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Computation of the wood temperature conductivity above the hygroscopic range during wood freezing

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Abstract: *Computation of the wood temperature conductivity above the hygroscopic range during wood freezing*. An approach for the computation of the temperature conductivity *a* of wood above the hygroscopic range during freezing of the wood has been suggested. The approach takes into account the physics of the freezing process of both the free and the hygroscopically bound water in the wood. It reflects also the influence of the fiber saturation point of wood species on the value of their *a* during wood freezing and the influence of the temperature on the fiber saturation point of the wood during its freezing. A software program has been prepared for the computation of *a* according to the suggested approach, which has been input in the calculation environment of Visual Fortran Professional. With the help of the program, computations have been done for the determination of the themperature conductivity in radial direction of often used in veneer and plywood production beech and poplar wood with moisture content $0.4\ \mathrm{kg{\cdot}kg^{-1}} \leq u \leq 1.2\ \mathrm{kg{\cdot}kg^{-1}}$ at the temperature range between 0 ºC and –60 ºC during freezing of the wood.

Key words: wood, freezing, temperature conductivity, mathematical description, bound water, free water, computation

INTRODUCTION

For the technological and other engineering calculations of processes of thermal and hydrothermal treatment of wood materials the wood temperature conductivity coefficient *a* is often used. It is known that it represents the relationship of the thermal conductivity coefficient λ to the multiplication of the specific heat capacity *c* and density ρ of the material. During calculations of heating or cooling of non-frozen wood its temperature conductivity coefficient can be determined according to that relationship using the values of *c*, λ, and ρ of the wood for specific temperature and moisture content. During the calculation of the freezing or defrosting processes of wood, however, it is necessary to take into account the impact both of the specific heat capacity of the wood itself, and of the heat of the phase transition of water in the wood from its liquid to hard aggregate condition and vise versa upon the wood temperature conductivity coefficient [5].

The heat of the water phase transition in the wood can be represented by the specific heat capacity of the frozen hygroscopically bound and the frozen free water in the wood. As a result of in-depth dissertation studies [1] it has been discovered that the melting of the frozen free water in the wood takes place at temperatures in the range between −2 ºC and −1 ºC. It has been also discovered that the melting of the frozen bound water in the wood ends at −2 ºC, and besides this, the quantity of this frozen water increases with the decrease in temperature, but even during extremely small climatic temperatures on earth, a definite part of it remains in a non-frozen state.

The precise determination of the wood temperature conductivity coefficient besides this needs to take into account the impact of the fiber saturation point of the wood u_{fsp}, which for the various wood species changes in a large range between $0.2\ \mathrm{kg{\cdot}kg^{-1}}$ and $0.4\ \mathrm{kg{\cdot}kg^{-1}}$ [2, 4, 9, 10, 13, 14].

The aim of the present work is to suggest an approach for the computation of the temperature conductivity of the wood during freezing of the water in it above the hygroscopic range, using the mathematical descriptions of thermo-physical characteristics of frozen and non-frozen wood, made earlier by the one of the authors.

EQUATION FOR THE CALCULATION OF THE WATER FREEZING TEMPERATURE IN THE WOOD

According to Chudinov [1] and Topgaard and Söderman [12], if the wood has a significant quantity of free water, i.e. if the cell holes and the gaps among the cells are almost completely filled with water, the centres of crystallization during the cooling arise in the water at temperatures around –5 °C ÷ –6 °C. If the wood moisture content is slightly larger than the fiber saturation point, u_{fsp}, i.e. a small quantity of free water is present in the wood, then the centres of crystallization in it arise at temperatures around –12 °C ÷ –15 °C.

Based on the results from personal experimental studies, Chudinov in [1] suggests a graph for the change of the temperature of freezing of the water in birch wood with fiber saturation point at $T = 293.15$ K (i.e. at $t = 20$ °C) $u_{\mathrm{fsp}}^{293.15} = 0.3\,\mathrm{kg{\cdot}kg^{-1}}$, depending on u. Due to the lack of other published data for the water freezing temperature in the wood, t_{fr}, for the mathematical description of this temperature below, the data obtained in [1] for the change of t_{fr} depending on u at $u_{\mathrm{fsp}}^{293.15} = 0.3\ \mathrm{kg \cdot kg^{-1}}$ has been used. Taking into account the influence of u_{fsp} on t_{fr}, the shown in [1] graphical dependency $t_{\mathrm{fr}}(u)$ can be approximated with the help of the following equation:

$$T_{\mathrm{fr}} = 268.15 - 118.85\exp[-9.9(0.3 + u - u_{\mathrm{fsp}}^{293.15})^{1.3}] \quad @ \quad 0.12\ \mathrm{kg.kg^{-1}} \le u \le u_{\max}. \qquad (1)$$

With the help of the expression $(0.3 + u - u_{\mathrm{fsp}}^{293.15})$ in equation (1) the determined in [1] relationship's character of the influence of u on T_{fr} (in K) for birch wood with $u_{\mathrm{fsp}}^{293.15} = 0.30\ \mathrm{kg \cdot kg^{-1}}$ is accepted as valid for all wood species taking into account the concrete value of their $u_{\mathrm{fsp}}^{293.15}$. It is only possible to make a future clarification of equation (1) when having extensive experimental data for the change in T_{fr} depending on u for wood species with different value of $u_{\mathrm{fsp}}^{293.15}$.

The calculated according to equation (1) change in t_{fr} (in °C) for birch wood with $u_{\mathrm{fsp}}^{293.15} = 0.30\ \mathrm{kg \cdot kg^{-1}}$, beech wood with $u_{\mathrm{fsp}}^{293.15} = 0.31\ \mathrm{kg \cdot kg^{-1}}$, and poplar wood with $u_{\mathrm{fsp}}^{293.15} = 0.35\ \mathrm{kg \cdot kg^{-1}}$ [3, 4, 9] depending on u in the range $0.2\ \mathrm{kg \cdot kg^{-1}} \le u \le 1.0\ \mathrm{kg \cdot kg^{-1}}$ is shown on Fig. 1. The graph for birch wood shown on this figure coincides completely with the suggested by Chudinov [1] graph.

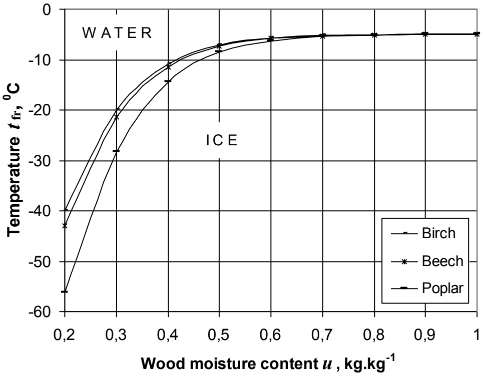

Fig. 1. Change in t_{fr} for birch, beech and poplar wood, depending on u

The equation (1) is used for the determination of T_{fr} in the mathematical descriptions of the thermal conductivity, and the specific heat capacity of the wood during freezing of the water in it, which are needed for the computation of the temperature conductivity of the wood during its freezing.

EQUATUON FOR THE COMPUTATION OF a DURING FREEZING OF THE WOOD

As it was described in the introduction, during the calculations of the wood freezing process above the hygroscopic range, the wood temperature conductivity must be determined according to the following equations [2, 5]:

$$a_{\mathrm{bwm}}(T,u,u_{\mathrm{fsp}}) = \frac{\lambda(T,u,u_{\mathrm{fsp}})}{\left[c(T,u,u_{\mathrm{fsp}}) + c_{\mathrm{bwm}}(T,u,u_{\mathrm{fsp}})\right]\rho(\rho_{\mathrm{b}},u)} \quad @ \quad u > u_{\mathrm{fsp}} \,\&\, 213.15\ \mathrm{K} \le T \le T_{\mathrm{fr}}, \qquad (2)$$

where a_{bwm} is temperature conductivity of the wood with maximum possible amount of frozen bound water in it ($\mathrm{m^2 \cdot s^{-1}}$), λ is thermal conductivity of the frozen wood ($\mathrm{W \cdot m^{-1} \cdot K^{-1}}$), c is specific heat capacity of the frozen wood itself ($\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$), c_{bwm} is specific heat capacity of the maximum possible amount of frozen bound water in the wood, ($\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$), ρ is wood density ($\mathrm{kg \cdot m^{-3}}$), ρ_{b} is basic wood density equal to dry mass divided to green volume ($\mathrm{kg \cdot m^{-3}}$), u is wood moisture content ($\mathrm{kg \cdot kg^{-1}}$), u_{fsp} is wood moisture content at fibre saturation point ($\mathrm{kg \cdot kg^{-1}}$), T is temperature (K).

The thermal conductivity λ and the own specific heat capacity c of the wood during its freezing is described mathematically using the experimentally determined in the dissertations of Kanter [7] and Chudinov [1] data for its change as a function of t and u. The same experimental data for λ and c, obtained by Kanter and Chudinov, are widely used in both the European [10, 13, 14] and the American specialized literature [8, 11] when calculating various processes of thermal treatment of wood. The wood thermal conductivity λ, the wood density ρ, and the specific heat capacities c and c_{bwm}, which participate in equation (2), can be calculated with the help of the equations given in [2, 3, 4].

RESULTS AND DISCUSSION

For the computation of the wood temperature conductivity according to equation (2) a software program has been prepared in the calculation environment of Visual Fortran. With the help of the program computations have been made for the determination of a of often used in the veneer and plywood production beech *(Fagus Silvatica* L.*)* and poplar *(Populus alba* L.*)* wood in the ranges $0.4\ \mathrm{kg \cdot kg^{-1}} \le u \le 1.2\ \mathrm{kg \cdot kg^{-1}}$ and $213.15\ \mathrm{K} \le \mathrm{T} \le 273.15\ \mathrm{K}$, i.e. $-60\ ^{\circ}\mathrm{C} \le t \le 0\ ^{\circ}\mathrm{C}$.

On Fig. 2 the calculated change in the temperature conductivity in radial direction, a_{r}, of beech and poplar wood respectively during the freezing of the water in the wood, depending on t and u is shown. The values of a_{r} for wood not containing ice are calculated according to the equations for non-frozen wood, which are given in [2, 3, 4].

On the graphs of Fig. 2 it can be seen that an increase in t at a given value for u leads to a decrease in a_{r} for wood containing ice and to an increase in a_{r} for wood, which does not contain ice. Also the slope for the change in a_{r} of wood, which contains frozen bound water depending on t is much larger than the slope for the change in a_{r} of wood without ice. The change in a_{r} depending on t with sufficient for practical calculations precision can be taken as being linear.

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

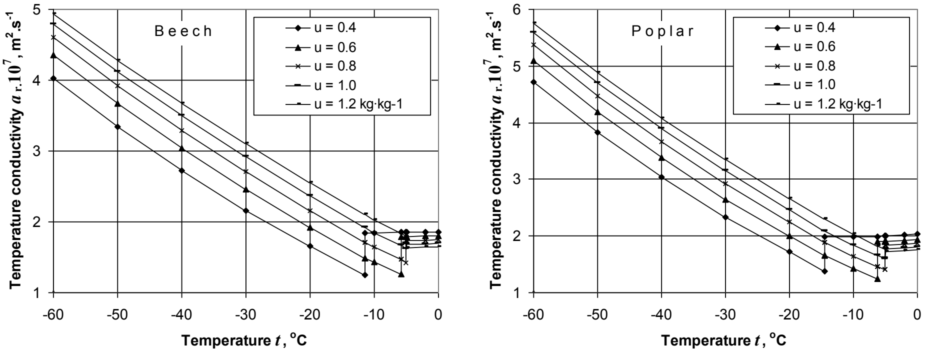

Fig. 2. Change in a_r of beech (left) and poplar (right) wood during freezing of the water in the wood, depending on t and $u > u_{fsp}$

The presence of such a jump in a_r demonstrates the correct reflection in equation (2), respectively in the mathematical description of λ and c in [2, 3, 4] of the setting in the theory of wood thermal treatment [1], according to which exactly at temperature t_{fr} for a given value of u the freezing of the bound water in the wood has started. The larger value of the basic density $\rho_b = 560$ kg·m^{-3} of beech wood in comparison with $\rho_b = 355$ kg·m^{-3} of poplar wood [4, 9] causes smaler values of a_r of the beech wood than a_r of the poplar wood at given values of t and u.

CONCLUSIONS

The present paper describes the suggested by the authors approach for the computation of the temperature conductivity of wood materials, a, during their freezing. The approach reflects the influence of the temperature, wood density, wood moisture content, and fiber saturation point of wood species on the value of their themperature conductivity during water freezing in the wood.

A software program has been prepared for the computation of a according to the suggested approach, which has been input in the calculation environment of Visual Fortran Professional. With the help of the program, computations have been done for the determination of the themperature conductivity in radial direction of often used in veneer and plywood production beech and poplar wood with moisture content 0.4 kg·kg^{-1} $\leq u \leq$ 1.2 kg·kg^{-1} in the temperature range between 0 °C and –60 °C during freezing of the wood.

The obtained results can be used for mathematical modeling of the wood freezing process and for technological analysis of processes of thermal and hydrothermal treatment of wood materials, as well as in software of systems for model based automatic control [6] of such treatment.

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Streszczenie: *Wyznaczanie przewodnictwa cieplnego drewna w ponadhigroskopijnym zakresie wilgotności podczas zamrażania*. Zaproponowano metodykę wyznaczania przewodnictwa temperatury drewna w ponadhigroskopijnym zakresie wilgotności, podczas zamrażania. Metodyka bierze pod uwagę fizykę zamrażania zarówno wody związanej jak i wolnej. Odzwierciedla także wpływ nasycenia włókien drewna na wartość a podczas zamrażania jak I wpływ temperatury na punkt nasycenia włókien drewna podczas jego zamrażania. Sporządzono program komputerowy do obliczeń wg proponowanego modelu. Przeprowadzono obliczenia przewodności temperatury w kierunku promieniowym – najczęściej jużywanym w produkcji forniru i sklejek- drewna buka i topoli w zakresie wilgotności $0.4\ \mathrm{kg{\cdot}kg^{-1}} \leq u \leq 1.2\ \mathrm{kg{\cdot}kg^{-1}}$ oraz temperatur 0 ^{o}C and –60 ^{o}C podczas zamrażania.

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