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MODELLING OF THE ENERGY NEEDED FOR MELTING OF THE ICE IN FROZEN WOOD ABOVE THE HYGROSCOPIC DIAPASON

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ABSTRACT

A mathematical model and an approach for calculation of the specific heat energy needed for melting of the ice in the wood above the hydroscopic diapason, q_{ice}, have been suggested. The model takes into account to a maximum degree the physics of the processes of melting of the ice, formed by both bound and free water in the wood. It reflects the influence of the temperature, wood moisture content, wood density, and for the first time also the influence of fiber saturation point u_{fsp} of each wood type on q_{ice} during wood defrosting and the influence of temperature on u_{fsp} of frozen wood.

An equation for calculation of the specific heat energy needed for melting of the frozen bound water in the wood above the hygroscopic diapason, q_{bwm}, has been derived, depending on the basic density of the wood ρ_{b}, on the wood moisture content *u*, on the fiber saturation point u_{fsp}, and on the initial temperature of the frozen wood t_0. An equation for easy determination of the specific heat energy needed for melting of the frozen free water in the wood, q_{fw}, has been derived as well, depending on ρ_{b}, *u*, and u_{fsp}. The specific heat energy q_{ice} equals to $q_{\text{fw}} + q_{\text{bw}}$.

For calculation of the q_{bwm}, q_{fw}, and q_{ice} according to the suggested model and approach, a software program has been prepared in MS Excel 2010. By means of the program, calculations have been carried out for determination of q_{bwm}, q_{fw}, and q_{ice} for frozen oak and poplar wood with moisture content from $u = 0.4\ \text{kg}\cdot\text{kg}^{-1}$ to $u = 1.0\ \text{kg}\cdot\text{kg}^{-1}$ at a temperature ranging from t_0 = –20 $^{\text{o}}$C to t_0 = –1 $^{\text{o}}$C, at which melting of the frozen water in the wood is completed.

Key words: wood defrosting, frozen bound water, frozen free water, specific heat energy

1. INTRODUCTION

When sizing the power of the sources of heat energy which are used for supply of the equipment for defrosting of wood materials, it is necessary to take into consideration the need for energy both for heating the frozen wood and for melting of the ice in it during winter (Sergovsky, 1975), (Shubin, 1990), (Pervan, 2000), (Videlov, 2003), (Trebula, Klement, 2002).

In Deliiski (2003, 2011, 2013c) 3-, 2-, and 1-dimensional models have been created, solved, and verified of the transient non-linear heat conduction and energy consumption in frozen wood materials with prismatic and cylindrical shape during their thermal treatment. The solution of these models, in which the mechanism for distribution of the temperature in wood materials is described by rather complex differential equations with partial derivatives, was carried out with the help of specialized software, developed by the author. For calculation of the energy needed for heating the frozen wood materials and melting of the ice in them with the help of non-stationary mathematical models, it is necessary to have the mentioned specialized software, whose accessibility, however, is very limited (Deliiski, 2003, 2004, 2009).

The aim of the present work is to suggest an easy way for engineering applications for a mathematical model of the specific heat energy consumption, which is needed for melting of the ice in the wood, q_{ice}, above the hydroscopic diapason. With the purpose of achieving this goal, mathematical models of the two consisting parts of q_{ice} have been also suggested, as follows: of the energy needed for melting of the frozen bound water in the wood, q_{bwm}, and of the energy needed for melting of the frozen free water in the wood, q_{fw}.

2. MATERIAL AND METHODS

Classical approach for calculation of the energy needed for heating of solid bodies

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

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

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

An approach for calculation of the energy needed for melting of the frozen water in the wood above the hygroscopic diapason

It is known that above the hygroscopic diapason the wood contains the maximum possible amount of bound water for the given wood type and it contains free water too. This means that the heating of the frozen wood from an initial mass temperature T_0 to final mass temperature T_1 above the hygroscopic diapason includes 3 phases: melting of the frozen bound water between T_0 and $T_{\text{dfr}}^{\text{bwm}}$; melting of the frozen free water between $T_{\text{dfr}}^{\text{bwm}}$ and $T_{\text{dfr}}^{\text{fw}}$, and heating of the defrosted wood from $T_{\text{dfr}}^{\text{fw}}$ to T_1 (Figure 1).

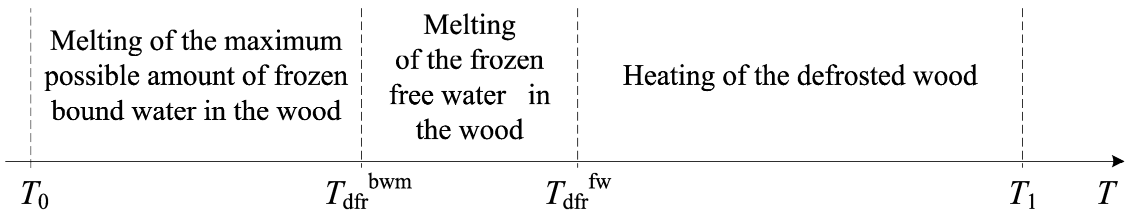

Figure 1. *Phases of heating frozen wood above the hygroscopic diapason*

The specific heat energy needed for melting of the ice, which is formed from both bound and free water in the wood, q_{ice}, is equal to

$$q_{\text{ice}} = q_{\text{bwm}} + q_{\text{fw}} \tag{2}$$

Based on eq. (1) and on Figure 1, the participants of eq. (2) can be calculated according to the following equations (Deliiski, 2013d):

• The specific heat energy needed for melting of the maximum possible amount of frozen bound water in the wood:

$$q_{\text{bwm}} = \frac{c_{\text{bwm}} \rho_{\text{fw}}}{3.6 \cdot 10^6}\left(T_{\text{dfr}}^{\text{bwm}} - T_0\right) \quad @ \quad u > u_{\text{fsp}}^{271.15} \;\&\; T_0 < T_{\text{dfr}}^{\text{bwm}} \tag{3}$$

• The specific heat energy needed for the melting of the frozen free water in the wood:

$$q_{\text{fw}} = \frac{c_{\text{fw}} \rho_{\text{fw}}}{3.6 \cdot 10^6} \left(T_{\text{dfr}}^{\text{fw}} - T_{\text{dfr}}^{\text{bwm}} \right) \quad @ \quad u > u_{\text{fsp}}^{271.15} \ \& \ T_{\text{dfr}}^{\text{bwm}} < T_{\text{dfr}}^{\text{fw}} \tag{4}$$

For practical usage of eqs. (3) and (4) it is needed to have mathematical descriptions of the specific heat capacities of both frozen bound and free water in the wood and also of the density of frozen wood above the hygroscopic diapason. Such descriptions are given below.

Mathematical model of the specific heat capacities of frozen water in the wood

Mathematical description of the specific heat capacity of frozen bound water in the wood

Using data by (Chudinov, 1966, 1968), the following equation for calculation of the specific heat capacity of the ice, formed in the wood from freezing of the hygroscopically bound water in it, has been obtained (Deliiski, 2003, 2013a):

$$c_{\text{bw}} = 1.8938 \cdot 10^4 \left(u_{\text{fsp}}^{\text{fr}} - 0.12 \right) \frac{\exp[0.0567(T - 271.15)]}{1 + u} \quad @ \ T \le 271.15 \ \text{K} \tag{5}$$

After substituting $u_{\text{fsp}}^{\text{fr}} = u_{\text{fsp}}^{293.15} - 0.001(T_{\text{dfr}}^{\text{bw}} - 293.15)$ taken from (Deliiski, 2013b) and T with the average arithmetic value $T = \dfrac{T_0 + T_{\text{dfr}}^{\text{bw}}}{2}$ into equation (5), it obtains the following form which is suitable for engineering calculations in the hygroscopic diapason:

$$c_{\text{bw}} = 1.8938 \cdot 10^4 \left(u_{\text{fsp}}^{293.15} - 0.001 T_{\text{dfr}}^{\text{bw}} + 0.17315 \right) \cdot \frac{\exp\left[0.0567 \left(\dfrac{T_0 + T_{\text{dfr}}^{\text{bw}}}{2} - 271.15 \right) \right]}{1 + u} \tag{6}$$

It has been determined, using the studies in (Chudinov, 1966), that melting of the frozen bound water in the wood takes place gradually in the entire range, from the initial temperature of the frozen wood $t_0 < -2\ ^{\text{o}}\text{C}$ (i.e. $T_0 < 271.15$ K) until reaching the temperature $t_{\text{dfr}}^{\text{bwm}} = -2\ ^{\text{o}}\text{C}$ (i.e. $T_{\text{dfr}}^{\text{bwm}} = 271.15$ K). After substituting of $T_{\text{dfr}}^{\text{bw}}$ in eq. (6) with $T_{\text{dfr}}^{\text{bwm}} = 271.15$ K for wood with $u > u_{\text{fsp}}^{271.15}$, this equation obtains the following form, which is fully suitable for engineering calculations above the hygroscopic diapason:

$$c_{\text{bwm}} = 1.8938 \cdot 10^4 \left(u_{\text{fsp}}^{293.15} - 0.098 \right) \cdot \frac{\exp\left[0.0567 \left(\dfrac{T_0 + 271.15}{2} - 271.15 \right) \right]}{1 + u} \tag{7}$$

The calculated according to eq. (7) change in c_{bwm} for oak wood with $u_{\text{fsp}}^{293.15} = 0.29\ \text{kg} \cdot \text{kg}^{-1}$ and for poplar wood with $u_{\text{fsp}}^{293.15} = 0.35\ \text{kg} \cdot \text{kg}^{-1}$ (Nikolov, Videlov, 1987) at $t_0 = -2\ ^{\text{o}}\text{C}$, $t_0 = -10\ ^{\text{o}}\text{C}$, and $t_0 = -20\ ^{\text{o}}\text{C}$ depending on u is shown in Figure 2.

It can be seen in Figure 2 that c_{bwm} decreases at a given value of t_0 according to an exponential dependence when the wood moisture content u increases. It can be also seen that the decrease of t_0 and the increase of $u_{\text{fsp}}^{293.15}$ of the wood type cause a decrease in c_{bwm} at a given value of u.

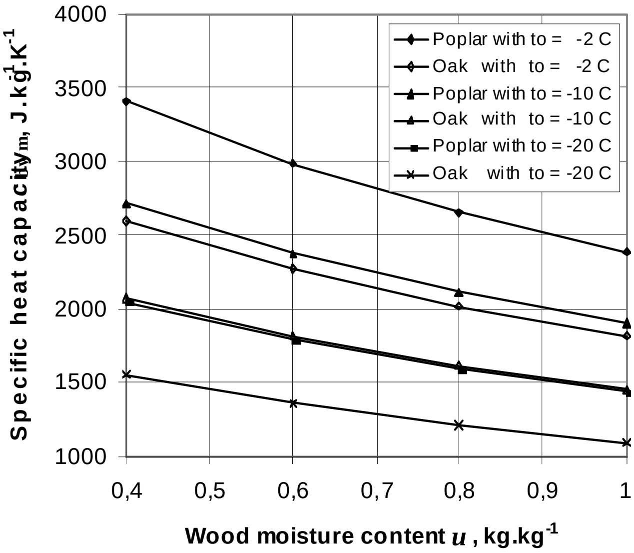

Figure 2. *Change in c_{bwm} during defrosting of poplar and oak wood, depending on u and t_0*

Mathematical description of the specific heat capacity of the frozen free water in the wood

The specific heat capacity, expressing the heat of the phase transition of the water in the wood during wood defrosting is separated into two parts, since melting of the ice, formed from the free and from the hygroscopically bound water in the wood takes place in different temperature diapasons.

The amount of free water u_{fw} corresponding to 1 kg wood, can be determined according to the equation

$$u_{\mathrm{fw}} = \frac{u - u_{\mathrm{fsp}}^{271.15}}{1+u} \quad @ \quad u > u_{\mathrm{fsp}}^{271.15} \tag{8}$$

It has been determined that melting of the ice, formed from the free water in the wood, takes place in the temperature range between –2 °C and –1 °C, i.e. between 271.15 K and 272.15 K (Chudinov, 1966, 1968). Consequently, during calculation of technological and energy-related problems related to defrosting of the wood, one needs to take into account the heat consumption for melting of the existing amount of ice formed from the free water in the wood, u_{fw}, only in the given temperature diapason.

The quantity of heat which is needed for melting of the ice formed from the free water in the wood can be determined as a product of u_{fw} with the heat in the phase transition (crystallization) of the wood, h_{crw}. When relating this quantity of heat to the temperature range of 1 K and taking into account that $h_{\mathrm{crw}} = 3.34 \cdot 10^5$ J.kg^{-1} (Chudinov, 1966), it leads to

$$c_{\mathrm{fw}} = 3.34 \cdot 10^5 \frac{u - u_{\mathrm{fsp}}^{271.15}}{1+u} \quad @ \quad u > u_{\mathrm{fsp}}^{271.15} \ \& \ \ 271.15 \text{ K} < T \leq 272.15 \text{ K} \tag{9}$$

Computations have been made for determination of c_{fw} depending on u above the hygroscopic diapason from $u = 0.4$ kg·kg^{-1} to $u = 1.0$ kg·kg^{-1}. With the help of the results obtained according to eq. (9), the dependences $c_{\mathrm{fw}} = f(u)$ of frozen free water in oak and poplar wood in Figure 3 have been drawn. The analysis of the obtained results leads to the following conclusions:

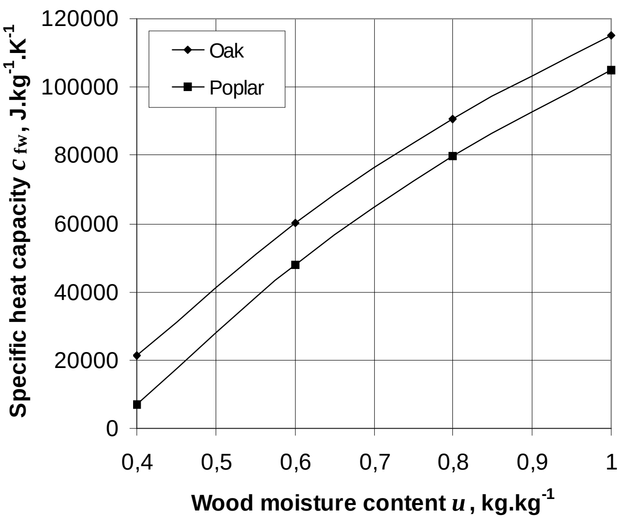

Figure 3. *Change in c_{fw} during defrosting of poplar and oak wood, depending on u*

1. The increase in u **c**auses a non-linear increase in c_{fw} due to increment of the amount of frozen free water in the more moist wood. The increase of u from $u = 0.4\ \mathrm{kg\cdot kg^{-1}}$ to $u = 1.0\ \mathrm{kg\cdot kg^{-1}}$ causes an increase in c_{fw} by 5.42 times for oak wood and by 15.18 times for poplar wood.

2. The increase of $u_{\mathrm{fsp}}^{293.15}$ of the wood type causes a decrease in c_{fw} at a given value of u.

3. The value of c_{fw} for frozen wood with moisture content $u = 0.6\ \mathrm{kg\cdot kg^{-1}}$, which is often encountered in the production of veneer and plywood, is greater than the respective values of c_{bwm} at $t_0 = -2\ ^{\circ}\mathrm{C}$, $t_0 = -10\ ^{\circ}\mathrm{C}$ and $t_0 = -20\ ^{\circ}\mathrm{C}$, as follows:

- by 26.5 times, by 33.3 times and by 44.2 times respectively for oak wood;
- by 16.0 times, by 20.1 times and by 26.7 times respectively for poplar wood.

This means that the energy needed for of the frozen free water is expected to be more than 10 times the energy needed for melting of the frozen bound water in the wood.

Mathematical description of the density of frozen wood above the hygroscopic diapason

The necessary values of the density of the frozen wood above the hygroscopic diapason, ρ_{fw}, which is needed for the solution of eqs. (3) and (4), can be calculated using the following equation (Chudinov, 1968), (Deliiski, 2003):

$$\rho_{\mathrm{fw}} = \rho_{\mathrm{b}}(1+u) \quad @ \quad u \ge u_{\mathrm{fsp}}^{271.15} \tag{10}$$

The calculated change in ρ_{fw} according to eq. (10) depending on u for oak wood with $\rho_{\mathrm{b}} = 670\ \mathrm{kg\cdot m^{-3}}$ and for poplar wood with $\rho_{\mathrm{b}} = 355\ \mathrm{kg\cdot m^{-3}}$ (Nikolov, Videlov, 1987), is shown in Figure 4.

As it can be seen in Figure 4, the density of frozen wood increases according to linear dependency when the wood moisture content u increases.

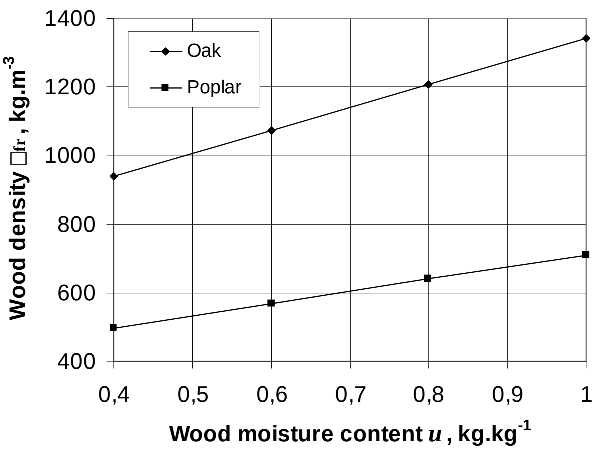

Figure 4. *Change in ρ_{fw} of oak and poplar wood, depending on u*

Each increase of u by $0.01\ \mathrm{kg\cdot kg^{-1}}$ causes an increase in ρ_{fw} by 3.55 $\mathrm{kg{\cdot}m^3}$ for poplar and by 6.70 $\mathrm{kg{\cdot}m^3}$ for oak wood, i.e. by 1% from the basic density ρ_{b} of the given wood type.

According to eq. (10), the wood density above the hygroscopic diapason does not depend on the initial temperature of the frozen wood.

Final equations for calculation of the specific heat energies q_{bwm} and q_{fw}

After substituting eqs. (7) and (10) in (3), the following final equation for calculation of q_{bwm} at $u > u_{\mathrm{fsp}}^{271.15}$ & $T_0 < 271.15\ K$ is obtained:

$$q_{\mathrm{bwm}} = 5.26 \cdot 10^{-3}\left(u_{\mathrm{fsp}}^{293.15} - 0.098\right)\exp\left[0.0567\left(\frac{T_0 + 271.15}{2} - 271.15\right)\right] \cdot \rho_{\mathrm{b}}\left(271.15 - T_0\right) \tag{11}$$

After substituting eqs. (9) and (10) in (4), the following final equation for calculation of q_{fw} at $u > u_{\mathrm{fsp}}^{271.15}$ & $271.15\ \mathrm{K} < T \le 272.15\ \mathrm{K}$ is obtained:

$$q_{\mathrm{fw}} = 9.27778 \cdot 10^{-2}\left(u - u_{\mathrm{fsp}}^{271.15}\right) \cdot \rho_{\mathrm{b}} \tag{12}$$

3. RESULTS

For the solution of eqs. (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 q_{bwm} depending on $T_0 = \mathrm{var}$ and in q_{fw} depending on $u = \mathrm{var}$ has been calculated as frequently used in the production of veneer oak wood (*Quercus petraea* Libl.) and poplar wood (*Populus nigra* L.).

For calculations, values of the basic density and of the fiber saturation point at 20 $^{\mathrm{o}}$C derived in the literature for the studied types have been used, namely: $\rho_{\mathrm{b}} = 670\ \mathrm{kg{\cdot}m^{-3}}$ and $u_{\mathrm{fsp}}^{291.15} = 0.29\ \mathrm{kg{\cdot}kg^{-1}}$ for oak wood and $\rho_{\mathrm{b}} = 355\ \mathrm{kg{\cdot}m^{-3}}$ and $u_{\mathrm{fsp}}^{291.15} = 0.35\ \mathrm{kg{\cdot}kg^{-1}}$ for poplar wood (Nikolov, Videlov, 1987).

The influence of the initial wood temperature on q_{bwm} has been studied for wood containing ice in the range $253.15\ \mathrm{K} \le T_0 \le 271.15\ \mathrm{K}$ (i.e. $-20\ ^{\mathrm{o}}\mathrm{C} \le t_0 \le -2\ ^{\mathrm{o}}\mathrm{C}$).

The determination of q_{fw} is done according to the wood moisture content u above the hygroscopic range (i.e. at $u > u_{\mathrm{fsp}}^{271.15}$), which guarantees formation of ice from the free water in the wood.

The influence of u on q_{fw} is studied in the range $0.4\ \mathrm{kg\cdot kg^{-1}} \le u \le 1.0\ \mathrm{kg\cdot kg^{-1}}$, in which usually the wood moisture content of wood materials subjected to thermal treatment during the winter with the aim of their plasticizing for veneer and plywood production falls.

The calculated according to eq. (11) change in $q_{\mathrm{bwm}} = f(t_0)$ is shown in Figure 5.

The calculated according to eq. (12) change in $q_{\mathrm{fw}} = f(u)$ is shown in Figure 6.

The change in q_{ice}, i.e. in the sum of q_{bwm} and q_{fw} (see eq. (2)), is shown in Figure 7 depending on u at $t_0 = -5\ ^{\mathrm{o}}\mathrm{C}$, $t_0 = -10\ ^{\mathrm{o}}\mathrm{C}$, and $t_0 = -20\ ^{0}\mathrm{C}$.

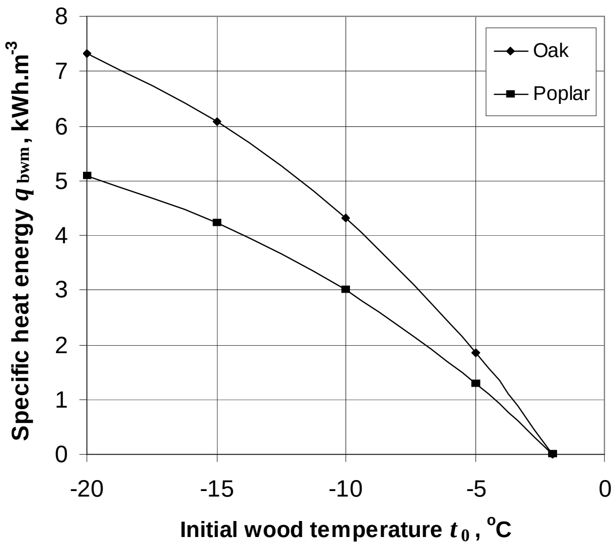

Figure 5. *Change in q_{bwm} during defrosting of poplar and oak wood, depending on t_0*

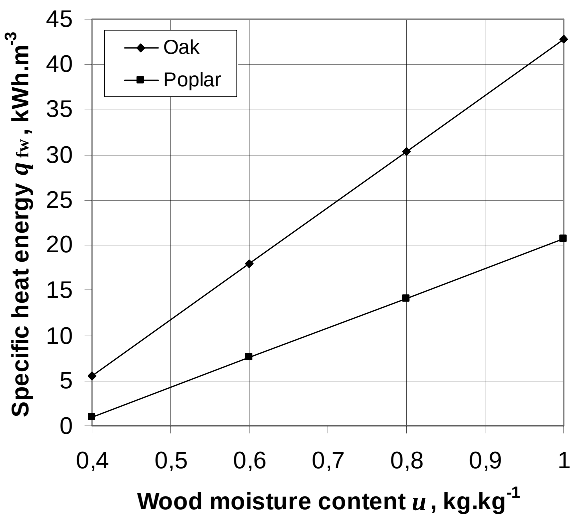

Figure 6. *Change in q_{fw} during defrosting of poplar and oak wood, depending on u*

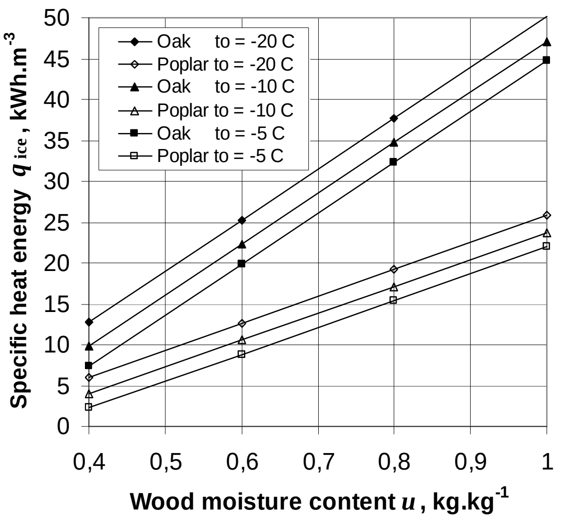

Figure 7. *Change in q_{ice} during defrosting of poplar and oak wood, depending on u and t_0*

The analysis of the results shown in Figure 5, Figure 6, and Figure 7 leads to the following conclusions:

1. The specific heat energy q_{bwm} which is needed for melting of the frozen bound water in the wood above the hygroscopic diapason decreases according to a slight curvilinear dependence when the initial temperature of the wood t_0 is increased (Figure 5).

According to eq. (11), the values for q_{bwm} for each of the wood types increase with the increase in ρ_{b}, c_{bwm}, and the temperature difference $271.15 - T_0$. According to eq. (11), the values of q_{bwm} do not depend on u. This is natural, since above the hygroscopic diapason the wood contains the maximum possible for any given wood type amount of bound water for melting of the ice from which one and the same value of q_{bwm} is needed at a particular t_0.

At $t_0 = -20\ ^{\mathrm{o}}\mathrm{C}$ for melting of the frozen bound water in the wood, the following values for q_{bwm} are needed: 5.085 kWh·m^{-3} for poplar wood and 7.312 kWh·m^{-3} for oak wood. These values of q_{bwm} are a few times lower than the ones shown in Figure 6 values for q_{fw}. A reason for this are the few times lower values for c_{bwm}, determined according to eq. (7), in comparison with the determined according to eq. (9) values for c_{fw}. With increase in u the difference between q_{fw} and q_{bwm} increases.

If the slightly curvilinear dependencies $q_{\mathrm{bwm}} = f(t_0)$ in Figure 5 are approximated with straight lines, which connect their initial and final points, it turns out that each increase in t_0 with 1 $^{\mathrm{o}}$C causes a decrease in q_{bwm} with approximately 0.2825 kWh·m^{-3} for poplar wood and 0.4062 kWh·m^{-3} for oak wood.

2. The specific heat energy consumption q_{fw} which is needed for melting of the frozen free water in the wood, increases proportionally to wood moisture content u (Figure 6).

According to eq. (12), the values of q_{fw} are proportional to the product of ρ_{b} and the moisture difference $u - u_{\mathrm{fsp}}^{271.15}$ for each of the wood species and do not depend on the initial temperature of the frozen wood.

When $u \leq u_{\mathrm{fsp}}^{271.15}$, then according to eq. (8) there is no free water in the wood, and consequently ice from it, and then $q_{\mathrm{fw}} = 0$.

At $u = 1.0$ kg.kg^{-1} the following values for q_{fw} are needed for melting of the frozen free water in the wood: 20.717 kWh·m^{-3} for poplar and 42.829 kWh·m^{-3} for oak wood. These high values for q_{fw} are caused by the extremely high values of the specific heat capacity of the frozen free water, determined according to eq. (9) (refer to Figure 3).

Since according to the equation $u_{\mathrm{fsp}}^{\mathrm{fr}} = u_{\mathrm{fsp}}^{293.15} - 0.001(T_{\mathrm{dfr}}^{\mathrm{bw}} - 293.15)$ derived by (Deliiski, 2013a) the values of $u_{\mathrm{fsp}}^{271.15} = 0.372$ kg·kg^{-1} for poplar and $u_{\mathrm{fsp}}^{271.15} = 0.312$ kg·kg^{-1} for oak wood, then, consequently, each change in u with 0.01 kg·kg^{-1} causes the following change in q_{fw}: 0.3294 kWh·m^{-3} for poplar and 0.6216 kWh·m^{-3} for oak wood.

3. The total specific heat energy $q_{\mathrm{ice}} = q_{\mathrm{bwm}} + q_{\mathrm{fw}}$ needed for melting of both frozen bound and free water in the wood above the hygroscopic diapason increases proportionally to the wood moisture content u (Figure 7). This total energy consumption increases with the decrease of T_0. Each change in u with 0.01 kg·kg^{-1} causes the following change in q_{ice}:

▪ for poplar wood : 0.3505 kWh·m^{-3} at t_0 = −5 $^{\mathrm{o}}$C, 0.3777 kWh·m^{-3} at t_0 = −10 $^{\mathrm{o}}$C and 0.4109 kWh·m^{-3} at $t_0 = -20\ ^{\mathrm{o}}\mathrm{C}$;

▪ for oak wood: 0.06496 kWh·m^{-3} at t_0 = −5 $^{\mathrm{o}}$C, 0.6852 kWh·m^{-3} at t_0 = −10 $^{\mathrm{o}}$C and 0.7277 kWh·m^{-3} at t_0 = −20 $^{\mathrm{o}}$C.

The total specific heat energy consumption q_{ice} at a random value of t_0 in the range from t_0 = −20 $^{\mathrm{o}}$C to t_0 = −2 $^{\mathrm{o}}$C for the condition of $u > u_{\mathrm{fsp}}^{271.15}$ can be determined when the values of q_{bwm} from Figure 5 and of q_{fw} from Figure 6 are summed up for a specific given value of t_0.

5. CONCLUSIONS

The present paper describes the mathematical model suggested by the author and an engineering approach for calculation of the specific heat energy which is needed for melting of the ice in the wood, q_{ice}, above the hygroscopic diapason. The model takes into utmost account the physics of the processes of melting of the ice formed by both bound and 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 types on q_{ice} during wood defrosting and the influence of the temperature on the fiber saturation point of frozen wood.

An equation for calculation of the specific heat energy needed for melting of the frozen bound water in the wood above the hygroscopic diapason, q_{bwm}, has been derived, depending on the basic density of the wood ρ_b, on the wood moisture content *u*, on and the fiber saturation point u_{fsp}, and on the initial temperature of the frozen wood t_0. An equation for easy determination of the specific heat energy needed for melting of the frozen free water in the wood, q_{fw}, has been derived as well, depending on ρ_b, *u*, u_{fsp}. The specific heat energy q_{ice} equals to $q_{fw} + q_{bw}$.

For calculation of the q_{bwm}, q_{fw}, and q_{ice} according to the suggested model, a software program has been prepared in MS Excel 2010. With the help of the program calculations have been carried out for determination of q_{bwm}, q_{fw}, and q_{ice} for oak and poplar frozen wood with moisture content in the range from u = 0.4 kg·kg^{-1} to u = 1.0 kg·kg^{-1} at a temperature range from t_0 = –20 °C to t_0 = –1 °C, at which melting of the frozen water in the wood is completed.

The results obtained show that q_{bwm} does not depend on *u* and the change in q_{bwm} depending on t_0 is non-linear. At t_0 = –20 °C, for melting of the frozen bound water in the wood, the following values for q_{bwm} are needed: 5.085 kWh·m^{-3} for poplar and 7.312 kWh·m^{-3} for oak. With an increase in t_0 the specific heat energy q_{bwm} decreases to a value of q_{bwm} = 0 at t_0 = –2 °C, since at this temperature the frozen bound water in the wood melts completely.

The results also show that q_{fw} does not depend on t_0 of the frozen wood and the change in q_{fw} depending on *u* is linear. With an increase of *u* the specific heat energy q_{fw} grows fast and at $u = 1.0$ kg.kg^{-1} it reaches the following very high values: 20.717 kWh·m^{-3} for poplar, and 42.829 kWh·m^{-3} for oak. These values of q_{fw} are a few times higher than the values of q_{bwm}. A reason for this are the a few times higher values of the specific heat capacity of the frozen free water c_{fw} in comparison to these of c_{bwm}.

The obtained results can be used for a scientifically-based determination of the energy needed for defrosting of wood materials with the aim of their plasticizing for the production of veneer and plywood. They are also of specific importance for optimization of the technology and of the model based automatic control of the wood defrosting processes (Deliiski, 2004), (Hadjiiski, 2003).

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Symbols

c = specific heat capacity (W·kg^{-1}·K^{-1})
exp = exponent
h = heat (J·kg^{-1}) − for the latent heat of the water crystallization
q = specific heat energy (kWh.m^{-3})
T = temperature (K): $T = t + 273.15$

t = temperature (°C): $t = T - 273.15$
u = moisture content (kg·kg^{-1}): $u = W/100$
W = moisture content (%): $W = 100u$
ρ = density (kg·m^{-3})
& = and simultaneously with this
@ = at

Subscripts and superscripts:

b = basic (for density, based on dry mass divided to green volume)
bw = bound water (for the hygroscopic diapason)
bwm = maximum possible amount of bound water
crw = crystallization of water
dfr = defrosting (for the temperature)
fr = frozen (for the state of the body)
fsp = fiber saturation point of the wood
fw = free water (for above the hygroscopic diapason)
ice = ice
0 = initial (for the average mass temperature of the wood at the beginning of the heating)
1 = end (for the average mass temperature of the wood at the end of the heating)
271.15 = at 271.15 K, i.e. at −2 °C (for the fiber saturation point of the wood)
272.15 = at 272.15 K, i.e. at −1 °C (for the fiber saturation point of the wood)
293.15 = at 293.15 K, i.e. at 20 °C (for the fiber saturation point of the wood)

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