Annals of Warsaw University of Life Sciences - SGGW
Forestry and Wood Technology № 86, 2014: 61-66
(Ann. WULS - SGGW, For. and Wood Technol. 86, 2014)

# Calculation of the energy consumption for the melting of the ice in wood chips

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**Abstract:** *Calculation of the energy consumption for the melting of the ice in wood chips.* An approach for the calculation of the specific mass energy consumption (in kWh.t$^{-1}$) for the melting of the ice in the wood chips has been suggested. Equations for the calculation of the specific mass energy consumptions for the melting of the frozen bound water in the wood chips above the hygroscopic diapason, $q_{\text{bwm}}$, and for the melting of the frozen free water in wood chips, $q_{\text{fw}}$, have been presented and solved. The specific heat energy consumption $q_{\text{ice}}$ equals to $q_{\text{bwm}} + q_{\text{fw}}$.

For the calculation of the $q_{\text{ice}}$ a software program has been prepared in MS Excel 2010. With the help of the program calculations have been carried out for the determination of $q_{\text{ice}}$ 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$^{-1}$ at a temperature range from $t_0$ = –40 $^{\text{o}}$C to $t_0$ = –1 $^{\text{o}}$C. At $t_0$ = –1 $^{\text{o}}$C the melting of the ice in the wood chips has been fully completed.

*Keywords:* wood chips, frozen bound water, frozen free water, melting, specific mass energy consumption, MS Excel 2010

## INTRODUCTION

The possibility for the calculation of the energy consumption, which is needed for the heating of frozen wood chips until the starting of the chemical reaction during their cooking in the production of cellulose is of certain scientific and practical interest (Stamm 1964). Such possibility is of interest also for the calculation of the energy needed for the heating of the wood chips at the beginning of their drying when the chips are used as a fuel or for the production of briquettes, pellets, or particle boards (Yosifov 1989, 2005).

The aim of the present work is to suggest an engineering approach for the calculation of the specific mass energy consumption needed for the melting of the ice in wood chips, which has been formed from both the frozen bound and free water in the chips.

## THEORETICAL BASIS FOR THE CALCULATION OF THE ENERGY CONSUMPTION FOR THE MELTING OF THE ICE IN THE WOOD CHIPS

It is known that the specific energy consumption for the heating of 1 m$^3$ of solid materials with an initial mass temperature $T_0$ to a given mass temperature $T_1$ is determined using the equation (Chudinov 1966, Deliiski 2003)

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

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

After dividing of the right part of eq. (1) by the wood density ρ the following equation for the determination of the specific mass energy consumption for the 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 the practical needs it is more convenient to determine the energy consumption $q_{\mathrm{m}}$ in kWh·t$^{-1}$ (i.e. for the heating of 1 ton of wood chips) according to equation

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

The moisture content of the subjected to defrosting wood chips in the practice usually is above the fiber saturation point. This means that the chips contain the maximum possible amount of bound water for the given wood specie and chips contain free water too. Consequently, the specific heat energy needed for the melting of the ice, which is formed from both bound and free water in the chips, $q_{\mathrm{ice}}$, can be calculated according to following equation:

$$q_{\mathrm{ice}}^{\mathrm{m/t}} = q_{\mathrm{bwm}}^{\mathrm{m/t}} + q_{\mathrm{fw}}^{\mathrm{m/t}}. \quad (4)$$

It has been determined, using the studies in Chudinov (1966), that the melting of the frozen bound water in the wood takes place gradually in the entire range from the initial temperature of the frozen wood $t_0 < -2\ ^{\mathrm{o}}\mathrm{C}$ (i.e. $T_0 < 271.15\ \mathrm{K}$) until the reaching of 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 the melting of the maximum possible amount of frozen bound water in the chips can be calculated according to following equation:

$$q_{\mathrm{bwm}}^{\mathrm{m/t}} = \frac{c_{\mathrm{bwm}}}{3.6 \cdot 10^3}(271.15 - T_0) \quad @ \quad u > u_{\mathrm{fsp}}^{271.15} \ \& \ T_0 < 271.15\ \mathrm{K}. \quad (5)$$

where $c_{\mathrm{bwm}}$ is equal to (Deliiski et al. 2014a):

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

It has been determined that the melting of the frozen free water in the wood takes place in the temperature range between –2 $^{\mathrm{o}}$C and –1 $^{\mathrm{o}}$C, i.e. between 271.15 K and 272.15 K (Chudinov 1966). Based on this fact, the following equation for the calculation of the specific mass energy needed for the melting of the frozen free water in the wood chips has been derived (Deliiski et al. 2014b):

$$q_{\text{fw}}^{\text{m/t}} = \frac{c_{\text{fw}}}{3.6 \cdot 10^3} = 92.778 \; \frac{u - u_{\text{fsp}}^{293.15} - 0.022}{1+u} \; @$$

$u > u_{\text{fsp}}^{271.15}$ & $271.15 \text{ K} \le T \le 272.15 \text{ K}$, (7)

where

$$c_{\text{fw}} = 3.34 \cdot 10^5 \, \frac{u - u_{\text{fsp}}^{293.15} - 0.022}{1+u} \, .$$

(8)

RESULTS AND DISCUSSION

For the solution of eqs. (4) ÷ (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 $q_{\text{ice}}^{\text{m/t}}$ depending on $T_0$ = var and on $u$ = var above the hygroscopic diapason have been calculated for frequently used in the production of chips oak wood (*Quercus petraea* Libl.), acacia wood (*Robinia pseudoacacia* J.), beech wood (*Fagus silvatica* L), and poplar wood (*Populus nigra* L.).

For the calculations, standardized values of the fiber saturation point at 20 $^{\circ}$C derived in the literature for the studied species have been used, namely: $u_{\text{fsp}}^{293.15} = 0.29$ kg·kg$^{-1}$ for oak wood, $u_{\text{fsp}}^{293.15} = 0.30$ kg·kg$^{-1}$ for acacia wood, $u_{\text{fsp}}^{293.15} = 0.31$ kg·kg$^{-1}$ for beech wood, and $u_{\text{fsp}}^{293.15} = 0.35$ kg·kg$^{-1}$ for poplar wood (Videlov 2003, Deliiski and Dzurenda 2010). The influence of the initial wood temperature and of the wood moisture content on $q_{\text{ice}}^{\text{m/t}}$ have been studied for chips containing ice in the ranges $233.15 \text{ K} \le T_0 \le 271.15$ K (i.e. $-40\ ^{\circ}\text{C} \le t_0 \le -2\ ^{\circ}\text{C}$) and $0.4 \text{ kg} \cdot \text{kg}^{-1} \le u \le 1.0 \text{ kg} \cdot \text{kg}^{-1}$. The calculated according to eqs. (4), (5) and (7) change in $q_{\text{ice}}^{\text{m/t}} = f(u, t_0)$ at $t_0 = -10$ $^{\circ}$C, $t_0 = -20$ $^{\circ}$C, $t_0 = -30$ $^{\circ}$C, and $t_0 = -40$ $^{\circ}$C are shown on Figure 1.

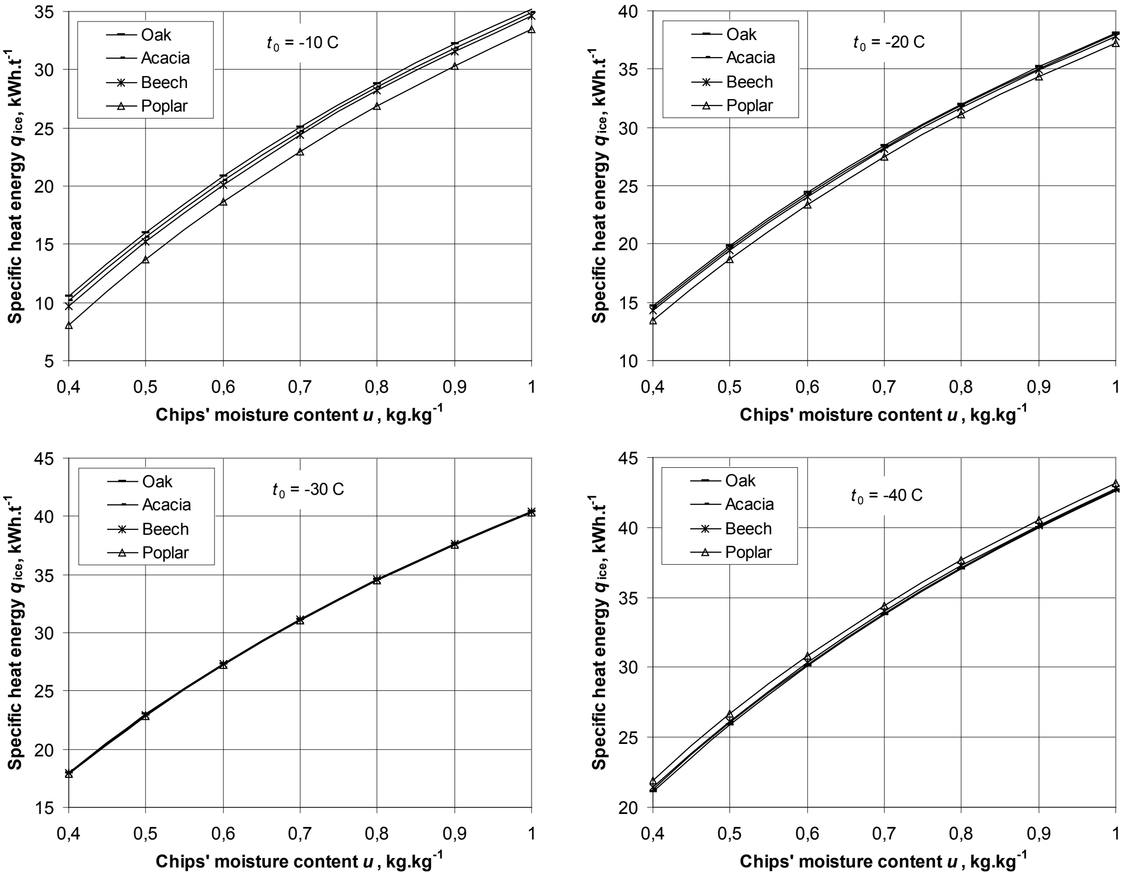


**Fig. 3.** Change in $q_{\text{ice}}^{\text{m/t}}$ of subjected to defrosting oak, acacia, beech, and poplar chips, depending on $u$ and $t_0$

The analysis of the obtained results leads to the following conclusions:

1. The increase in $u$ causes a non-linear increase in $q_{\text{ice}}^{\text{m/t}}$ due to the increasing of the amount of frozen free water in the more moist wood. For example, the increase of $u$ from $u = 0.4\ \text{kg}\cdot\text{kg}^{-1}$ to $u = 1.0\ \text{kg}\cdot\text{kg}^{-1}$ at $t_0 = -10$ °C causes an increase in $q_{\text{ice}}^{\text{m/t}}$ as follows:

- for oak wood: from 10.55 kWh·t$^{-1}$ to 35.22 kWh·t$^{-1}$, i.e. by 3.34 times;
- for acacia wood: from 10.13 kWh·t$^{-1}$ to 34.93 kWh·t$^{-1}$, i.e. by 3.45 times;
- for beech wood: from 9.72 kWh·t$^{-1}$ to 34.64 kWh·t$^{-1}$, i.e. by 3.56 times;
- for poplar wood: from 8.05 kWh·t$^{-1}$ to 33.47 kWh·t$^{-1}$, i.e. by 4.16 times.

2. The fiber saturation point $u_{\text{fsp}}^{293.15}$ causes a contradictory change in $q_{\text{ice}}^{\text{m/t}}$, depending on $T_0$:

- in the range 243.15 K < $T_0$ < 271.15 K (i.e. at −30 °C < $t_0$ < −2 °C) the increase of $u_{\text{fsp}}^{293.15}$ causes a larger decrease in $q_{\text{ice}}^{\text{m/t}}$ the more $T_0$ is larger than 243.15 K;
- at $T_0 \approx 243.15$ K (i.e. at $t_0 \approx -30$ °C): the increase of $u_{\text{fsp}}^{293.15}$ does not influence $q_{\text{ice}}^{\text{m/t}}$;
- in the range 233.15 K < $T_0$ < 243.15 K (i.e. at −40 °C < $t_0$ < −30 °C) the increase of $u_{\text{fsp}}^{293.15}$ causes a larger increase in $q_{\text{ice}}^{\text{m/t}}$ the more $T_0$ is lower then 243.15 K;

## CONCLUSIONS

The present paper describes the suggested by the authors engineering approach for the calculation of the specific mass energy consumption $q_{\text{ice}}^{\text{m/t}}$, needed for the melting of the ice in the wood chips, which has been formed from both the frozen bound and free water in the chips. Equations for easy calculation of $q_{\text{ice}}^{\text{m/t}}$ have been presented, depending on $u$, $u_{\text{fsp}}^{293.15}$, and $T_0$.

For the calculation of the $q_{\text{ice}}^{\text{m/t}}$ according to the suggested approach a software program has been prepared in MS Excel 2010. With the help of the program calculations have been carried out for the determination of $q_{\text{ice}}^{\text{m/t}}$ 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 $t_0 = -1$ °C. At $t_0 = -1$ °C the melting of the ice in the wood chips has been fully completed.

The obtained results show that $q_{\text{ice}}^{\text{m/t}}$ increases non-linearly with an increase of the chips' moisture content $u$. For example, when $u$ of the frozen beech chips increases from 0.4 kg·kg$^{-1}$ to 1.0 kg·kg$^{-1}$ at $t_0 = -10$ °C the value of $q_{\text{ice}}^{\text{m/t}}$ increases by 3.56 times from 9.72 kWh·t$^{-1}$ to 34.64 kWh·t$^{-1}$.

The increase of the fiber saturation point of the wood causes a contradictory change in $q_{\text{ice}}^{\text{m/t}}$, depending on $T_0$: $q_{\text{ice}}^{\text{m/t}}$ decreases when 243.15 K < $T_0$ < 271.15 K and $q_{\text{ice}}^{\text{m/t}}$ increases at $T_0$ < 243.15 K.

The obtained results can be used for a science-based determination of the energy consumption for the melting of the ice in the wood chips in the production of cellulose, briquettes, pellets or particle boards. They are also of specific importance for the optimization of the technology and of the model-based automatic control (Deliiski 2003) of the chips' defrosting process.

## ACKNOWLEDGEMENT

This document was supported by the grant No BG051PO001-3.3.06-0056, financed by the Human Resources Development Operational Programme (2007 – 2013) and co-financed jointly by the ESF of the EU and the Bulgarian Ministry of Education and Science.

## 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 (°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·m$^{-3}$) |
| & | = and simultaneously with this |
| @ | = at |

## SUBSCRIPTS AND SUPERSCRIPTS

| | |
|---|---|
| bwm | = maximum possible amount of the bound water in the wood |
| dfr | = defrosting (for the temperature) |
| fw | = free water |

fsp = fiber saturation point of the wood
ice = ice
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/m3 = volume (for the specific volume energy consumption in $kWh \cdot m^{-3}$)
0 = initial (for the average mass temperature of the frozen chips at the beginning of its deftosting)
1 = end (for the average mass temperature of the chips at the end of its defrosting)
271.15 = at 271.15 K, i.e. at –2 °C (for the fiber saturation point of the wood)
293.15 = at 293.15 K, i.e. at 20 °C (for the standard values of the wood fiber saturation point)


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**Streszczenie:** *Obliczeniowe zapotrzebowanie energii na topnienie lodu w zrębkach.* Zaproponowano metodę wyliczenia jednostkowej energii ($kWh.t^{-1}$) topnienia lodu w zrębkach. Zaprezentowano i rozwiązano równania na zapotrzebowanie energii na rozmrożenie wody związanej i wolnej w zrębkach. Jednostkowe zapotrzebowanie energii na cały process jest sumą powyższych składowych. Obliczono zapotrzebowanie energii dla różnych gatunków drewna – dębu, akacji, buka oraz topoli w zakresie wilgotności od $u$ = 0.4 $kg \cdot kg^{-1}$ do $u$ = 1.0 $kg \cdot kg^{-1}$ i zakresie temperatur od $t_0$ = –40 °C do $t_0$ = –1 °C. Przy temperaturze $t_0$ = –1 °C topnienie lodu w zrębkach zakończyło się.



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