Annals of Warsaw University of Life Sciences - SGGW
Forestry and Wood Technology № 82, 2013: 170-177
(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 1. Calculation of the wood density and the specific heat capacity of the frozen wood in the hygroscopic diapason

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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 1. Calculation of the wood density and the specific heat capacity of the frozen wood in the hygroscopic diapason.* An engineering approach for the calculation of the wood density in the hygroscopic diapason, ρ_w and the specific heat capacity of the frozen wood in the same diapason, c_{wfr} has been suggested. The approach takes into account the physics of the process of thawing of the ice, which is formed from the freezing of the hygroscopically bounded water in the wood. It reflects for the first time the influence of the fiber saturation point u_{fsp} of the separate wood species on ρ_w and c_{wfr} during wood defrosting in the hygroscopic diapason and also the influence of the temperature on u_{fsp}, ρ_w, and c_{wfr}. For the calculation of ρ_w and c_{wfr} according to the suggested approach 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 ρ_w and c_{wfr} of oak, pine, beech, and poplar frozen wood with initial temperatures of -10 ^oC and -20 ^oC, and with moisture content in the hygroscopic range equal to $0.2\ kg.kg^{-1} \le u \le u_{fsp}$ during its defrosting.

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

INTRODUCTION

The main factors influencing the wood density in the hygroscopic diapason ρ_w are the wood moisture content, *u*, the basic density of the wood, ρ_b and the volume shrinkage of the wood, S_v (Chudinov 1966, Trebula and Klement 2002, Videlov 2003). The density of wood as a capillary porous body in the hygroscopic diapason also depends on the fiber saturation point u_{fsp}. The fiber saturation point of the separate wood species changes in significant ranges (see Table 1 below). It has also been determined that u_{fsp} changes depending on the temperature *T* of the wood (Stamm 1964).

The specific heat capacity of the frozen wood in the hygroscopic diapason, c_{wfr} depends on *u*, on the temperature *T*, and on the content of non-frozen water in the wood at given *T* and u_{nfw} (Deliiski 2003, 2011).

The aim of the present first part of the work is to suggest an engineering approach for the calculation of ρ_w of frozen wood in the hygroscopic diapason and of c_{wfr} during wood defrosting depending on the mentioned above influencing factors taking into account for the first time the fiber saturation point u_{fsp} of separate wood species and the influence of the temperature on u_{fsp}. The mathematical descriptions of ρ_w and c_{wfr}, which have been created in this approach, are used in the second part of this work for the suggestion of 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.

CALCULATION OF THE WOOD DENSITY IN THE HYGROSCOPIC DIAPASON DURING WOOD DEFROSTING

Based on the results of wide experimental studies obtained from numerous publications Chudinov (1966) in his DSc. thesis suggests an equation for the calculation of the density of all wood species in the hygroscopic diapason depending on the wood moisture content, u, on the basic density of the wood, ρ_b, and on the volume shrinkage of the wood, S_v. After inserting into this equation the fiber saturation point u_{fsp} for separate wood species instead of participated in it generally accepted in the specialized literature average value of $u_{fsp} = 0.3$ kg.kg^{-1} for all wood species the equation obtains the following form:

$$\rho_w = \rho_b \frac{1+u}{1-\frac{S_v}{100}\left(u_{fsp}-u\right)} \quad @ \quad 0 \le u < u_{fsp} \qquad (1)$$

where:

ρ_w is the wood density, kg.m^{-3};

ρ_b – basic density of the wood, kg.m^{-3};

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

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

S_v – volume shrinkage of a given wood specie, % .

Aiming for a more precise calculation of ρ_w in the hygroscopic diapason it is necessary to insert into equation (2) the dependence of u_{fsp} on the temperature.

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 u_{fsp} of non-frozen wood:

$$u_{fsp} = u_{fsp}^{293,15} - 0.001(T-293.15) \qquad (2)$$

where:

$u_{fsp}^{293.15}$ is the fiber saturation point of the wood at temperature T = 293.15 K, i.e. at t = 20 ^{o}C, kg.kg^{-1};

T – temperature, K.

Since equation (2) is generally accepted in the specialized literature and is valid for all wood species, this equation is used below for the reflection of the influence of T on u_{fsp} in equation (1) at temperatures $t < 0$ ^{o}C after the occurrence of complete thawing of the ice, formed from the bounded water in the wood, i.e:

$$u_{fsp} = u_{fsp}^{293.15} - 0.001(T-293.15) \quad @ \quad T > T_{dfr} \qquad (3)$$

where:

T_{dfr} is the temperature, at which the ice formed from the bounded water in the wood, is transformed completely into a liquid state, K.

While the thawing of the ice formed from bounded water is taking place, a constant value of u_{fsp} is used in the calculation of the density of frozen wood ρ_{w} according to equation (1), which is held by the wood at the temperature of complete thawing of the ice T_{dfr}, i. e.:

$$u_{\text{fsp}} = u_{\text{fsp}}^{293.15} - 0.001(T_{\text{dfr}} - 293.15) \quad @ \quad T \le T_{\text{dfr}} \qquad (4)$$

The temperature T_{dfr}, at which the ice, formed in the wood from the freezing of the bounded water, is transformed completely into a liquid state, can be calculated according to the following equations depending on u_{fsp} and u_{nfw} (Deliiski 2003, 2011):

$$T_{\text{dfr}} = 271.15 + \frac{\ln \dfrac{u_{\text{nfw}} - 0.12}{u_{\text{fsp}} - 0.12}}{0.0567} \quad @ \quad 0.12 \ \text{kg.kg}^{-1} \le u = u_{\text{nfw}} < u_{\text{fsp}}^{271.15} \qquad (5)$$

$$T_{\text{dfr}} = 271.15 \quad @ \quad u \ge u_{\text{fsp}}^{271.15} \qquad (6)$$

where:

$u_{\text{fsp}}^{271.15}$ is the fiber saturation point of the wood at temperature $T = 271.15$ K, i.e. at $t = -2$ °C, at which t

u_{nfw} – content of non-frozen water in the wood in kg.kg^{-1}, equal to (Deliiski 2011):

$$u_{\text{nfw}} = 0.12 + \left(u_{\text{fsp}} - 0.12\right)\exp\left[0.0567\left(T - 271.15\right)\right] \qquad (7)$$

After substituting equation (4) into equation (1) the following final equation is obtained for the calculation of the density of frozen wood from all wood species in the hygroscopic diapason:

$$\rho_{\text{w}} = \rho_{\text{b}} \frac{1+u}{1 - \dfrac{S_{\text{v}}}{100}\left[u_{\text{fsp}}^{293.15} - 0.001\left(T_{\text{dfr}} - 293.15\right) - u\right]} \quad @ \quad u_{\text{nfw}} < u \le u_{\text{fsp}}^{271.15} \ \& \ T \le T_{\text{dfr}} \qquad (8)$$

During engineering calculations of various processes for thermal and hydro-thermal processing of wood it is necessary to be able to determine the density of frozen wood with an initial temperature T_{w0} to a final temperature T_{dfr}, at which the ice formed from the bounded water in the wood is transformed completely into water. For the calculation of the value of T_{dfr} according to equation (5), which participates in the denominator of the equation (8), it is necessary before that to determine the participating in the equation (5) value of u_{nfw}.

After substituting u_{fsp} with $u_{\text{fsp}} = u_{\text{fsp}}^{293.15} - 0.001(T_{\text{dfr}} - 293.15)$ taken from equation (4) and *T* with $T = T_{\text{w0}}$ into equation (7) it obtains the following form:

$$u_{\text{nfw}} = 0.12 + \left(u_{\text{fsp}}^{293.15} - 0.001T_{\text{dfr}} + 0.17315\right)\exp\left[0.0567\left(T_{\text{w0}} - 271.15\right)\right] \qquad (9)$$

Equation (9) can be used for the determination of T_{dfr} according to equation (5) and then using equation (8) it is possible to calculate ρ_{w} in the hygroscopic diapason.

CALCULATION OF THE SPECIFIC HEAT CAPACITY OF THE FROZEN WOOD IN THE HYGROSCOPIC DIAPASON DURING WOOD DEFROSTING

The specific heat capacity of the frozen wood, c_{wfr}, has been described mathematically by Deliiski (2003, 2011) using the experimentally determined data for its change as a function of the temperature *t* and wood moisture content *u* in the PhD thesis of Kanter (1955) and in the DSc. thesis of Chudinov (1966). The following equations for $c_{\text{wfr}}(T, u, u_{\text{nfw}})$ have been derived, which are valid for all wood species when the wood contains ice:

$$c_{\text{wfr}} = K_{\text{c}} \frac{526 + 2.95T + 0.0022T^2 + 2261u + 1976u_{\text{nfw}}}{1 + u} \qquad (10)$$

where:

$$K_{\text{c}} = 1.06 + 0.04u + \frac{0.00075(T - 271.15)}{u_{\text{nfw}}} \qquad (11)$$

and the content of non-frozen water in the wood u_{nfw} can be determined according to equation (9).

Using equations (10), (11), and (9) the value of the specific heat capacity of the frozen wood c_{wfr} can be determined at an arbitrary value of the wood moisture content in the range $u_{\text{nfw}} \le u \le 1.2$ kg.kg^{-1} and of the temperature *T* in the range 223.15 K ≤ *T* ≤ 271.15 K.

For engineering calculations it is necessary to be able to determine the specific energy needed for the heating of 1 m^3 frozen wood with an initial temperature T_{w0} to a final temperature T_{dfr}, when the melting is completed of the ice formed in the wood from the freezing of the bounded water. For this case for the value of *T* in equations (10) and (11) one must use the average arithmetic value between T_{w0} and T_{dfr}, i.e. $T = \frac{T_{\text{w0}} + T_{\text{dfr}}}{2}$. After substituting *T* in these equations with the average arithmetic value $T = \frac{T_{\text{w0}} + T_{\text{dfr}}}{2}$, they obtain the following forms:

$$c_{\text{wfr}} = K_{\text{c}} \frac{526 + 2.95\left(\frac{T_{\text{w0}} + T_{\text{dfr}}}{2}\right) + 0.0022\left(\frac{T_{\text{w0}} + T_{\text{dfr}}}{2}\right)^2 + 2261u + 1976u_{\text{nfw}}}{1 + u} \qquad (12)$$

$$K_c = 1.06 + 0.04u + \frac{0.00075\left(\frac{T_{w0} + T_{dfr}}{2} - 271.15\right)}{u_{nfw}} \quad (13)$$

where the content of non-frozen water in the wood u_{nfw} is determined according to equation (9).

RESULTS FROM SIMULATION STUDIES OF ρ_w AND c_{wfr} IN THE HYGROSCOPIC DIAPASON

For the calculation of ρ_w according to equation (8) and of c_{wfr} according to equations (12), (13), and (9) a program has been prepared in the calculation environment of MS Excel 2010 (refer to http://www.gcflearnfree.org/excel2010). With the help of the program calculations have been made for the determination of ρ_w and c_{wfr} of frozen wood with initial temperatures $t_{w0} = -10\ ^{o}C$ and $t_{w0} = -20\ ^{o}C$ depending on u in the hygroscopic diapason.

As an example, the density of 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. During the computations of the dependences $\rho_w(\rho_b, u, u_{fsp}^{293.15}, S_v)$ and $c_{wfr}\left(u, u_{fsp}^{293.15}, T_{w0}\right)$ the values of ρ_b, $u_{fsp}^{293.15}$, and S_v for the studied wood species from Table 1 are used. The calculated 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 the studied four wood species with $t_{w0} = -10\ ^{o}C$ and $t_{w0} = -20\ ^{o}C$ in the range from $u = 0.20\ kg.kg^{-1}$ to $u = u_{fsp}^{271.15}$ are shown on Fig. 1 and Fig. 2 correspondingly.

Tab.1 Basic density, fiber saturation point at T = 293.15 K (i.e. at 20 ^{o}C), and volume shrinkage of some wood species (according to Nikolov – Videlov 1987, Videlov 2003)

№	Wood specie	Basic density ρ_b, kg.m^{-3}	Fiber saturation point $u_{fsp}^{293.15}$, kg.kg^{-1}	Volume shrinkage S_v, %
1.	Poplar	355	0.35	13.3
2.	Pine	430	0.30	11.8
3.	Beech	560	0.31	17.3
4.	Oak	670	0.29	11.9

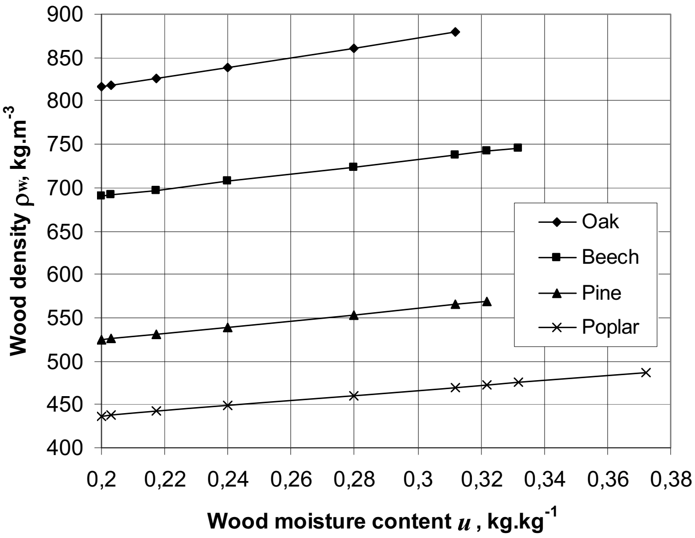
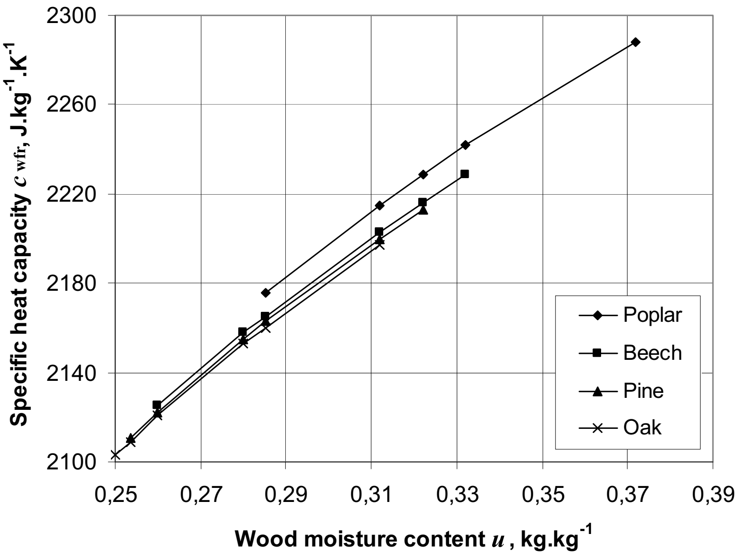


Fig. 1 Change in ρ_w during defrosting of wood with t_{w0} = -20 °C depending on *u* and on wood specie

The analysis of the shown on Fig. 3 and Fig. 4 results gives the basis for the following conclusions:

1. The density of frozen wood ρ_w in the hygroscopic diapason increases according to a linear dependence when the wood moisture content *u* increases. A reason for this is the proportionality of the wood mass depending on *u*.



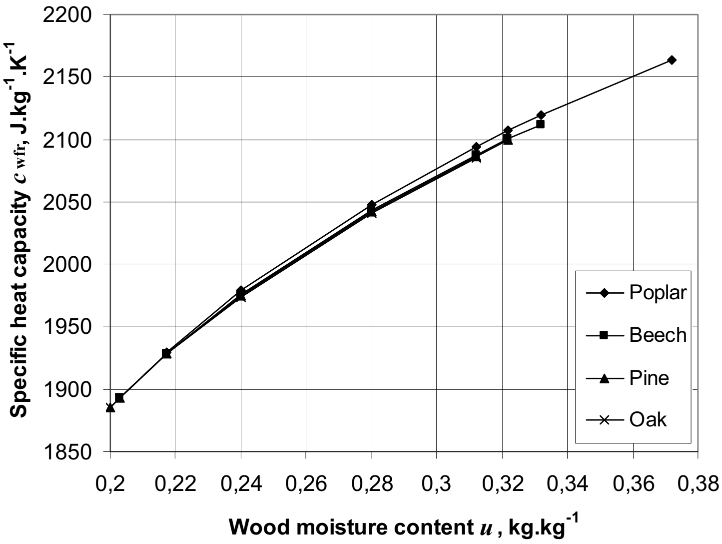


Fig. 2 Change in c_{wfr} during defrosting of wood with t_{w0} = -10 °C (above) and t_{w0} = -20 °C (below) depending on u and on wood specie

2. The specific heat capacity of the frozen wood c_{wfr} increases in the hygroscopic diapason according to an exponential dependence when the wood moisture content u. The capacity c_{wfr} increases when the initial wood temperature t_{w0} decreases. The increase of c_{wfr} is proportionally dependent on the fiber saturation point of the separate wood species u_{fsp}. The influence of u_{fsp} on c_{wfr} decreases strong when t_{w0} decreases.

CONCLUSIONS

In the present paper an engineering approach for the calculation of the density, ρ_w, and of the specific heat capacity of frozen wood, c_{wfr}, in the hygroscopic diapason depending on the respective influencing factors has been suggested. The mathematical descriptions of ρ_w and c_{wfr}, which have been created in this approach, take into account for the first time the fiber saturation point u_{fsp} of separate wood species and the influence of the temperature on u_{fsp}. These descriptions of ρ_w and c_{wfr} are used in the second part of this work for the creation of 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.

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Streszczenie: *Obliczenie energii topnienia lodu w drewnie w zakresie higroskopijnym metodą inżynierską. Część 1. Określanie gęstości drewna i jednostkowej pojemności cieplnej drewna zamrożonego w zakresie higroskopijnym*. Zaproponowano metodę inżynierską obliczania gęstości drewna w zakresie higroskopijnym, oraz pojemności cieplnej zamrożonego drewna. Metoda bierze pod uwagę fizykę procesu topnienia lodu powstałego z zamrażania wody higroskopijnej w drewnie. Po raz pierwszy brano pod uwagę wpływ punktu nasycenia włókien w poszczególnych gatunkach drewna oraz wpływ temperatury na badane czynniki. Dla przeprowadzania obliczeń opracowano program w środowisku MS Excel 2010. Sporządzono obliczenia dla drewna dębowego, sosnowego, buka oraz topoli przy wyjściowych temperaturach -10 ^{o}C and -20 ^{o}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.*

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