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COMPUTATION OF THE WOOD THERMAL CONDUCTIVITY DURING DEFROSTING OF THE WOOD

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ABSTRACT

An approach for the computation of wood thermal conductivity λ during defrosting of wood has been suggested. The approach takes into account the physics of the process of thawing of ice, which is created in wood by both the hygroscopically bounded and free water. It reflects for the first time also the influence of the fiber saturation point of wood species on the value of their λ during wood defrosting and the influence of the temperature on the fiber saturation point of frozen and non-frozen wood.

For the computation of λ according to the suggested approach a software program has been prepared in FORTRAN, which has been input in the developed by Microsoft calculation environment of Visual Fortran Professional. With the help of program computations have been made for the determination of λ of often used in the veneer and plywood production beech wood with moisture content $0 \le u \le 1.2$ kg.kg^{-1} at the temperature range between 0°C and -60°C during defrosting of wood.

The created mathematical description of λ for frozen and non-frozen wood has been input in the earlier suggested by the author non-stationary models of defrosting processes in prismatic and cylindrical wood materials. The updated models have been solved with the help of explicit schemes of the finite difference method. The change in the transient temperature distribution in ¼ of the longitudinal section of subjected to defrosting beech frozen logs is graphically presented, analyzed and visualized with the help of 2D color plots.

KEYWORDS: Wood, defrosting, thermal conductivity, bounded water, free water, computation.

INTRODUCTION

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

From the view point of the theory of heat conduction, the moist wood represents a

3-component dispersion capillary porous material, which includes a wood substance, water, and air. Thermal conductivity of each of the three components, as well as of the water and the ice, is different. The thermal conductivity of the water at t = 0 °C is equal to 0.551 $W.m^{-1}.K^{-1}$, and of ice at the same temperature it is 1.047 $W.m^{-1}.K^{-1}$, i.e. almost twice as large and it increases to 2.780 $W.m^{-1}.K^{-1}$ at t = -50°C (Chudinov 1966, 1968). That is why wood moisture content u is one of the most important factors, which influences the wood thermal conductivity. The replacement of the air in the wood pores by water causes a significant increase in λ according to a complex dependency. The wood thermal conductivity increases if the water in the wood is in a frozen state and decreases after the thawing of the ice in the wood.

According to the theory of wood thermal treatment, the impact of temperature t on thermal conductivity of wood, which contains ice, is different in comparison to the wood, which does not contain ice. If t decreases, the thermal conductivity of the wood, which contains ice, increases (Kanter 1955, Chudinov 1966, Steinhagen 1986, 1991, Shubin 1990, Trebula and Klement 2002). A reason for this on one hand is the decrease with decreasing of t of the quantity of non-frozen hygroscopically bounded water in the wood, which has a significantly smaller λ according to that of the ice, and on another hand – the increase of λ of the ice in the wood when t decreases. The increase of t in the wood, which does not contain ice, causes an increase of its λ (MacLean 1941, Kollmann 1951, Kanter 1955, Vorreiter 1958, Chudinov 1966, Požgaj et al. 1997).

The wood density, which indirectly reflects its porosity, also has a significant impact on λ. The change of wood density causes the change of partial participation of the separate components of the wood, for which the thermal conductivity is different. With density increase, i.e. with the porosity decrease, λ increases (Vorreiter 1958, Chudinov 1966, 1968, Deliiski 2003). Not only the porosity, but also the form, dimensions, and position of the pores influence λ. Since the dimensions of the pores are different for the separate anatomical directions of the wood, this causes anisotropy of λ.

Besides this the precise determination of wood thermal conductivity needs to take into account the impact of the fiber saturation point of wood u_{fsp} , which for the various wood species changes in a large range between 0.2 $kg.kg^{-1}$ and 0.4 $kg.kg^{-1}$ (Kollmann 1951, Požgaj et al. 1997, Videlov 2003, Deliiski and Dzurenda 2010).

The aim of the present work is to suggest an approach for computation of thermal conductivity of wood during defrosting of ice, which is created by both hygroscopically bounded and free water in the wood, using experimental data of different authors and the mathematical descriptions of wood thermo-physical characteristics, made earlier by the author (Deliiski 1977, 2003, 2009, 2011) For the first time the influence of the fiber saturation point of wood species on the value of its λ is taken into account during wood defrosting and the influence of temperature on fiber saturation point of frozen and non-frozen wood.

Symbols:

L – length (m),
R – radius (m),
r – radial coordinate: $0 \leq r \leq R$ (m),
T – temperature (K): T = t + 273.15,
t – temperature (°C): t = T – 273.15,
u – moisture content ($kg.kg^{-1}$ = %/100),
z – longitudinal coordinate: $0 \leq z \leq L/2$ (m),
λ – thermal conductivity ($W.m^{-1}.K^{-1}$),
ρ – density ($kg.m^{-3}$),
τ – time (s).

Subscripts:

ad – anatomical direction,
b – basic (for wood density, based on dry mass divided to green volume),
dfr – defreezing,
fsp – fiber saturation point,
m – medium,
nfw – non-frozen water,
0 – initial (at 0 °C for λ),
p – parallel to the fibers,
r – radial direction,
t – tangential direction.

Superscripts:

max – maximum possible value,
271.15 – at 271.15 K, i.e. at -2 °C,
293.15 – at 293.15 K, i.e. at 20 °C.

METHODS

Mathematical description of the amount of non-frozen bounded water in wood and water defreezing temperature in wood

The mathematical description of water defreezing temperature in wood and the thermal conductivity of frozen wood reveals the facts determined experimentally by Chudinov (1966), that the thawing of the ice from the situated in the wood free water occurs in the temperature range between 271.15 and 272.15 K, and the thawing of the ice from the situated in the wood bounded water depends on the temperature, which is $T \leq 271.15$ K. Besides this, at $T < 271.15$ K, a certain portion $u_{nfw} = f(T)$ from the bounded water is found in a non-frozen state.

Based on the analysis of the most probable way in the change of the specific amount of non-frozen bounded water in wood u_{nfw} during ice the thawing of, Chudinov (1966, 1968) suggests a graphical dependence for the change in u_{nfw} for wood with u_{fsp} = 0.30 kg.kg^{-1} depending on t, as well as an equation for the determination of $u_{nfw} = f(t)$. According to his data, the u_{nfw} is equal to: u_{nfw} = 0.131 kg.kg^{-1} at t = - 50 °C, u_{nfw} = 0.141 kg.kg^{-1} at t = -40 °C, u_{nfw} = 0.156 kg.kg^{-1} at t = -30 °C, u_{nfw} = 0.185 kg.kg^{-1} at t = -20 °C, u_{nfw} = 0.234 kg.kg^{-1} at t = -10 °C, and u_{nfw} = 0.300 kg.kg^{-1} at $t \geq$ -2 °C.

For the mathematical description of u_{nfw} , the above quoted data by Chudinov for the change of u_{nfw} depending on t at u_{fsp} = 0.30 kg.kg^{-1} has been used. Taking into account the influence of u_{fsp} on u_{nfw}, the Chudinov's graphical dependency $u_{nfw} = f(t)$ can be approximated with the help of the following equation $u_{nfw} = f(T, u_{fsp})$:

$$u_{\mathrm{nfw}} = 0.12 + \left(u_{\mathrm{fsp}} - 0.12\right)\exp\left[0.0567\left(T - 271.15\right)\right] \quad @ \quad 213.15\ \mathrm{K} \leq T \leq 271.15\ \mathrm{K} \tag{1}$$

Calculated according to equation (1) change in u_{nfw} for birch wood with u_{fsp} = 0.30 kg.kg^{-1}, beech wood with u_{fsp} = 0.31 kg.kg^{-1} and poplar wood with u_{fsp} = 0.35 kg.kg^{-1} is shown on Fig. 1. The values of u_{fsp} in (1) have been determined depending on temperature with the help of the equation (4).

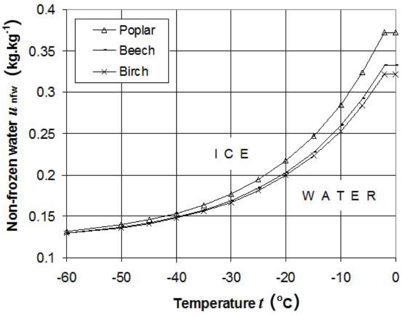

Fig. 1: Change in u_{nfw} for birch, beech and poplar wood, depending on temperature.

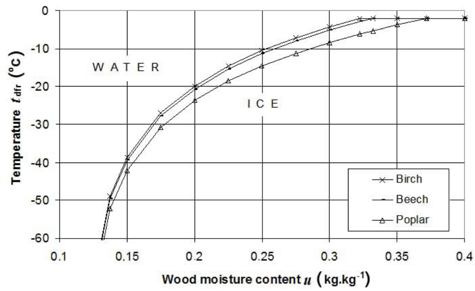

Fig. 2: Change in t_{dfr} for birch, beech and poplar wood, depending on moisture content.

After solving the equation (1) it might be determined that temperature at which the ice, formed in the wood from the freezing of the bounded water, is transformed completely into a liquid state, can be calculated according to the following equation depending on u_{fsp} and u_{nfw} :

$$T_{\mathrm{dfr}} = 271.15 + \frac{\ln \dfrac{u_{\mathrm{nfw}} - 0.12}{u_{\mathrm{fsp}} - 0.12}}{0.0567} \quad @ \quad 0.12 \ \mathrm{kg.kg}^{-1} \leq u = u_{\mathrm{nfw}} < u_{\mathrm{fsp}}^{271.15} \tag{2}$$

$$T_{\mathrm{dfr}} = 271.15 \quad @ \quad u \geq u_{\mathrm{fsp}}^{271.15} \tag{3}$$

The calculated according to equations (2) and (3) change in t_{dfr} for birch, beech, and poplar wood depending on u is shown on Fig. 2. The graph for birch wood shown on this figure, completely coincides with the suggested by Chudinov (1966) graph.

The influence of temperature on the fiber saturation point

Based on the results of wide experimental investigations, A. J. Stamm (1964) suggests the following equation, which reflects the influence of temperature on fiber saturation point of the non-frozen wood:

$$u_{\mathrm{fsp}} = u_{\mathrm{fsp}}^{293.15} - 0.001(T - 293.15) \tag{4}$$

In the specialized literature there are too few records concerning the influence of T on u_{fsp} of wood, which contains ice. Kübler et al. (1973) noted that below 0°C the bounded water diffused out of the cells' walls and crystallized as ice in the cells' cavities even when free water was present. The formation of ice from diffused bound water causes significant swelling of the frozen wood (Kübler 1962, Shmulsky and Svetts 2006). A proportional reduction of the maximum amount of bound water that cell's walls can hold at freezing temperatures have been experimentally determined by Shmulsky and Shvets (2006). Chudinov (1966, 1968) also points out that with a decrease in T, it is expected that u_{fsp} of wood, which contains ice also decreases, because the portion of bounded water, which is transformed into ice, stops being bounded and becomes free. Consequently, it can be inferred that at a given temperature lower than the water freezing temperature in wood a decrease of u_{fsp} can be expected while u increases in the hygroscopic range.

Since equation (4) is generally accepted in the specialized literature, then during the mathematical description of λ below, this equation is used for reflection of the influence of T on

u_{fsp} for wood at $t < 0°C$ after the occurrence of complete thawing of ice, formed from the free and bounded water in the wood, i.e:

$$u_{\text{fsp}} = u_{\text{fsp}}^{293.15} - 0.001(T - 293.15) \quad @ \quad T > T_{\text{dfr}} \tag{5}$$

While the thawing of ice from free and bounded water is taking place, a constant value of u_{fsp} is used in the description of λ, which the wood has at the temperature of complete thawing of the ice T_{dfr} , i.e.:

$$u_{\text{fsp}} = u_{\text{fsp}}^{293.15} - 0.001(T_{\text{dfr}} - 293.15) \quad @ \quad T \le T_{\text{dfr}} \tag{6}$$

In Fig. 3 the computed according to equation (5) change in u_{fsp} is shown for beech wood, with an inclined line which does not contain ice depending on t. The (6) horizontal lines computed by equation with u_{fsp} =const

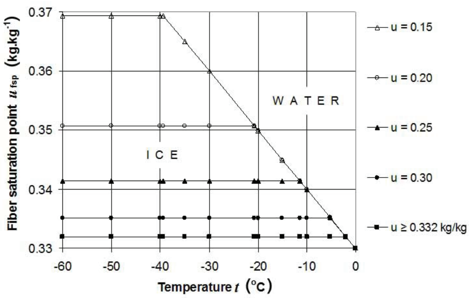

Fig. 3: Change in ufsp during defrosting of beech wood, depending on temperature and moisture content.

cross on the figures the inclined line at temperatures, which correspond to the calculated according to equation (2) and (3) and presented on Fig. 2 values of t_{dfr} for the shown in the legend on Fig. 3 values for u at 0.15 kg.kg^{-1} $\le u \le u_{fsp}^{271.15}$.

Mathematical description of λ during defrosting of wood

Mathematical description of the wood thermal conductivity λ during defrosting of the wood has been done using the experimentally determined dissertations data by Kanter (1955) and Chudinov (1966) for its change as a function of t and u. This data for $\lambda(t, u)$ finds a wide use in both the European (Shubin 1990, Požgaj et al. 1997, Trebula and Klement 2002, Videlov 2003) and the American specialized literature (Steinhagen 1986, 1991, Khattaby and Steinhagen 1992, 1993) when calculating various processes of the thermal processing of wood. The approach used in the mathematical description of λ is analogous to this, which has been used earlier by us in the description of $\lambda(t, u, \rho_b)$ of non-frozen wood (Deliiski 1977) and of frozen and non-frozen wood without taking into account the influence of the fiber saturation point of wood species on the value of its λ and the influence of the temperature on the fiber saturation point (Deliiski 2003, 2004, 2011).

The wood thermal conductivity during the wood defrosting can be calculated with the help of the following equations for $\lambda(T, u, \rho_b, u_{fsp})$:

$$\lambda = \lambda_0 \gamma [1 + \beta (T - 273.15)] \tag{7}$$

$$\lambda_0 = K_{ad} \nu [0.165 + (1.39 + 3.8u)(3.3.10^{-7} \rho_b^2 + 1.015.10^{-3} \rho_b)] \tag{8}$$

$$v = 0.15 - 0.07u \quad @ \quad u \le u_{fsp} + 0.1 \text{ kg.kg}^{-1} \tag{9}$$

$$v = 0.1284 - 0.013u \quad @ \quad u > u_{fsp} + 0.1 \text{ kg.kg}^{-1} \tag{10}$$

The equations, which have been suggested by Chudinov (1966, 1968) and shown in (Deliiski 1977) can be used for the determination of the coefficient K_{ad} values in equation (8), which takes into account the influence on λ_0 of the heat flux towards the separate anatomic directions of wood, i.e. for the determination of λ_r, λ_t and λ_p. in work of Deliiski (2003) and Deliiski and Dzurenda (2010) more precise values of K_{ad} for ten wood species have been determined. For beech wood the following values of K_{ad} have been determined: K_r = 1.35, K_t = 1.21 and K_p = 2.36.

The coefficients γ and β in equation (7) are calculated by the following equations:

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

$$\gamma = 1.0 \tag{11}$$

$$\beta = (2.05 + 4u)\left(\frac{579}{\rho_y} - 0.124\right).10^{-3} \quad @ \quad u \le u_{fsp} + 0.1 \text{ kg.kg}^{-1} \tag{12}$$

$$\beta = 3.65\left(\frac{579}{\rho_y} - 0.124\right).10^{-3} \quad @ \quad u > u_{fsp} + 0.1 \text{ kg.kg}^{-1} \tag{13}$$

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

$$\gamma = 1 + 0{,}34[1.15(u - u_{fsp})] \tag{14}$$

$$\beta = 0.002(u - u_{fsp}) - 0.0038\left(\frac{579}{\rho_b} - 0.124\right) \tag{15}$$

The values of u_{fsp} in equations the above are calculated with the help of the equations (5) and (6).

For the calculation of λ in the cases, when during wood defrosting $T \le T_{dfr}$ and simultaneously with this $u_{nfw} \le u < u_{fsp}$, the value of λ_{dfr} must be initially determined by substituting $T = T_{dfr}$ in equation (7) as well as the values of γ from equation (11) and of β from equation (12). After this, with the usage of the coefficient β from equation (15), the values of λ of the frozen wood are calculated with the help of the following equation:

$$\lambda = \lambda_{dfr} [1 + \beta (T - T_{dfr})] \quad @ \quad T \le T_{dfr} \ \& \ u_{nfw} \le u \le u_{fsp} \tag{16}$$

RESULTS AND DISCUSSION

For the computation of λ according to equations (7) ÷ (16) a software program has been prepared in FORTRAN, which has been input in the developed Microsoft calculation environment of Visual Fortran Professional. With the help of the program, computations have been made for the determination of λ in the ranges 213.15 $K \le T \le$ 273.15 K, i.e. -60°C $\le t \le$ 0°C and $0 \leq u \leq 1.2$ kg.kg^{-1}. As an example, the thermal conductivity in the radial direction of often used in the veneer and plywood production beech (*Fagus sylvatica* L.) wood has been calculated below. The linear character of the dependences $\lambda_r(t)$ allows for the calculation of the change of λ to start from temperature -60°C, even though the lowest temperature of the experimental data for λ used in the mathematical description of λ was 40°C. During the computations of $\lambda_r(T, u, \rho_b, u_{fsp})$ the values of ρ_b = 560 kg.m^{-3} and $u_{fsp}^{293.15}$ = 0.31 kg.kg^{-1} for the beech wood are used (Videlov 2003, Deliiski 2003, 2011).

Change in λ_r at $u < u_{fsp}$

In Fig. 4 the calculated change in $\lambda_r(t, u)$ of beech wood during thawing of the ice according to equations (7) ÷ (16) which has been created by the bounded water in the wood, depending on t and u is shown. For easier practical usage of the $\lambda_r(t, u)$ -diagram the values of u on the figure are presented in percentages instead of in kg.kg^{-1} as used during the calculations.

On the graphs of Fig. 4 it can be seen that an increase in t at a given value for u leads to a decrease in λ for wood containing ice as a consequence of the decrease in ice quantity with the increase of t, and to an increase in λ for wood, which does not contain ice. The change in λ of frozen and non-frozen wood depending on t, calculated according to equation (7) is linear. Based on analysis in Fig. 4 it can also be seen that at a given value of t an increase in u for wood both not containing and containing ice, formed in it from freezing of bounded water, causes a non-linear increase in λ. This means that for one and the same change in u at given t, for example by 5 %, causes less and less increase of λ with increasing of u.

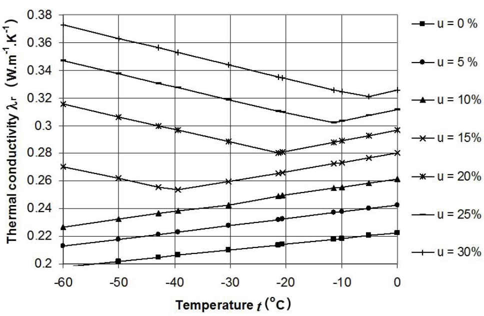

Fig. 4: Change in λ_r of beech wood during thawing of the ice from the bounded water, depending on temperature and moisture content.

On the graphs of Fig. 4 it can be also seen that for a given value of u if the wood moisture content is in the range $u_{nfw} < u < u_{fsp}$, at temperature $t = t_{dfr}$, at which the thawing of the frozen bound water ends, a breaking and a change of the slope of the dependences $\lambda(t, u, \rho_b, u_{fsp})$ are observed.

With decreasing of u below the u_{fsp} the breaking of the dependences $\lambda(t, u, \rho_b, u_{fsp})$ moves to smaller values of $t = t_{dfr}$ because of the fact, that at smaller values of u the frozen bound water in wood thaws completely at lower temperatures (Chudinov 1966). Such breaking and a change of slope of the dependences $\lambda(t, u)$ at $u_{nfw} < u \leq u_{fsp}$ and at given values of t_{dfr} during wood defrosting have been experimentally determined by Kanter (1955) and Chudinov (1966) in their dissertations and by Shubin (1990) in his studies. The exact values of t_{dfr} at a given value of u can be determined by equation (2) after substitution of $u_{nfw} = u$ in it.

Change in λ_r at $u > u_{fsp}$

In Fig. 5 the calculated change in the thermal conductivity of beech wood according to equations (7) ÷ (16) during thawing of the ice which is created from the free water in the wood, depending on t and u is shown.

On the graphs of Fig. 5 it can be seen that an increase in t at a given value for u and an increase in u at a given value for t leads to the change in λ both for wood not containing and containing ice from the free water, which is the same as the one shown above for wood, containing ice only from bounded water.

On the graphs of Fig. 5 it can also be seen that at $t = t_{dfr}$ jumps take place in λ for wood with $u > u_{fsp}$. These jumps are explained by phase transition into water of the whole amount of ice, formed by the free water in wood at $t = t_{dfr}$ during wood defrosting. Namely, at the values of $t = t_{dfr}$ the influence on λ of a significant difference in the thermal conductivity of water in a liquid and hard aggregate state occurs.

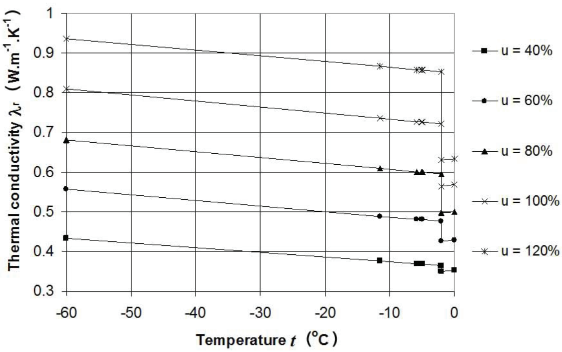

Fig. 5: Change in λ_r of beech wood during thawing of the ice from the free water, depending on temperature and moisture content.

Computation and visualization of 2D non-stationary temperature distribution in logs

The above created mathematical description of $\lambda = f(T, u, \rho_b, u_{fsp})$ for frozen and non-frozen wood is introduced in the earlier suggested by non-stationary models of defrosting processes in prismatic and cylindrical wood materials (Deliiski 2003, 2004, 2009, 2011), in which until now the influence of T on u_{fsp} does not participate. The updated models have been solved out with the help of explicit schemes of the finite difference method in a way, analogously to the one used and described in (Deliiski 1977, 2003, 2009, 2011) for solution of a model of the heating process of prismatic and cylindrical wood materials.

For solution of the updated with the new description of λ (and also with new mathematical descriptions of the specific heat capacities of frozen and non-frozen wood) a software program has been prepared in the calculation environment of Visual Fortran Professional, which is a part of the office-package of Windows. With the help of the program as example computations have been made for the determination of 2D change the temperature in subjected to defrosting frozen beech logs with $R = 0.2$ m, $L = 0.8$ m, $t_0 = -40°C$ and $u = 0.6$ kg.kg^{-1} during its 20 hours of thermal treatment in agitated hot water with $t_m = 80°C$.

In Fig. 6 the computed change in the surface temperature of the logs, which is equal to t_m, and also in the temperature in 4 characteristic points in the ¼ of the longitudinal section of logs (because of its symmetry to the rest ¾ of the section) with u = 0.6 kg.kg^{-1} containing ice both from bounded and free water is shown. The four characteristic points in the longitudinal log's section have the following coordinates related to the log's surfaces: (R/2, L/4), (R/2, L/2), (R, L/4) и (R, L/2 – the central point of the section).

In the curves of situated on the log's axis characteristic points with coordinates (R, L/4) and (R, L/2) on Fig. 6 the specific almost horizontal sections of retention of the temperature for a long period of time in the range from -2 to -1°C can be seen, while in these points a complete thawing of ice from free water in wood occurs. Such retention of temperature 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, Deliiski 2011). Analogically, the 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.

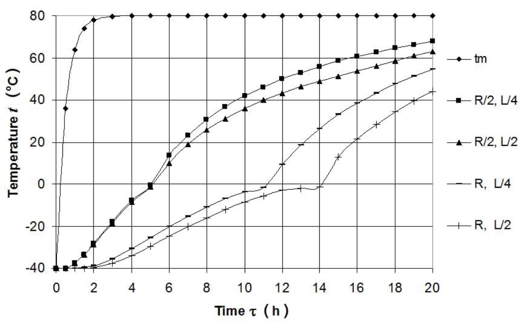

Fig. 6: Change in t in the longitudinal section of beech log with R = 0.2 m, L = 0.8 m, t_0 = -40°C, and u = 0.6 kg.kg^{-1} during its defrosting at t_m = 80°C.

Color plots in the Fig. 7 are shown, which illustrate the temperature distribution in ¼ of the longitudinal section of the beech log with t_0 = -40°C and u = 0.6 kg.kg^{-1} after duration τ = 5 h and τ = 10 h of the wood defrosting process at t_m = 80°C.

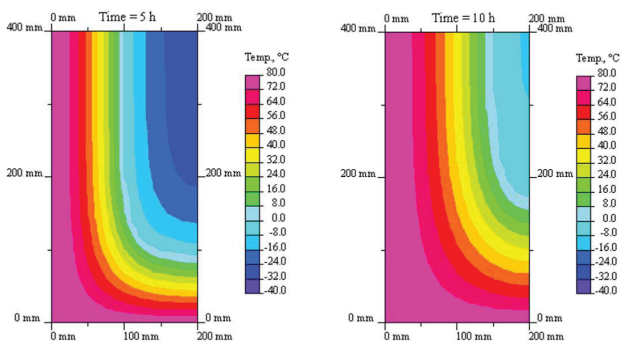

Fig. 7: 2D color plots with temperature distribution in ¼ of the longitudinal section of beech log with t_0 = -40°C and u = 0.6 kg.kg^{-1} after duration τ = 5 h and τ = 10 h of the wood defrosting process at t_m = 80°C.

On the plots of Fig. 7 it can be seen that during the defrosting of the log, which contains ice from the free water, the usual smoothness of the border between adjacent temperature zones in the legend of this figure is disturbed only in the temperature zones from –8 to 0°C and from 0 to 8°C. A reason for this is the shown in the analysis of Fig. 6 above retention of the temperature into the central points of the material for a too long period of time in the range from -2 to -1°C, while the ice in them, formed from the freezing of the free water in the wood, is completely thawed. While the points with not completely thawed ice are still located in the color area from -8 to 0°C, their adjacent points from the calculation mesh after the complete thawing of the ice go into the zone from 0 to 8°C. This explains the deformation of the smoothness of the border between these zones of color plots at τ = 5 h and τ = 10 h.

On the plots of Fig.7 it can also be seen that the non-linear increasing of the temperature along the log's length is faster than along the log's radius. The reason for this is the noted above almost 1.75 time bigger coefficient K_p than the coefficient K_r, with the help of which the thermal conductivities of beech wood in longitudinal and radial direction are computed.

CONCLUSIONS

The present paper describes the suggested approach for computation of the wood thermal conductivity of frozen and non-frozen wood, which takes into account to a maximum degree the physics of the processes of thawing of ice, formed by both bounded and free water in wood. It reflects the influence of the temperature, wood moisture content, and wood density and for the first time also the influence of the fiber saturation point of each wood species on its thermal conductivity during wood defrosting and the influence of the temperature on the fiber saturation point of frozen and non-frozen wood.

Equations for determination of water defrosting temperature in the wood t_{dfr} have been derived depending on the wood moisture content u and the fiber saturation point. For computation of the thermal conductivity of the wood with frozen and non-frozen water in it, equations have been suggested as well.

For computation of wood thermal conductivity of frozen and non-frozen wood according to a suggested approach and according to the mathematical description a software program has been prepared in FORTRAN, which has been input in the developed by Microsoft calculation environment of Visual Fortran Professional. With the help of the program computations have been carried out for determination of thermal conductivity in the radial direction of beech wood with moisture content $0 \leq u \leq 1.2$ kg.kg^{-1} at a temperature range from 213.15 to 273.15 K, i.e. from -60 to 0°C.

The obtained computed results show that a decrease in t at a given value for u leads to an increase in λ for wood containing ice as a consequence of the increase in the ice quantity with decreasing of t, and to a decrease in λ for wood, which does not contain ice. The change in λ depending on t is linear. The results show also that at a given value of t an increase in u for non-frozen wood and for wood containing ice, formed in it from the freezing of the both bounded and free water, causes a non-linear increase in λ.

If frozen wood with $u > u_{fsp}$ is subjected to heating and the wood temperature increases and reaches a temperature $t = t_{dfr}$, a jump take place in λ . This jump is explained by the phase transition into water of the whole amount of the ice, formed by the free water in wood at $t = t_{dfr}$ during wood defrosting.

If frozen wood with $u_{nfw} < u \leq u_{fsp}$ is subjected to heating and during the increase of the wood temperature it reaches a temperature $t = t_{dfr}$, at which the thawing of the ice formed by the bounded water ends, a breaking and a change of the slope of the dependences $\lambda(t, u, \rho_b, u_{fsp})$ are observed. With the decrease of u below the u_{fsp} the breaking of the dependences $\lambda(t, u, \rho_b, u_{fsp})$ moves to smaller values of $t = t_{dfr}$ because of the experimentally determined by different authors fact, that at smaller values of u the frozen bound water in the wood thaws completely at lower temperatures.

The created mathematical description of $\lambda = f(T, u, \rho_b, u_{fsp})$ for frozen and non-frozen wood has been input in the earlier suggested by the author non-stationary models of defrosting processes in prismatic and cylindrical wood materials, in which until now the influence of T on u_{fsp} did not participate. The updated models have been solved out with the help of explicit schemes of the finite difference method. The change in the transient temperature distribution in ¼ of longitudinal section of subjected to defrosting beech frozen logs is graphically presented, analyzed and visualized with the help of 2D color plots.

The validated high precision of the created mathematical description of λ and the other thermo-physical characteristics of wood and also of the models of non-stationary defrosting and heating processes of wood materials make them user friendly for contemporary systems for model-based and model predictive automatic control (Hadjyiski 2003) of different processes of thermal and hydrothermal treatment. This way, for example, we have input these updated models into software of the microprocessor programmable controller in order to control automatically the thermal treatment processes of lumber and of logs and wooden prisms in the veneer production (Fig. 8).

Fig. 8: Programmable controller for model predictive control of the thermal treatment processes of frozen and non-frozen wood materials.

The long use of numerous implemented in the industry automated installation for wood thermal treatment (Deliiski 2004, Deliiski and Dzurenda 2010) confirmed completely the validity of the calculating and controlling algorithms used in the controller. It proves its high energy efficiency, reliable functioning and suitability to assure the appropriate parameters of the processing mediums, required for the optimal plasticizing and ennoblement of the subjected to thermal treatment frozen and non-frozen wood materials from different species.

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