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MODELLING OF THE ENERGY CONSUMPTION NEEDED FOR DEFROSTING OF THE WOOD CHIPS

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ABSTRACT

A mathematical model for the calculation of the specific mass energy consumption, which is needed for defrosting of frozen wood chips above the hydroscopic range, q_{dfr} (in kWh·t^{-1}), have been suggested. Equations for easy calculation of q_{dfr} and its components have been derived, depending on the initial temperature of the frozen chips, T_0, on the wood moisture content, u, and on the fiber saturation points of the wood species at 20 °C and at –2 °C (i.e. at 293.15 K and at 271.15 K). For the calculation of the q_{dfr} according to the suggested model 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 the energy consumption q_{dfr} and of its components, which is needed for defrosting of oak, acacia, beech, and poplar frozen chips with an initial temperature in the range from t_0 = –40 °C to t_0 = –2 °C and with moisture content in the range from 40 % to 100 %. The obtained results can be used for a science-based determination of the energy consumption for 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 of the chips' defrosting process.

Key words: frozen wood chips, oak, acacia, beech, poplar, defrosting, modelling, specific mass energy consumption.

INTRODUCTION

The wood processing in the form of chips in winter, especially for pulp, has some specifics in terms of energy and technology. These specifications relate to the increased heat consumption, and also postpone the beginning of the chemical reactions.

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 has certain scientific and practical interest (STAMM 1964, DELIISKI *et al*. 2014). Such possibility is interesting also for the calculation of the energy needed for the heating of frozen wood chips in 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 a mathematical model for easy calculation of the specific mass energy consumption for the defrosting of wood chips, which contain both frozen bound and free water.

MATERIAL AND METHODS

Theoretical basis for the calculation of the mass energy consumption for defrosting of wood chips

The specific mass energy consumption for the heating of 1 ton (in $\text{kWh}\cdot\text{t}^{-1}$) of materials with an initial mass temperature T_0 to a given mass temperature T_1 is determined using the equation (DELIISKI *et al.* 2014a, 2014b, 2014c)

$$q = \frac{c \cdot (T_1 - T_0)}{3.6 \cdot 10^3} \; . \tag{1}$$

The moisture content of wood chips subjected to defrosting 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 a definite amount of free water, too.

Consequently, the specific mass energy consumption needed for defrosting of wood chips, which contain both frozen bound and free water, q_{dfr}, can be calculated according to the following equation (DELIISKI 2013, DELIISKI *et al.* 2016):

$$q_{\text{dfr}} = q_{\text{dfr-bwm}} + q_{\text{bwm}} + q_{\text{dfr-fw}} + q_{\text{fw}} \; . \tag{2}$$

An equation (2) represents in common form a mathematical model of the specific energy consumption, which is needed for the defrosting of the wood chips above the hygroscopic range. For the calculation of the separate components of q_{dfr} in this model an equation (1) can be used. For this purpose it is necessary to have mathematical descriptions of the specific heat capacity of each of these 4 components and also to know the values of the temperatures T_0 and T_1 for each of them.

Mathematical description of the specific energy consumption needed for the heating of the wood chips until melting of the maximum possible amount of frozen bound water in them $q_{\text{dfr-bwm}}$

It has been determined in (CHUDINOV 1966, 1968, DELIISKI *et al.* 2015), 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 $t_0 < -2$ °C (i.e. $T_0 < 271.15$ K) until the reaching of the temperature $t_{\text{dfr-bwm}} = -2$ °C (i.e. $T_1 = T_{\text{dfr-bwm}} = 271.15$ K).

This means that based on eq. (1), the specific mass energy consumption for the heating of the wood chips until melting of the maximum possible amount of frozen bound water in them can be calculated according to the following equation (DELIISKI *et al.* 2014b)

$$q_{\text{dfr-bwm}} = \frac{c_{\text{dfr-bwm}}}{3.6 \cdot 10^3}\left(271.5 - T_0\right)$$

$$@ \; u > u_{\text{fsp}}^{271.15} \; \& \; 213.15 \text{ K} \le T_0 \le 271.15 \text{ K}, \tag{3}$$

where (DELIISKI 2013)

$$c_{\text{dfr-bwm}} = \frac{K_{\text{c-bwm}}}{1+u}\left[\begin{array}{l} 526 + 2.95\left(\dfrac{T_0 + 271.15}{2}\right) + \\ 2261u + 0.0022\left(\dfrac{T_0 + 271.15}{2}\right)^2 + 1976u_{\text{nfw-bwm}} \end{array}\right], \tag{4}$$

$$K_{\text{c-bwm}} = 1.06 + 0.04u + \frac{0.00075\left(\frac{T_0 + 271.15}{2} - 271.15\right)}{u_{\text{nfw-bwm}}}, \tag{5}$$

$$u_{\text{nfw-bwm}} = 0.12 + \left(u_{\text{fsp}}^{293.15} - 0.098\right)\exp\left[0.0567\left(\frac{T_0 + 271.15}{2} - 271.15\right)\right]. \tag{6}$$

Mathematical description of the specific enenrgy consumption for the melting of the maximum possible amount of frozen bound water in them q_{bwm}

Analogously to the given above mathematical description of $q_{\text{dfr-bwm}}$, the specific mass energy consumption needed for the melting of the maximum possible amount of frozen bound water in the chips can be calculated according to the following equation (DELIISKI *et al.* 2014c):

$$q_{\text{bwm}} = \frac{c_{\text{bwm}}}{3.6 \cdot 10^3}\left(271.15 - T_0\right)$$
$$@\, u > u_{\text{fsp}}^{271.15} \;\&\; 213.15\ \text{K} \le T_0 \le 271.15\ \text{K}, \tag{7}$$

where the specific heat capacity of the maximum possible amount of frozen bound water in the chips, c_{bwm}, can be calculated using the equation (DELIISKI 2013)

$$c_{\text{bwm}} = 1.8938 \cdot 10^4\left(u_{\text{fsp}}^{293.15} - 0.098\right) \cdot \frac{\exp\left[0.0567\left(\frac{T_0 + 271.15}{2} - 271.15\right)\right]}{1+u}. \tag{8}$$

Mathematical description of the specific energy consumption for the melting of the frozen free water in the wood chips q_{fw}

It has been determined that the melting of the frozen free water in the wood takes place in the temperature range between –2 ºC and –1 ºC, i.e. between T_0 = 271.15 K and T_1 = 272.15 K (CHUDINOV 1966, 1968). Based on this fact and on eq. (1), 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.* 2014a):

$$q_{\text{fw}} = \frac{c_{\text{fw}}}{3.6 \cdot 10^3} = 92.7778\ \frac{u - u_{\text{fsp}}^{293.15} - 0.022}{1+u}$$
$$@\ u > u_{\text{fsp}}^{271.15} \;\&\; 271.15\ \text{K} \le T \le 272.15\ \text{K}. \tag{9}$$

Mathematical description of the specific energy consumption for the heating of the wood chips until melting ot the frozen free water in them $q_{\text{dfr-fw}}$

Because of the circumstance that in the range 271.15 K ≤ T ≤ 272.15 K there in no more frozen bound water in the chips, the specific mass energy consumption needed for the heating of the wood chips in this range until melting of the frozen free water in them can be calculated using the equation

$$q_{\text{dfr-fw}} = \frac{c_{\text{dfr-fw}}}{3.6 \cdot 10^3}$$
$$@\ u > u_{\text{fsp}}^{271.15} \;\&\; 271.15\ \text{K} < T \le 272.15\ \text{K}, \tag{10}$$

where the specific heat capacity of the wood with only frozen free water in it can be calculated according to the following equation (DELIISKI 2013):

$$c_{\mathrm{dfr-fw}} = \frac{4353u + 1622.1}{1+1}$$

$$@ \ u > u_{\mathrm{fsp}}^{271.15} \ \& \ 271.15 \ \mathrm{K} < T \leq 272.15 \ \mathrm{K} \,. \qquad (11)$$

RESULTS AND DISCUSSION

For the solution of eqs. (2) ÷ (11) a program in the calculation environment of MS Excel 2010 has been created. With the help of the program, the change in the energy q_{dfr} and its components depending on T_0 = var and on u = var above the hygroscopic range have been calculated for frequently used in chips production of oak wood (*Quercus petraea* Libl.), acacia wood (*Robinia pseudoacacia* J.), beech wood (*Fagus sylvatica* L.), and poplar wood (*Populus nigra* L.).

For the calculations, standardized values of the fiber 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 (TREBULA – KLEMENT 2002, DELIISKI – DZURENDA 2010). The influence of the initial chips' temperature and of the wood moisture content on q_{dfr} have been studied for frozen chips in the ranges 233.15 K ≤ T_0 ≤ 271.15 K (i.e. –40 °C ≤ t_0 ≤ – 2 °C) and 0.4 kg·kg^{-1} ≤ u ≤ 1.0 kg·kg^{-1} respectively.

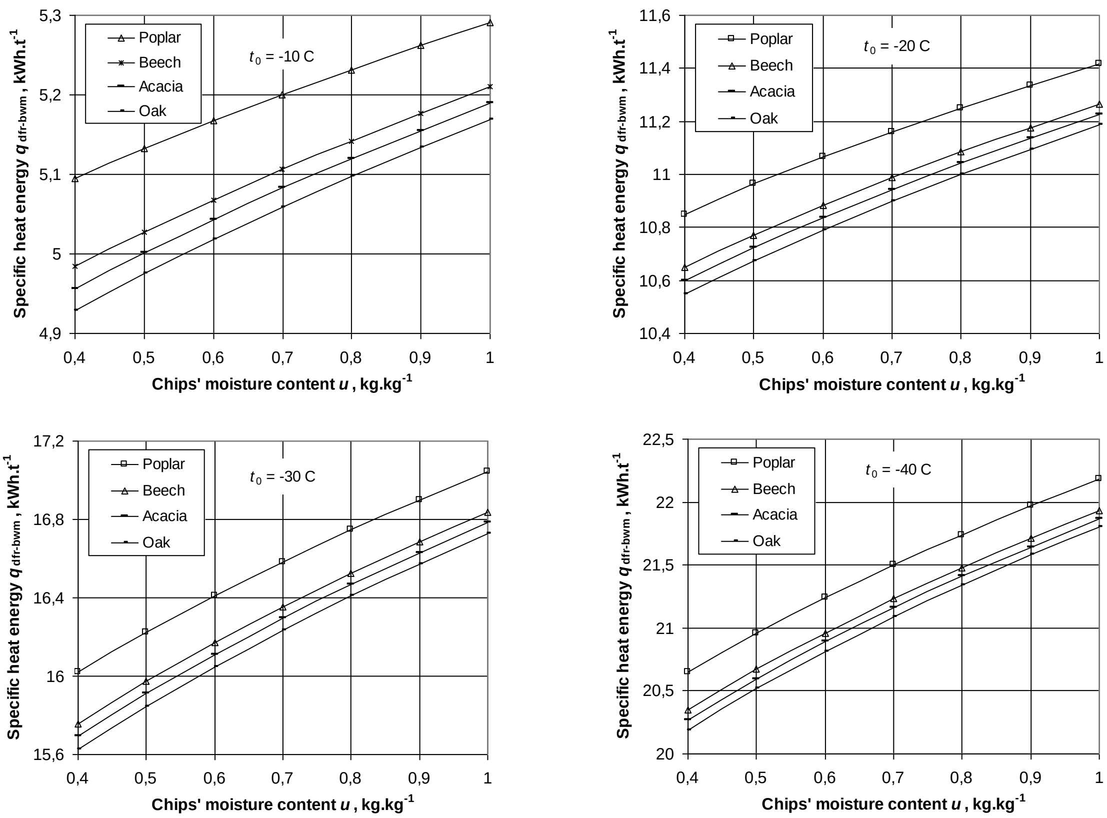

Fig. 1 Change in $q_{\mathrm{dfr-bwm}}$ of subjected to defrosting oak, acacia, beech, and poplar chips, depending on u and t_0.

The calculated according to eq. (3) change in $q_{dfr\text{-}bwm} = f(t_0, u)$ and according to eq. (7) change in $q_{bwm} = f(t_0, u)$ for the studied wood species at $u = 0.4$ kg·kg^{-1}, $u = 0.6$ kg·kg^{-1}, $u = 0.8$ kg·kg^{-1}, and $u = 1.0$ kg·kg^{-1} is shown on Fig.1 and Fig. 2 respectively.

The calculated according to eqs. (9) and (10) change in $q_{fw} = f(t,u)$ and in $q_{dfr\text{-}fw} = f(u)$ for the studied wood species is shown on Fig. 3.

The calculated according to eq. (2) change in $q_{dfr} = f(t_0, u)$ for the studied wood species at $u = 0.4$ kg·kg^{-1}, $u = 0.6$ kg·kg^{-1}, $u = 0.8$ kg·kg^{-1}, and $u = 1.0$ kg·kg^{-1} is shown on Fig. 4.

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

1. The increase in u causes a non-linear increase in $q_{dfr\text{-}bwm}$ (Fig. 1), in q_{fw}, and in $q_{dfr\text{-}fw}$ (Fig. 3) and a non-linear decrease in q_{bwm} (Fig. 2).
2. The increase in u causes a non-linear increase in q_{dfr} (Fig. 4) due to the increasing of the amount of frozen free water in the more moist wood.
3. The components $q_{dfr\text{-}bwm}$, q_{bwm}, and q_{fw} of q_{dfr} depend on the fiber saturation point $u_{fsp}^{293.15}$and the component $q_{dfr\text{-}fw}$does non depend on $u_{fsp}^{293.15}$.
4. The specific energy consumption q_{dfr} decreases according to a slight curvilinear dependence when the initial temperature t_0 of the frozen chips increases.

If the slightly curvilinear dependences $q_{dfr} = f(t_0)$ on Fig. 4 are approximated with straight lines, which connect their initial and final points, it turns out that each decrease in t_0 with 1 °C in the range –40 °C ≤ t_0 ≤ –2 °C causes an increase in q_{dfr} with approximately following values:

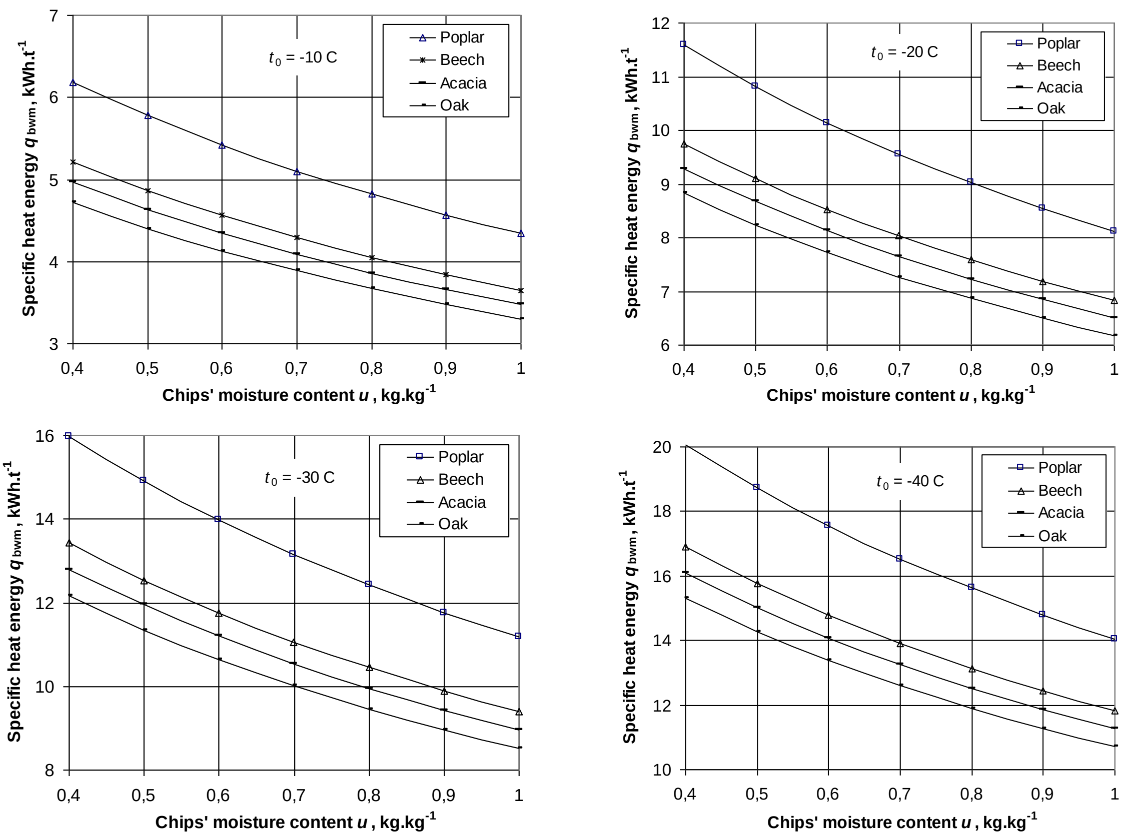

Fig. 2 Change in q_{bwm} of subjected to defrosting oak, acacia, beech, and poplar chips, depending on u and t_0.

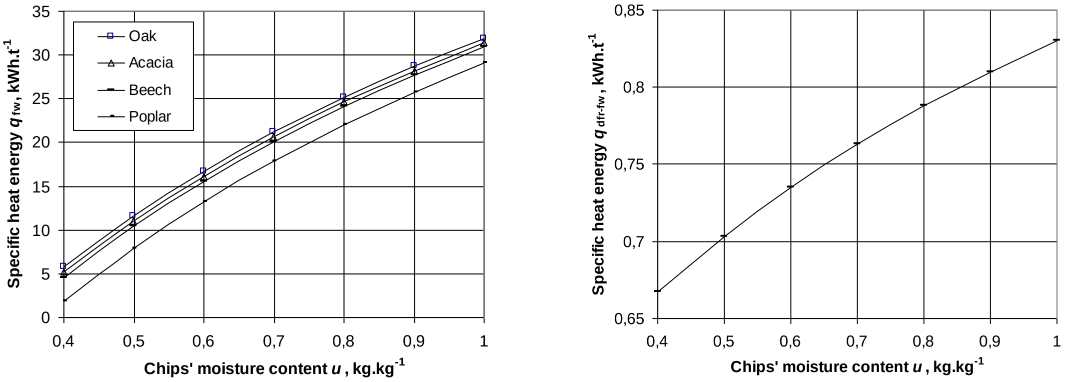

Fig. 3. Change in q_{fw} of subjected to defrosting oak, acacia, beech, and poplar chips (left) and in q_{dfr-fw} of all wood species (right), depending on *u*.

• at $u = 0.4$ kg·kg^{-1}: 0.9339 kWh·t^{-1}·K^{-1} for oak, 0.9568 kWh·t^{-1}·K^{-1} for acacia, 0.9800 kWh·t^{-1}·K^{-1} for beech, and 1.0718 kWh·t^{-1}·K^{-1} for poplar;

• at $u = 0.6$ kg·kg^{-1}: 0.8999 kWh·t^{-1}·K^{-1} for oak, 0.9201 kWh·t^{-1}·K^{-1} for acacia, 0.9404 kWh·t^{-1}·K^{-1} for beech, and 1.0214 kWh·t^{-1}·K^{-1} for poplar;

• at $u = 0.8$ kg·kg^{-1}: 0.8747 kWh·t^{-1}·K^{-1} for oak, 0.8926 kWh·t^{-1}·K^{-1} for acacia, 0.9108 kWh·t^{-1}·K^{-1} for beech, and 0.9832 kWh·t^{-1}·K^{-1} for poplar;

• at $u = 1.0$ kg·kg^{-1}: 0.8553 kWh·t^{-1}·K^{-1} for oak, 0.8718 kWh·t^{-1}·K^{-1} for acacia, 0.8882 kWh·t^{-1} for beech, and 0.9537 kWh·t^{-1}·K^{-1} for poplar.

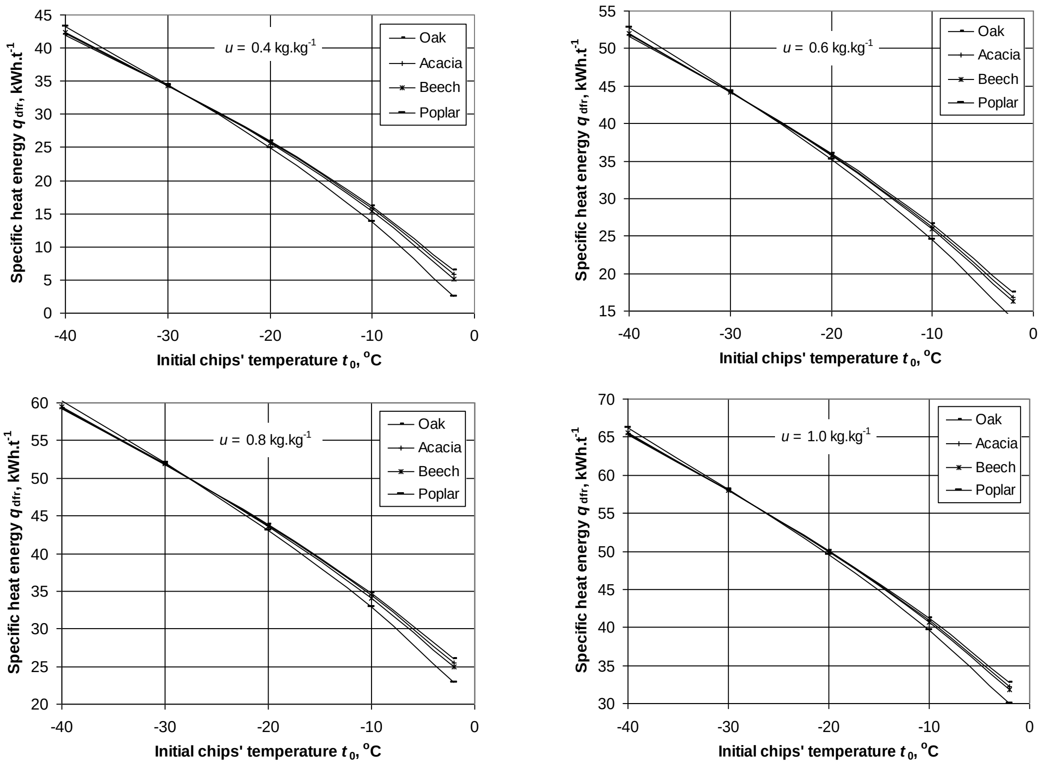

Fig. 4. Change in q_{dfr} of subjected to defrosting oak, acacia, beech, and poplar chips, depending on t_0 and *u*.

5. Using the presented on Fig. 4 computed data for q_{dfr} and also the above obtained results for the increase of q_{dfr} for the case of decrease of t_0 by 1 ^oC at given value of u as proportionality coefficient K_{dfr}, the value of q_{dfr} can be calculated according to the following equations:

$$q_{dfr} = q_{dfr}^{271.15} + K_{dfr}(T_0 - 271.15) \quad @ \; 233.15 \text{ K} \le T_0 \le 271.15 \text{ K}. \tag{12}$$

For different wood species and different values of u, which are shown on Fig. 4, equation (12) obtains the following forms:

• at u = 0.4 kg·kg^{-1}:

$q_{ice}^{oak} = 6.5 + 0.9339(T_0 - 271.15)$, $q_{ice}^{acacia} = 5.84 + 0.9568(T_0 - 271.15)$,

$q_{ice}^{beech} = 5.17 + 0.98(T_0 - 271.15)$, $q_{ice}^{poplar} = 2.52 + 1.0718(T_0 - 271.15)$.

• at u = 0.6 kg·kg^{-1}:

$q_{ice}^{oak} = 17.44 + 0.8999(T_0 - 271.15)$, $q_{ice}^{acacia} = 16.86 + 0.9201(T_0 - 271.15)$,

$q_{ice}^{beech} = 16.28 + 0.9404(T_0 - 271.15)$, $q_{ice}^{poplar} = 13.96 + 1.0214(T_0 - 271.15)$.

• at u = 0.8 kg·kg^{-1}:

$q_{ice}^{oak} = 25.94 + 0.9747(T_0 - 271.15)$, $q_{ice}^{acacia} = 25.43 + 0.8926(T_0 - 271.15)$,

$q_{ice}^{beech} = 24.91 + 0.9108(T_0 - 271.15)$, $q_{ice}^{poplar} = 22.85 + 0.9832(T_0 - 271.15)$.

• at u = 1.0 kg·kg^{-1}:

$q_{ice}^{oak} = 32.75 + 0.8553(T_0 - 271.15)$, $q_{ice}^{acacia} = 32.28 + 0.9718(T_0 - 271.15)$,

$q_{ice}^{beech} = 31.82 + 0.8882(T_0 - 271.15)$, $q_{ice}^{poplar} = 29.96 + 0.9537(T_0 - 271.15)$.

6. The fiber saturation point $u_{fsp}^{293.15}$ causes a contradictory change in q_{dfr}, depending on T_0:

• in the range 243.15 K < T_0 < 271.15 K (i.e. at −30 ^oC < t_0 < −2 ^oC) the increase of $u_{fsp}^{293.15}$ causes a larger decrease in q_{dfr} the more T_0 is larger than 243.15 K;

• at $T_0 \approx 243.15$ K (i.e. at $t_0 \approx -30$ ^oC) the increase of $u_{fsp}^{293.15}$ does not influence q_{dfr};

• in the range 233.15 K < T_0 < 243.15 K (i.e. at −40 ^oC < t_0 < −30 ^oC) the increase of $u_{fsp}^{293.15}$ causes a larger increase in q_{dfr} the more T_0 is lower then 243.15 K.

CONCLUSIONS

The present paper presents a mathematical model for the calculation of the specific energy consumption, q_{dfr}, which is needed for defrosting of the wood chips above the hygroscopic range. The model takes into account a maximum degree the physics of the melting processes of both the frozen bound and the frozen free water in chips. It reflects the influence of the initial temperature of the frozen chips, t_0, the chips' moisture content, u, and the fiber saturation point of wood species at 20 ^oC and at –2 ^oC (i.e. at 293.15 K and at 271.15 K), $u_{fsp}^{293.15}$ and $u_{fsp}^{271.15}$, on the value of q_{dfr}.

For the calculation of the q_{ice} according to the suggested model 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} and its components $q_{dfr\text{-}bwm}$, q_{bwm}, $q_{dfr\text{-}fw}$, and q_{fw} for oak, acacia, beech, and poplar frozen chips with moisture content in the range from u = 0.4

$kg \cdot kg^{-1}$ to $u = 1.0$ $kg \cdot kg^{-1}$ and at a temperature range from $t_0 = -40$ °C to $t_0 = -2$ °C. At $t_0 = -2$ °C the melting process of the frozen bound water in the wood chips has been fully completed. In the practice it is not possible to have wood chips with only frozen free water, i.e. without frozen bound water.

The obtained results show that q_{dfr} increases non-linearly with an increase of the chips' moisture content u. For example, when u of the frozen poplar chips increases from 0.4 $kg \cdot kg^{-1}$ to 1.0 $kg \cdot kg^{-1}$ at $t_0 = -10$ °C the value of q_{dfr} increases by 2.87 times from 13.81 $kWh \cdot t^{-1}$ to 39.59 $kWh \cdot t^{-1}$.

The results also show that q_{dfr} decreases according to a slight curvilinear dependence when the initial temperature t_0 of the frozen chips increases. For example, when t_0 of the frozen poplar chips increases from –40 °C to –2 °C at $u = 1.0$ $kg \cdot kg^{-1}$ the value of q_{dfr} decreases by 2.21 times from 66.20 $kWh \cdot t^{-1}$ to 29.96 $kWh \cdot t^{-1}$.

The increase of the fiber saturation point of the separate wood species causes a contradictory change in q_{dfr}, depending on T_0: q_{dfr} decreases when $243.15 \text{ K} < T_0 \leq 271.15$ K (i.e. when -30 °C $< t_0 \leq -2$ °C and q_{dfr} increases at $T_0 < 243.15$ K (i.e. at $t_0 < -30$ °C).

The obtained results can be used for a science-based determination of the energy consumption, which is needed for the defrosting of the frozen 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 (HADJISKI 2003, HADJISKI – DELIISKI 2015, 2016) of the chips' defrosting process.

Symbols:

c – specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)
exp – exponent
q – specific mass energy consumption ($kWh \cdot t^{-1}$)
t – temperature (°C): $t = T - 273.15$
T – temperature (K): $T = t + 273.15$
u – moisture content ($kg \cdot kg^{-1}$): $u = W/100$
W – moisture content (%): $W = 100u$
& – and simultaneously with this
@ – at

Subscripts and superscripts:

bw – bound water
bwm – maximum possible amount of bound water (for the specific heat capacity of this water in frozen state in the wood chips or for the energy needed for the melting of this water)
dfr – defrosting (of the wood chips)
dfr-bwm – for the energy needed for heating of the chips until melting of the maximum possible amount of frozen bound water in them
dfr-fw – for the energy needed for heating of the chips until melting of the frozen free water in them
fw – free water (for the specific heat capacity of the frozen free water in the wood chips or for the energy needed for melting of this water)
fsp – fiber saturation point of the wood specie
0 – initial (for the average mass temperature of the chips at the beginning of the 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 temperature, at which the melting of the frozen free water in the wood chips has been completed or for the calculated value of the wood fiber saturation point of the wood specie at this temperature)
293.15 – at 293.15 K, i.e. at 20 °C (for the temperature of the standardized value of the fiber saturation point of wood species)

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