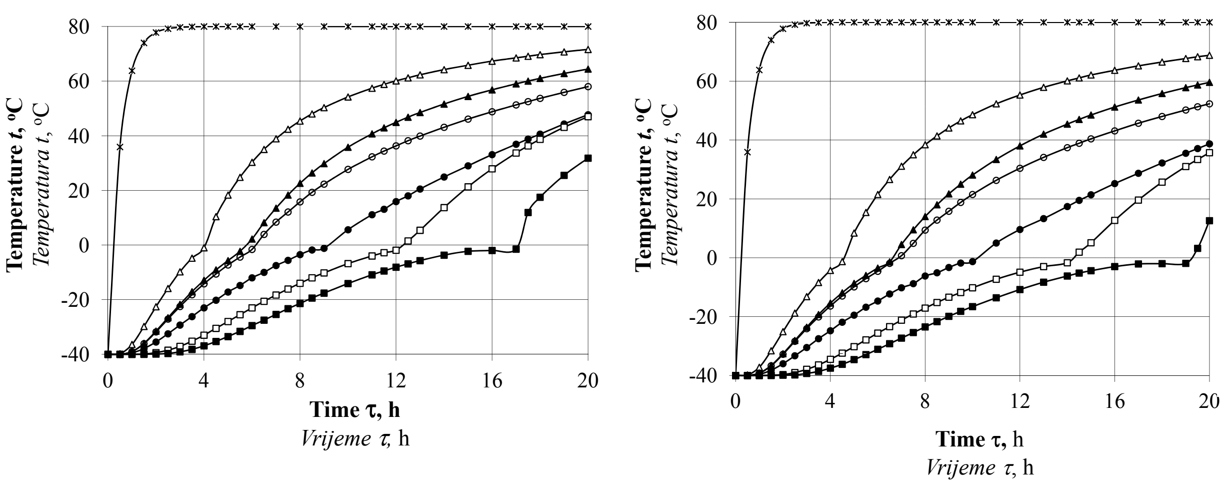

Figure 5 3D change in *t* of frozen beech (left) and oak (right) prism with dimensions 0.4 x 0.4 x 0.8 m, t_0 = -40°C, and $u = 0.6$ kg·kg^{-1} during defrosting at t_m = 80°C, depending on τ
Slika 5. 3D promjene temperature smrznutih bukovih (lijevo) i hrastovih (desno) prizmi dimenzija 0,4 x 0,4 x 0,8 m, t_0 = -40°C, i $u = 0{,}6$ kg·kg^{-1} tijekom njihova odmrzavanja pri temperaturi t_m = 80°C, u ovisnosti o τ

change in *t* compared to the temperature change in the fifth characteristic point.

The computed values of temperature of the third, fourth, and sixth characteristic points during corresponding moments of the defrosting process are underlined in Fig. 2 and 3. Apart from them, the corresponding input data, which is used for the solution of the 3D model, is also underlined. The remaining input data, which is not underlined in the figures, is mainly related to the parameters of the equipment with which the thermal treatment of the wood materials (aimed at defrosting) is carried out. Using this input data, the energy parameters of the defrosting process and the efficiency of the equipment are calculated.

Fig. 4 and 5 shows that the change in temperature in the wood materials is significantly slower during ice melting then in the periods that follow when the materials are heated since there is no ice in the wood. This slowing down is increased in the presence of ice in the materials formed not only from bound water, but also from free water in the wood.

The curves in Fig. 5 show, through characteristic points located on the prism inner layers, the specific almost horizontal sections of long temperature retention in the range from –2 °C to –1 °C, while in these points a complete melting of the ice formed from free water in the wood occurs (Chudinov, 1968). However, the greater the distance of a given characteristic point from the prism surfaces, the higher are its temperature retention values.

For example, it takes about 0.5 h for melting of the ice formed from free water in the point with coordinates *d*/4, *b*/2, *L*/2; in the point with coordinates *d*/2, *b*/2, *L*/4 – about 1.2 h, and in the point with coordinates *d*/2, *b*/2, *L*/2 (central point of the prism volume) – about 2.5 h.

Such temperature retention in the range from –2 °C to –1 °C has been widely observed in experimental studies during the defrosting process of pine logs containing ice from free water (Steinhagen, 1986; Khattabi and Steinhagen, 1992, 1993).

It must be noted that there are no such almost horizontal sections in the change of wood temperature during defrosting of the ice formed only by bound water in the wood (Fig. 4). The reason lies in the fact that melting of the ice, formed by bound water, does not take place in a tight temperature range, but gradually throughout the whole range from the initial temperature of the frozen wood t_0 = -40°C to $t = -2\ ^{\mathrm{o}}\mathrm{C}$. After the final melting of the ice formed from bound water, wood temperature increases more rapidly. This is evidenced by the increase in steepness of the curves in Fig. 4 after $t > -2\ ^{\mathrm{o}}\mathrm{C}$, especially the curves in the inner layers of prisms subjected to defrosting.

A complete melting of the ice formed only from bound water in the center of the studied prisms with dimensions 0.4 x 0.4 x 0.8 m, t_0 = -40°C and u = 0.3 kg·kg^{-1} takes place approximately after 12.5 h of heating at t_m = 80°C for a beech prism and after 14.5 h for an oak prism (Fig. 4). I takes 4.5 h and 5.0 h, respectively, fFor melting the ice formed from free water in beech and oak prisms with u = 0.6 kg·kg^{-1}, under the same conditions, i.e. the final defrosting of the prisms takes place after 17.0 h of thermal treatment for a beech prism and after 19.5 h for an oak prism (Fig. 5). The longer duration of the defrosting process in oak wood is caused by the higher density of the oak wood compared to that of the beech wood.

3.2 Color visualization of 3D non-stationary temperature distribution in prisms during defrosting
3.2. Vizualizacija pomoću boja 3D nestacionarne raspodjele temperature u prizmi za vrijeme odmrzavanja

The results obtained by Visual Fortran for 3D temperature distribution in the volume of wooden prisms undergoing defrosting have been subjected to the following visualization with the help of the software Excel 2010. The color contour plots prepared by this software are exhibited in Fig. 6 and 7, showing the non-stationary temperature distribution in 12 cross sections equally distributed from each other in 1/8 of the volume of the prisms after 5 h and 10 h of heating.

The temperature distribution in oak prisms during their defrosting is analogical to the temperature distribution in beech prisms, as shown in Fig. 6 and 7. A certain slowing down of the defrosting process can be seen in oak prisms, which corresponds to the slowing down in the temperature change in denser oak wood compared to that in beech wood, as shown in Fig. 4 and 5.

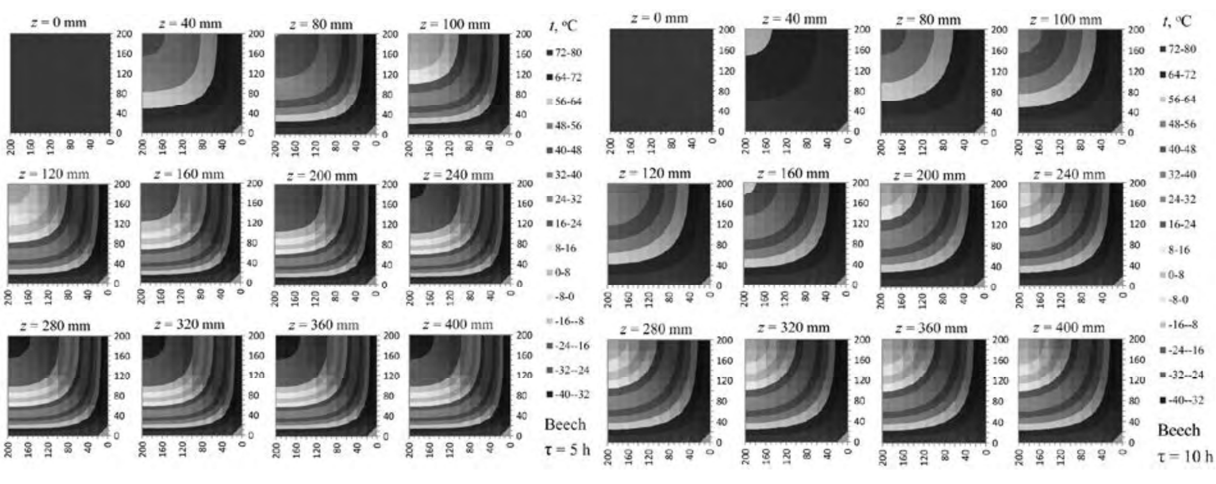

Figure 6 Contour plots of temperature distribution in 1/8 of the volume of the beech prism subjected to defrosting with t_0 = –40 °C and u = 0.3 kg.kg^{-1} after 5 h (left) and 10 h (right) heating at t_m = 80 °C

Slika 6. Konturni crteži raspodjele temperature u 1/8 volumena bukovih prizmi koje se odmrzavaju pri t_0 = –40 °C i uz u = 0,3 kg·kg^{-1} nakon 5 h (lijevo) i nakon 10 h (desno) zagrijavanja na temperaturi t_m = 80 °C

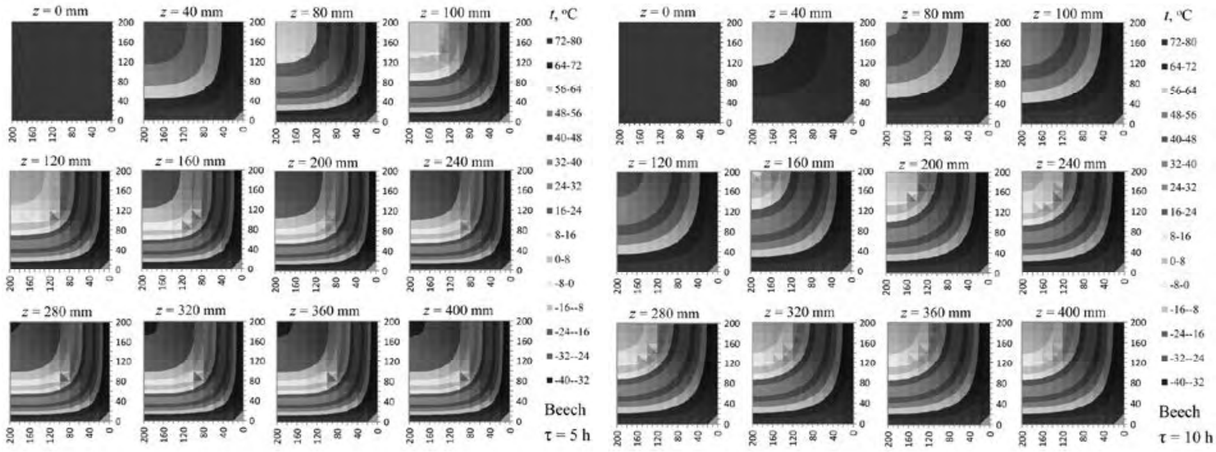

Figure 7 Contour plots of temperature distribution in 1/8 of the volume of the beech prism subjected to defrosting with t_0 = –40 °C and u = 0.6 kg.kg^{-1} after 5 h (left) and 10 h (right) heating at t_m = 80 °C
Slika 7. Konturni crteži raspodjele temperature u 1/8 volumena bukovih prizmi koje se odmrzavaju pri t_0 = –40 °C i uz u = 0,6 kg·kg^{-1} nakon 5 h (lijevo) i nakon 10 h (desno) zagrijavanja na temperaturi t_m = 80 °C

The analysis of the contour plots in Fig. 6 and 7 shows the following:

- When the prisms subjected to defrosting contain ice only formed from bound water in the wood, then all the borders between the adjacent temperature zones on the contour plots are represented by smooth, curved lines (Fig. 6);
- When the prisms contain ice formed from both bound and free water in the wood, then the smoothness of the curved lines of the borders between the adjacent temperature zones from -8 °C to 0 °C and from 0 °C to 8 °C (Fig. 7) is deformed. A reason for this is shown in the analysis presented in the above Fig. 5, when the temperature remains for a long period of time in the range from -2 °C to -1 °C in the points located in the inner layers of the prisms. The temperature ranges between -2 °C and -1 °C until the ice in these points, formed from free water in the wood, is completely melted (Chudinov, 1968). While the points with ice not completely melted are still located in the color zone from -8 °C to 0 °C, some of their adjacent points from the calculation mesh after complete melting of the ice go into the zone from 0 °C to 8 °C. This explains the deformation of the smoothness of the borders between these zones of the contour plots at τ = 5 h and τ = 10 h in prisms with u = 0.6 kg·kg^{-1} (Fig. 7).

A significantly faster temperature increase along the length of the prisms can be seen on the contour plots compared to the increase of the temperature in the cross sectional direction to the wood fibers. The reason for this is a much higher thermal conductivity in the direction longitudinal to the fibers than in the cross sectional direction: 1.76 times for oak and 1.88 times for beech wood (Deliiski, 2003a). For example, after 10 h of defrosting of the beech prism with u = 0.6 kg·kg^{-1} in the temperature zone from 0 °C to 8 °C moves inside the prism as follows (Fig. 7 – right side):

- to a distance equal to $x = y$ = 110 mm from the surfaces forming the central cross section with z = 400 mm, in which the heat transfer perpendicular to the fibers prevails;
- to a distance equal to $x = y$ = 180 mm from the surfaces forming the cross section with z = 160 mm, on which the heat transfer longitudinal to the fibers has a dominant impact.

4 CONCLUSIONS
4. ZAKLJUČCI

This paper describes the development and solution of a 3D non-linear mathematical model for the transient heat conduction in frozen wood with prismatic shape and with any $u \geq 0$ kg·kg^{-1} at arbitrary, initial and boundary conditions encountered in practice. The model takes into account for the first time the fiber saturation point of each wood species, u_{fsp}, and the impact of the temperature on u_{fsp} of frozen and non-frozen wood, which are then used to compute the current values of the thermal and physical characteristics in each separate volume point of the material subjected to defrosting (Deliiski, 2013).

Heat distribution in the entire volume of the prisms is described by the 3D partial differential equation of heat conduction. For the solution of the model, an explicit form of the finite-difference method is used, with the possibility of excluding any model simplifications.

For the numerical solution of the model a software package has been developed in FORTRAN and integrated in the calculation environment of Visual Fortran Professional developed by Microsoft.

Reliability and precision of the model, according to the results of our own experimental studies and studies by other authors, allow various calculations related to the non-stationary temperature distribution in frozen prismatic materials from various wood species during their defrosting.

The results presented in the figures of this paper show that the procedures for the calculation of non-stationary 3D temperature change, developed by the software, are efficient in cases of defrosting of frozen wooden prisms with ice formed of bound water in the wood as well as of both bound and free water in the wood.

The results obtained in the calculation environment of Visual Fortran for the 3D non-stationary temperature distribution in the wooden prism volume undergoing defrosting have been subjected to visualization with Excel 2010. Using this software, the prepared color contour plots show the change of the temperature in cross sections equally distant from each other in 1/8 of the volume of the prisms after the desired durations of their heating. The contour plots can be displayed not only individually at each time step of the defrosting process for detailed examination, but they can also be displayed together as an animation for the overall trend observation, which can be very helpful for the industry operators to easily foresee the overall changes of the process.

The visualization with color contour plots allows tracking and analyzing the movement of the border of ice melting in the volume of the prisms during their heating. Also the change in the temperature perpendicular and longitudinal to the fibers can be seen. With the help of the visualization of contour plots, it is easy to determine the moment of reaching the zone of optimal temperatures in the volume of different wood species, guaranteeing the necessary plasticizing of the wood and producing high-quality veneer.

The updated model is incorporated in the software for microprocessor programmable controllers used for model predictive automatic control (Hadjiyski, 2003) of the process of thermal treatment of prismatic wood with or without ice. The controllers ensure the improved science-based energy- and resource-saving control of plasticized veneer production, compared to that used in a previous version of the software (Deliiski, 2003b; Deliiski and Dzurenda, 2010).

Acknowledgment – Zahvala

This paper was written as a part of the solution of the project “Modelling and Visualization of Wood Defrosting Processes in Technologies for Wood Thermal Treatment”, supported by the Scientific Research Sector of the University of Forestry in Sofia (Project 114/2011).

Symbols - Simboli

b – width, m
c – specific heat capacity, J·kg^{-1}·K^{-1}
d – thickness, m
L – length, m
T – temperature, K
t – temperature, C
u – moisture content, kg·kg^{-1} = %/100
x – coordinate along thickness: $0 \leq x \leq d/2$, m
y – coordinate along width: $0 \leq y \leq b/2$, m
z – longitudinal coordinate: $0 \leq z \leq L/2$, m
β, γ – coefficients in equations for determining of λ, given in Deliiski (2011, 2013)
λ – thermal conductivity, W·m^{-1}·K^{-1}
ρ – density, kg·m^{-3}
τ – time, s
Δx – distance between mesh points in space coordinates, m
Δτ – interval between time levels, s

Subscripts:

b – basic (for density, based on dry mass divided to green volume)
bw – bound water
c – center (of prisms)
cr – cross sectional to wood fibers
e – effective (for specific heat capacity)
fsp – fiber saturation point
fw – free water
i – nodal point along prism thickness: i = 1, 2, 3,…, M=1+[$d/(2\Delta x)$]
j – nodal point along prism width: j = 1, 2, 3, …, N=1+[($b/(2\Delta x)$]
k – nodal point in longitudinal direction of the prism: k = 1, 2, 3, …, KD=1+[$L/(2\Delta x)$]
m – medium (for heating substance)
r – radial to wood fibers
t – tangential to wood fibers
0 – initial (for *t* or at 0 °C for λ)
p – parallel to wood fibers
p/cr– parallel to cross sectional

Superscripts:

n – time level: n = 0, 1, 2, …
20 – 20 °C

5 REFERENCES
5. LITERATURA

1. Chudinov, B. S., 1968: Theory of Thermal Treatment of Wood. Publisher “Nauka”, Moscow (in Russian).
2. Chudinov, B. S., 1984: Water in Wood. Publisher “Nauka”, Moscow (in Russian).
3. Deliiski, N., 2003a: Modeling and Technologies for Steaming of Wood Materials in Autoclaves. DSc. Thesis, University of Forestry, Sofia, 2003 (in Bulgarian).
4. Deliiski, N., 2003b: Microprocessor System for Automatic Control of Logs’ Steaming Process. Drvna industrija, 54 (4), 191-198.
5. Deliiski, N., 2004: Modelling and Automatic Control of Heat Energy Consumption Required for Thermal Treatment of Logs. Drvna Industria, Volume 55 (4), 181-199.
6. Deliiski, N., 2011: Transient Heat Conduction in Capillary Porous Bodies, p.149-176. In: Convection and Conduction Heat Transfer. InTech Publishing House, Rieka, http://dx.doi.org/10.5772/21424
7. Deliiski, N., 2013: Computation of the Wood Thermal Conductivity during Defrosting of the Wood. Wood research, 58 (4) (637-650).
8. Deliiski, N.; Dzurenda, L., 2010: Modeling of the Thermal Processes in the Technologies for Wood Thermal Treatment. TU Zvolen, Slovakia (In Russian).

9. Hadjiyski, M., 2003: Mathematical Models in Advanced Technological Control Systems. Automatic & Informatics, 37 (3): 7-12 (in Bulgarian).
10. Khattabi, A.; Steinhagen, H. P., 1992: Numerical Solution to Two-dimensional Heating of Logs. Holz Roh-Werkstoff, 50: 308-312, http://dx.doi.org/10.1007/BF02615359
11. Khattabi, A.; Steinhagen, H. P., 1993: Analysis of Transient Non-linear Heat Conduction in Wood Using Finite-difference Solutions. Holz Roh- Werkstoff, 51: 272-278, http://dx.doi.org/10.1007/ BF02629373
12. Khattabi, A.; Steinhagen, H. P., 1995: Update of "Numerical Solution to Two-dimensional Heating of Logs". Holz Roh- Werkstoff, 53: 93-94, http://dx.doi.org/10.1007/BF02716399
13. Pervan, S., 2009: Technology for Treatment of Wood with Water Steam. University in Zagreb (In Croatian).
14. Požgaj, A.; Chovanec, D.; Kurjatko, S.; Babiak, M., 1997: Structure and Properties of Wood. 2nd edition, Priroda a.s., Bratislava (In Slovakian).
15. Shubin, G. S., 1990: Drying and Thermal Treatment of Wood. Publisher "Lesnaya promyshlennost", Moskow, URSS (In Russian).
16. Steinhagen, H. P., 1986: Computerized Finite-difference Method to Calculate Transient Heat Conduction with Thawing. Wood Fiber Sci. 18 (3): 460-467.
17. Steinhagen, H. P., 1991: Heat Transfer Computation for a Long, Frozen Log Heated in Agitated Water or Steam - A Practical Recipe. Holz Roh- Werkstoff, 49: 287-290, http://dx.doi.org/10.1007/ BF02663790
18. Steinhagen, H. P.; Lee, H. W., 1988: Enthalpy Method to Compute Radial Heating and Thawing of Logs. Wood Fiber Sci. 20 (4): 415-421.
19. Steinhagen, H. P.; Lee, H. W.; Loehnertz, S. P., 1987: LOGHEAT: A Computer Program of Determining Log Heating Times for Frozen and Non-frozen Logs. Forest Prod. J., 37 (11/12): 60-64.
20. Trebula, P.; Klement, I., 2002: Drying and Hydrothermal Treatment of Wood. TU Zvolen, Slovakia (in Slovakian).
21. Videlov, H., 2003: Drying and Thermal Treatment of Wood. Publishing House of the University of Forestry, Sofia (in Bulgarian).

Corresponding address:

Professor NENCHO DELIISKI, Ph.D. Dsc.
Faculty of Forest Industry
University of Forestry
Kliment Ohridski Blvd. 10
1756 Sofia, BULGARIA
E-mail: deliiski@netbg.com