INNOVATION IN WOODWORKING INDUSTRY AND ENGINEERING DESIGN, 1/2014 (5): 94–102

MODELLING OF THE ENERGY NEEDED FOR DEFROSTING OF WOOD MATERIALS IN THE HYGROSCOPIC RANGE

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ABSTRACT

A mathematical model of the specific heat energy, which is needed for defrosting of wood materials in the hygroscopic range, q_{dfr}, has been suggested. The specific heat energy q_{dfr} consist of two parts: the energy needed for heating of the frozen wood until melting of the ice in it, q_{wfr}, and the energy needed for the melting of the ice formed from the bound water in the wood, q_{bw}. Using the suggested model computations have been carried out for the determination of q_{wfr}, q_{bw}, and $q_{\mathrm{dfr}}=q_{\mathrm{wfr}}+q_{\mathrm{bw}}$ during defrosting of oak, pine, beech, and poplar frozen wood with moisture content from 0.2 kg·kg^{-1} up to the border of the hygroscopic diapason and with initial temperature in the range from −20 $^{\mathrm{o}}$C to −2 $^{\mathrm{o}}$C, at which the thawing of the ice formed from the bounded water is completed.

Key words: modelling, wood defrosting, specific heat energy, wood specie, hygroscopic range

INTRODUCTION

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

In Deliiski (2003, 2004, 2011) 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 the wood materials is described by rather complex differential equations with partial derivatives, is carried out with the help of specialized software, developed by the author.

For the calculation of the need of thermal energy for the heating of the frozen 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, whose accessibility however is very limited.

The aim of the present work is to suggest an easy for engineering applications mathematical model of the specific heat energy consumption, q_{dfr}, which is needed for defrosting of frozen wood materials in the hygroscopic range. For the achieving of this goal mathematical models of the two consisting parts of q_{dfr} have been also suggested, as follows: of the energy needed for heating of the frozen wood until melting of the ice formed from the bounded water in it, q_{wfr}, and of the energy needed for melting of the mentioned ice, q_{bw}.

1. MODEL OF THE ENERGY NEEDED FOR HEATING OF THE FROZEN WOOD UNTIL MELTING OF THE ICE IN IT IN THE HYGROSCOPIC RANGE

The specific energy needed for heating of frozen wood until melting of the ice in it in the hygroscopic range, q_{wfr}, can be determined according to equation given in Deliiski (2003):

$$q_{\mathrm{wfr}} = \frac{\rho_{\mathrm{w}} c_{\mathrm{wfr}} \left(T_{\mathrm{dfr}} - T_{\mathrm{w0}}\right)}{3.6.10^{6}} \quad @ \; u_{\mathrm{nfw}} < u \le u_{\mathrm{fsp}}^{271.15} \;\; \& \;\; T_{\mathrm{w0}} < T_{\mathrm{dfr}}, \qquad \mathbf{(1)}$$

where q_{wfr} is the specific heat energy needed for heating of frozen wood until melting of the ice in it, kWh·m^{-3};

ρ_{w} – density of the frozen wood in the hygroscopic range, kg·m^{-3};

c_{wfr} – specific heat capacity of the frozen wood, J·kg^{-1}·K^{-1};

T_{w0} – temperature of the frozen wood at the beginning of its defrosting, K;

T_{dfr} – wood defrosting temperature, i.e. the temperature at which the ice formed from the bounded water in the wood is transformed completely into a liquid state, K. The temperature T_{dfr} is determined according to equation (6) given below when $0.12\ \mathrm{kg \cdot kg^{-1}} \le u < u_{\mathrm{fsp}}^{271.15}$ or according to equation (7) if $u \ge u_{\mathrm{fsp}}^{271.15}$;

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

u_{fsp} – fiber saturation point of a given wood specie, kg·kg^{-1}. The value of u_{fsp} is determined according to a suggested by Stamm (1964) equation, given in Deliiski (2013);

$u_{\mathrm{fsp}}^{271.15}$ – fiber saturation point of the wood at temperature T = 271.15 K, i.e. at t = −2 °C, at which the thawing of the ice formed from the bounded water is completed (Chudinov 1968), kg·kg^{-1}. The values of $u_{\mathrm{fsp}}^{271.15}$ are determined according to the equation given in Deliiski (2013);

u_{nfw} – content of non-frozen water in the wood at given temperature $T_{\mathrm{w0}} \le 271.15$ K, kg·kg^{-1}. The value of u_{nfw} is determined according to equation (5) given below.

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

For practical usage of equation (1) for the determination of q_{wfr} it is needed to have mathematical descriptions of ρ_{w} and c_{wfr} in the hygroscopic range. In Deliiski (2013) the following descriptions of ρ_{w} and c_{wfr} in the hygroscopic range have been suggested:

$$\rho_{\mathrm{w}} = \rho_{\mathrm{b}} \frac{1+u}{1 - \dfrac{S_{\mathrm{v}}}{100}\left[u_{\mathrm{fsp}}^{293.15} - 0.001\left(T_{\mathrm{dfr}} - 293.15\right) - u\right]} \quad @ \; u_{\mathrm{nfw}} < u \le u_{\mathrm{fsp}}^{271.15} \; \& \;\; T \le T_{\mathrm{dfr}}, \qquad \mathbf{(2)}$$

$$c_{\mathrm{wfr}} = K_{\mathrm{c}} \frac{526 + 2.95\left(\dfrac{T_{\mathrm{w0}} + T_{\mathrm{dfr}}}{2}\right) + 0.0022\left(\dfrac{T_{\mathrm{w0}} + T_{\mathrm{dfr}}}{2}\right)^{2} + 2261u + 1976u_{\mathrm{nfw}}}{1+u}, \qquad \mathbf{(3)}$$

$$K_c = 1.06 + 0.04u + \frac{0.00075\left(\frac{T_{w0} + T_{dfr}}{2} - 271.15\right)}{u_{nfw}}, \qquad \mathbf{(4)}$$

$$u_{nfw} = 0.12 + \left(u_{fsp}^{293.15} - 0.001T_{dfr} + 0.17315\right)\exp\left[0.0567\left(T_{w0} - 271.15\right)\right], \qquad \mathbf{(5)}$$

$$T_{dfr} = 271.15 + \frac{\ln\frac{u_{nfw} - 0.12}{u_{fsp} - 0.12}}{0.0567} \ @ \ 0.12\ \text{kg.kg}^{-1} \le u = u_{nfw} < u_{fsp}^{271.15}, \qquad \mathbf{(6)}$$

$$T_{dfr} = 271.15 \ @ \ u \ge u_{fsp}^{271.15}, \qquad \mathbf{(7)}$$

where $u_{fsp}^{293.15}$ is the fiber saturation point of the wood at temperature T = 293.15 K, i.e. at t = 20 °C, whose values for separate wood species are given in the specialized literature, kg·kg^{-1};

ρ_b – basic density of the wood given in the specialized literature, kg·m^{-3};

S_v – volume shrinkage of a given wood specie given in the specialized literature, % .

The calculated according to equations (2) to (6) change in $\rho_w(\rho_b, u, u_{fsp}^{293.15}, S_v)$ and in $c_{wfr}\left(u, u_{fsp}^{293.15}, T_{w0}\right)$ for oak, beech, pine and poplar wood with $t_{w0} = -20\ ^{o}\text{C}$ in the range from $u = 0.20\ \text{kg}\cdot\text{kg}^{-1}$ to $u = u_{fsp}^{271.15}$ are shown on Fig. 1.

The calculated according to equation (1) change in $q_{wfr} = f(u)$ for the studied four wood species with $t_{w0} = -10\ ^{o}\text{C}$ and $t_{w0} = -20\ ^{o}\text{C}$ are shown on Fig. 2.

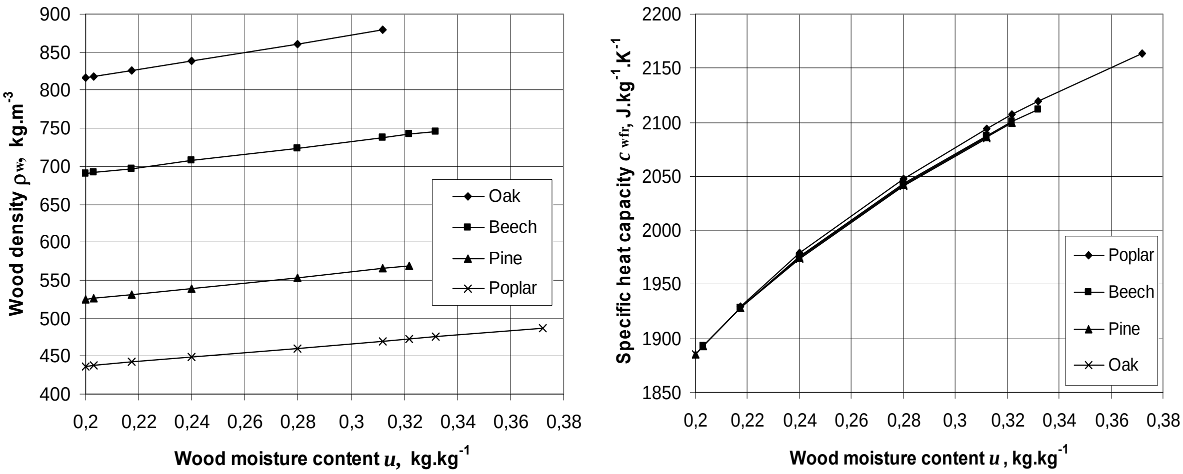

Figure 1: Change in ρ_w (left) and in c_{wfr} (right) during defrosting of wood with $t_{w0} = -20\ ^{o}\text{C}$ depending on u and on the wood specie

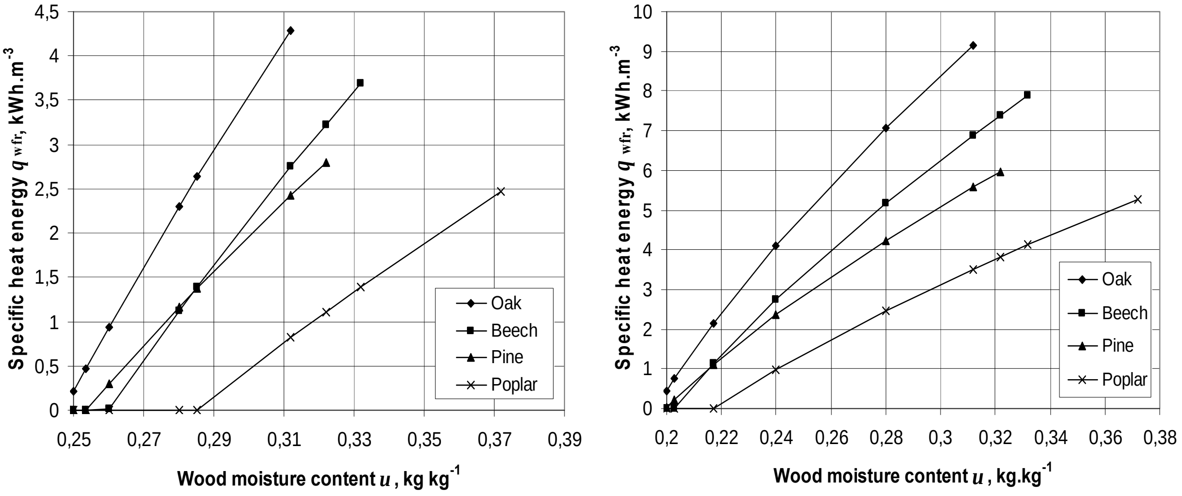

Figure 2: Change in q_{wfr} during defrosting of wood with $t_{\text{w0}} = -10$ °C (left) and with $t_{\text{w0}} = -20$ °C (right) depending on u and on the wood specie

2. MODEL OF THE ENERGY NEEDED FOR MELTING OF THE ICE IN FROZEN WOOD IN THE HYGROSCOPIC RANGE

The specific energy needed for melting of the ice formed from the freezing of bounded water in the wood, q_{bw}, can be determined according to the equation given in Deliiski (2013b)

$$q_{\text{bw}} = \frac{\rho_{\text{w}} c_{\text{bw}} \left(T_{\text{dfr}} - T_{\text{w0}}\right)}{3.6.10^6} \quad @ \ u_{\text{nfw}} < u \le u_{\text{fsp}} \ \& \ T_{\text{w0}} < 271.15\,\text{K}, \tag{8}$$

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

c_{bw} – specific heat capacity of the ice formed from the freezing of the bounded water in the wood, whose values (in J·kg^{-1}·K^{-1}) in the ranges $u_{\text{nfw}} < u \le u_{\text{fsp}}$ & $T \le 271.15$ K can be calculated according to the following equation, given in Deliiski (2013):

$$c_{\text{bw}} = 1.8938 \cdot 10^4 \left(u_{\text{fsp}}^{293.15} - 0.001 T_{\text{dfr}} - 0.17315\right) \frac{\exp\left[0.0567\left(\frac{T_{\text{w0}} + T_{\text{dfr}}}{2} - 271.15\right)\right]}{1+u}. \tag{9}$$

The meaning of the other variables involved in equations (8) and (9) are given above when clarifying equations (1) to (7).
The calculated according to equation (9) change in c_{bw} for the studied four wood species with $t_{\text{w0}} = -10$ °C and $t_{\text{w0}} = -20$ °C depending on u is shown on Fig. 3.

The calculated according to equation (8) change in q_{bw}, using also equations (2) and (8), for frozen wood with $t_{\text{w0}} = -10$ °C and $t_{\text{w0}} = -20$ °C depending on u is shown on Fig. 4.

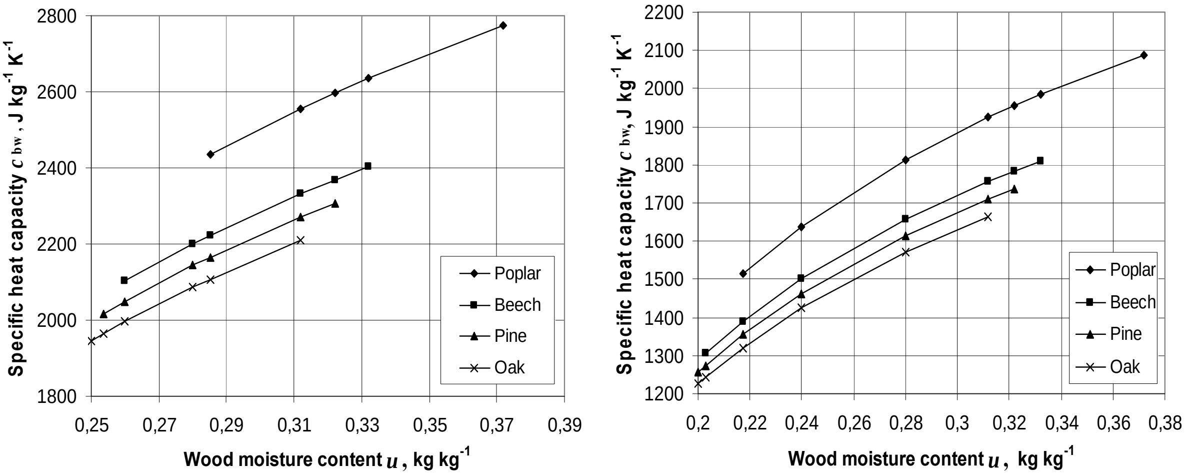

Figure 3: Change in c_{bw} during defrosting of wood with $t_{\text{w0}} = -10$ °C (left) and with $t_{\text{w0}} = -20$ °C (right) depending on *u* and on the wood specie

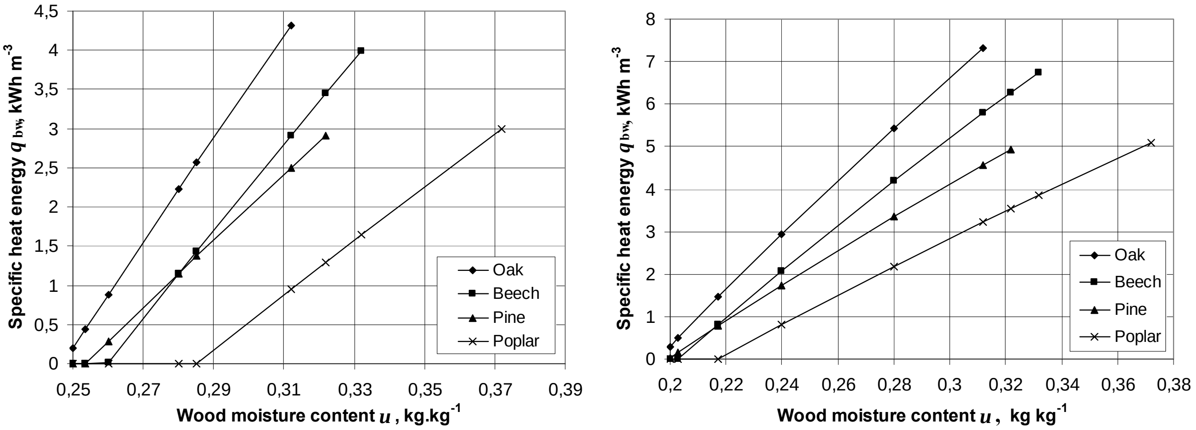

Figure 4: Change in q_{bw} during defrosting of wood with $t_{\text{w0}} = -10$ °C (left) and with $t_{\text{w0}} = -20$ °C (right) depending on *u* and on the wood specie

3. MODEL OF THE ENERGY NEEDED FOR DEFROSTING OF WOOD MATERIALS IN THE HYGROSCOPIC RANGE

The specific energy, which is needed for defrosting of the wood in the hygroscopic range, q_{dfr}, is equal to the sum of the energy needed for heating of frozen wood until melting of the ice in it in the hygroscopic diapason, q_{wfr}, and of the energy needed for the melting of the ice formed in the wood from the freezing of the bound water in it, q_{bw}, i.e. q_{dfr} can be determined according to the equation

$$q_{\text{dfr}} = q_{\text{wfr}} + q_{\text{bw}} . \qquad \textbf{(10)}$$

The calculated according to equations (10), (1), and (8) change in q_{dfr} for the studied four wood species with $t_{\text{w0}} = -10$ °C and $t_{\text{w0}} = -20$ °C depending on *u* is shown on Fig. 5.

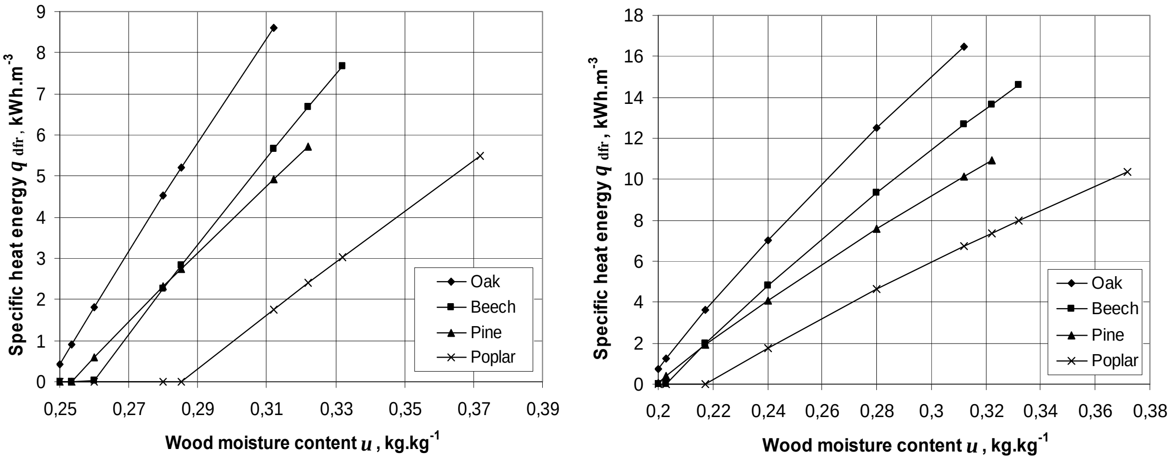

Figure 5: Change in q_{dfr} during defrosting of wood with $t_{\text{w0}} = -10\ ^{\text{o}}\text{C}$ (left) and with $t_{\text{w0}} = -20\ ^{\text{o}}\text{C}$ (right) depending on u and on the wood specie

The calculated according to equations (10), (1), and (8) change in q_{dfr} for frozen wood with $u = 0.3\ \text{kg} \cdot \text{kg}^{-1}$ and the calculated according to equation (5) change in the content of non-frozen water in the wood u_{nfw} depending on initial wood temperature t_{w0} is shown on Fig. 6.

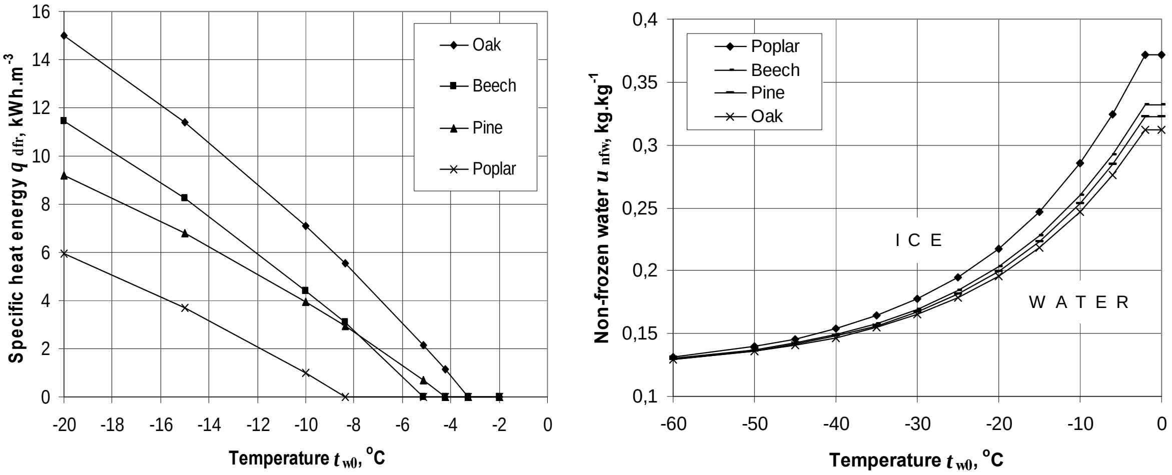

Figure 6: Change in q_{dfr} of wood with $u = 0.3\ \text{kg} \cdot \text{kg}^{-1}$ (left) and in u_{nfw} (right) during defrosting of wood materials depending on wood initial temperature t_{w0} and on the wood specie

4. DISCUSSION

The analysis of the shown on Fig. 1 to 6 results gives the basis for the following conclusions:

1. The density of frozen wood ρ_{w} in the hygroscopic range increases according to a linear dependence when the wood moisture content u increases (Fig. 3 − left). A reason for this is the proportionality of the wood mass depending on u.
2. The specific heat capacity of the frozen wood c_{wfr} and the specific heat capacity of the ice formed in the wood from the freezing of the bound water in it, c_{bw}, increase in the hygroscopic range according to a logarithmic dependences when the

wood moisture content u increases (Fig. 1 – right and Fig. 3 – right).

3. The specific heat energy consumption, q_{wfr}, which is needed for heating of frozen wood until melting of the ice in it in the hygroscopic range, increases almost proportionally to the wood moisture content u (Fig. 2).
4. The specific heat energy consumption, q_{bw}, which is needed for melting of the formed in the wood ice from the bound water in it, increases proportionally to the wood moisture content u (Fig. 4).
5. The specific energy, which is needed for defrosting of the wood in the hygroscopic range, q_{dfr}, increases almost proportionally to the wood moisture content u (Fig. 5).
6. The specific heat energy consumption q_{dfr} decreases according to a slight curvilinear dependence when the initial wood temperature t_{w0} increases (Fig. 6 – left).
7. The content of non-frozen water in the wood increases according to exponential dependence when the initial wood temperature t_{w0} increases (Fig. 6 – right).
8. When the wood contains the maximum possible quantity of bound water, i.e. when $u = u_{\mathrm{fsp}}^{271.15}$ (Chudinov 1968), for the defrosting of wood, which contains ice formed from the freezing of the mentioned water the following values for q_{dfr} are needed (Fig. 5):
   - kWh·m^{-3} at $t_{\mathrm{w0}} = -10$ °C and 16.477 kWh·m^{-3} at $t_{\mathrm{w0}} = -20$ °C for oak wood with $u_{\mathrm{fsp}}^{271.15} = 0.312\ \mathrm{kg \cdot kg^{-1}}$;
   - 7.678 kWh·m^{-3} at $t_{\mathrm{w0}} = -10$ °C and 14.624 kWh·m^{-3} at $t_{\mathrm{w0}} = -20$ °C for beech wood with $u_{\mathrm{fsp}}^{271.15} = 0.332\ \mathrm{kg \cdot kg^{-1}}$;
   - 5.711 kWh·m^{-3} at $t_{\mathrm{w0}} = -10$ °C and 10.903 kWh·m^{-3} at $t_{\mathrm{w0}} = -20$ °C for pine wood with $u_{\mathrm{fsp}}^{271.15} = 0.372\ \mathrm{kg \cdot kg^{-1}}$;
   - 5.479 kWh·m^{-3} at $t_{\mathrm{w0}} = -10$ °C and 10.356 kWh·m^{-3} at $t_{\mathrm{w0}} = -20$ °C for poplar wood with $u_{\mathrm{fsp}}^{271.15} = 0.322\ \mathrm{kg \cdot kg^{-1}}$.
9. If the increase in q_{dfr} depending on u is taken to be fully linear in the range from u_{nfw} to $u_{\mathrm{fsp}}^{271.15}$ at which the thawing of the ice formed from the bound water in the wood is completed, then each increase of u by 0.01 kg.kg^{-1} in this range causes an increase in q_{dfr} for the studied wood species as follows:
   - by 1.3260 kWh·m^{-3} at $t_{\mathrm{w0}} = -10$ °C and by 1.4168 kWh·m^{-3} at $t_{\mathrm{w0}} = -20$ °C for oak;
   - by 1.0634 kWh·m^{-3} at $t_{\mathrm{w0}} = -10$ °C and by 1.1328 kWh·m^{-3} at $t_{\mathrm{w0}} = -20$ °C for beech;
   - by 0.8325 kWh·m^{-3} at $t_{\mathrm{w0}} = -10$ °C and by 0.8886 kWh·m^{-3} at $t_{\mathrm{w0}} = -20$ °C for pine;
   - by 0.6312 kWh·m^{-3} at $t_{\mathrm{w0}} = -10$ °C and by 0.6694 kWh·m^{-3} at $t_{\mathrm{w0}} = -20$ °C for poplar.

This results show that the most influencing factor on q_{dfr} is the basic density of the wood.

The obtained above results for the increase of q_{dfr} when u increases by

0.01 kg·kg^{-1} at $t_{\mathrm{w0}} = -10$ °C differs by not more than 6.8% from the results for the increase of q_{wfr} at $t_{\mathrm{w0}} = -20$ °C.

Using the multiplied by 100 average values of the obtained above results for the increase of q_{bw} for the case of increase of u by 0.01 kg·kg^{-1} at $t_{\mathrm{w0}} = -10$ °C and $t_{\mathrm{w0}} = -20$ °C as proportionality coefficient, K_{dfr}, the value of q_{dfr} can be calculated according to the following equation:

$$q_{\mathrm{dfr}} = K_{\mathrm{dfr}}\left(u - u_{\mathrm{nfw}}\right) \ @ \ u_{\mathrm{nfw}} < u \le u_{\mathrm{fsp}}^{271.15} \ \ \& \ \ T_{\mathrm{w0}} < T_{\mathrm{dfr}}, \qquad \textbf{(11)}$$

where u is the wood moisture content in the hygroscopic range, kg·kg^{-1};

K_{dfr} – coefficient equals to 137.14 for oak, 109.81 for beech, 86.06 for pine, and 65.03 for poplar wood;

u_{nfw} – the content of non-frozen water in the wood at given temperature $T_{\mathrm{w0}} \le 271.15$ K, kg·kg^{-1}. The values of u_{nfw} can be easy determined with the help of Fig. 6 (right), which has been drawn using results obtained according to equation (5).

The calculated according to equation (11) values for q_{dfr} differ from their corresponding values of q_{dfr} on Fig. 5 and Fig. 6 (left) by not more than $\pm 5\%$. This accuracy of equation (11) is enough for different technological and/or engineering calculations of q_{dfr} in the whole hygroscopic range when $u_{\mathrm{nfw}} < u \le u_{\mathrm{fsp}}^{271.15}$ & $T_{\mathrm{w0}} < T_{\mathrm{dfr}}$ during wood defrosting.

Equation (11) can be used for calculation of q_{dfr} during wood defrosting for all wood species. Data for basic density, ρ_{b}, fiber saturation point, $u_{\mathrm{fsp}}^{293.15}$, and volume shrinkage of the wood, S_{v}, for separate wood species needed for the determination of participating in this equation values of u_{nfw} and K_{dfr} can be found in the specialized literature (Shubin 1990, Pervan 2000, Trebula and Klement 2002, Videlov 2003, etc.).

CONCLUSIONS

In the present paper easy for engineering applications mathematical model of the specific heat energy consumption needed for defrosting of frozen wood materials in the hygroscopic range, q_{dfr}, has been suggested. The model takes into account the influence on q_{dfr} of the following factors: wood moisture content, initial wood temperature of the frozen wood, basic density of the wood, volume shrinkage of the wood, and for the first time the fiber saturation point u_{fsp} of separate wood species and the influence of the temperature on u_{fsp}.

For the calculation of q_{dfr} according to the suggested model a software program has been prepared in the calculation environment of Visual Fortran Professional. Using the program computations have been carried out for the determination q_{dfr} of oak, pine, beech, and poplar frozen wood with initial temperatures in the range from t = −20 °C to t = −2 °C, at which the thawing of the ice formed from the bound water is completed (Chudinov 1968) and with moisture content in the hygroscopic range $0.2\ \mathrm{kg\cdot kg^{-1}} \le u \le u_{\mathrm{fsp}}$ during wood defrosting.

Based on the obtained results, a very simple and easy for use equation for the calculation of q_{dfr} depending only on the wood moisture content and on the content of non-frozen water in the wood at given initial wood temperature has been suggested. This equation can be used for precise enough ($\pm 5\%$) technological and engineering calculations of various processes for thermal and hydro-thermal treatment of frozen wood materials aimed at their defrosting.

The obtained results are of specific importance for the optimization of the technology and for the model based automatic control (Deliiski 2003, 2004) of different defrosting and/or frosting processes of wood and other capillary porous materials.

The suggested model and the obtained results can be of interest also for the educational process at specialized technical universities and engineering schools.

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