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CALCULATION OF THE ENERGY CONSUMPTION FOR DEFROSTING OF THE WOOD CHIPS

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ABSTRACT

An approach for the calculation of the specific mass energy consumption q_{dfr} (in kWh.t^{-1}) needed for defrosting of the wood chips, which contain both frozen bound an free water, has been suggested. For the calculation of the q_{dfr} 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_{dfr} 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 with an initial temperature at the range from t_0 = –40 °C to t_0 = –1 °C. At temperature equal to –1 °C the defrosting process of the wood chips has been fully completed.

Key words: wood chips, defrosting, frozen bound water, frozen free water, specific mass energy consumption.

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 frozen 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 for the defrosting of wood chips, which contain both frozen bound and free water.

THEORETICAL BASIS FOR THE CALCULATION OF THE ENERGY CONSUMPTION FOR DEFROSTING OF 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)

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

The multiplier $3.6 \cdot 10^6$ 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 is obtained:

$$q^{\text{m/kg}} = \frac{c \cdot \left(T_1 - T_0\right)}{3.6 \cdot 10^6}. \qquad \textbf{(2)}$$

For the practical needs it is more convenient to determine the energy consumption q_{m} in kWh·t[-1] (i.e. for the heating of 1 ton of wood chips) according to equation

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

The moisture content of the subjected to defrosting wood chips in the practice usually is above the fibre saturation point. This means that the chips contain the maximum possible amount of bound water for the given wood species and chips contains free water, too. Consequently, the specific mass energy for defrosting of the wood chips, which contain both frozen bound and free water, $q_{\mathrm{dfr}}^{\mathrm{m/t}}$, can be calculated according to the following equation (Deliiski 2013):

$$q_{\mathrm{dfr}}^{\mathrm{m/t}} = q_{\mathrm{fr\text{-}bwm}}^{\mathrm{m/t}} + q_{\mathrm{bwm}}^{\mathrm{m/t}} + q_{\mathrm{nfr\text{-}fw}}^{\mathrm{m/t}} + q_{\mathrm{fw}}^{\mathrm{m/t}}. \qquad \textbf{(4)}$$

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 heating of the wood chips until melting of the maximum possible amount frozen bound water in them can be calculated according to following equation:

$$q_{\mathrm{fr-bwm}}^{\mathrm{m/t}} = \frac{c_{\mathrm{fr-bwm}}}{3.6\cdot 10^3}\left(271.5 - T_0\right), \qquad \textbf{(5)}$$

where $c_{\mathrm{fr}}^{\mathrm{bwm}}$ is equal to (Deliiski 2013)

$$c_{\mathrm{fr}}^{\mathrm{bwm}} = K_{\mathrm{cfr}}^{\mathrm{bwm}}\,\frac{526 + 2.95\left(\dfrac{T_0 + 271.15}{2}\right) + 0.0022\left(\dfrac{T_0 + 271.15}{2}\right)^2 + 2261u + 1976u_{\mathrm{fsp}}^{271.15}}{1+u}$$

$$@\ u > u_{\mathrm{fsp}}^{271.15}\ \&\ \ 213.15\ \mathrm{K} \le T_0 \le 271.15\ \mathrm{K}, \qquad \textbf{(6)}$$

$$K_{\mathrm{cfr}}^{\mathrm{bwm}} = 1.06 + 0.04u + \frac{0.00075\left(\dfrac{T_0 + 271.15}{2} - 271.15\right)}{u_{\mathrm{fsp}}^{271.15}}, \qquad \textbf{(7)}$$

$$u_{\mathrm{fsp}}^{\mathrm{fr}} = u_{\mathrm{fsp}}^{293.15} - 0.001(T_{\mathrm{dfr}}^{\mathrm{bw}} - 293.15)\ @\ T \le T_{\mathrm{dfr}}^{\mathrm{bw}}. \qquad \textbf{(8)}$$

Analogously, 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 the equation

$$q_{\mathrm{bwm}}^{\mathrm{m/t}} = \frac{c_{\mathrm{bwm}}}{3.6\cdot 10^3}\left(271.15 - T_0\right)\ @\ u > u_{\mathrm{fsp}}^{271.15}\ \&\ \ 213.15\ \mathrm{K} \le T_0 \le 271.15\ \mathrm{K}, \qquad \textbf{(9)}$$

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

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

It has been determined that the melting of the frozen free water in the wood takes place in the temperature range between –2 °C and –1 °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 for the melting of the frozen free water in the wood chips has been derived (Deliiski et al. 2014b):

$$q_{\mathrm{fw}}^{\mathrm{m/t}} = \frac{c_{\mathrm{fw}}}{3.6\cdot 10^3} = 92.7778\,\frac{u - u_{\mathrm{fsp}}^{293.15} - 0.022}{1+u} \quad @ \; u > u_{\mathrm{fsp}}^{271.15} \;\&\; 271.15\mathrm{K} \le T \le 272.15\mathrm{K}, \quad \mathbf{(11)}$$

$$\text{where } c_{\mathrm{fw}} = 3.34\cdot 10^5\,\frac{u - u_{\mathrm{fsp}}^{293.15} - 0.022}{1+u}. \quad \mathbf{(12)}$$

Because of the circumstance that in the range $271.15\ \mathrm{K} \le T \le 272.15\ \mathrm{K}$ there in not more frozen bound water in the chips, the specific mass energy consumption for the heating of the wood chips in this range until melting of the frozen free water in them can be calculated according to following equations (Deliiski 2013):

$$q_{\mathrm{nfr-fw}}^{\mathrm{m/t}} = \frac{c_{\mathrm{nfr-fw}}}{3.6\cdot 10^3},$$

where

$$c_{\mathrm{nfr\text{-}fw}} = \frac{4353u + 1622.1}{1+u} \quad @ \; u > u_{\mathrm{fsp}}^{271.15} \;\&\; 271.15\ \mathrm{K} < T \le 272.15\ \mathrm{K}. \quad \mathbf{(13)}$$

RESULTS AND DISCUSSION

For the solution of eqs. (4) ÷ (13) 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 $q_{\mathrm{dfr}}^{\mathrm{m/t}}$ depending on $T_0 = \mathrm{var}$ and on $u = \mathrm{var}$ above the hygroscopic diapason has been calculated for frequent use 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 fibre saturation point at 20 °C derived in the literature for the studied wood species have been used, namely: $u_{\mathrm{fsp}}^{293.15} = 0.29\ \mathrm{kg\cdot kg^{-1}}$ for oak wood, $u_{\mathrm{fsp}}^{293.15} = 0.30\ \mathrm{kg\cdot kg^{-1}}$ for acacia wood, $u_{\mathrm{fsp}}^{293.15} = 0.31\ \mathrm{kg\cdot kg^{-1}}$ for beech wood, and $u_{\mathrm{fsp}}^{293.15} = 0.35\ \mathrm{kg\cdot kg^{-1}}$ for poplar wood (Nikolov and Videlov 1987, Videlov 2003, Deliiski and Dzurenda 2010). The influences of the initial wood temperature and of the wood moisture content on $q_{\mathrm{dfr}}^{\mathrm{m/t}}$ have been studied for chips containing ice in the ranges $0.4\ \mathrm{kg\cdot kg^{-1}} \le u \le 1.0\ \mathrm{kg\cdot kg^{-1}}$ and $233.15\ \mathrm{K} \le T_0 \le 272.15\ \mathrm{K}$ (i.e. $-40\ ^{\mathrm{o}}\mathrm{C} \le t_0 \le -1\ ^{\mathrm{o}}\mathrm{C}$).

The calculated at $t_0 = -10$ °C according to eqs. (5), (9), (13), and (11) change in $q_{\mathrm{fr\text{-}bwm}}^{\mathrm{m/t}}$, $q_{\mathrm{bwm}}^{\mathrm{m/t}}$, $q_{\mathrm{nfr\text{-}fw}}^{\mathrm{m/t}}$, and $q_{\mathrm{fw}}^{\mathrm{m/t}}$, which present the separate components of $q_{\mathrm{dfr}}^{\mathrm{m/t}}$, is shown on Figure 1.

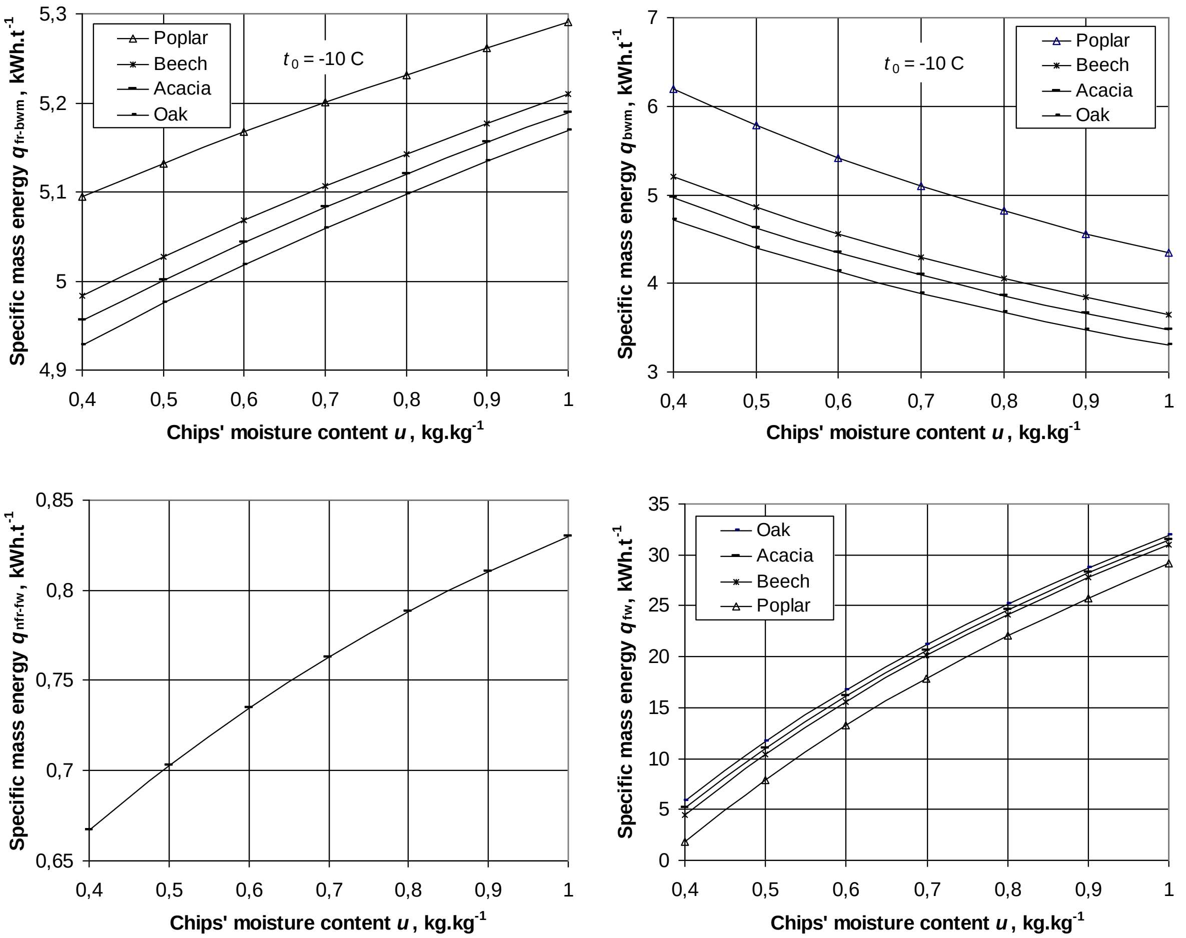
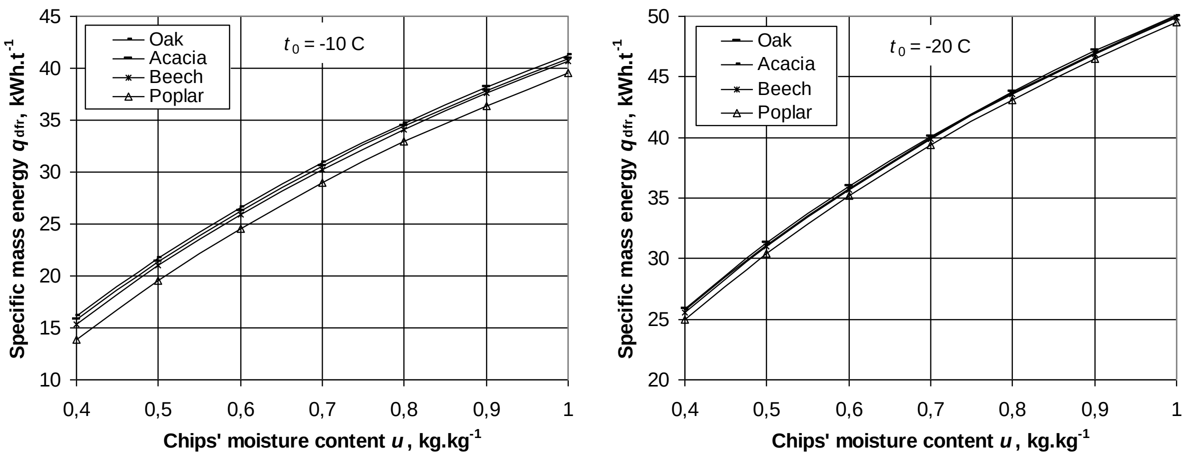


Figure 1: Change in the separate components of $q_{\mathrm{dfr}}^{\mathrm{m/t}}$: $q_{\mathrm{fr\text{-}bwm}}^{\mathrm{m/t}}$, $q_{\mathrm{bwm}}^{\mathrm{m/t}}$, $q_{\mathrm{nfr\text{-}fw}}^{\mathrm{m/t}}$, and $q_{\mathrm{fw}}^{\mathrm{m/t}}$ of subjected to defrosting oak, acacia, beech, and poplar chips with $t_0 = -10$ °C, depending on *u* and t_0

The calculated according to eq. (4) change in $q_{\mathrm{dfr}}^{\mathrm{m/t}} = f(u,t_0)$ at $t_0 = -10$ °C, $t_0 = -20$ °C, $t_0 = -30$ °C, and $t_0 = -40$ °C is shown on Figure 2.



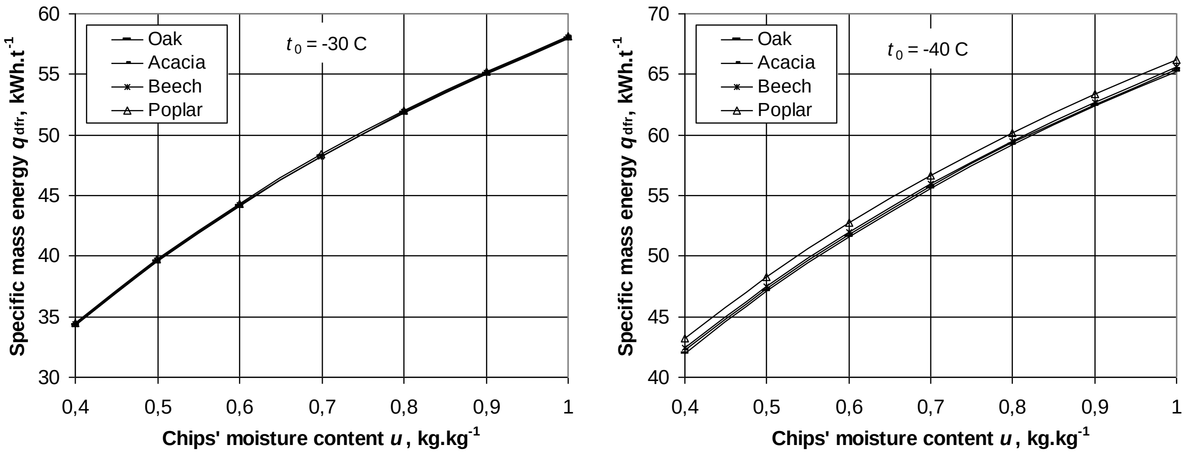


Figure 2: Change in $q_{\text{dfr}}^{\text{m/t}}$ of subjected to defrosting oak, acacia, beech, and poplar chips, depending on *u* and t_0

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

1. The increase in *u* causes a non-linear increase in $q_{\text{fr-bwm}}^{\text{m/t}}$, $q_{\text{nfr-fw}}^{\text{m/t}}$, and $q_{\text{fw}}^{\text{m/t}}$, and a non-linear decrease in $q_{\text{bwm}}^{\text{m/t}}$ (refer to Fig. 1).The energy $q_{\text{nfr-fw}}^{\text{m/t}}$ has the lowest values and $q_{\text{fw}}^{\text{m/t}}$ has the largest values. All components of $q_{\text{dfr}}^{\text{m/t}}$, except $q_{\text{nfr-fw}}^{\text{m/t}}$, depend on the wood specie.

2. The increase in *u* causes a non-linear increase in $q_{\text{dfr}}^{\text{m/t}}$ 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 $q_{\text{dfr}}^{\text{m/t}}$ as follows:

- for oak wood: from 16.55 $\text{kWh}\cdot\text{t}^{-1}$ to 41.22 $\text{kWh}\cdot\text{t}^{-1}$, i.e. by 2.55 times;
- for acacia wood: from 15.76 $\text{kWh}\cdot\text{t}^{-1}$ to 40.95 $\text{kWh}\cdot\text{t}^{-1}$, i.e. by 2.60 times;
- for beech wood: from 15.37 $\text{kWh}\cdot\text{t}^{-1}$ to 40.67 $\text{kWh}\cdot\text{t}^{-1}$, i.e. by 2.65 times;
- for poplar wood: from 13.81 $\text{kWh}\cdot\text{t}^{-1}$ to 39.59 $\text{kWh}\cdot\text{t}^{-1}$, i.e. by 2.86 times.

3. The fibre saturation point $u_{\text{fsp}}^{293.15}$ causes a contradictory change in $q_{\text{dfr}}^{\text{m/t}}$, 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 $q_{\text{dfr}}^{\text{m/t}}$ the more T_0 is larger than 243.15 K;
- at T_0 ≈ 243.15 K (i.e. at t_0 ≈ −30 °C): the increase of $u_{\text{fsp}}^{293.15}$ does not influence $q_{\text{dfr}}^{\text{m/t}}$;
- 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 $q_{\text{dfr}}^{\text{m/t}}$ 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 $q_{\text{dfr}}^{\text{m/t}}$ for defrosting of the wood chips, which contain both frozen bound and free water. Equations for easy calculation of $q_{\text{dfr}}^{\text{m/t}}$ have been presented, depending on u, $u_{\text{fsp}}^{293.15}$, and T_0.

For the calculation of the $q_{\text{dfr}}^{\text{m/t}}$ 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 $q_{\text{dfr}}^{\text{m/t}}$ and its components $q_{\text{fr-bwm}}^{\text{m/t}}$, $q_{\text{bwm}}^{\text{m/t}}$, $q_{\text{nfr-fw}}^{\text{m/t}}$, and $q_{\text{fw}}^{\text{m/t}}$ 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 defrosting process of the wood chips has been fully completed.

The obtained results show that $q_{\text{dfr}}^{\text{m/t}}$ 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 $q_{\text{dfr}}^{\text{m/t}}$ increases by 2.65 times from 15.37 kWh·t^{-1} to 40.67 kWh·t^{-1}. It must be noted that the components $q_{\text{fr-bwm}}^{\text{m/t}}$ and $q_{\text{bwm}}^{\text{m/t}}$ of $q_{\text{dfr}}^{\text{m/t}}$ depend on the initial chips' temperature t_0, but its components $q_{\text{nfr-fw}}^{\text{m/t}}$ and $q_{\text{fw}}^{\text{m/t}}$ do not depend on t_0.

The increase of the fibre saturation point of the wood causes a contradictory change in $q_{\text{dfr}}^{\text{m/t}}$, depending on T_0: $q_{\text{dfr}}^{\text{m/t}}$ decreases when 243.15 K < T_0 < 271.15 K and $q_{\text{dfr}}^{\text{m/t}}$ increases at T_0< 243.15 K. The reason for this are the different degree and directions of the influence of u on the separate components of $q_{\text{dfr}}^{\text{m/t}}$ (refer to Fig. 1).

The obtained results can be used for a science-based determination of the energy consumption for the defrosting of 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, Hadjiiski 2003; Deliiski and Dzurenda 2010) of the chips' defrosting process.

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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 and for the energy consumption)
fr-bwm = frozen chips with maximum possible amount of the bound water in them
fsp = fibre saturation point of the wood
fw = free water
ice = ice
m/kg = mass (for the specific mass energy consumption in kWh·kg^{-1})

m/t = mass (for the specific mass energy consumption in $kWh \cdot t^{-1}$)
nfr-fw = chips with non-frozen bound water and frozen free water in them
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 their defrosting)
1 = end (for the average mass temperature of the chips at the end of their defrosting) 271.15 = at 271.15 K, i.e. at –2 °C (for the fibre saturation point of the wood and for the temperature, at which the melting of the frozen bound water in the wood chips has been completed)
272.15 = at 272.15 K, i.e. at –1 °C (for the temperature, at which the melting of the frozen free water in the wood chips has been completed)
293.15 = at 293.15 K, i.e. at 20 °C (for the standard values of the wood fibre saturation point)

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