Annals of Warsaw University of Life Sciences - SGGW
Forestry and Wood Technology № 82, 2013: 178-184
(Ann. WULS - SGGW, For. and Wood Technol. 82, 2013)

An engineering approach for the calculation of the energy needed for heating of frozen wood until melting of the ice in it in the hygroscopic diapason. Part 2. Calculation of the specific heat energy needed for heating of frozen wood until melting of the ice, which is created in it from the hygroscopically bounded water

NENCHO DELIISKI

Department of Machine Knowledge and Automation of the Production,
Faculty of Forest Industry, University of Forestry, Sofia, Bulgaria

Abstract: *An engineering approach for the calculation of the heat energy needed for the heating of frozen wood until melting of the ice in it in the hygroscopic diapason. Part 2. Calculation of the specific heat energy needed for heating of frozen wood until melting of the ice, which is created in it from the hygroscopically bounded water***.** Using the suggested in the first part of this work mathematical descriptions of the density of frozen wood in the hygroscopic diapason, ρ_w, and of the specific heat capacity of the frozen wood, c_{wfr}, an engineering approach for the calculation of the specific heat energy needed for heating of frozen wood until melting of the ice in it in the hygroscopic diapason, q_{wfr}, has been suggested in the present second part of the work. For the calculation of ρ_w, c_{wfr}, and q_{wfr} according to the suggested approaches a software program has been prepared in the calculation environment of MS Excel 2010. Using the program computations have been carried out for the determination of q_{wfr} of oak, pine, beech, and poplar frozen wood with initial temperatures -10 °C and -20 °C and with moisture content in the hygroscopic range during its defrosting.

Keywords: wood density, specific heat capacity, specific heat energy, ice formed from hygroscopically bounded water, defrosting of the wood, wood specie

INTRODUCTION

When sizing the power of the sources of heat energy, which are used for the supply of the equipment for defrosting and for the following heating of wood materials, it is necessary 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 (Deliiski 2003).

The aim of the present second part of the work is to suggest an engineering approach for the calculation of the specific heat energy needed for heating of frozen wood until melting of the ice in it in the hygroscopic diapason, q_{wfr}.

For the realization of this aim the suggested in the first part of the work mathematical descriptions of the density of frozen wood in the hygroscopic diapason, ρ_w during wood defrosting and of the specific heat capacity of the frozen wood, c_{wfr} have been used.

The approach for the calculation of q_{wfr} takes into account for the first time the influence of the fiber saturation point u_{fsp} of separate wood species on the values of their ρ_w, c_{wfr}, and q_{wfr}, as well the influence of the temperature on u_{fsp} of frozen and non-frozen wood and of the initial wood temperature of the frozen wood on the content of non-frozen water in the wood, u_{nfw}, and on the wood defrosting temperature, T_{dfr}, in the hygroscopic diapason.

CALCULATION OF THE SPECIFIC HEAT ENERGY NEEDED FOR HEATING OF FROZEN WOOD UNTIL MELTING OF THE ICE IN IT IN THE HYGROSCOPIC DIAPASON

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

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

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 diapason, 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 wate

same reference if $u \geq u_{\mathrm{fsp}}^{271.15}$;

u – wood moisture content of 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 equation (4) 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 th

u_{nfw} – content of non-frozen water in the wood at given temperature $T_{\mathrm{w0}} \leq 271.15\,\mathrm{K}$, kg.kg^{-1}. The value of u_{nfw} is determined according to equation (9) given in Deliiski (2013).

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 diapason. Such descriptions are given in the first part of this work (Deliiski 2013). After substituting these descriptions of ρ_{w} and c_{wfr} into equation (1) it obtains the following form:

$$q_{\mathrm{wfr}} = K_{\mathrm{c}} \frac{526 + 2.95\left(\dfrac{T_{\mathrm{w0}} + T_{\mathrm{dfr}}}{2}\right) + 0.0022\left(\dfrac{T_{\mathrm{w0}} + T_{\mathrm{dfr}}}{2}\right)^{2} + 2261u + 1976u_{\mathrm{nfw}}}{3.6.10^{6}\left\{1 - \dfrac{S_{\mathrm{v}}}{100}\left[u_{\mathrm{fsp}}^{293.15} - 0.001\left(T_{\mathrm{dfr}} - 293.15\right) - u\right]\right\}} \rho_{\mathrm{b}}\left(T_{\mathrm{dfr}} - T_{w0}\right)$$

(2)

where:

u is the wood moisture content, kg.kg^{-1};

S_{v} – volume shrinkage of the wood, % (see Table 1 in Deliiski 2013);

$u_{\mathrm{fsp}}^{293.15}$ – fiber saturation point of the wood at temperature T = 293.15 K, i.e. at t = 20 °C, kg.kg^{-1}. The v

ρ_{b} – basic density of the wood, kg.m^{-3}. It is known that the values of ρ_{b} for the separate wood species are determined as dry mass of the wood divided by the green volume of the wood, i.e. divided by its volume at $u \geq u_{\text{fsp}}$ (Trebula – Klement 2002, Videlov 2003);

The values of K_{c}, n_{nfw}, and T_{dfr} in equation (2) according to equations (11), (9), and (5) given in Deliiski (2013) are determined correspondingly and the values of S_{v} and $u_{\text{fsp}}^{293.15}$ are taken from the specialized literature (refer to Table 1 in Deliiski (2013)).

Equation (2) can be used for the determination of the specific heat energy q_{wfr} for separate wood species in the ranges $u_{\text{nfw}} < u \leq u_{\text{fsp}}^{271.15}$ & $T_{\text{w0}} \leq T_{\text{dfr}}$.

RESULTS AND DISCUSSION

For the solution of equation (2) 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 calculations have been done for the determination of the specific heat energy q_{wfr} for frozen wood with initial temperatures $t_{\text{w0}} = -10\ ^{\circ}\text{C}$ and $t_{\text{w0}} = -20\ ^{\circ}\text{C}$ depending on u in the hygroscopic diapasons $0.25\ \text{kg.kg}^{-1} \leq u \leq u_{\text{fsp}}^{271.15}$ and $0.20\ \text{kg.kg}^{-1} \leq u \leq u_{\text{fsp}}^{271.15}$ respectively.

As an example, the specific heat energy q_{wfr} needed for heating of frozen wood until melting of the ice in it in the hygroscopic diapason in frequently used in the woodworking industry oak (*Quercus petraea libl*), beech (*Fagus silvatica L.*), pine (*Pinus silvestris L.*), and poplar (*Populus nigra L.*) wood has been calculated below. For the calculations, values of ρ_{b} and $u_{\text{fsp}}^{293.15}$ for these wood species are taken from Table 1 given in Deliiski (2013).

The calculated according to equation (5), which is given in Deliiski (2013), change in the wood defrosting temperature, T_{dfr}, in the range $0.20\ \text{kg.kg}^{-1} \leq u \leq u_{\text{fsp}}^{271.15}$ is shown on Fig. 1.

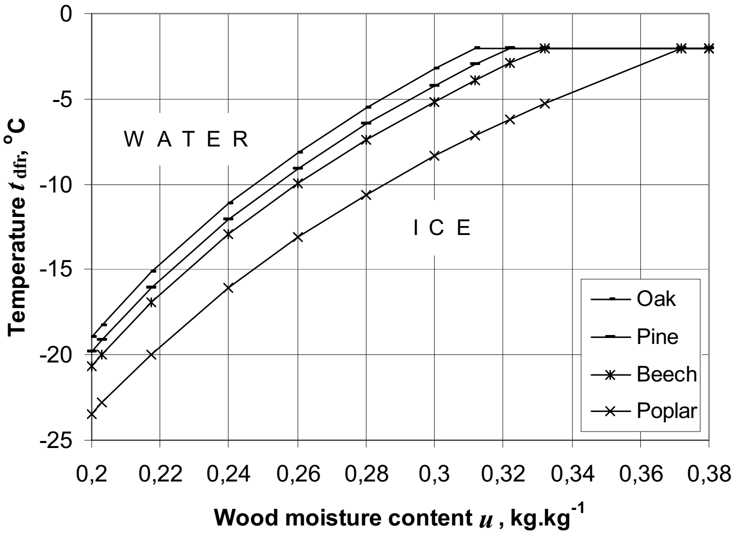

Fig. 1 Change in t_{dfr} for oak, pine, beech and poplar wood depending on u

The calculated according to equation (2) change in $q_{\text{wfr}} = f(u)$ for the studied four wood species with $t_{\text{w0}} = -10\ ^{\circ}\text{C}$ in the range from $u = 0.25\ \text{kg.kg}^{-1}$ to $u = u_{\text{fsp}}^{271.15}$ are shown on Fig. 2.

The calculated according to equation (2) change in $q_{\mathrm{wfr}} = f(u)$ for the studied four wood species with $t_{\mathrm{w0}} = -20\ ^{\circ}\mathrm{C}$ in the range from $u = 0.20\ \mathrm{kg.kg^{-1}}$ to $u = u_{\mathrm{fsp}}^{271.15}$ are shown on Fig. 3.

The ranges of u on Fig. 2 and Fig. 3 have been chosen because of the fact, that according to Fig. 1 there is practically no ice in the wood with $t_{\mathrm{w0}} = -10\ ^{\circ}\mathrm{C}$ and $u < 0.25\ \mathrm{kg.kg^{-1}}$ or in the wood with $t_{\mathrm{w0}} = -20\ ^{\circ}\mathrm{C}$ and $u < 0.20\ \mathrm{kg.kg^{-1}}$.

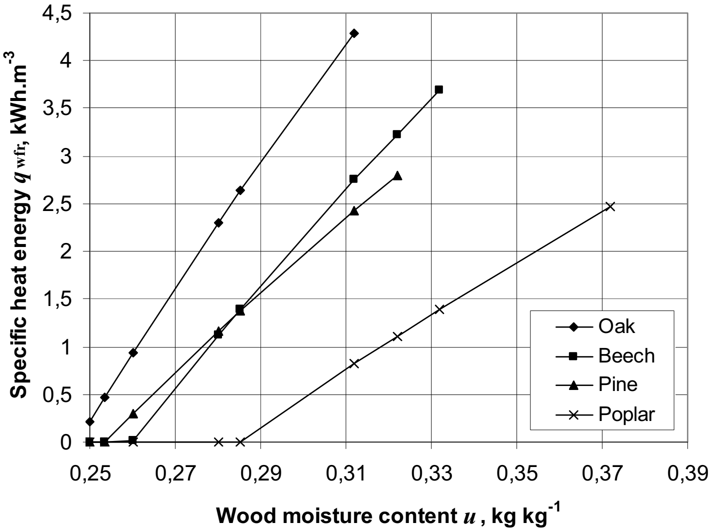

Fig. 2 Change in q_{wfr} during defrosting of wood with t_{w0} = -10 °C depending on u and on wood specie

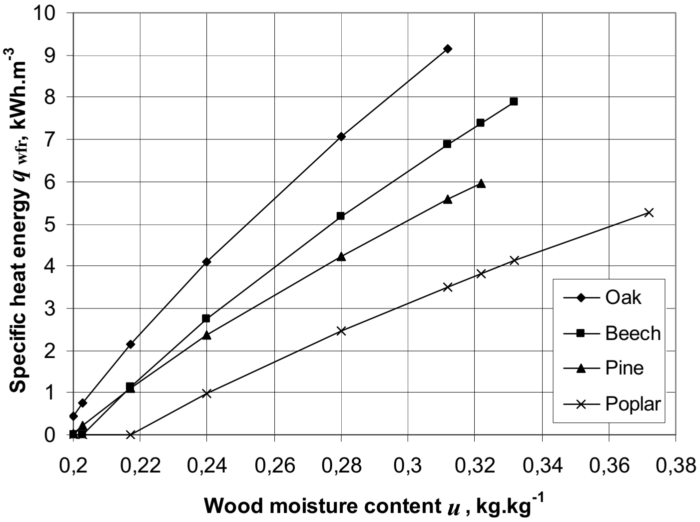

Fig. 3. Change in q_{wfr} during defrosting of wood with t_{w0} = -20 °C depending on u and on wood specie

The analysis of the shown on Fig. 2 and Fig. 3 results gives the basis for the following conclusions:

1. 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 diapason, increases almost proportionally to the wood moisture content u. According to equation (1) at $u_{\mathrm{nfw}} < u \le u_{\mathrm{fsp}}^{271.15}$ & $T_{\mathrm{w0}} < T_{\mathrm{dfr}}$ the values for q_{wfr} for each of the wood species increase with the increase in ρ_{b}, c_{wfr}, and the temperature difference $T_{\mathrm{dfr}} - T_{\mathrm{w0}}$. All of these variables are

unique for the separate wood species and for the concrete boundary conditions of the wood defrosting process.

2. When the wood contains the maximum possible quantity of bounded water, i.e. when $u = u_{\mathrm{fsp}}^{271.15}$, for the heating of frozen wood until melting of the ice in it in the hygroscopic diapason the following values for q_{wfr} are needed:

▪ 4.291 kWh.m^{-3} at t_{w0} = -10 °C and 9.164 kWh.m^{-3} at t_{w0} = -20 °C for oak wood with $u_{\mathrm{fsp}}^{271.15} = 0.312\ \mathrm{kg.kg}^{-1}$;

▪ 3.695 kWh.m^{-3} at t_{w0} = -10 °C and 7.877 kWh.m^{-3} at t_{w0} = -20 °C for beech wood with $u_{\mathrm{fsp}}^{271.15} = 0.332\ \mathrm{kg.kg}^{-1}$;

▪ 2.796 kWh.m^{-3} at t_{w0} = -10 °C and 5.966 kWh.m^{-3} at t_{w0} = -20 °C for pine wood with $u_{\mathrm{fsp}}^{271.15} = 0.322\ \mathrm{kg.kg}^{-1}$.

▪ 2.477 kWh.m^{-3} at t_{w0} = -10 °C and 5.271 kWh.m^{-3} at t_{w0} = -20 °C for poplar wood with $u_{\mathrm{fsp}}^{271.15} = 0.372\ \mathrm{kg.kg}^{-1}$;

1. If the increase in q_{wfr} 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 bounded 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_{wfr} for the studied wood species as follows:

▪ by 0.6329 kWh.m^{-3} at t_{w0} = -10 °C and by 0.7542 kWh.m^{-3} at t_{w0} = -20 °C for oak wood;

▪ by 0.5118 kWh.m^{-3} at t_{w0} = -10 °C and by 0.6105 kWh.m^{-3} at t_{w0} = -20 °C for beech wood;

▪ by 0.4076 kWh.m^{-3} at t_{w0} = -10 °C and by 0.4863 kWh.m^{-3} at t_{w0} = -20 °C for pine wood;

▪ by 0.2854 kWh.m^{-3} at t_{w0} = -10 °C and by 0.3407 kWh.m^{-3} at t_{w0} = -20 °C for poplar wood.

These results show that the most influencing factor on q_{wfr} is the basic density of the wood (refer to Table 1 in Deliiski 2013).

The given above results for the increase of q_{wfr} when u increases by 0.01 kg.kg^{-1} at t_{w0} = -10 °C differs by 16.2% from the results for the increase of q_{wfr} at t_{w0} = -20 °C.

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

$$q_{\mathrm{wfr}} = K_{\mathrm{wfr}}\left(u - u_{\mathrm{nfw}}\right) \ @ \ u_{\mathrm{nfw}} < u \le u_{\mathrm{fsp}}^{271.15} \ \& \ T_{\mathrm{w0}} < T_{\mathrm{dfr}} \qquad (3)$$

where:

u is the wood moisture content in the hygroscopic diapason, kg.kg^{-1};

u$_{\mathrm{nfw}}$ – content of non-frozen water in the wood at a given temperature $T_{\mathrm{w0}} \le 271.15$ K, kg.kg^{-1}. The value of u_{nfw} is determined according to equation (7) given in Deliiski (2013).

K_{bw} – coefficient, which is equal to:

▪ 63.29 at t_{w0} = -10 °C and 75.42 at t_{w0} = -20 °C for oak wood;

▪ 51.18 at t_{w0} = -10 °C and 61.05 at t_{w0} = -20 °C for beech wood;

- 40.76 at t_{w0} = -10 °C and 48.63 at t_{w0} = -20 °C for pine wood;
- 28.54 at t_{w0} = -10 °C and 34.07 at t_{w0} = -20 °C for poplar wood.

CONCLUSIONS

In the present paper an engineering approach for the calculation of the specific heat energy needed for heating of frozen wood until melting of the ice in it, q_{wfr}, during wood defrosting in the hygroscopic diapason has been suggested. The approach takes into account the influence on q_{wfr} 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}.

Using the suggested approach for the calculation of q_{wfr} the dependencies $q_{\mathrm{wfr}} = f(u)$ separately for frozen poplar, pine, beech, and oak wood all with initial temperature $t_{\mathrm{w0}} = -10\ ^{\mathrm{o}}\mathrm{C}$ and $t_{\mathrm{w0}} = -20\ ^{\mathrm{o}}\mathrm{C}$ during wood defrosting have been calculated and graphically presented and analyzed for the change of the wood moisture content in the hygroscopic diapason from $u = 0.25\ \mathrm{kg.kg^{-1}}$ for $t_{\mathrm{w0}} = -10\ ^{\mathrm{o}}\mathrm{C}$ and from $u = 0.2\ \mathrm{kg.kg^{-1}}$ for $t_{\mathrm{w0}} = -20\ ^{\mathrm{o}}\mathrm{C}$ to the value of $u = u_{\mathrm{fsp}}^{271.15}$ at which the thawing of the ice from the bounded water in the wood is completed.

Based on the obtained results, a very simple and easy for use equation for the calculation of q_{wfr} 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.

The obtained results can be used for precise technological and engineering calculations of various processes for thermal and hydro-thermal treatment of wood materials. They are also of specific importance for the optimization of the technology and for the model based automatic control of different processes in the production of furniture and other wood-based goods.

REFERENCES

1. CHUDINOV B. S. 1966: Theoretical research of thermo physical properties and thermal treatment of wood. DSc. thesis, SibLTI, Krasnoyarsk, USSR (in Russian).
2. DELIISKI N. 2003: Modeling and technologies for steaming of wood materials in autoclaves. Dissertation for DSc., University of forestry, 358 p., Sofia (in Bulgarian).
3. DELIISKI N. 2011: Transient heat conduction in capillary porous bodies, p.149-176. In: Convection and conduction heat transfer. InTech Publishing House, Rieka; 394 p., ISBN 978-953-307-582-2, http://dx.doi.org/10.5772/21424.
4. DELIISKI N. 2013: An engineering approach for the calculation of the energy needed for heating of frozen wood until melting of the ice in it in the hygroscopic diapason. Part 1. Calculation of the wood density and the specific heat capacity of the frozen wood in the hygroscopic diapason. Annals of Warsaw University of Life Sciences, Forestry and Wood Technology, No .., (In print).
5. TREBULA P. KLEMENT, I., 2002: Drying and hydrothermal treatment of wood. TU Zvolen, 449 p., Slovakia (in Slovakian).
6. VIDELOV H. 2003: Drying and thermal treatment of wood, University of Forestry, 335 p., Sofia (In Bulgarian).

Streszczenie: *Obliczenie energii topnienia lodu w drewnie w zakresie higroskopijnym metodą inżynierską. Część 2. Obliczenia energii jednostkowej potrzebnej do ogrzania drewna w celu stopnienia lodu powstałego z wody związanej higroskopijnie.* Używając metody opisanej w pierwszej części pracy, dokonano obliczeń gęstości drewna w zakresie higroskopijnym, pojemności cieplnej zamrożonego drewna. Dla przeprowadzania obliczeń opracowano program w środowisku MS Excel 2010. Sporządzono obliczenia dla drewna dębowego, sosnowego, buka oraz topoli przy wyjściowych temperaturach -10 °C and -20 °C, przy wilgotności w zakresie higroskopijnym.

ACKNOWLEDGEMENT. *This paper was composed as a part of the solution of the project 114/2011 „Modeling and visualization of the wood defrosting processes in the technologies for wood thermal treatment", which is supported by the Scientific Research Sector in the University of Forestry, Sofia.*

Corresponding author:

Nencho Deliiski
Faculty of Forest Industry,
University of Forestry,
Kliment Ohridski Bd. 10,
1756 Sofia,
BULGARIA
e-mail: deliiski@netbg.com