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CALCULATION OF THE HEAT ENERGY NEEDED FOR MELTING OF THE ICE IN WOOD MATERIALS FOR VENEER PRODUCTION

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ABSTRACT

An approach for the calculation of the specific heat energy, q_{ice}, needed for melting of the ice in the wood has been suggested. The approach takes into account to a maximum degree the physics of the processes of thawing of the ice, formed by both the bounded and the free water in the wood. It reflects the influence of the temperature, wood moisture content, wood density, and for the first time also of the influence of the fiber saturation point of each wood specie on q_{ice} during wood defrosting and the influence of the temperature on the fiber saturation point of frozen and non-frozen wood.

An equation for the easy determination of the specific heat energy, q_{fw}, needed for the melting of the ice, which is formed by the free water in the wood has been derived, depending on the basic density of the wood ρ_b, the wood moisture content u, and the fiber saturation point u_{fsp}. An equation for the determination at $u \geq u_{fsp}$ of the specific heat energy q_{bw}, needed for the melting of the ice, which is formed by the bounded water in the wood has been derived as well, depending on ρ_b, u, u_{fsp}, and the initial temperature of the frozen wood t_{w0}. The specific heat energy q_{ice} equals to $q_{fw} + q_{bw}$.

For the calculation of the q_{fw} and q_{bw} according to a suggested approach and according to the mathematical description of q_{fw} and q_{bw} a software program has been prepared in MS Excel 2010. With the help of the program calculations have been carried out for the determination of q_{fw} and q_{bw} for oak, beech, pine and poplar frozen wood with moisture content $u_{fsp} \leq u \leq 1.0$ kg·kg^{-1} at a temperature range for t_{w0} from – 20 °C to – 1 °C.

Keywords: wood, defrosting, ice from bounded water, ice from free water, specific heat energy, basic density, specific heat capacity, fiber saturation point

INTRODUCTION

For the optimization of the control of the thermal treatment processes of wood materials in veneer/plywood mills, it is required that the distribution of the temperature field in the materials and consumed energy for their heating are known. The intensity of heating and the consumption of energy depend on the dimensions and the initial temperature of the materials, on the texture and micro-structural features of the wood species, on the anisotropy of the wood and on the content and aggregate condition of the water in it, on the law of change and the values of the temperature of the heating medium (the steam or hot water), etc. (TREBULA – KLEMENT 2002, VIDELOV 2003, PERVAN 2009). There are many publications, which are dedicated to the distribution of the temperature in the subjected to thermal treatment wood materials at different initial and boundary conditions of the process and there are too few records (DELIISKI 2004, 2009, DELIISKI − DZURENDA 2010) that present the influence of various factors on the change of the heat energy, which is needed for the heating of frozen and non-frozen materials.

Considerate contribution to the calculation of the non-stationary distribution of the temperature in frozen and non-frozen logs and to the duration of their heating has been made by H. P. Steinhagen. For this purpose, he, alone, (STEINHAGEN 1986, 1991) or with co-authors (STEINHAGEN – LEE 1988) has created and solved a 1-dimensional, and later a 2-dimensional (KHATTABI – STEINHAGEN 1992, 1993, 1995) mathematical model, whose application is limited only for wood moisture content $u \geq 0{,}3$ kg·kg^{-1}. The development of these models is dominated by the usage of the method of enthalpy, which is rather more complicated than its competing temperature method. The 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. The heat energy, which is needed for the melting of the ice, which has been formed from the freezing of the hygroscopically bounded water in the wood, although the specific heat capacity of that ice is comparable by value to the capacity of the frozen wood itself (CHUDINOV 1968), has not been taken into account in the models.

These models assume that the fiber saturation point is identical for all wood species and that the melting of the ice, formed by the free water in the wood, which is found in the inter-cellular areas, occurs at 0 ºC. However, it is known that there are significant differences between the fiber saturation point of the separate wood species and that the dependent on this point quantity of ice, formed from the free water in the wood, thaws at a temperature in the range between –2 ºC and –1 ºC (CHUDINOV 1966, 1968).

Besides this, for the precise determination of the temperature distribution in subjected to thermal treatment wood materials and the required specific heat energy one 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 kg·kg^{-1} and 0.4 kg·kg^{-1} (KOLLMANN 1951, POŽGAJ *et al.* 1997, VIDELOV 2003, KUDELA 2005, DELIISKI – DZURENDA 2010).

In DELIISKI (1977, 2003, 2004, 2009, 2011) 3-, 2-, and 1-dimensional mathematical models have been created, solved, and verified of the transient non-linear heat conduction and energy consumption in frozen and non-frozen wood materials with prismatic and cylindrical shape during their thermal treatment. In these models the indicated complications and incompletenesses in existing analogous models have been overcome. The solutions include the non-stationary temperature distribution in the volume of the materials, as well as the specific energy consumption at every moment of the heating for each $u \geq 0$ kg·kg^{-1}.

The solution of these models, in which the mechanism for distribution of the temperature in the wood materials is described by rather complex differential equations with partial derivatives, is carried out with the help of a specialized software, developed by the author. This software has been adapted for usage in microprocessor programmable controllers for model based automatic control (HADJIYSKI 2003) of the processes of thermal treatment of containing and non containing ice wood materials with the aim of their ennoblement or plasticizing during the production of veneer (DELIISKI 2003, 2004, DELIISKI – DZURENDA 2010).

When sizing the power of the sources of heat energy, which are used for the supply of the equipment for plasticizing of wood materials in the production of veneer, it is necessery to take into consideration the need for thermal energy both for the heating of the wood and for the thawing of the ice in it during the winter. As it is known, the ice in the wood forms from the freezing of hygroscopically bounded and free water in it (when $u > u_{\text{fsp}}$) (KOLLMANN 1951, POŽGAJ *et al.* 1997, CHUDINOV 1968, SHUBIN 1990, TREBULA – KLEMENT 2002, VIDELOV 2003).

For the calculation of the need of thermal energy for the heating of the wood and melting of the ice in it with the help of non-stationary mathematical models it is necessary to have the mentioned specialized software. The establishment of a methodology for the calculation of this energy with the help of only fragments of these models without usage of the specialized software is of certain scientific and practical interest.

The aim of the present work is to suggest an approach for the calculation of the specific heat energy needed for melting of the ice, which is formed by both the free (q_{fw}) and bounded (q_{bw}) water in subjected to thermal treatment frozen wood materials aimed at their plasticizing in the veneer production. The approach takes into account for the first time the influence of the fiber saturation point of wood species on the values of their q_{fw} and q_{bw} during wood defrosting and the influence of the temperature on the fiber saturation point of frozen and non-frozen wood.

SPECIFIC HEAT ENERGY FOR MELTING OF THE ICE IN THE WOOD MATERIALS WITH MOISTURE CONTENT ABOVE THE FIBER SATURATION POINT

As a rule, in the production of veneer materials are used with wood moisture content *u* above the fiber saturation point u_{fsp}, i.e. with $u > u_{\text{fsp}}$. This means that during the winter these materials contain ice, formed in them from the freezing of both the free and the bounded water in the wood. Consequently it is both of scientific and practical interest the determination of the specific heat energy needed for the melting of both types of ice in the wood, which are contained in 1 m^3 subjected to defrosting wood materials.

The specific energy needed for the heating of 1 m^3 of a given solid body with an initial temperature T_0 to a temperature T_1 is determined using the equation

$$q = \frac{\rho \cdot c \cdot (T_1 - T_0)}{3.6 \cdot 10^6}, \tag{1}$$

where *q* is the specific heat energy, kWh·m^{-3};

ρ – density of the material of the body, kg·m^{-3};

c – specific heat capacity of the material of the body, J·kg^{-1}·K^{-1};

T_0 – temperature of the body at the beginning of the heating, K;

T_1 – temperature of the body at the end of the heating, K.

The multiplier 3.6·10^6 in the denominator of equation (1) ensures that the values of *q* are obtained in kWh·m^{-3}, instead of in J·m^{-3}.

Mathematical description of the specific heat energy needed for melting of the ice formed from the free water in the wood

The calculation of the specific heat energy needed to melt the ice, formed from the freezing of the free water in the wood can be done using an equation analogous to equation (1). Using the studies in CHUDINOV (1966, 1968) it has been determined that the melting of the ice formed from the free water in the wood, takes place in the range from – 2 $^{\circ}$C to – 1 $^{\circ}$C. Taking this fact into account, in accordance with the participating in equation (1) difference $T_1 - T_0$ is equal to $T_1 - T_0 = 1$, and this equation for the case under consideration takes the following form:

$$q_{\mathrm{fw}} = \frac{\rho_{\mathrm{w}} \cdot c_{\mathrm{fw}}}{3.6 \cdot 10^6} \quad @\, 271.15 \le T \le 272.15\,, \tag{2}$$

where q_{fw} is the specific heat energy needed to melt the ice formed from the freezing of the free water in 1 m^3 wood, kWh·m^{-3};

ρ_{w} – wood density, determined according to equation (4), kg·m^{-3};

c_{fw} – specific heat capacity of the ice formed from the freezing of the free water in the wood, J·kg^{-1}·K^{-1}.

For practical usage of equation (2) it is needed to have mathematical descriptions of ρ_{w} and c_{fw}. Such descriptions are given below.

Mathematical description of the specific heat energy needed for melting of the ice formed from the bounded water in the wood

The calculation of the specific heat energy needed for the melting of the ice formed from the freezing of the hygroscopically bounded water in the wood can also be done using an equation analogous to equation (1).

It has been determined, using the studies in CHUDINOV (1966, 1968), that the thawing of the ice formed from the bounded water in the wood takes place gradually in the entire range from the initial temperature of the frozen wood $t_{\mathrm{w0}} < -\,2\ ^{\circ}\mathrm{C}$ (i.e. $T_{\mathrm{w0}} < 271.15\ \mathrm{K}$) until the reaching of the temperature $t_{\mathrm{w1}} = -\,2\ ^{\circ}\mathrm{C}$ (i.e. $T_{\mathrm{w1}} = 271.15\ \mathrm{K}$). Taking into consideration the fact that the full defrosting of the ice from the bounded water in the wood takes place at $T_{\mathrm{w1}} = 271.15\ \mathrm{K}$ for the considered case, equation (1) obtains the following form:

$$q_{\mathrm{bw}} = \frac{\rho_{\mathrm{w}} \cdot c_{\mathrm{bw}}}{3.6 \cdot 10^6}\left(271.15 - T_{\mathrm{w0}}\right) \quad @\; T < 272.15\,, \tag{3}$$

where q_{bw} is the specific heat energy needed for the defrosting of the ice formed from the freezing of the bounded water in 1 m^3 wood, kWh·m^{-3};

ρ_{w} – wood density, determined according to equation (4), kg·m^{-3};

c_{bw} – specific heat capacity of the ice, formed by the freezing of bounded water in the wood, J·kg^{-1}·K^{-1};

T_{w0} – initial temperature of the wood containing ice, K.

For practical usage of equation (3) it is necessary to have mathematical descriptions for ρ_{w} and c_{bw}. Such descriptions are given below.

MATHEMATICAL DESCRIPTION OF THE WOOD DENSITY ABOVE THE FIBER SATURATION POINT

The necessary values of ρ_{w} for the solution of equations (2) and (3) can be calculated using the following equation (CHUDINOV 1968, DELIISKI 2003, 2011):

$$\rho_{\mathrm{w}} = \rho_{\mathrm{b}}(1 + u) \quad @\; u \ge u_{\mathrm{fsp}}\,, \tag{4}$$

where ρ_{w} is the wood density, kg·m^{-3};

ρ_{b} – basic density of the wood, kg·m^{-3}. The values for ρ_{b} for the various wood types are determined as a relation of the wood mass in a completely dry state to its volume at $u \geq u_{\mathrm{fsp}}$ (TREBULA – KLEMENT 2002, VIDELOV 2003) and are given in the specialized literature;

u – wood moisture content, kg·kg^{-1};

u_{fsp} – fiber saturation point of the wood specie, kg·kg^{-1}.

SPECIFIC HEAT CAPACITY OF THE ICE FORMED FROM THE FREE AND BOUNDED WATER IN THE WOOD

Mathematical description of the specific heat capacity of the ice formed from the free water in the wood

The quantity of free water u_{fw}, which corresponds to 1 kg moisture wood, can be determined using the equation

$$u_{\mathrm{fw}} = \frac{u - u_{\mathrm{fsp}}}{1+u}, \tag{5}$$

As it was noted above, the thawing of the ice, formed from the free water in the wood, takes place in the temperature range between –2 $^{\mathrm{o}}$C and –1 $^{\mathrm{o}}$C, i.e. between 271.15 K and 272.15 K. Consequently while solving engineering and technological problems, connected with the defrosting of the wood, one needs to take into consideration the heat energy consumption for melting of the corresponding to u_{fw} ice only in the given temperature range. Outside the range this heat energy consumption needs to be taken as equal to zero. If the content of water in the wood is equal or smaller than u_{fsp}, then this heat energy consumption is also equal to zero.

The quantity of heat needed to defrost the ice formed from the free water in the wood can be determined as a product of u_{fw} with the heat of the phase transition (crystalization) of the water r_{cr}. In treating of this quantity of heat to the temperature interval of 1 K and taking into consideration that r_{cr} = 3.34·10^5 J·kg^{-1} (CHUDINOV 1968) the following equation is obtained

$$c_{\mathrm{fw}} = 3.34 \cdot 10^5 \frac{u - u_{\mathrm{fsp}}}{1+u} \;\; @ \;\; 271.15 \text{ K} \leq T \leq 272.15 \text{ K} \;\; \& \;\; u > u_{\mathrm{fsp}}, \tag{6}$$

where c_{fw} is the specific heat capacity of the ice formed from the freezing of the free water in the wood, J·kg^{-1}·K^{-1};

u – wood moisture content, kg·kg^{-1};

u_{fsp} – fiber saturation point of the wood, kg·kg^{-1}.

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

$$u_{\mathrm{fsp}} = u_{\mathrm{fsp}}^{293.15} - 0.001(T - 293.15), \tag{7}$$

where $u_{\mathrm{fsp}}^{293.15}$ is the fiber saturation point of the wood at temperature T = 293.15 K, i.e. at t = 20 $^{\mathrm{o}}$C.

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 $^{\mathrm{o}}$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 - SHVETTS 2006). A proportional reduction of the maximum amount of bound water that cells' walls can hold at freezing temperatures have been experimentally determined by SHMULSKY - SHVETTS (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 the wood a decrease of u_{fsp} can be expected while *u* increases in the hygroscopic range.

Since equation (7) is generally accepted in the specialized literature, then during the mathematical description of c_{fw} according to (6), this equation is used for the reflection of the influence of *T* on u_{fsp} for wood at $t < 0\ ^{\mathrm{o}}\mathrm{C}$ after the occurrence of complete thawing of the ice, formed from the free water in the wood. This means that after substituting into equation (7) of $T = 272.15\ \mathrm{K}$ (i.e. $t = -1\ ^{\mathrm{o}}\mathrm{C}$) the value of u_{fsp} in (6) can be determined using the equation

$$u_{\mathrm{fsp}} = u_{\mathrm{fsp}}^{293.15} + 0.021 \ @\ T = 272.5\,, \tag{8}$$

Mathematical description of the specific heat capacity of the ice formed from the bounded water in the wood

Using data by CHUDINOV (1968) the following equation for the determination of the specific heat capacity of the ice, formed in the wood from the freezing of the hygroscopically bounded water in it, has been obtained (DELIISKI 2003):

$$c_{\mathrm{bw}} = 1.8938 \cdot 10^{4} \left(u_{\mathrm{fsp}} - 0.12\right) \frac{\exp\left[0.0567\left(T - 271.15\right)\right]}{1+u} \ @\ T \le 271.15\ \mathrm{K}\,, \tag{9}$$

where c_{bw} is the specific heat capacity of the ice, formed from the freezing of the bounded water in the wood, J·kg^{-1}·K^{-1};

u – wood moisture content, kg·kg^{-1};

u_{fsp} – fiber saturation point of the wood, kg·kg^{-1};

T – temperature, K.

Since the full defrosting of the ice from the bounded water in the wood takes place at $T = 271.15\ \mathrm{K}$ (CHUDINOV 1968), then by substituting in equation (7) of this value of the temperature *T* the value of u_{fsp} in (9) can be determined using the equation

$$u_{\mathrm{fsp}} = u_{\mathrm{fsp}}^{293,15} + 0.022 \ @\ T = 271.15\,. \tag{10}$$

FINAL EQUATIONS FOR THE CALCULATION OF q_{fw} AND q_{bw}

After substituting (3), (6) and (8) in (2) the following final equation for the calculation of q_{fw} at $271.15\ \mathrm{K} \le T \le 272.15\ \mathrm{K}\ \ \&\ \ u \ge u_{\mathrm{fsp}}$ is obtained:

$$q_{\mathrm{fw}} = 9.27778 \cdot 10^{-2}[u - (u_{\mathrm{fsp}}^{293.15} + 0.021)]\rho_{\mathrm{b}}\,. \tag{11}$$

After substituting (3), (9) and (10) in (4) the following final equation for the calculation of q_{bw} at $T_{\mathrm{w0}} \le 271.15\ \mathrm{K}\ \ \&\ \ u \ge u_{\mathrm{fsp}}$ is obtained:

$$q_{\mathrm{bw}} = 5.26\cdot 10^{-3}\left(u_{\mathrm{fsp}}^{293.15} - 0.098\right)\exp\left[0.0567\left(\frac{T_{\mathrm{w0}} + 271.15}{2} - 271.15\right)\right]\rho_{\mathrm{b}}\left(271.15 - T_{\mathrm{w0}}\right). \qquad (12)$$

The meaning of the variables involved in equations (11) and (12) are given above when clarifying equations (2) to (10).

RESULTS AND DISCUSSION

For the solution of equations (11) and (12) a program in the calculation environment of MS Excel 2010 has been created (refer to http://www.gcflearnfree.org/excel2010).

With the help of the program the change in q_{fw} has been calculated depending on $u = \mathrm{var}$ and in q_{bw} depending on $T_{\mathrm{w0}} = \mathrm{var}$ of frequently used in the production of veneer materials from oak (*Quercus petraea* Libl.), beech (*Fagus silvatica* L.), pine (*Pinus silvestris* L.), and polar (*Populus nigra* L.).

For the calculations, values of the basic density and of the fiber saturation point at 20 $^{\mathrm{o}}$C derived in the literature for the relevant wood species have been used, namely: $\rho_{\mathrm{b}} = 670$ kg·m^{-3} and $u_{\mathrm{fsp}}^{291.15} = 0.29$ kg·kg^{-1} for oak; $\rho_{\mathrm{b}} = 560$ kg·m^{-3} and $u_{\mathrm{fsp}}^{291.15} = 0.31$ kg·kg^{-1} for beech; $\rho_{\mathrm{b}} = 430$ kg·m^{-3} and $u_{\mathrm{fsp}}^{291.15} = 0.30$ kg·kg^{-1} for pine, and $\rho_{\mathrm{b}} = 355$ kg·m^{-3} and $u_{\mathrm{fsp}}^{291.15} = 0.35$ kg·kg^{-1} for poplar (VIDELOV 2003, DELIISKI - DZURENDA 2010).

The determination of q_{fw} is done according to the wood moisture content *u* above the hygroscopic range (i.e. at $u > u_{\mathrm{fsp}}$), which guarantees the formation of ice from the free water in the wood. The influence of *u* on q_{fw} in the range $u_{\mathrm{fsp}} \le u \le 1.0$ kg·kg^{-1}, in which usually the wood moisture content of subjected to thermal treatment during the winter wood materials with the aim of their plasticizing for veneer production falls.

The influence of the initial wood temperature on q_{bw} has been studied for wood containing ice in the range $253.15\ \mathrm{K} \le T_{\mathrm{w0}} \le 271.15\ \mathrm{K}$ (i.e. $-20\ ^{\mathrm{o}}\mathrm{C} \le t_{\mathrm{w0}} \le -2\ ^{\mathrm{o}}\mathrm{C}$).

The calculated according to equation (11) change in $q_{\mathrm{fw}} = f(u)$ is shown on Fig. 1.

The calculated according to equation (12) change in $q_{\mathrm{bw}} = f(t_{\mathrm{w0}})$ is shown on Fig. 2.

The change in the sum of q_{fw} and q_{bw} has been shown on Fig. 3 depending on *u* at $t_{\mathrm{w0}} = -10\ ^{\mathrm{o}}\mathrm{C}$ and $t_{\mathrm{w0}} = -20\ ^{\mathrm{o}}\mathrm{C}$.

The analysis of the shown on Fig. 1, Fig. 2, and Fig. 3 results warrants the making of the following conclusions:

1. The specific heat energy consumption q_{fw}, which is needed for melting of the formed in the wood ice from the freezing of the free water in it, increases proportionally to wood moisture content *u* (Fig. 1).

   According to equation (11) the values of q_{fw} are proportional to the product of ρ_{b} and c_{fw} for each of the wood species and does not depend on the initial temperature of the frozen wood.

   When $u = u_{\mathrm{fsp}}$, then according to (5) there is no free water in the wood, and consequently ice from it, and then $q_{\mathrm{fw}} = 0$.

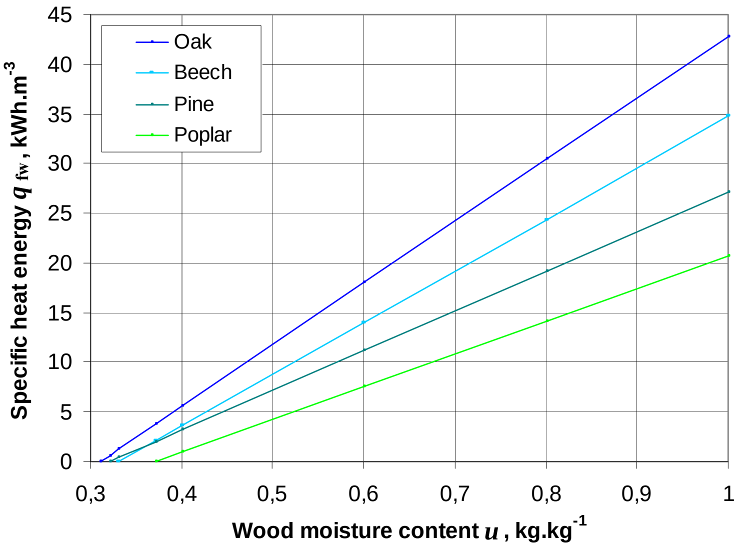

Fig. 1 Change in $q_{\rm fw}$ depending on *u* at $u > u_{\rm fsp}$ and wood specie.

At $u = 1{,}0$ kg.kg^{-1} the following valus for $q_{\rm fw}$ are needed for melting the ice formed from the free water in the wood: 20.717 kWh·m^{-3} for poplar, 27.088 kWh·m^{-3} for pine, 34.758 kWh·m^{-3} for beech и 42.829 kWh·m^{-3} for oak. These large values for $q_{\rm fw}$ are caused by the extremely large values of the specific heat capacity of the ice from the free water, determined according to equation (6).

Since according to equation (8) for this case $u_{\rm fsp} = 0.371$ kg·kg^{-1} for poplar, $u_{\rm fsp} = 0.321$ kg·kg^{-1} for pine, $u_{\rm fsp} = 0.331$ kg·kg^{-1} for beech, and $u_{\rm fsp} = 0.311$ kg·kg^{-1} for oak, then, consequently, each change in u with 0.01 kg.kg^{-1} causes the following change in $q_{\rm fw}$: 0.3294 kWh·m^{-3} for polar, 0.3989 kWh·m^{-3} for pine, 0.5196 kWh·m^{-3} for beech, and 0.6216 kWh·m^{-3} for oak.

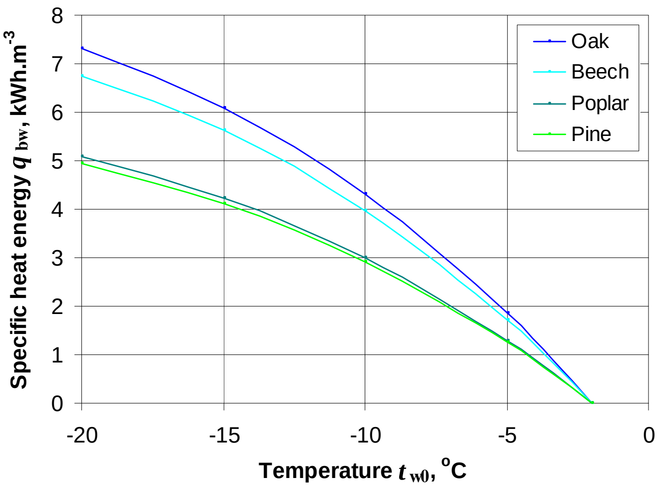

Fig. 2 Change in $q_{\rm bw}$ depending on $t_{\rm w0}$ and wood specie.

2. The specific heat energy consumption $q_{\rm bw}$, which is needed for the thawing of the formed in the wood ice from the freezing of the hygroscopically bounded water in it, decreases according to a slight curvilinear dependence when the initial temperature of the frozen wood $t_{\rm w0}$ is increased (Fig. 2).

According to equation (12) at $T_{w0} \le 271.15$ K & $u \ge u_{fsp}$ the values for q_{bw} for each of the wood species increase with the increase in ρ_b, c_{bw}, and the temperature difference $271.15 - T_{w0}$.

According to equation (12) the values of q_{bw} do not depend on *u*. Ths is natural, since for all studied values where $u \ge u_{fsp}$ the wood contains the maximum possible for any given wood specie quantity of bounded water, for the melting of the ice from which one and the same value of q_{bw} is needed at a particular t_{w0}.

At $t_{w0} = -20$ °C for the thawing of the ice from the bounded water in the wood the following values for q_{bw} are needed: 4.937 kWh·m^{-3} for pine, 5.085 kWh·m^{-3} for poplar, 6.748 kWh·m^{-3} for beech, and 7.312 kWh·m^{-3} for oak. These values of q_{bw} are a few times smaller than the shown on Fig. 1 values for q_{fw}. A reason for this are the few times smaller values for c_{bw}, determined according to equation (9) in comparison with the determined according to equation (6) values for c_{fw}. With the increase in *u* the difference between q_{fw} and q_{bw} increases.

If the slightly curvilinear dependencies $q_{bw} = f(t_{w0})$ on Fig. 2 are approximated with straight lines, which connect their initial and final points, it turns out that each increase in t_{w0} with 1 °C causes a decrease in q_{bw} with approximately 0.2743 kWh·m^{-3} for pine, 0.2825 kWh·m^{-3} for poplar, 0.3749 kWh·m^{-3} for beech, and 0.4062 kWh·m^{-3} for oak.

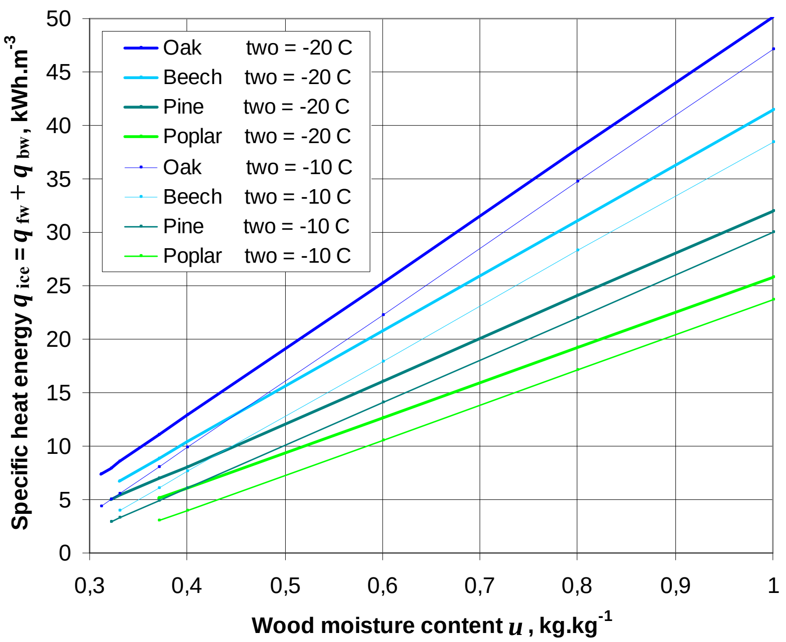

Fig. 3 Change in q_{ice} depending on t_{w0}, u at $u > u_{fsp}$, and wood specie.

3. The total specific heat energy consumption of thermal energy $q_{ice} = q_{fw} + q_{bw}$, which is needed for the thawing of the formed in the wood ice from the freezing of the free and bounded water in it, increases proportionally to the wood moisture content *u* (Fig. 3). This total consumption increases with the decrease of T_{w0}.

   Each change in *u* with 0.01 kg·kg^{-1} causes the following change in the total specific heat energy consumption q_{ice}:

▪ for poplar: 0.3771 kWh·m^{-3} at $t_{w0} = -10$ °C and 0.4102 kWh·m^{-3} at $t_{w0} = -20$ °C ;

▪ for pine: 0.4418 kWh·m^{-3} at $t_{w0} = -10$ °C and 0.4716 kWh·m^{-3} at $t_{w0} = -20$ °C ;

▪ for beech: 0.5750 kWh·m^{-3} at $t_{w0} = -10$ °C and 0.6204 kWh·m^{-3} at $t_{w0} = -20$ °C ;

▪ for oak: 0.6842 kWh·m^{-3} at $t_{w0} = -10$ °C and 0.7277 kWh·m^{-3} at $t_{w0} = -20$ °C .

The total specific heat energy consumption q_{ice} at a random value of t_{w0} in the range $-20\ ^{o}\mathrm{C} \le t_{w0} \le -2\ ^{o}\mathrm{C}$ for the condition of $u \ge u_{fsp}$ can be determined when the values of q_{fw} from Fig. 1 and of q_{bw} from Fig. 2 are summed for a specific given value of t_{w0} .

CONCLUSIONS

The present paper describes the suggested by the authors approach for the calculation of the specific heat energy q_{ice}, which is needed for melting of the ice in the wood. The approach takes into account to a maximum degree the physics of the processes of thawing of the ice, formed by both the bounded and the free water in the 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 q_{ice} during wood defrosting and the influence of the temperature on the fiber saturation point of frozen and non-frozen wood.

An equation for easy determination of the specific heat energy q_{fw}, needed for melting of the ice, which is formed by the free water in the wood has been derived depending on the basic density of the wood ρ_b, the wood moisture content u, and the fiber saturation point u_{fsp}. An equation for determination at $u \ge u_{fsp}$ of the specific heat energy q_{bw}, needed for the melting of the ice, which is formed by the bounded water in the wood has been derived as well depending on ρ_b, u, u_{fsp}, and the initial temperature of the frozen wood t_{w0} .

For the calculation of the q_{fw} and q_{bw} according to a suggested approach and according to the created mathematical description of q_{fw} and q_{bw} a software program has been prepared in MS Excel 2010. With the help of the program calculations have been carried out for the determination of q_{fw} and q_{bw} for oak, beech, pine and poplar frozen wood with moisture content $u_{fsp} \le u \le 1.0$ kg·kg^{-1} at a temperature range of t_{w0} from –20 °C to –1 °C.

The obtained results show that q_{fw} does not depend on t_{w0} of the frozen wood and the change in q_{fw} depending on u is linear. When $u \le u_{fsp}$, there is no free water in the wood and then $q_{fw} = 0$. With an increase of u in comparison to u_{fsp} the specific heat energy q_{fw} grows fast and at $u = 1.0$ kg·kg^{-1} reaches the following very large values: 20.717 kWh·m^{-3} for poplar, 27.088 kWh·m^{-3} for pine, 34.758 kWh·m^{-3} for beech, and 42.829 kWh·m^{-3} for oak. A reason for this is the very large specific heat capacity of the ice formed from the free water in the wood c_{fw} .

The results also show that q_{bw} at $u > u_{fsp}$ does not depend on u and the change in q_{bw} depending on t_{w0} is non-linear. At $t_{w0} = -20$ °C for the thawing of the ice from the bounded water in the wood the following values for q_{bw} are needed: 4.937 kWh·m^{-3} for pine, 5.085 kWh·m^{-3} for poplar, 6.748 kWh·m^{-3} for beech, and 7.312 kWh·m^{-3} for oak.

These values of q_{bw} are a few times smaller than the values of q_{fw}. A reason for this are the few times smaller values of the specific heat capacity of the ice from the bounded water c_{bw} in comparison to these of c_{fw}. With an increase in t_{w0} the specific heat energy q_{bw} decreases to a value of $q_{\mathrm{bw}} = 0$ at $t_{\mathrm{w0}} = -2$ $^{\mathrm{o}}$C, since at this temperature the ice from the bounded water in the wood thaws completely.

The obtained results can be used for a science-based determination of the heat energy, which is needed for the defrosting of wood materials containing ice with the aim of their plasticizing for the production of veneer and plywood. They are also of specific importance for the optimization of the technology and control of the wood defrosting processes.

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