Nencho Deliiski[1]

Modeling and automatic control of heat energy consumption required for thermal treatment of logs

Modeliranje i automatska kontrola potrošnje toplinske energije potrebne za termičku obradu trupaca

Original scientific paper • Izvorni znanstveni rad
Prispjelo - received: 24. 10. 2004. • Prihvaćeno - accepted: 24. 5. 2005.
*UDK 630*844.53; 630*846; 674.046*

ABSTRACT • *A summarized 2-dimensional mathematical model has been developed, solved, and verified for the transient non-linear heat conduction and energy consumption in frozen and non-frozen logs at arbitrary, initial and boundary conditions met in practice. For the first time the model takes into account the fiber saturation point of each wood species and the specific heat capacity of wood as well as its ice content, formed by freezing of free and hygroscopically bounded water. This paper presents solutions of the model and the simulative investigation of the impact of the processing medium temperature and the initial wood temperature (in presence and absence of ice in the wood) on the change of heat energy required by wood for reaching different temperatures in the centre of logs. The results are used for the development of the algorithm and system for optimizing automatic control of the process of thermal treatment of logs in veneer production.*

Key words: *heat energy, mathematical model, automatic control, thermal conductivity, FORTRAN, logs*

SAŽETAK • *U radu je razvijen i provjeren zajednički dvodimenzionalni matematički model za prijelaznu nelinearnu toplinsku vodljivost i potrošnju energije pri termičkoj obradi smrznutih i nesmrznutih trupaca uz proizvoljne početne i rubne uvjete koje susrećemo u praksi. Model je prvi put uzeo u obzir točku zasićenosti vlakanaca pojedinih vrsta drva i specifični toplinski kapacitet drva, jednako kao i njegov sadržaj leda što je nastao smrzavanjem slobodne i higroskopski vezane vode. Rad prikazuje rješenja modela i simulacijska istraživanja utjecaja temperature procesnog medija i početne temperature drva (pri postojanju ili nepostojanju leda u drvu) na promjene toplinske energije potrebne za postizanje različitih temperatura u središtu trupca. Rezultati se koriste za razvoj algoritma i sustava za optimizaciju automatske kontrole postupaka termičke obrade trupaca u proizvodnji furnira.*

Ključne riječi: *toplinska energija, matematički model, automatska kontrola, toplinska vodljivost, programski jezik FORTRAN, trupci*

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1 INTRODUCTION
1 UVOD

In order to optimize the control of the heating process of logs in veneer and plywood mills, the distribution of the temperature field in the logs must be known at every moment of the process as well as the energy consumed for their heating. There are many publications, which deal with the distribution of the temperature in the logs at different initial and boundary conditions of the process and there are practically none that present the influence of various factors on non-stationary change of heat energy, necessary for heating frozen and non-frozen logs.

H. P. Steinhagen has made considerable contribution to the calculation of non-stationary distribution of temperature in frozen and non-frozen logs and to the duration of their heating. For this purpose, he alone, (Steinhagen, 1986, 1991) or with co-authors (Steinhagen et al. 1987; Steinhagen and Lee, 1988) has developed and solved a 1-dimensional, and later a 2-dimensional (Khattabi and Steinhagen, 1992, 1993, 1995) mathematical model, whose application is only limited to $u \geq 0.3$ kg·kg^{-1}.

These models contain two systems of equations, one of which is used for the calculation of the change in temperature at the axis of the log, and the other - for the calculation of the temperature distribution in the remaining points of its volume.

This paper presents the development, verification and solutions of the summarized 2-dimensional mathematical model of the transient non-linear heat conduction and energy consumption in frozen and non-frozen logs, where the indicated complications and incompleteness in existing analogous models have been overcome. The paper presents the results of simulative investigation of the impact of the processing medium temperature and the initial wood temperature (in presence and absence of ice in the wood) on the change of the heat energy consumption, required by wood for reaching different temperatures in the centre of logs. The results are used for the development of the algorithm and system for optimizing automatic control of the process of thermal treatment of logs in veneer production.

2 MATHERIALS AND METHODS
2 MATERIJALI I METODE

2.1 Mathematical model for heating of logs
2.1 Matematički model za grijanje trupaca

The process of heat transfer in the logs can be described by a non-linear differential equation of thermo-conductivity, which takes the following form in polar coordinates (Deliiski, 1979):

$$\rho_{\mathrm{w}} \cdot c_{\mathrm{we}} \cdot \frac{\partial T(r,z,\tau)}{\partial \tau} = \lambda_{\mathrm{wr}} \cdot \left[\frac{\partial^2 T(r,z,\tau)}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial T(r,z,\tau)}{\partial r}\right] + \frac{\partial \lambda_{\mathrm{wr}}}{\partial T} \cdot \left[\frac{\partial T(r,z,\tau)}{\partial r}\right]^2 + \lambda_{\mathrm{wz}} \cdot \frac{\partial^2 T(r,z,\tau)}{\partial z^2} + \frac{\partial \lambda_{\mathrm{wz}}}{\partial T} \cdot \left[\frac{\partial T(r,z,\tau)}{\partial z}\right]^2 \quad (1)$$

The heat energy, required for melting the ice, which has been formed by freezing of hygroscopically bounded water in wood, has not been taken into account although the value of the specific heat capacity of that ice is comparable to the capacity of the frozen wood itself (Chudinov, 1966). The models assume that the fiber saturation point is identical for all wood species and that the melting of the ice, formed by free water in the wood, which is found in the inter-cellular areas, occurs at 0 °C. However, it is known that there are significant differences between the fiber saturation points of individual wood species and that depending on this point, the quantity of ice developed from free water in the wood, thaws at a temperature ranging between -2 °C and -1 °C (Chudinov, 1984).

with an initial condition

$$T_{\mathrm{w}}(r,z,0) = T_{\mathrm{w0}}\,, \quad (2)$$

and a boundary condition

$$T_{\mathrm{w}}(0,z,\tau) = T_{\mathrm{w}}(r,0,\tau) = T_{\mathrm{m}}(\tau)\,. \quad (3)$$

For the solution of the system of equations (1) ÷ (3), a mathematical description must be provided of the components of thermo-physical characteristics of wood, c_{we}, λ_{wr}, λ_{wz}, and of its density, ρ_{w}.

We have prepared this description by use of experimental data for the thermal characteristics of wood, obtained by Kanter (1955) and Chudinov (1966, 1984) during the development of their dissertations.

Equations in (Deliiski, 2002a) present a mathematical description of the effective specific heat capacity coefficient, c_{we}, of wood as a sum of the capacities of the wood itself, c_w, and the ice formed in it by freezing of free water, c_{fw}, and hygroscopically bounded water, c_{bw}.

The following equations have been derived for the calculation of the heat energy consumption required by logs, and valid for all wood species:

$$c_{we} = c_w + c_{fw} + c_{bw} \ , \tag{4}$$

where, if $271.15 \text{ K} < T \leq 272.15 \text{ K}$ and $u > u_{fsp}$:

$$c_{fw} = 3{,}34 \cdot 10^5 \cdot \frac{u - u_{fsp}}{1+u} \ , \tag{5}$$

and if $T \leq 271.15$ K and $u > u_{nfw}$:

$$c_{bw} = 1{,}8938 \cdot 10^4 \cdot \left(u_{fsp} - 0{,}12\right) \frac{e^{0{,}0567 \cdot (T - 271{,}15)}}{1+u} \cdot \tag{6}$$

When T and u are outside the intervals indicated in equations (5) and (6), the values of c_{fw} and c_{bw} have been assumed to be equal to zero in the solution of the mathematical model.

The values of c_w are mathematically described with the following equations:

a) When $T > 271.15$ K, or when $T \leq 271.15$ K and simultaneously with this $u \leq u_{nfw}$:

- if $u < u_{fsp}$:

$$c_w = \frac{2097 \cdot u + 826}{1+u} + \frac{9{,}92 \cdot u + 2{,}55}{1+u} + \frac{0{,}0002}{1+u} T^2 \tag{7}$$

- if $u \geq u_{fsp}$:

$$c_w = \frac{2862 \cdot u + 555}{1+u} + \frac{5{,}49 \cdot u + 2{,}95}{1+u} + \frac{0{,}0036}{1+u} T^2 \tag{8}$$

b) When $T \leq 271.15$ K and simultaneously with this $u > u_{nfw}$:

$$c_w = K_{wc} \cdot \frac{526 + 2{,}95 \cdot T + 0{,}0022 \cdot T^2 + 2261 \cdot u + 1976 \cdot u_{nfw}}{1+u} , \tag{9}$$

$$K_{wc} = \frac{1{,}06 + 0{,}04 \cdot u + 0{,}00075 \cdot (T - 271{,}15)}{u_{nfw}} , \tag{10}$$

where if $T \leq 271.15$ K, the content of non-frozen water in the wood u_{nfw} is equal to

$$u_{nfw} = 0{,}12 + \left(u_{fsp} - 0{,}12\right) e^{0{,}0567 \cdot (T - 271{,}15)} . \tag{11}$$

Figure 1 shows the change calculated in accordance with the equations (7) ÷ (11), in c_w of pine wood (*Pinus silvestris* L.) with $u_{fsp} = 0.28$ kg·kg^{-1} (Videlov, 2003) depending on T and on u.

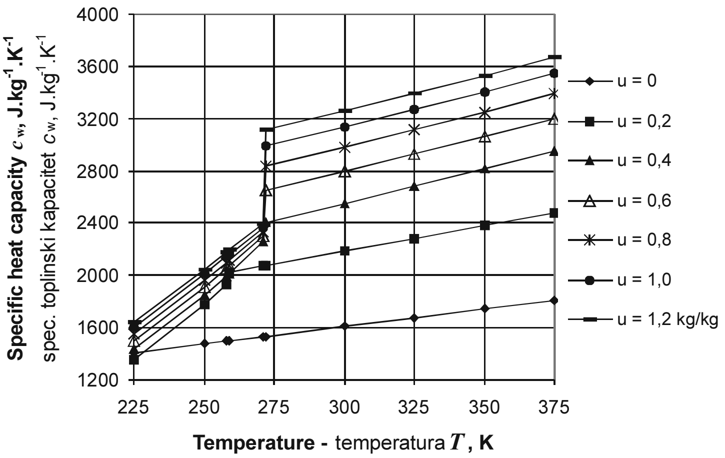

Figure 1
*Change in c_w of pine wood (*Pinus silvestris *L.), depending on T and on u*
Slika 1.
*Promjena specifičnoga toplinskog kapaciteta (c_w) borovine (*Pinus silvestris *L.) u ovisnosti o temperaturi (T) i relativnom sadržaju vode (u)*

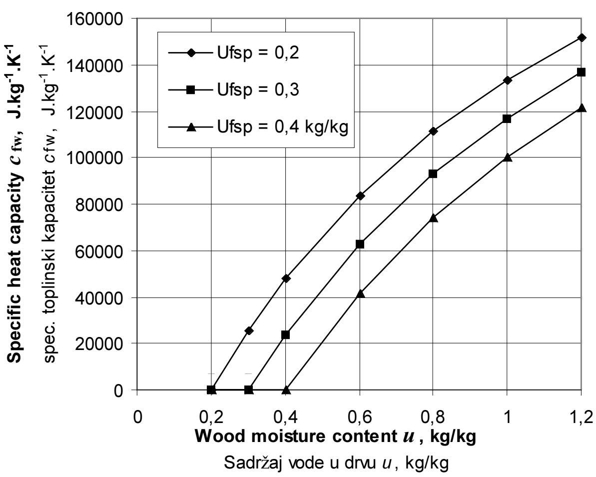

Figure 2
Change in c_{fw}, depending on u and on u_{fsp}
Slika 2.
Promjena specifičnoga toplinskog kapaciteta leda nastaloga u drvu smrzavanjem slobodne vode (c_{fw}) u ovisnosti o u i u_{fsp}

Figure 2 shows the change calculated in accordance with the equation (5) in c_{fw} depending on u and on u_{fsp}. The calculations have been done with a generally accepted average of u_{fsp} = 0.3 kg/kg, and also for the lowest value of u_{fsp} = 0.2 kg/kg and the highest value of u_{fsp} = 0.4 kg/kg, which different wood species can take (Videlov, 2003).

The following equations, which are applicable to all wood species, have been derived for determining of ρ_w (Deliiski, 2002b, 2003a):

- if $u \le u_{fsp}$:

$$\rho_w = \rho_b \cdot \frac{1+u}{1-9{,}3\cdot10^{-4}\,\acute{n}_b \cdot (u_{fsp}-u)}, \quad (14)$$

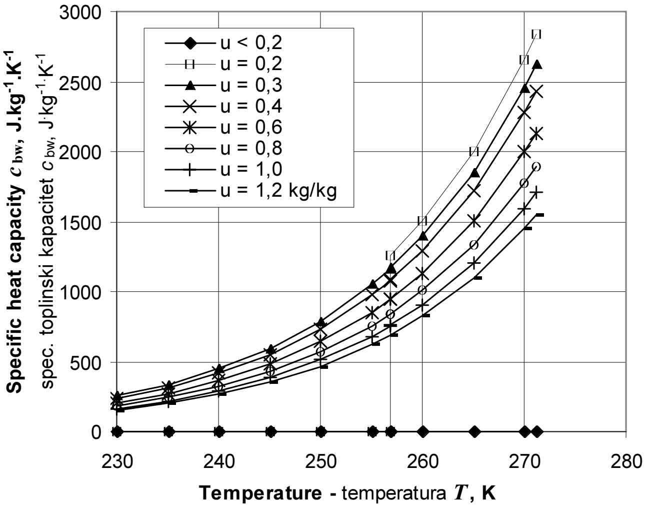

Figure 3
Change in c_{bw} of pine wood with u_{fsp} = 0.28 kg/kg, depending on T and on u
Slika 3.
Promjena specifičnoga toplinskog kapaciteta vezane vode (c_{bw}) borova drva (u_{fsp} = 0.28 kg/kg) u ovisnosti o temperaturi (T) i relativom sadržaju vode (u)

Equations in (Deliiski, 2002b, 2003a) present a mathematical description of wood density, ρ_w, and its thermal conductivity in different anatomical directions, where the following equations have been obtained for λ_{wr} and λ_{wz}:

$$\lambda_{wr} = \lambda_{w0r} \cdot b \cdot [1+\beta\cdot(T-273{,}15)] \quad (12)$$

$$\lambda_{wz} = \lambda_{w0z} \cdot b \cdot [1+\beta\cdot(T-273{,}15)] \quad (13)$$

where the coefficients b and β like λ_{w0r} and λ_{w0z}, depend on u and on wood basic density ρ_b.

Figure 4 shows the change, calculated in accordance with the mathematical description, in λ_{wr} of pine wood depending on T and on u.

- if $u > u_{fsp}$:

$$\rho_w = \rho_b \cdot (1+u) \ . \quad (15)$$

Figure 5 shows the changes calculated in accordance with the equations (14) and (15) in ρ_w of different wood species depending on u and on ρ_b.

2.2 Computation of the temperature distribution in logs during their heating
2.2 Izračun raspodjele temperature u trupcima za vrijeme njihova grijanja

The following system of equations has been derived by adopting final increases in equation (1) with the use of the same, as well as by the explicit form of the finite-difference method (Deliiski, 1977, 2003a) and with the use of equation (12) and (13):

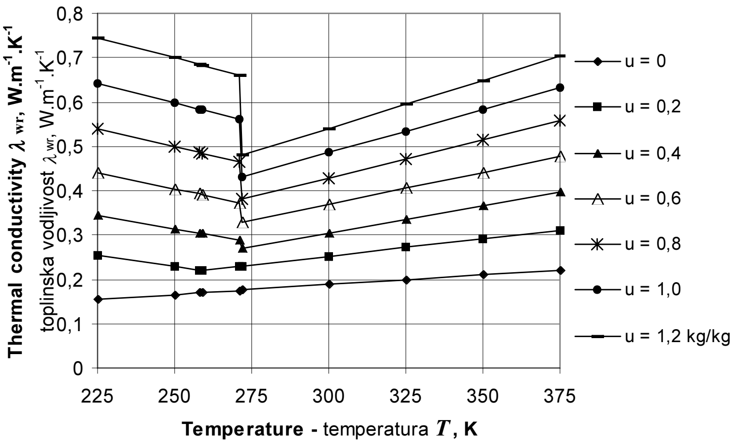

Figure 4
*Change in λ_{wr} of pine wood (*Pinus silvestris *L.), depending on T and on u*
Slika 4.
*Promjena koeficijenta λ_{wr} borova drva (*Pinus silvestris *L.) u ovisnosti o temperaturi (T) i relativnom sadržaju vode (u)*

$$T_{i,k}^{n+1}=T_{i,k}^{n}+\frac{\Delta\tau\cdot b\cdot\lambda_{\mathrm{w0r}}}{\rho_{\mathrm{w}}\cdot c_{\mathrm{we}}\cdot\Delta r^{2}}\left\{\begin{array}{l}\left[1+\beta\cdot\left(T_{i,k}^{n}-273{,}15\right)\right]\left[\begin{array}{l}T_{i-1,k}^{n}+T_{i+1,k}^{n}+K_{\mathrm{wpr}}\cdot\left(T_{i,k-1}^{n}+T_{i,k+1}^{n}\right)-\left(2+2K_{\mathrm{wpr}}\right)T_{i,k}^{n}+\\+\frac{1}{i-1}\cdot\left(T_{i-1,k}^{n}-T_{i,k}^{n}\right)\end{array}\right]+\\+\beta\cdot\left[\left(T_{i-1,k}^{n}-T_{i,k}^{n}\right)^{2}+K_{\mathrm{wpr}}\cdot\left(T_{i,k-1}^{n}-T_{i,k}^{n}\right)^{2}\right]\end{array}\right\} \tag{16}$$

with an initial condition

$$T_{i,k}^{0}=T_{\mathrm{w0}} \tag{17}$$

and a boundary condition

$$T_{0,k}^{n}=T_{i,0}^{n}=T_{\mathrm{m}}(\tau) \tag{18}$$

The presentation of non-linear particular differential equation (1) from the mathematical model through its discrete analogue (16) corresponds to the setting of the coordinate system and positioning of the nodes in the network shown in figure 6, in which the temperature distribution in the log is calculated. The calculation network for the solution of the model through the finite-difference method is built on a 1/4 part from the longitudinal section of the log, because of its symmetry with the remaining 3/4 parts of this section.

The setting of the coordinate system, shown in figure 6 allows, with the help of only one system of equations (16), to calculate the temperature change at any network node of the log volume at the moment $(n+1)\cdot\Delta t$ using already calculated values of T at the preceding moment $n\cdot\Delta t$. This setting differs from the setting of the system, used by Khattabi and Steinhagen (1992, 1993, 1995). Their coordinate system needs two systems of equations, one for calculating the temperature change on the axis of the log, and the second one for calculating the temperature distribution in the remaining network nodes of its volume. The authors also used to apply a more complicated method of enthalpy for the solution of the model instead of the temperature method (Deliiski, 1977 and Steinhagen, 1986). A more rational temperature method is used for the solution of the model in the present paper.

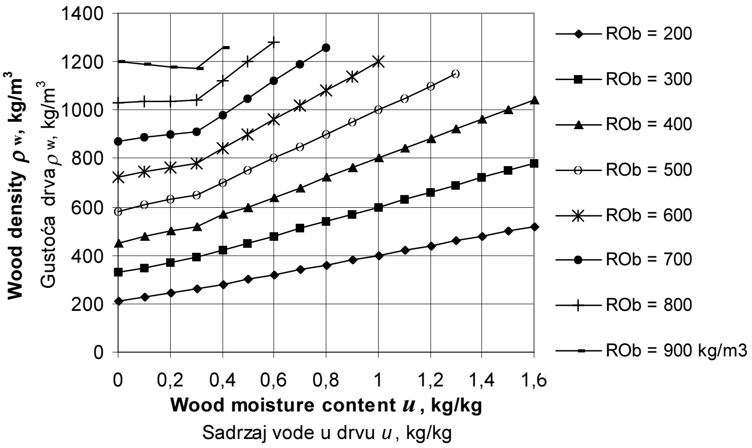

Figure 5
Change in ρ_w of wood from different wood species, depending on u and on ρ_b
Slika 5.
Promjena gustoće (ρ_w) različitih vrsta drva u ovisnosti o relativnom sadržaju vode (u) i nominalnoj gustoći drva (ρ_b)

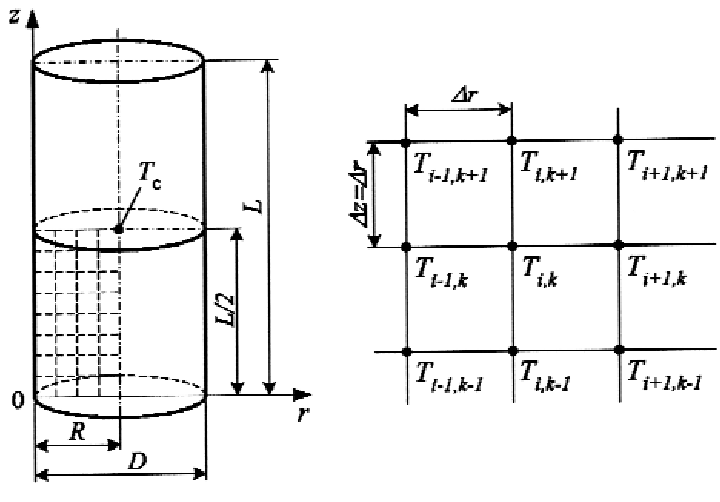

Figure 6
Positioning of the network nodes in a discretized log
Slika 6.
Pozicioniranje čvorova mreže u trupcu podijeljenome u pravilne dijelove

We have performed comprehensive experimental studies for the determination of a 1- and 2-dimensional temperature distribution in the volume of frozen and non-frozen pine, beech, and poplar logs.

The values of the coefficient $K_{\mathrm{wpr}} = \dfrac{\lambda_{\mathrm{w0p}}}{\lambda_{\mathrm{w0r}}}$ in equation (16) have been determined through the solution of the model under 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_{wpr} has the following values: for pine K_{wpr} = 2.37, for beech K_{wpr} = 1.78, and for poplar K_{wpr} = 1.96.

2.3 Computation of specific energy consumption during heating of logs
2.3 Izračun potrošnje specifične toplinske energije pri zagrijavanju trupaca

The average temperature of the log at any moment of heating is calculated by the following equation, which involves numerical integration with the help of the Simpson method (Dorn McCracken, 1972) of the result obtained as the solution of the model of non-stationary distribution of T in the log:

$$T_{\mathrm{wavg}}^{n} = \frac{1}{S_{\mathrm{w}}} \cdot \iint_{(S_{\mathrm{w}})} T_{i,k}^{n} dS_{\mathrm{w}} \ , \tag{19}$$

where

$$S_{\mathrm{w}} = \frac{L \cdot D}{4} \ . \tag{20}$$

The distribution of T in the log volume and the calculation of T_{wavg} are obtained from the solution of the model with an interval between time levels $\Delta\tau$, when the instantaneous values for the boundary conditions and thermo-physical characteristics of wood during heating are taken into consideration. Simultaneously, a calculation is performed of the specific consumption of thermal energy, which is used for heating wood until the moment $n{\cdot}\Delta\tau$, according to equation

$$Q_{\mathrm{wh}}^{n} = \frac{\rho_{w}}{3{,}6 \cdot 10^{6} S_{\mathrm{w}}} \left\{ \iint_{(S_{\mathrm{w}})} \left(T_{i,k}^{n} - T_{i,k}^{0} \right) \frac{c_{\mathrm{we}}(r,z,n\cdot\Delta\tau) + c_{\mathrm{we}}(r,z,0)}{2} dS_{\mathrm{w}} \right\} \tag{21}$$

By using the software prepared by us for the solution of the model in the calculation environment of VISUAL FORTRAN PROFESSIONAL, during the computation of Q_{wh} the average arithmetical values of c_{we} on the right side of the equation (21) are calculated at every interval of Δ_{τ} separately for the interval $T_{\mathrm{w0}} \leq T \leq 271.15$ K in the presence of ice in the wood and separately for the entire interval $T \leq T_{\mathrm{w0}}$ in the absence of ice in it, depending on the instantaneous value of T at every node of the calculation network. In the cases of the presence of ice in the log subjected to heating, the value of c_{we} at the initial moment $c_{\mathrm{we}}(r,z,0) = c_{\mathrm{w}}(r,z,0) + c_{\mathrm{bw}}(r,z,0)$ is calculated for $T = T_{\mathrm{w0}}$. After the "thawing" of the ice in the respective nodes of the network, the calculation of $c_{\mathrm{we}}(r,z,0) = c_{\mathrm{w}}(r,z,0)$ in these nodes is made for T = 271.15 K. In the absence of ice in the log subjected to heating, the value of c_{we} at the initial moment $c_{\mathrm{we}}(r,z,0) = c_{\mathrm{w}}(r,z,0)$ is calculated for $T = T_{\mathrm{w0}}$.

In order to ensure a smooth change of Q_{wh} in the course of the progress of thawing of the ice in the log, formed from free water in the wood, the calculations are performed for a sufficiently large number of network nodes. At the moment when each network node reaches for the first time the temperature of $271.15 < T \leq 272.15$ K, corresponding to the thawing of this ice, the heat of the phase transition cfw, calculated by equation (5) and divided by the entire number of the network nodes, is added to the current heat energy calculated by equation (21).

3 RESULTS AND DISCUSSION
3 REZULTATI I RASPRAVA

With the help of this model, the changes in T and Q_{wh} are studied for frozen and non-frozen pine (*Pinus silvestris* L.) logs with D = 0.4 m, L = 4.0 m and u = 0.6 kg·kg^{-1} during their heating at different T_{m}. The values of D, L and u have been so selected, as to correspond to cases most frequently met in practice.

The influence of T_{m} on the duration τ_{p} has been studied, required for reaching a certain temperature in the centre of the logs T_{c}, which must be achieve at the end of the thermal treatment before the rotary cutting

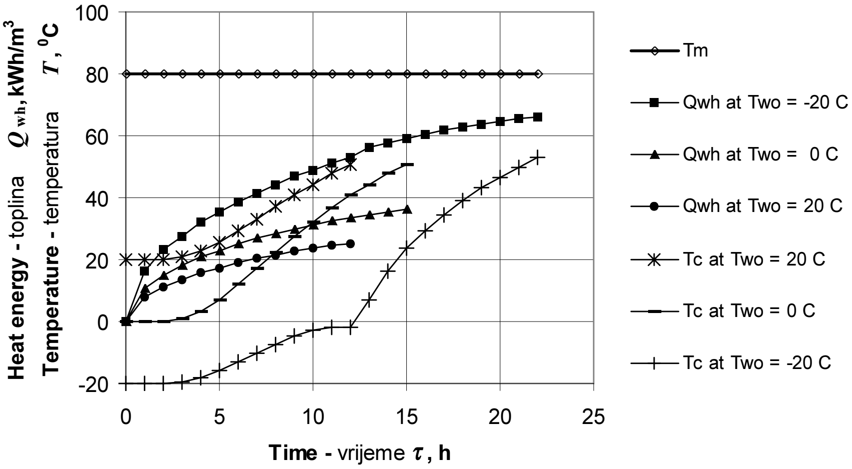

Figure 7
Change in Q_{wh} and T_c of frozen and non-frozen pine logs with D = 0.4 m, L = 4.0 m and u = 0.6 kg/kg during their heating at T_m = 80 °C, depending on T_{w0}
Slika 7.
Promjena jedinične potrošnje toplinske energije (Q_{wh}) i temperature u sredini trupca (T_c) smrznutih i nesmrznutih borovih trupaca promjera D = 0.4 m i dužine L = 4.0 m, relativnog sadržaja vode u = 0.6 kg/kg, za vrijeme grijanja na T_m = 80 °C u ovisnosti o T_{w0}

or slicing of veneer, and also on the specific heat energy consumption Q_{wh} during the heating process. The calculations have been done with average values of ρ_b = 430 kg/m^3 and u_{fsp} = 0.28 kg/kg of the pine wood (Videlov, 2003) and number of knots in the calculation network, equal to 20 along the r coordinate and 200 along the z coordinate.

Figure 7 shows the change in T_c and Q_{wh} of the frozen pine logs (with T_{wo} = -20 °C) and non-frozen (with T_{wo}= 0 °C and T_{wo} = 20 °C) pine logs during their heating at T_m = 80 °C. The influence of T_{wo}, T_m and T_c on Q_{wh} and τ_p of frozen and non-frozen pine logs are shown in Figure 8 and Figure 9, respectively.

The obtained results lead to the following conclusions:

1. The increase of Q_{wh} during the heating occurs approximately at exponents, which begin at 0 and asymptotically approach the maximum values Q_{wh}^{max}, depending increasingly on T_m and decreasingly on T_{wo}. The steepness of these exponents depends decreasingly on T_{wo} and increasingly on T_m.
2. The increase of T_{wo} causes a proportional decrease of Q_{wh} with a slope, which is practically identical for both frozen and non-frozen wood. This slope decreases insufficiently with the decrease of T_m.
3. The increase of T_m causes a proportional increase of Q_{wh} with a coefficient equal to 0.33 kWh/(m^3·K) for frozen and to 0.31 kWh/(m^3·K) for non-frozen pine logs.
4. The increase of T_c causes a proportional increase of Q_{wh} with a coefficient equal to 0.26 kWh/(m^3·K) for both frozen and non-frozen logs.
5. When T_{wo} < 2 °C and $u > u_{fsp}$, a jump in the change of Q_{wh} between -2 °C and -1 °C is observed, caused by the need for additional energy for thawing of the ice, formed from the free water in the wood. For the studied values of D, L and u of pine logs this jump in the change of the specific heat energy consumption Q_{wh} is equal to 19.2 kWh/m^3.

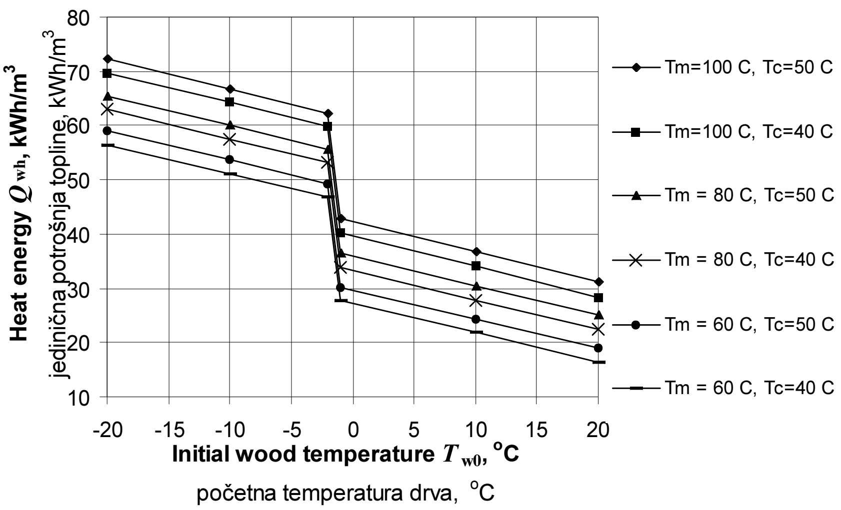

Figure 8
Change in Q_{wh} of frozen and non-frozen pine logs with D = 0.4 m, L = 4.0 m and u = 0.6 kg/kg, depending on T_{w0}, T_m and T_c
Slika 8.
Promjena jedinične potrošnje toplinske energije (Q_{wh}) za smrznute i nesmrznute borove trupce promjera D = 0.4 m i dužine L = 4.0 m, relativnog sadržaja vode u = 0.6 kg/kg u ovisnosti o T_{w0}, T_m i temperaturi u sredini trupca (T_c)

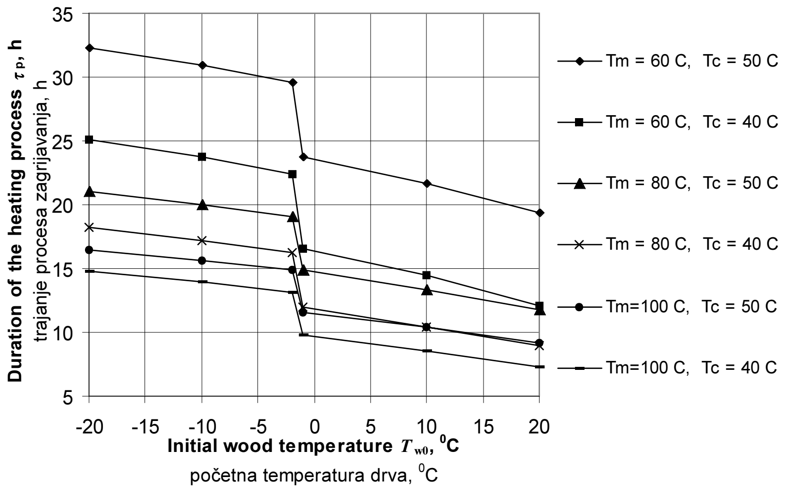

Figure 9
Change in τ_p of frozen and non-frozen pine logs with D = 0.4 m, L = 4.0 m and u = 0.6 kg/kg, depending on T_{w0}, T_m and T_c
Slika 9.
Promjena τp smrznutih i nesmrznutih borovih trupaca promjera D = 0.4 m i dužine L = 4.0 m, relativnog sadržaja vode u = 0.6 kg/kg u ovisnosti o T_{w0}, T_m i temperaturi u sredini trupca (T_c)

6. The increase of T_{wo} causes a proportional decrease of τ_p with a slope higher by approximately 30 - 40 % with non-frozen logs than with frozen logs. This slope decreases with the increase of the medium temperature T_m.
7. The increase of T_m and the decrease of T_c cause an accelerated non-linear decrease of τ_p. This important fact and its quantitative parameters under different initial and boundary conditions must be taken into consideration during the automatic control of the thermal treatment of logs, when a compromise between the decrease of the specific heat energy consumption and the corresponding increase of the duration of this treatment is investigated.

4 CONCLUSION
4 ZAKLJUČAK

The present paper describes the development and solution of a 2-dimensional mathematical model for non-stationary heating of frozen and non-frozen logs. The model takes into account the physics of the process and allows the calculation of the temperature distribution in the logs volume of different wood species subjected to heating, and also of the specific consumption of thermal energy required by logs during their heating.

The development of the model and algorithms and software for its solution is consistent with the possibility for their use in automatic systems with a model predicting control (Hadjiyski, 2003) of different technological processes for logs' thermal treatment.

At this stage the solutions of the model, obtained using a personal computer, are adequately processed and input into a computing and controlling algorithm of microprocessor programmable logic controllers (PLC). This algorithm reflects the above described quantitative influence of T_m and T_{wo} (both in the presence and absence of ice in the wood) on Q_{wh} and T_c for different wood species (Deliiski 2003b).

As a result of the adoption of such PLC for the automatic calculation, regulation and optimization of steaming of logs in pits, chambers and autoclaves, the quality and quantity of veneer output have been improved and the specific heat energy consumption has been significantly decreased.

Symbols
Oznake

a = temperature conductivity (*toplinska vodljivost*), $m^2 \cdot s^{-1}$
c = specific heat capacity (*specifični toplinski kapacitet*), $W \cdot kg^{-1} \cdot K^{-1}$
D = diameter (*promjer*), m
e = exponent (*eksponent*)
L = length (*duljina*), m
Q = specific heat energy (*jedinična toplinska energija*), $kWh \cdot m^{-3}$
r = radial coordinate (*radijalne koordinate*): $0 \leq r \leq R$, m
R = radius (*polumjer*), m
S = area (*površina*), m^2
T = temperature (*temperatura*), K
t = temperature (*temperatura*), ^oC
u = moisture content (*sadržaj vode*), kg/kg = %/100
z = longitudinal coordinate (*longitudinalne koordinate*): $0 \leq z \leq L/2$, m
λ = thermal conductivity (*toplinska vodljivost*), $W \cdot m^{-1} \cdot K^{-1}$
ρ = density (*gustoća*), $kg \cdot m^{-3}$
τ = time (*vrijeme*), s
Δr = distance between mesh points in space coordinates (*udaljenost među točkama mreže u prostornim koordinatama*), m
$\Delta\tau$ = interval between time levels (*interval između vremenskih razina*), s

Subscripts
Donji indeksi

a = anatomical direction (*anatomski smjer*)
avg = average (*srednji*)
b = basic (for density, based on dry mass divided by green volume) / nominalni (*za*

gustoću, utemeljeno na suhoj masi podijeljenoj volumenom u svježem stanju)
bw = bound water (*vezana voda*)
c = center (of logs) / *sredina (trupaca)*
fsp = fiber saturation point (*točka zasićenosti vlakanaca*)
fw = free water (*slobodna voda*)
i = nodal point in radial direction: 1, 2, 3,…, (R/Δr)+1 / *čvorna točka u radijalnom smjeru: 1, 2, 3,…, (R/Δr)+1*
h = heat (*toplina*)
k = nodal point in longitudinal direction: 1, 2, 3,…, (R/Δr)+1 / *čvorna točka u longitudinalnom smjeru: 1, 2, 3,…, (R/Δr)+1*
m = medium (*medij*)
nfw = non-frozen water (*nesmrznuta voda*)
0 = initial (at 0°C for λ) / *početni (pri 0°C za λ)*
p = parallel to the fibers (*paralelno s vlakancima*)
p = process (for duration of the heating process) / *postupak (za vrijeme zagrijavanja)*
pr = parallel to the radial direction (*paralelno s radijalnim smjerom*)
r = radial direction (radial to the fibers) / *radijalni smjer (radijalno s obzirom na vlakanca)*
w = wood (*drvo*)
we = wood effective (for specific heat capacity) / *efektivno drvo (za specifični toplinski kapacitet)*
z = longitudinal direction (parallel to the fibers) / *longitudinalni smjer (paralelno s vlakancima)*

Superscripts
Gornji indeksi

n = time level 0, 1, 2, … / *vremenski nivo 0, 1, 2, …*

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