Original scientific paper
UDC: 674.82

MODELLING OF ENERGY CONSUMPTION NEEDED FOR MELTING FROZEN BOUND WATER IN WOOD CHIPS

Nencho Deliiski[1], Veselin Brezin[1], Anton Geffert[2], Jarmila Geffertova[2], Natalia Tumbarkova[1]

[1]*University of Forestry, Faculty of Forest Industry, Sofia, Bulgaria,*
e-mail: deliiski@netbg.com, brezin@abv.bg, nataliq_manolova@abv.bg
[2]*Technical University in Zvolen, Faculty of Wood Science and Technology, Zvolen, Slovakia,*
e-mail: geffert@tuzvo.sk, geffertova@tuzvo.sk

ABSTRACT

A mathematical model and an engineering approach for calculation of the specific mass energy consumption, which is needed for melting frozen bound water in wood chips above the hydroscopic diapason, $q_{\mathrm{bwm}}^{\mathrm{m/t}}$, have been suggested.

An equation for easy calculation of $q_{\mathrm{bwm}}^{\mathrm{m/t}}$ has been derived, depending on the wood moisture content u, on the fiber saturation point at 20 °C (i.e. at 293.15 K), $u_{\mathrm{fsp}}^{293.15}$, and on the initial temperature T_0 of the frozen chips. According to this equation, the values of $q_{\mathrm{bwm}}^{\mathrm{m/t}}$ increase with increase of $u_{\mathrm{fsp}}^{293.15}$and of the difference 271.15 – T_0, then they decrease when u or T_0 increase. For calculation of the $q_{\mathrm{bwm}}^{\mathrm{m/t}}$ according to the suggested model, a software program has been prepared in MS Excel 2010. By means of this program, calculations have been carried out to determine $q_{\mathrm{bwm}}^{\mathrm{m/t}}$ for oak, acacia, beech, and poplar frozen chips with moisture content in the range from $u = 0.4$ kg·kg^{-1} to $u = 1.0$ kg·kg^{-1} and at a temperature range from $t_0 = -40$ °C to $t_0 = -2$ °C. At $t_0 = -2$ °C the melting of frozen bound water in wood chips has been completed.

Key words: wood chips, frozen bound water, melting, specific mass energy consumption

1. INTRODUCTION

It is known that cellulose fibers, which are suited to produce quality pulp products, come from various wood species. Raw materials enter the mill as logs. The logs are then chipped into uniform pieces to facilitate the cooking process that follows. The cooking of the wood chips takes place at a definite temperature and pressure with specialized chemicals (Stamm, 1964).

Before the beginning of the chemical reaction between the wood chips and the processing medium during the cooking, the chips undergo a pure heating process. The creation of a mathematical model for calculation of the energy consumption for heating of frozen and non-frozen wood chips until the starting of the chemical reaction during its cooking is of certain scientific and practical interest. Such model is of interest also for calculation of the energy, needed for heating of the wood chips at the beginning of their drying when they are used as fuel, for production of briquettes and pellets (Yosifov, 2005), or for production of particle boards (Yosifov, 1989).

The aim of the present work is to suggest a mathematical model and an engineering approach for calculation of the energy consumption for melting frozen bound water in wood chips above the hygroscopic scope.

2. MATERIAL AND METHODS

Theoretical basis for modeling of energy consumption for melting frozen bound water in wood chips

It is known that the specific energy consumption for heating of 1 m^3 of solid materials with an initial mass temperature T_0 to a given mass temperature T_1 is determined by using the equation (Deliiski, 2013a, 2013b):

$$q^{\mathrm{v/m3}} = \frac{c \cdot \rho \cdot (T_1 - T_0)}{3.6 \cdot 10^6}. \quad (1)$$

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

After dividing the right part of eq. (1) by the wood density ρ, the following equation for determination of the specific mass energy consumption for heating of 1 kg of different materials is obtained:

$$q^{\mathrm{m/kg}} = \frac{c \cdot (T_1 - T_0)}{3.6 \cdot 10^6}. \quad (2)$$

For practical needs it is more convenient to determine the energy consumption q_{m} in $\mathrm{kWh \cdot t^{-1}}$ (i.e. for heating of 1 ton of wood chips) according to the equation:

$$q^{\mathrm{m/t}} = \frac{c \cdot (T_1 - T_0)}{3.6 \cdot 10^3}. \quad (3)$$

Moisture content of the wood chips subject to defrosting in practice is usually above the fiber saturation point. This means that the chips contain the maximum possible amount of bound water for the given wood species and chips contain free water too.

It has been determined, using the studies by Chudinov (1966), that melting of frozen bound water in wood takes place gradually in the entire range, starting from the initial temperature of the frozen wood $t_0 < -2\ ^{\mathrm{o}}\mathrm{C}$ (i.e. $T_0 < 271.15\ \mathrm{K}$) until reaching the temperature $t_{\mathrm{dfr}}^{\mathrm{bwm}} = -2\ ^{\mathrm{o}}\mathrm{C}$ (i.e. $T_{\mathrm{dfr}}^{\mathrm{bwm}} = 271.15\ \mathrm{K}$). This means that based on eq. (3), the specific mass energy consumption for melting of the maximum possible amount of frozen bound water in the chips can be calculated by the following equation:

$$q_{\mathrm{bwm}}^{\mathrm{m/t}} = \frac{c_{\mathrm{bwm}}}{3.6 \cdot 10^3}(271.15 - T_0) \quad @ \quad u > u_{\mathrm{fsp}}^{271.15} \ \&\ T_0 < 271.15\ \mathrm{K}. \quad (4)$$

For practical usage of eq. (4), it is needed to have mathematical description of the specific heat capacity of frozen bound water in wood. Such a description is given below.

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

Using data by Chudinov (1966, 1968), the following equation for calculation of the specific heat capacity of frozen bound water in wood has been obtained (Deliiski 2003, 2013a, 2013b):

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

Fig. 1 shows the calculated change according to eq. 5 in c_{bw} depending on u in the range from 0.2 kg.kg^{-1} to 1.2 kg.kg^{-1} and on T in the range from 213.15 K to 271.15 K (i.e. from − 60 $^{\circ}$C to − 2 $^{\circ}$C) for the poplar wood ((*Populus nigra* L.).

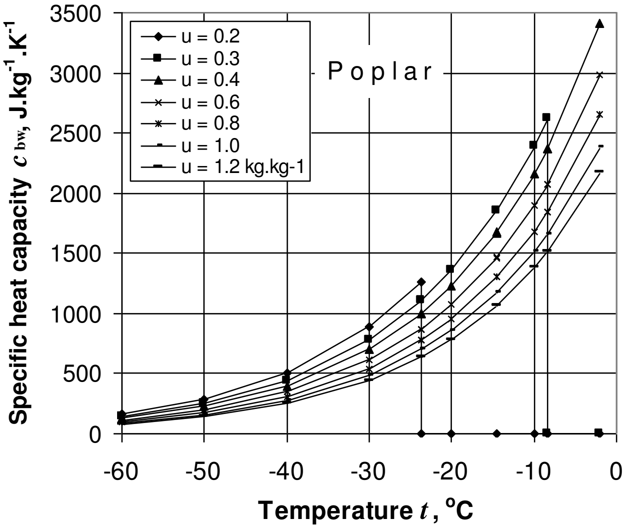

Figure 1. *Change in c_{bw} of frozen bound water in poplar wood, depending on t and u*

After substituting $u_{\text{fsp}}^{\text{fr}} = u_{\text{fsp}}^{293.15} - 0.001(T_{\text{dfr}}^{\text{bw}} - 293.15)$ taken from Deliiski (2013a) and T with the average arithmetic value $T = \dfrac{T_0 + 271.15}{2}$ into equation (5), the following equation has been derived in Deliiski (2013b):

$$c_{\text{bwm}} = 1.8938 \cdot 10^4 \left(u_{\text{fsp}}^{293.15} - 0.098\right) \cdot \frac{\exp\left[0.0567\left(\dfrac{T_0 + 271.15}{2} - 271.15\right)\right]}{1+u}. \tag{6}$$

Eq. (6) is suitable for precise enough engineering calculations of c_{bwm} in the range of $253.15\ \text{K} \le T_0 < 271.15\ \text{K}$ (i.e. $-20\ ^{\circ}\text{C} \le t_0 < -2\ ^{\circ}\text{C}$) because of the almost linear character of the dependences $c_{\text{bw}} = f(T)$ in this range. For more precise calculation of c_{bwm} a mean arithmetic value between c_{bw} at $T = T_0$ and c_{bw} at $T = 271.15$ K in the whole range of t_0 in Fig. 1 from − 60 $^{\circ}$C to − 2 $^{\circ}$C, the following equation can be used:

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

Final equation for calculation of the specific heat energy q_{bwm}

After substituting eq. (6) in eq. (4), the following final equation for calculation of $q_{\text{bwm}}^{\text{m/t}}$ at $u > u_{\text{fsp}}^{271.15}$ & $T_0 < 271.15$ K is obtained:

$$q_{\text{bwm}}^{\text{m/t}} = \frac{\dfrac{1.8938 \cdot 10^4 \left(u_{\text{fsp}}^{293.15} - 0.098\right)}{1+u}\left(1 + \exp[0.0567(T_0 - 271.15)]\right)}{7.2 \cdot 10^3}\left(271.15 - T_0\right). \tag{8}$$

3. RESULTS AND ANALYSIS

For the solution of eqs. (7) and (8) 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 c_{bwm} and in $q_{\mathrm{bwm}}^{\mathrm{m/t}}$ depending on $T_0 = \mathrm{var}$ and on $u = \mathrm{var}$ above the hygroscopic range have been calculated for frequently used in the production of chips poplar wood (*Populus nigra* L.), beech wood (*Fagus silvatica* L), acacia wood (*Robinia pseudoacacia* J.) and oak wood (*Quercus petraea* Libl.).

For the calculations, values of the basic density and of fiber saturation point at 20 °C derived in the literature for the studied species have been used, namely: $\rho_{\mathrm{b}} = 355$ kg·m^{-3} and $u_{\mathrm{fsp}}^{293.15} = 0.35$ kg·kg^{-1} for poplar wood; $\rho_{\mathrm{b}} = 560$ kg·m^{-3} and $u_{\mathrm{fsp}}^{293.15} = 0.31$ kg·kg^{-1} for beech wood; $\rho_{\mathrm{b}} = 660$ kg·m^{-3} and $u_{\mathrm{fsp}}^{293.15} = 0.30$ kg·kg^{-1} for acacia wood and $\rho_{\mathrm{b}} = 670$ kg·m^{-3} and $u_{\mathrm{fsp}}^{293.15} = 0.29$ kg·kg^{-1} for oak wood (Nikolov and Videlov, 1987); (Videlov, 2003).

The influence of the initial wood temperature and of the wood moisture content on c_{bwm} and $q_{\mathrm{bwm}}^{\mathrm{m/t}}$ have been studied for chips containing ice in the ranges $233.15\ \mathrm{K} \le T_0 \le 271.15\ \mathrm{K}$ (i.e. $-40\ ^{\circ}\mathrm{C} \le t_0 \le -2\ ^{\circ}\mathrm{C}$) and $0.4\ \mathrm{kg \cdot kg^{-1}} \le u \le 1.0\ \mathrm{kg \cdot kg^{-1}}$.

The changes in $c_{\mathrm{bwm}} = f(u, t_0)$ and in $q_{\mathrm{bwm}}^{\mathrm{m/t}} = f(u, t_0)$ at $t_0 = -10$ °C, $t_0 = -20$ °C, $t_0 = -30$ °C, and $t_0 = -40$ °C calculated according to eqs. (7) and (8) are shown in Figure. 2 and Figure 3 respectively.

Figure 4 shows the calculated change in $q_{\mathrm{bwm}}^{\mathrm{m/t}}$ for chips with u = 0.4 kg·kg^{-1} and u = 1.0 kg· kg^{-1}, depending on t_0 and the wood species.

Analysis of the results obtained leads to the following conclusions:

1. Both the specific heat capacity of frozen bound water in chips, c_{bwm}, and the energy consumption for melting this water, $q_{\mathrm{bwm}}^{\mathrm{m/t}}$, decrease at a given value of t_0 according to an exponential dependence, when the chips' moisture content u increases (Fig. 2 and Fig. 3).

When the chips' moisture content increases from 0.4 kg·kg^{-1} to 1.0 kg·kg^{-1}, the specific heat energy consumption for melting frozen bound water in chips, $q_{\mathrm{bwm}}^{\mathrm{m/t}}$, decreases as follows:

- from 4.72 kWh·t^{-1} to 3.30 kWh·t^{-1} at $t_0 = -10$ °C and

  from 15.30 kWh·t^{-1} to 10.71 kWh·t^{-1} at $t_0 = -40$ °C for oak chips;
- from 4.97 kWh·t^{-1} to 3.48 kWh·t^{-1} at $t_0 = -10$ °C and

  from 16.09 kWh·t^{-1} to 11.27 kWh·t^{-1} at $t_0 = -40$ °C for acacia chips;
- from 5.21 kWh·t^{-1} to 3.65 kWh·t^{-1} at $t_0 = -10$ °C and

  from 16.89 kWh·t^{-1} to 11.82 kWh·t^{-1} at $t_0 = -40$ °C for beech chips;
- from 6.19 kWh·t^{-1} to 4.34 kWh·t^{-1} at $t_0 = -10$ °C and

  from 20.08 kWh·t^{-1} to 14.05 kWh·t^{-1} at $t_0 = -40$ °C for poplar chips.

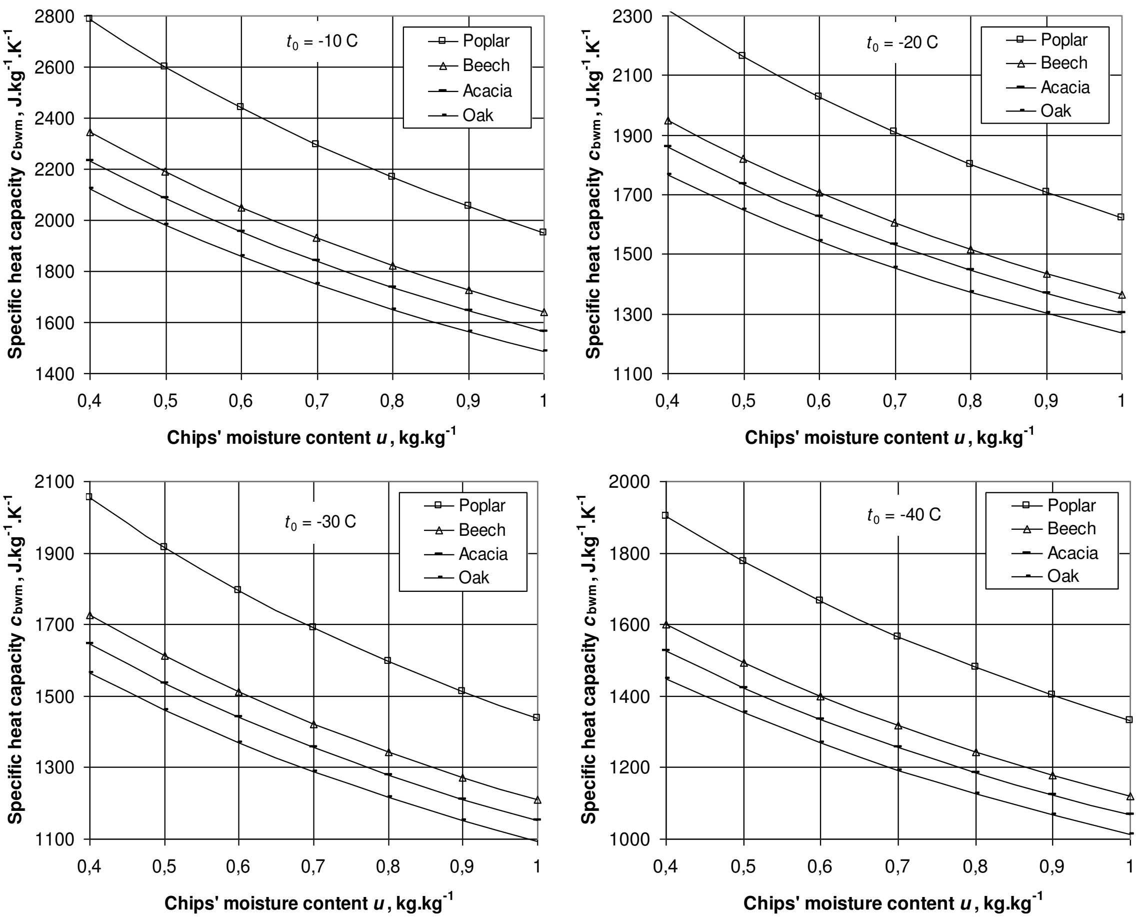

Figure 2. *Change in c_{bwm} of poplar, beech, acacia and oak chips subjected to defrosting, depending on u and t_0*

2. The values of c_{bwm} and of $q_{\text{bwm}}^{\text{m/t}}$ at a given value of u are proportionally dependent on the fiber saturation point $u_{\text{fsp}}^{293.15}$ of the chips' wood species. Each increase in $u_{\text{fsp}}^{293.15}$ with 0.01 kg·kg^{-1} causes an increase in $q_{\text{bwm}}^{\text{m/t}}$ with approximately 0.2 kWh·t^{-1} at $t_0 = -10$ °C, 0.4 kWh·t^{-1} at $t_0 = -20$ °C, 0.6 kWh·t^{-1} at $t_0 = -30$ °C and 0.8 kWh·t^{-1} at $t_0 = -40$ °C.

3. The specific heat energy consumption for melting frozen bound water in chips $q_{\text{bwm}}^{\text{m/t}}$ decreases according to a slight curvilinear dependence when the initial temperature of the frozen chips t_0 increases (Fig. 4).

If the slightly curvilinear dependences $q_{\text{bwm}}^{\text{m/t}} = f(t_0)$ in Fig. 4 are approximated with straight lines, which connect their initial and final points, it turns out that each increase in t_0 by 1 °C causes a decrease in $q_{\text{bwm}}^{\text{m/t}}$ to approximately the following values:

- 0.4026 kWh·t^{-1}·K^{-1} at $u = 0.4$ kg·kg^{-1} and 0.2818 kWh·t^{-1}·K^{-1} at $u = 1.0$ kg·kg^{-1} for oak;
- 0.4234 kWh·t^{-1}·K^{-1} at $u = 0.4$ kg·kg^{-1} and 0.2966 kWh·t^{-1}·K^{-1} at $u = 1.0$ kg·kg^{-1} for acacia;
- 0.4445 kWh·t^{-1}·K^{-1} at $u = 0.4$ kg·kg^{-1} and 0.3111 kWh·t^{-1}·K^{-1} at $u = 1.0$ kg·kg^{-1} for beech;
- 0.5284 kWh·t^{-1}·K^{-1} at $u = 0.4$ kg·kg^{-1} and 0.3697 kWh·t^{-1}·K^{-1} at $u = 1.0$ kg·kg^{-1} for poplar

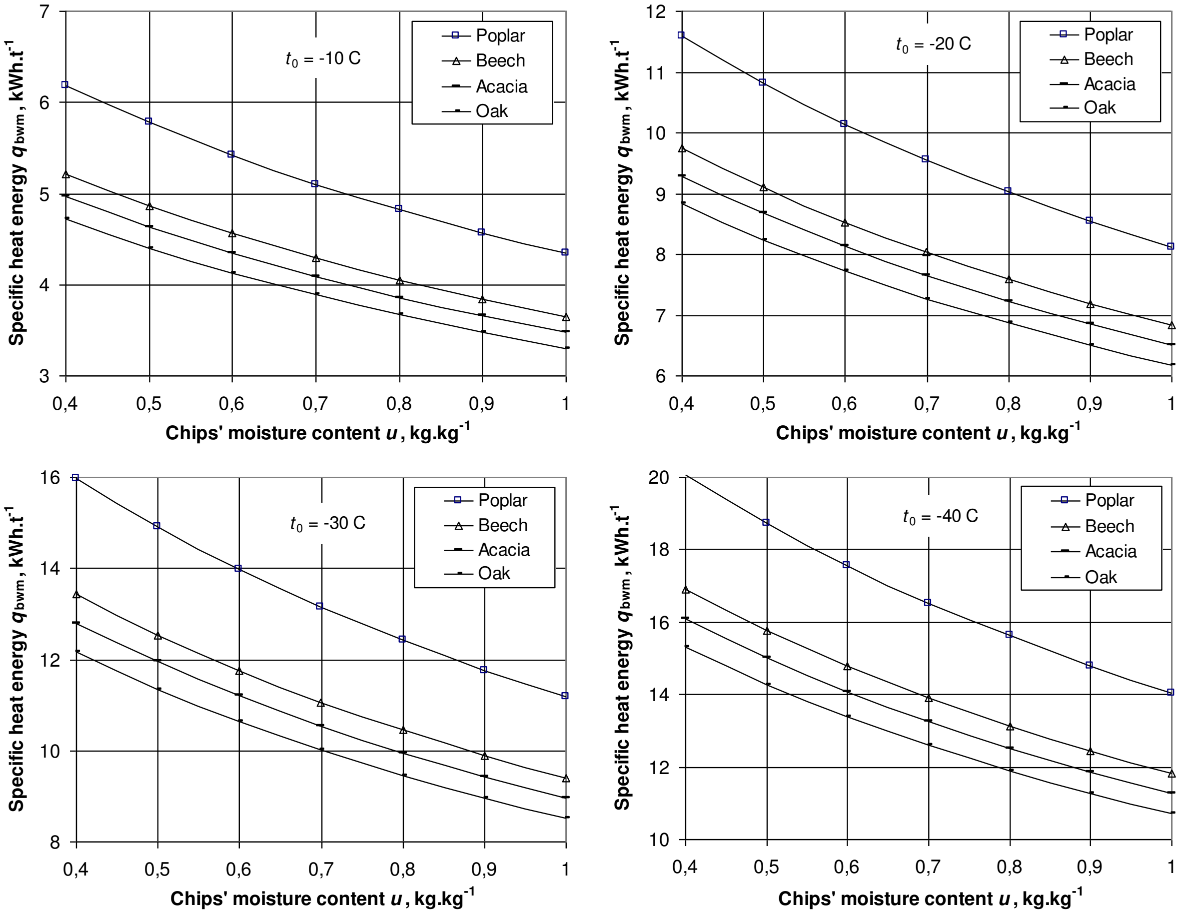

Figure 3. *Change in* $q_{\text{bwm}}^{\text{m/t}}$ *of poplar, beech, acacia and oak chips subjected to defrosting, depending on u and* t_0

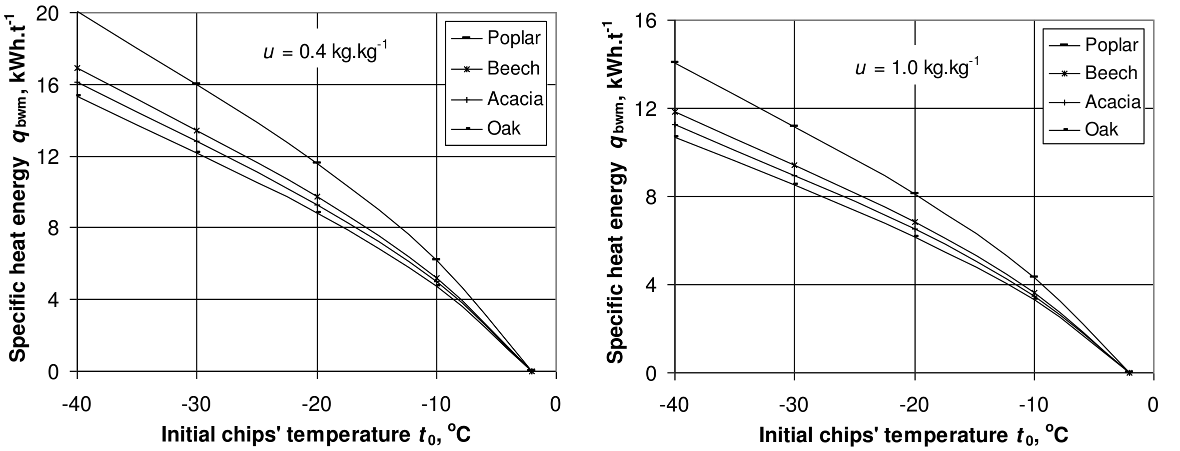

Figure 4. *Change in* $q_{\text{bwm}}^{\text{m/t}}$ *of chips with* $u = 0.4\ kg \cdot kg^{-1}$ *(left) and* $u = 1.0\ kg \cdot kg^{-1}$ *(right), depending on* t_0 *and the wood species*

4. CONCLUSIONS

The present paper describes the mathematical model suggested by the authors and an engineering approach to calculation of the specific mass energy consumption, which is needed for melting frozen bound water in wood chips subjected to defrosting above the hygroscopic range, $q_{\text{bwm}}^{\text{m/t}}$. The model reflects the influence of the initial temperature, the wood moisture content, and the fiber saturation point of each wood species on $q_{\mathrm{bwm}}^{\mathrm{m/t}}$ during wood defrosting, as well as the influence of the temperature on the fiber saturation point of the frozen wood.

An equation for easy calculation of the $q_{\mathrm{bwm}}^{\mathrm{m/t}}$ has been derived, depending on the wood moisture content u, on the fiber saturation point at 20 $^{\circ}$C (i.e. at 293.15 K), $u_{\mathrm{fsp}}^{293.15}$, and on the initial temperature of the frozen chips T_0. According to this equation, the values of $q_{\mathrm{bwm}}^{\mathrm{m/t}}$ increase with the increase of $u_{\mathrm{fsp}}^{293.15}$and of the difference 271.15 – T_0, and they decrease when u or T_0 increase.

For calculation of the $q_{\mathrm{bwm}}^{\mathrm{m/t}}$ according to the suggested model, a software program has been prepared in MS Excel 2010. By means of the respective program calculations have been carried out to determine $q_{\mathrm{bwm}}^{\mathrm{m/t}}$ for oak, acacia, beech, and poplar frozen chips with moisture content in the range from u = 0.4 kg·kg^{-1} to u = 1.0 kg·kg^{-1} and at a temperature range from $t_0 = -40$ $^{\circ}$C to $t_0 = -2$ $^{\circ}$C. At $t_0 = -2$ $^{\circ}$C melting of frozen bound water in wood has been completed (Chudinov, 1966).

The obtained results show that $q_{\mathrm{bwm}}^{\mathrm{m/t}}$ decreases exponentially with an increase of the chips' moisture content u at a given value of t_0. For example, when u of the frozen beech chips increases from 0.4 kg·kg^{-1} to 1.0 kg·kg^{-1} the value of $q_{\mathrm{bwm}}^{\mathrm{m/t}}$ decreases from 5.21 kWh·t^{-1} to 3.65 kWh·t^{-1} at $t_0 = -10$ $^{\circ}$C and from 16.89 kWh·t^{-1} to 11.82 kWh·t^{-1} at $t_0 = -40$ $^{\circ}$C.

The values of $q_{\mathrm{bwm}}^{\mathrm{m/t}}$ at given value of u are proportionally dependent on the fiber saturation point $u_{\mathrm{fsp}}^{293.15}$ of the chips' wood species. Each increase in $u_{\mathrm{fsp}}^{293.15}$ with 0.01 kg·kg^{-1} causes an increase in $q_{\mathrm{bwm}}^{\mathrm{m/t}}$, with approximately 0.24 kWh·t^{-1} at $t_0 = -10$ $^{\circ}$C, 0.46 kWh·t^{-1} at $t_0 = -20$ $^{\circ}$C, 0.63 kWh·t^{-1} at $t_0 = -30$ $^{\circ}$C and 0.80 kWh·t^{-1} at $t_0 = -40$ $^{\circ}$C.

The results also show that with increase of the initial temperature of the frozen chips, t_0, the specific mass energy consumption $q_{\mathrm{bwm}}^{\mathrm{m/t}}$ decreases according to a slight curvilinear dependence, until reaching the value $q_{\mathrm{bwm}}^{\mathrm{m/t}} = 0$ at $t_0 = -2$ $^{\circ}$C, since at $t_0 = -2$ $^{\circ}$C frozen bound water in wood becomes completely liquid.

The obtained results can be used for a science-based determination of the energy consumption, which is needed for melting frozen bound water in wood chips in the production of cellulose, briquettes, pellets or particle boards. They are also of specific importance for optimization of the technology and of the model-based automatic control (Deliiski, 2003); (Hadjiiski, 2003); (Deliiski and Dzurenda, 2010) of the chips' defrosting, heating and drying processes.

Introduction of urea-formaldehyde resins as sorbents shungite or aluminosilicates accelerates the hardening process of the glue composition, due to presence of reactive elements.

Use shungites or aluminosilicates as modifiers of urea-formaldehyde and phenol-formaldehyde resins to reduce their toxicity due to the composition, structure and adsorption properties of this natural material.

ACKNOWLEDGEMENTS

This paper was composed as part of the solution to the project BG051PO001-3.3.06-0056 supported by the European Social Fund of the EU.

Symbols

c = specific heat capacity (J·kg^{-1}·K^{-1})
exp = exponent
q = specific mass energy consumption (kWh·t^{-1}) or specific volume energy consumption (kWh·m^{-3})
t = temperature ($^{\circ}$C): $t = T - 273.15$
T = temperature (K): $T = t + 273.15$
u = moisture content (kg·kg^{-1}): $u = W/100$
W = moisture content (%): $W = 100u$

ρ = density ($kg \cdot m^{-3}$)
& = 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 range)
bwm = maximum possible amount of bound water
dfr = defrosting (for the temperature)
fr = frozen (for the state of the body)
fsp = fiber saturation point of the wood
m/kg = mass (for the specific mass energy consumption in $kWh \cdot kg^{-1}$)
m/t = mass (for the specific mass energy consumption in $kWh \cdot t^{-1}$)
v/m^3 = volume (for the specific volume energy consumption in $kWh \cdot m^{-3}$)
0 = initial (for the average mass temperature of the chips at the beginning of the heating)
1 = end (for the average mass temperature of the chips at the end of the heating)
293.15 = at 293.15 K, i.e. at 20 ^oC (for the standard values of the wood fiber saturation point)

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The Authors' Address

[1]University of Forestry, Faculty of Forest Industry,
10 Kl. Ohridski Blvd, 1756 Sofia, Bulgaria
[2] Technical University, Faculty of Wood Science and Technology,
Ul. T. G. Masaryka 2117/24, 960 53 Zvolen, Slovakia