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MODELING OF THE DEFROSTING PROCESS OF PRISMATIC BEECH MATERIALS

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ABSTRACT

By the first co-author earlier a 3-dimensional mathematical model has been created, solved, and verified for the transient non-linear heat conduction in frozen prismatic wood materials during their heating. Now in the model the dependence of the fiber saturation point of the separate wood species from the temperature has been incorporated.

The paper presents graphically solutions of the updated model of the obtained calculated results about the temperature distribution in the volume of beech frozen materials with prismatic shape with thickness 0,4 m, width 0,4 m, length 0,8 m, initial temperature -40 ^{o}C, and moisture content 0,3 kg.kg^{-1} and 0,6 kg.kg^{-1} during their defrosting at temperature of the processing medium of 80 ^{o}C.

Key words: frozen wood, beech prisms, defrosting, modeling, temperature distribution

INTRODUCTION

For the optimization of the defrosting processes in the wood materials, it is required that the distribution of the temperature fields in the materials at every moment of the process is known. The intensity of the defrosting processes depends on the dimensions and the initial temperature and moisture content of the materials, on the texture and micro-structural features of the wood, on their anisotropy and on the content and aggregate condition of the water in them, on the law of change and the values of the temperature of the defrosting medium, etc. (Deliiski 2003, 2011, Deliiski and Dzurenda 2010).

The correct and effective control of the defrosting processes is possible only when its physics and the weight of the influence of each of the mentioned above as well as of many other specific factors for the concrete wood specie are well understood. Summarizing the influence of a few dozen factors on the defrosting processes of the wood materials is a difficult task and its solution is possible only with the assistance of adequate for these processes mathematical models.

This paper presents shortly the creation and solution of the 3-dimensional mathematical model of the transient non-linear heat conduction in frozen wood materials with prismatic form during their defrosting.

3D MATHEMATICAL MODEL OF THE DEFROSTING PROCESS OF PRISMATIC WOOD MATERIALS

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

$$c_{\mathrm{e}}(T,u)\rho(T,u)\frac{\partial T(x,y,z,\tau)}{\partial\tau}=\frac{\partial}{\partial x}\left[\lambda_x(T,u)\frac{\partial T(x,y,z,\tau)}{\partial x}\right]+ \\ +\frac{\partial}{\partial y}\left[\lambda_y(T,u)\frac{\partial T(x,y,z,\tau)}{\partial y}\right]+\frac{\partial}{\partial z}\left[\lambda_z(T,u)\frac{\partial T(x,y,z,\tau)}{\partial z}\right], \qquad (1)$$

where c_{e} is the effective specific heat capacity of the frozen wood, $\mathrm{W.kg^{-1}.K^{-1}}$;

ρ – the density of the wood, $\mathrm{kg.m^{-3}}$;

u – the wood moisture content, $\mathrm{kg.kg^{-1}}$ = %/100;

T – temperature, K;

λ_x, λ_y and λ_z – the thermal conductivity of the wood in the radial, tangential and longitudinal anatomical directions of the prismatic materials respectively, which coincide with the coordinate axes x, y, and z, $\mathrm{W.m^{-1}.K^{-1}}$;

x – coordinate on the thickness d of subjected to defrosting materials: $0 \le x \le d/2$, m;

y – coordinate on the width b of subjected to defrosting materials: $0 \le y \le b/2$, m;

z – coordinate on the length L of subjected to defrosting materials: $0 \le z \le L/2$, m;

τ – time, s.

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 of the non-stationary defrosting of the subjected to thermal treatment wood materials with prismatic form is obtained:

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

with an initial condition

$$T(x,y,z,0)=T_0 \qquad \textbf{(3)}$$

and boundary condition

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

where T_0 is the initial temperature of the frozen wood materials, K;

T_{m} - the processing medium temperature during thermal treatment of the wood, K;

For the solution of the system of equations (2) ÷ (4), a mathematical description of the participant in it thermo-physical characteristics of the wood, c_{e}, λ_{r}, λ_{t}, λ_{z}, and of its density, ρ, is needed. Equations in (Deliiski 2003, 2011) present a mathematical description of the effective specific heat capacity coefficient, c_{e}, of the wood as a sum of the capacities of the wood itself, c, and the created in it ice from the freezing of the free water, c_{fw}, and of the hygroscopically bound water, c_{bw}.

Equations in (Deliiski 2003, 2011) present also a mathematical description of the density of the wood, ρ, and of its thermal conductivity λ in different anatomical directions.

COMPUTATION OF THE TEMPERATURE DISTRIBUTION IN WOOD MATERIALS DURING THEIR DEFROSTING

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

$$T_{i,j,k}^{n+1} = T_{i,j,k}^{n} + \\ + \frac{\gamma\Delta\tau}{c_e\rho}\left\{\begin{aligned} &\frac{\lambda_{0r}}{\Delta x^2}\left[\left[1+\beta\left(T_{i,j,k}^{n}-273{,}15\right)\right]\left(T_{i+1,j,k}^{n}+T_{i-1,j,k}^{n}-2T_{i,j,k}^{n}\right)+\beta\left(T_{i,j,k}^{n}-T_{i-1,j,k}^{n}\right)^2\right]+ \\ &+\frac{\lambda_{0t}}{\Delta y^2}\left[\left[1+\beta\left(T_{i,j,k}^{n}-273{,}15\right)\right]\left(T_{i,j+1,k}^{n}+T_{i,j-1,k}^{n}-2T_{i,j,k}^{n}\right)+\beta\left(T_{i,j,k}^{n}-T_{i,j-1,k}^{n}\right)^2\right]+ \\ &+\frac{\lambda_{0p}}{\Delta z^2}\left[\left[1+\beta\left(T_{i,j,k}^{n}-273{,}15\right)\right]\left(T_{i,j,k+1}^{n}+T_{i,j,k-1}^{n}-2T_{i,j,k}^{n}\right)+\beta\left(T_{i,j,k}^{n}-T_{i,j,k-1}^{n}\right)^2\right] \end{aligned}\right\}. \quad (5)$$

where i is the nodal point in the direction along the thickness for the prisms: i = 1, 2, 3, …, ($d/\Delta x$)+1;

j – the nodal point in the direction along the prisms' width: j = 1, 2, 3, …, ($b/\Delta x$)+1;

k – the nodal point in longitudinal direction of the prisms: k = 1, 2, 3, …, [$L/(2\Delta x)$]+1;

n – the nodal point in the direction along the time, n = 0, 1, 2, 3, …., ($\tau_{tr}/\Delta\tau$);

τ_{tr} – the duration of the thermal treatment of the prisms with aim of their defrosting, s;

$\Delta\tau$ – interval between time levels, s;

Δx, Δy, Δz, – distance between mesh points in space coordinates for the prisms, m.

λ_{0r}, λ_{0t} and λ_{0p} – the thermal conductivity of the wood the radial, tangential and longitudinal anatomical directions of the prisms at 0 ^{o}C, W.m^{-1}.K^{-1}.

β, γ – coefficients for determining of λ_x, λ_y and λ_z, given in Deliiski (2003, 2011).

The initial condition (2) in the 3D mathematical model is presented using the following finite differences equation:

$$T_{i,j,k}^{0} = T_0 . \quad \textbf{(6)}$$

The boundary conditions (3) get the following easy for programming form:

$$T_{1,j,k}^{n+1} = T_{i,1,k}^{n+1} = T_{i,j,1}^{n+1} = T_{m}^{n+1} . \quad \textbf{(7)}$$

RESULTS AND DISCUSSION

For the numerical solution of the above presented model a software package has been prepared in FORTRAN, which has been input in the developed by Microsoft calculation environment of Visual Fortran Professional (Deliiski 2011).

With the help of the program the 3D change in t in the volume of frozen beech prisms with initial temperature $t_0 = -40\ ^{0}C$ with d = 0,4 m, b = 0,4 m, L = 0,8 m, basic density $\rho_b = 560$ kg.kg^{-1}, fiber saturation point at 20 ^{o}C $u_{fsp}^{20} = 0{,}31$ kg.kg^{-1}, and two values of the wood moisture content: u = 0,3 kg.kg^{-1} and u = 0,6 kg.kg^{-1} has been calculated during the time of thermal processing during 20 hours at a prescribed surface temperature $t_m = 80^{0}$C.

On Fig. 1 and Fig. 2 the computed change in the surface temperature of the prisms, which is equal to t_m, and also in the temperature in 6 characteristic points in the ¼ of the volume of prisms (because of its symmetry to the rest ¾ of the volume) with $u = 0.3$ kg.kg^{-1} containing ice only from bounded water and with $u = 0.6$ kg.kg^{-1} containing ice both from bounded and free water is shown. The coordinates of the characteristic points are given in the legend of the graphs.

The increasing of t_m from the value of $t_{m0} = t_{w0}$ to t_m = 80 °C goes exponentially with time constant, equal to 1800 s. This increasing of t_m at the beginning of the defrosting process of prisms can be seen on the Fig. 1 and Fig. 2.

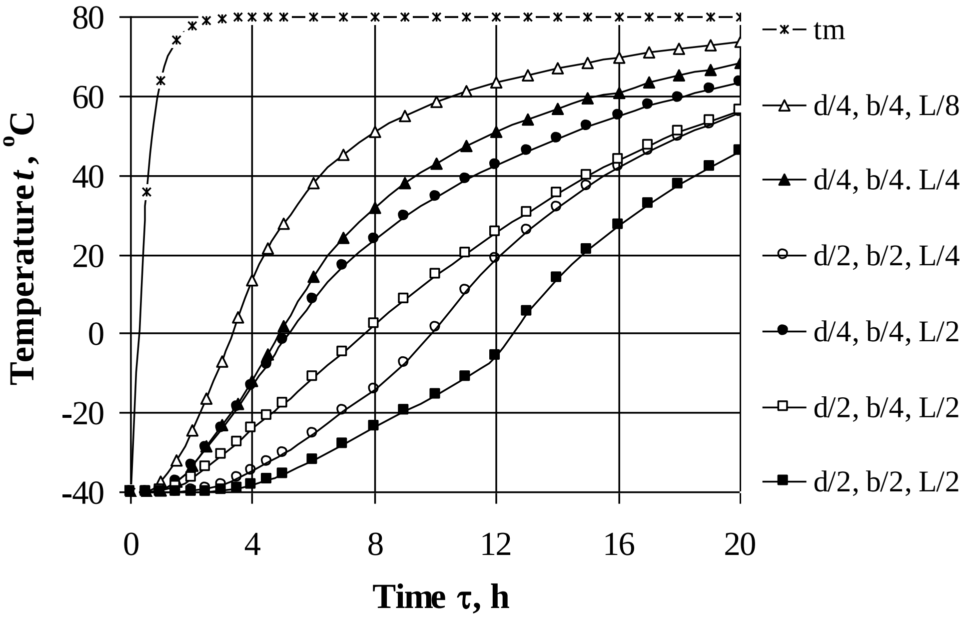

Figure 1: 3D defrosting at $t_m = 80$ °C of frozen beech prism with dimensions 0,4 x 0,4 x 0,8 m, $t_0 - 40$ °C , $\rho_b = 560$ kg.kg^{-1}, $u_{fsp}^{20} = 0,31$ kg.kg^{-1}, and $u = 0,3$ kg.kg^{-1}, depending on τ

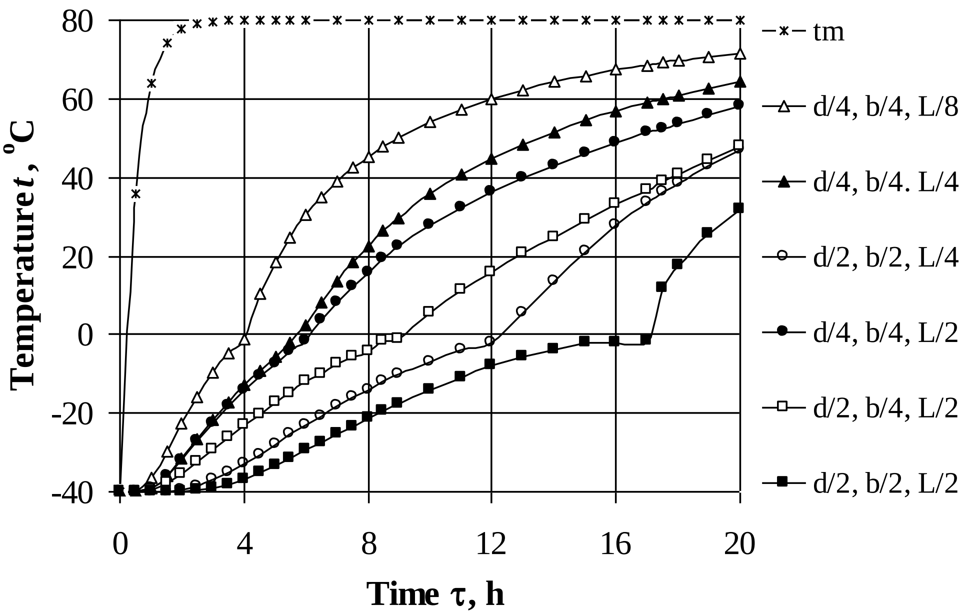

Figure 2: 3D defrosting at $t_m = 80$ °C of frozen beech prism with dimensions 0,4 x 0,4 x 0,8 m, $t_0 - 40$ °C, $\rho_b = 560$ kg.kg^{-1}, $u_{fsp}^{20} = 0,31$ kg.kg^{-1}, and $u = 0,6$ kg.kg^{-1}, depending on τ

On the curves on Fig. 2 in situated on the prism's inner layers characteristic points the specific almost horizontal sections of retention of the temperature for a long period of time in the range from -2 ^{o}C to -1 ^{o}C can be seen, while in these points a complete melting of the ice from the free water in the wood occurs (Chudinov 1968). However much a given characteristic point is distant from the prism's surfaces, this much its retention of the temperature in this range is longer.

For example, the duration of the melting of the ice from the free water in the point with coordinates d/2, b/4, L/2 lasts about 0,5 h; in the point with coordinates d/2, b/2, L/4 - about 0,5 h, and in the point with coordinates d/2, b/2, L/2 (central point of the prisms' volume) - 2,0 h.

Such retention of the temperature in the range from -2 ^{o}C to -1 ^{o}C has been observed in wide experimental studies during the defrosting process of pine logs containing ice from the free water (Steinhagen 1986, Khattabi and Steinhagen 1992, 1993).

It must be noted, that such almost horizontal sections in the change of the wood temperature are absent during defrosting of the ice, formed only by bounded water in the wood (Fig. 1). A reason for this is the fact that the melting of the ice, formed by the bounded water, takes place not in a tight temperature range, but gradually throughout the whole diapason from the initial temperature of the frozen wood equal to $t_0 = -40\ ^{o}\mathrm{C}$ to $t = -2\ ^{o}\mathrm{C}$. Following the final melting of the ice from the bounded water the increase of the wood temperature accelerates. This is evidenced by the increase in steepness of all curves on Fig. 1 after $t > -2\ ^{o}\mathrm{C}$.

A complete melting of the ice from the bounded water in the center of the studied beech prism with dimensions 0,4 x 0,4 x 0,8 m takes place approximately after 12.5 hours of thermal treatment (Fig. 1). For the melting of the ice from the free water in a beech prism with the same dimensions with $u = 0.6\ \mathrm{kg.kg^{-1}}$ are necessary another 4.5 hours, i.e. the final defrosting of the prism takes place after 17.0 hours of thermal treatment at t_m = 80 ^{o}C (Fig. 2).

CONCLUSIONS

This paper describes the approach for creation and solution of a 3D non-linear mathematical model for the transient heat conduction in frozen wood materials with prismatic shape and with any $u \geq 0$ kg.kg^{-1}. The mechanism of the heat distribution in the entire volume of the prisms is described by the partial differential equation of heat conduction. For the solution of the model an explicit form of the finite-difference method is used, which allows for the exclusion of any simplifications in the models.

For the numerical solution of the model a software package has been prepared in FORTRAN, which has been input in the developed by Microsoft calculation environment of Visual Fortran Professional.

The results presented on the figures show that the procedures for calculation of non-stationary change in t in the prepared software package functions well for the cases of defrosting of frozen wood prisms with ice in them, which is created by the freezing only of bounded water in the wood and by both the bounded and the free water in the wood as well.

The good adequacy and precision of the model towards the results from numerous own and foreign experimental studies allows for the carrying out of various calculations with the model, which are connected to the non-stationary distribution of t in frozen prismatic materials from various wood species and also to the heat energy consumption by the prisms during their defrosting.

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REFERENCES

1. Chudinov, B. S., (1968). Theory of the thermal treatment of wood. Publishing Company "Nauka", Moscow, USSR.
2. Deliiski, N., (2003). Modelling and technologies for steaming wood materials in autoclaves. Dissertation for Dr.Sc., University of Forestry, Sofia.
3. Deliiski, N., (2011). Transient heat conduction in capillary porous bodies. In Ahsan A (ed) Convection and conduction heat transfer. InTech Publishing House, Rieka: 149–176.
4. Deliiski, N., Dzurenda, L., (2010). Modelling of the thermal processes in the technologies for wood thermal treatment. TU Zvolen, Slovakia.
5. Khattabi, A., Steinhagen, H. P., (1992). Numerical solution to two-dimensional heating of logs. Holz Roh- Werkstoff 50(7-8): 308–312
6. Khattabi, A., Steinhagen, H. P., (1993). Analysis of transient non-linear heat conduction in wood using finite-difference solutions. Holz Roh- Werkstoff 51(4): 272–278
7. Steinhagen, H. P., (1986). Computerized finite-difference method to calculate transient heat conduction with thawing. Wood Fiber Science 18(3): 460–467