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CALCULATION OF THE ENERGY CONSUMPTION FOR HEATING OF WOOD CHIPS UNTIL MELTING OF THE FROZEN BOUND WATER IN THEM

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Abstract

A mathematical model and an engineering approach for the calculation of the specific mass energy consumption, which is needed for the heating of the wood chips until melting of the frozen bound water in them above the hygroscopic range, $q_{\text{fr-bwm}}^{\text{m/t}}$*, have been suggested. An equation for the easy calculation of* $q_{\text{fr-bwm}}^{\text{m/t}}$ *has been derived, depending on the wood moisture content u, on the fiber saturation point of the wood species at 20* ^{o}*C (i.e. at 293.15 K),* $u_{\text{fsp}}^{293.15}$*, and on the initial temperature* T_0 *of the frozen chips. According to this equation, the values of* $q_{\text{fr-bwm}}^{\text{m/t}}$ *increase with the increase of u and of* $u_{\text{fsp}}^{293.15}$*, and they decrease when* T_0 *increases.*

For the calculation of the $q_{\text{fr-bwm}}^{\text{m/t}}$ *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* $q_{\text{fr-bwm}}^{\text{m/t}}$ *for oak, acacia, beech, and poplar frozen chips with moisture content in the range from* $u = 0.4\ \text{kg}\cdot\text{kg}^{-1}$ *to* $u = 1.0\ \text{kg}\cdot\text{kg}^{-1}$ *and at a temperature range from* $t_0 = -40\ ^{o}\text{C}$ *to* $t_0 = -2\ ^{o}\text{C}$ *because of the fact that at* $t_0 = -2\ ^{o}\text{C}$ *the melting ot the frozen bound water in the wood chips has been completed.*

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

INTRODUCTION

It is known that the 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 following cooking process. The cooking of the wood chips takes place at a definite temperature and pressure with specialized chemicals (Stamm 1964).

Before the starting of the chemical reaction between the wood chips and the processing medium during the cooking, a pure heating process with the chips has been undergoing.

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The creation of a model for the calculation of the energy consumption for the 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 a model is of interest also for the calculation of the energy, which is needed for the heating of the wood chips at the beginning of their drying when they are used as fuel, for production of briquettes and pellets, or for the production of particle boards (Yosifov 2005).

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

MATERIAL AND METHODS

Theoretical basis for the calculation of the heat energy consumption

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 (Deliiski 2013a, 2013b)

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

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 of different materials is obtained:

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

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

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

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 the chips also contain free water, which amounts depends on u.

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 reaching of the temperature $t_{\mathrm{dfr-bwm}} = -2\ ^{\mathrm{o}}\mathrm{C}$ (i.e. $T_{\mathrm{dfr-bwm}} = 271.15\ \mathrm{K}$). This means that based on eq. (3), the specific mass energy consumption, which is needed 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:

$$q^{\mathrm{m/t}}_{\mathrm{fr\text{-}bwm}} = \frac{c_{\mathrm{fr\text{-}bwm}}}{3.6 \cdot 10^3}\left(271.15 - T_0\right) \quad @ \quad u > u_{\mathrm{fsp}}^{271.15} \ \& \ T_0 < 271.15 \ \mathrm{K}\,. \tag{4}$$

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

Mathematical description of the specific heat capacity of the frozen wood during its defrosting

The specific heat capacity of the frozen wood, c_{fr}, has been described mathematically by Deliiski (2003, 2013b) 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. dissertation of Chudinov (1966). The following equations for $c_{\mathrm{fr}}(T, u, u_{\mathrm{nfw}})$ have been derived, which are valid for all wood species when the wood contains ice:

$$c_{\mathrm{fr}} = K_{\mathrm{c}} \frac{526 + 2.95T + 0.0022T^2 + 2261u + 1976u_{\mathrm{nfw}}}{1 + u}, \tag{5}$$

where

$$K_{\mathrm{c}} = 1.06 + 0.04u + \frac{0.00075\left(T - 271.15\right)}{u_{\mathrm{nfw}}}, \tag{6}$$

and the content of non-frozen water in the wood u_{nfw} can be determined according to equation (Deliiski 2013a)

$$u_{\mathrm{nfw}} = 0.12 + \left(u_{\mathrm{fsp}}^{293.15} - 0.001T_{\mathrm{dfr}} + 0.17315\right)\exp\left[0.0567\left(T - 271.15\right)\right]. \tag{7}$$

Using eqs. (5), (6), and (7) the value of c_{fr} can be determined at an arbitrary value of the temperature *T* in the range 223 K ≤ *T* ≤ 271.15 K.

During engineering calculations it is necessary to be able to determine the specific energy needed for the heating of 1 ton frozen chips with an initial temperature T_0 to a final temperature T_1 = 271.15 K, when the melting of the frozen bound water in the wood is completed (Chudinov 1966). For this case, for the value of *T* in eqs. (5), (6), and (7), one must use the average arithmetic value between T_0 and $T_1 = 271.15 \ \mathrm{K}$, i.e. $T = \frac{T_0 + 271.15}{2}$. After substituting of *T* in these equations with $T = \frac{T_0 + 271.15}{2}$, and also the value of T_{dfr} in eq. (7) with $T_{\mathrm{dfr\text{-}bwm}} = 271.15 \ \mathrm{K}$, the eqs. (2), (3), and (4) obtain the following final forms:

$$c_{\mathrm{fr\text{-}bwm}} = K_{\mathrm{c\text{-}bwm}} \frac{526 + 2.95\left(\frac{T_0 + 271.15}{2}\right) + 0.0022\left(\frac{T_0 + 271.15}{2}\right)^2 + 2261u + 1976u_{\mathrm{nfw\text{-}bwm}}}{1 + u}, \tag{8}$$

$$K_{\text{c-bwm}} = 1.06 + 0.04u + \frac{0.00075\left(\dfrac{T_0 + 271.15}{2} - 271.15\right)}{u_{\text{nfw-bwm}}}, \tag{9}$$

$$u_{\text{nfw-bwm}} = 0.12 + \left(u_{\text{fsp}}^{293.15} - 0.098\right)\exp\left[0.0567\left(\frac{T_0 + 271.15}{2} - 271.15\right)\right]. \tag{10}$$

Final equation for the calculation of the specific heat energy $q_{\text{fr-bwm}}$

After substituting eq. (8) in eq. (4) the following final equation for the calculation of $q_{\text{fr-bwm}}^{\text{m/t}}$ at $u > u_{\text{fsp}}^{271.15}$ & $213.15\ \text{K} \le T_0 < 271.15\ \text{K}$ is obtained:

$$q_{\text{fr-bwm}}^{\text{m/t}} = \frac{K_{\text{c-bwm}}}{3.6 \cdot 10^3}\left(271.15 - T_0\right) \cdot$$

$$\cdot \frac{526 + 2.95\left(\dfrac{T_0 + 271.15}{2}\right) + 0.0022\left(\dfrac{T_0 + 271.15}{2}\right)^2 + 2261u + 1976u_{\text{nfw-bwm}}}{1 + u}, \tag{11}$$

where the values of $K_{\text{c-bwm}}$ and $u_{\text{nfw-bwm}}$ are calculated according to eqs. (9) and (10) correspondingly.

RESULTS AND DISCUSSION

For the solution of eqs. (8), (9), (10), and (11) a program in the calculation environment of MS Excel 2010 has been created. With the help of the program the change in $c_{\text{fr-bwm}}$ and in $q_{\text{fr-bwm}}^{\text{m/t}}$ depending on $t_0 = \text{var}$ and $u = \text{var}$ 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 the standardized fiber saturation point at 20 $^{\text{o}}$C (i.e. at 293.15 K) derived in the literature for the studied species have been used, namely: $\rho_{\text{b}} = 355$ kg·m^{-3} and $u_{\text{fsp}}^{293.15} = 0.35$ kg·kg^{-1} for poplar wood; $\rho_{\text{b}} = 560$ kg·m^{-3} and $u_{\text{fsp}}^{293.15} = 0.31$ kg·kg^{-1} for beech wood; $\rho_{\text{b}} = 660$ kg·m^{-3} and $u_{\text{fsp}}^{293.15} = 0.30$ kg·kg^{-1} for acacia wood and $\rho_{\text{b}} = 670$ kg·m^{-3} and $u_{\text{fsp}}^{293.15} = 0.29$ kg·kg^{-1} for oak wood (Nikolov and Videlov 1987, Trebula and Klement 2002).

The influence of the initial chips temperature and of the wood moisture content on $c_{\text{fr-bwm}}$ and $q_{\text{fr-bwm}}^{\text{m/t}}$ have been studied for chips containing ice in the ranges $233.15\ \text{K} \le T_0 \le 271.15\ \text{K}$ (i.e. $-40\ ^{\text{o}}\text{C} \le t_0 \le -2\ ^{\text{o}}\text{C}$) 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. (8) and (11) change in $c_{\text{fr-bwm}} = f(u, t_0)$ and in $q_{\text{fr-bwm}}^{\text{m/t}} = f(u, t_0)$ at $t_0 = -10$ $^{\text{o}}$C, $t_0 = -20$ $^{\text{o}}$C, $t_0 = -30$ $^{\text{o}}$C, and $t_0 = -40$ $^{\text{o}}$C are shown on Fig. 1 and Fig. 2 respectively.

On Fig. 3 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 studied wood species is shown.

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

1. Both the specific heat capacity of the chips with maximum possible amount of frozen bound water in it, $c_{\mathrm{fr\text{-}bwm}}$, and the energy consumption for the heating of this chips, $q_{\mathrm{fr\text{-}bwm}}^{\mathrm{m/t}}$, increase at a given value of t_0 according to a slight curvilinear dependence when the chips' moisture content u increases (Fig. 1 and Fig. 2).

When the chips' moisture content increases from 0.4 kg·kg^{-1} to 1.0 kg·kg^{-1} the specific heat energy consumption, which is needed for the heating of the chips until melting of the frozen bound water in it, $q_{\mathrm{fr\text{-}bwm}}^{\mathrm{m/t}}$, increases as follow:

- from 4.93 kWh·t^{-1} to 5.17 kWh·t^{-1} at $t_0 = -10$ °C and from 20.19 kWh·t^{-1} to 21.80 kWh·t^{-1} at $t_0 = -40$ °C for oak chips;
- from 4.96 kWh·t^{-1} to 5.19 kWh·t^{-1} at $t_0 = -10$ °C and from 20.27 kWh·t^{-1} to 21.87 kWh·t^{-1} at $t_0 = -40$ °C for acacia chips;
- from 4.99 kWh·t^{-1} to 5.21 kWh·t^{-1} at $t_0 = -10$ °C and from 20.35 kWh·t^{-1} to 21.94 kWh·t^{-1} at $t_0 = -40$ °C for beech chips;
- from 5.10 kWh·t^{-1} to 5.29 kWh·t^{-1} at $t_0 = -10$ °C and from 20.65 kWh·t^{-1} to 22.19 kWh·t^{-1} at $t_0 = -40$ °C for poplar chips.

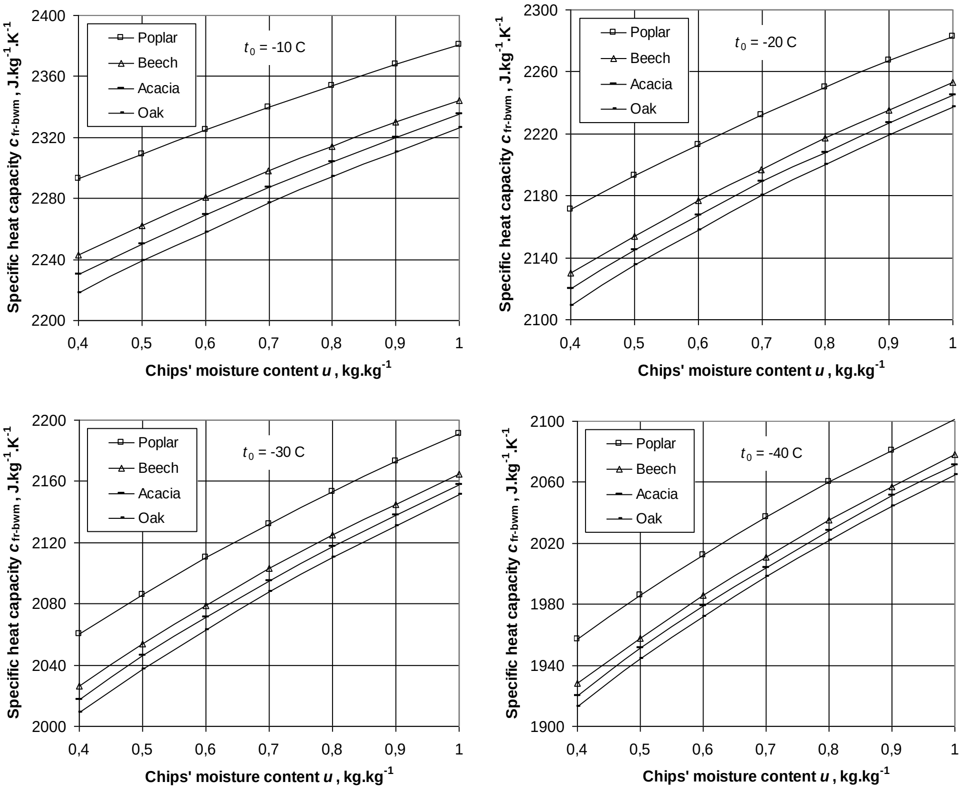

Fig. 1. Change in $c_{\mathrm{fr\text{-}bwm}}$ of subjected to defrosting poplar, beech, acacia and oak chips, depending on u and t_0

2. The values of $c_{\text{fr-bwm}}$ and of $q^{\text{m/t}}_{\text{fr-bwm}}$ at a given value of *u* are proportionally dependent on the fiber saturation point u^{29315}_{fsp} of the chips' wood specie. Each increase in u^{29315}_{fsp} with 0.01 kg·kg^{-1} causes an increase in $q^{\text{m/t}}_{\text{fr-bwm}}$ with approximately 0.03 kWh·t^{-1} at $t_0 = -10^{\circ}$C, 0.05 kWh·t^{-1} at $t_0 = -20^{\circ}$C, 0.07 kWh·t^{-1} at $t_0 = -30^{\circ}$C and 0.09 kWh·t^{-1} at $t_0 = -40^{\circ}$C.

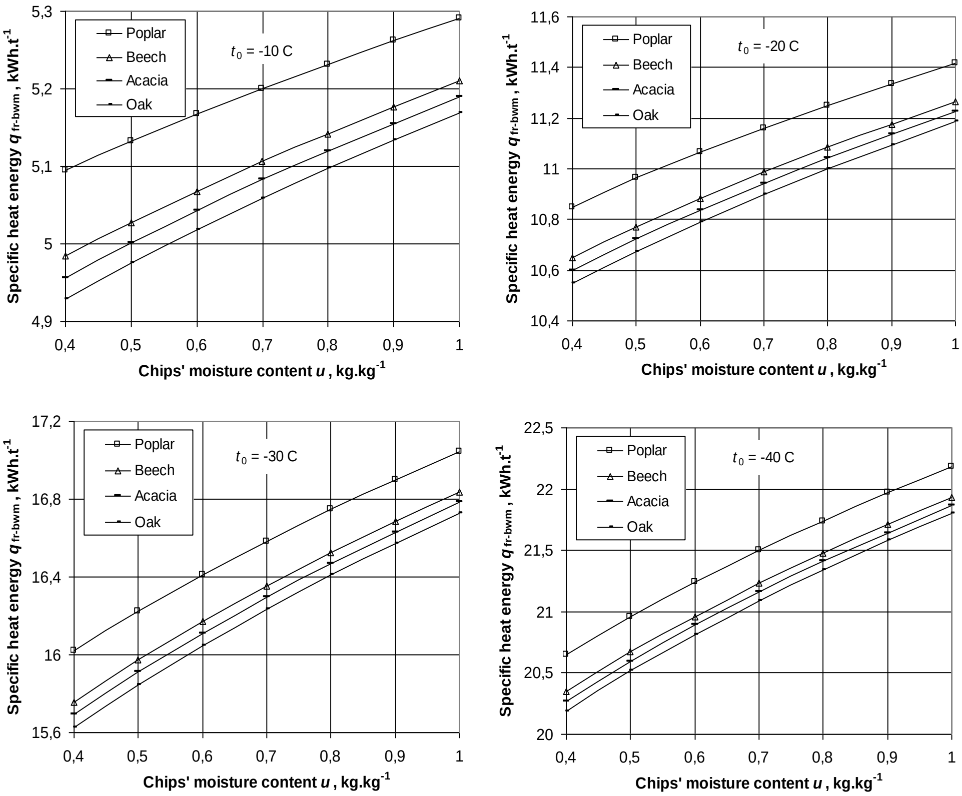

Fig. 2. Change in $q^{\text{m/t}}_{\text{fr-bwm}}$ of subjected to defrosting poplar, beech, acacia and oak chips, depending on *u* and t_0

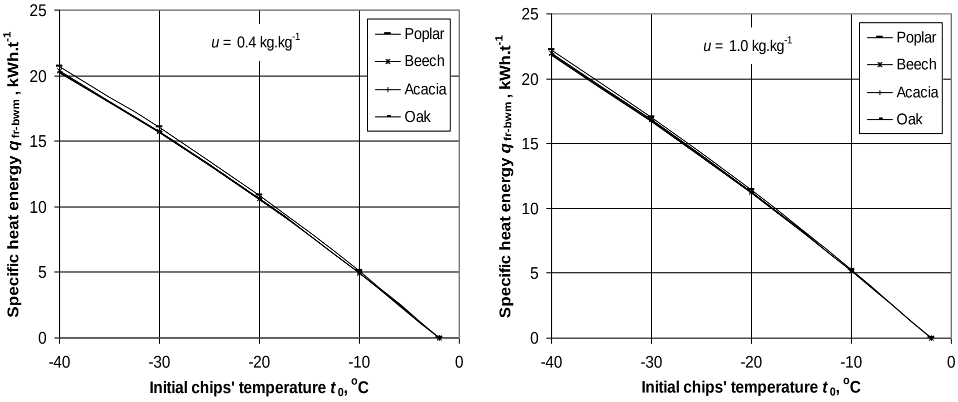

Fig. 3. Change in $q_{\text{fr-bwm}}^{\text{m/t}}$ of chips with $u = 0.4\ \text{kg}\cdot\text{kg}^{-1}$ and $u = 1.0\ \text{kg}\cdot\text{kg}^{-1}$, depending on t_0 and on the wood species

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

If the slightly curvilinear dependences $q_{\text{fr-bwm}}^{\text{m/t}} = f(t_0)$ on 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 $q_{\text{fr-bwm}}^{\text{m/t}}$ practically for all wood species by approximately the following values:

- 0.5376 kWh·t^{-1}·K^{-1} at u = 0.4 kg·kg^{-1};
- 0.5534 kWh·t^{-1}·K^{-1} at u = 0.6 kg·kg^{-1};
- 0.5671 kWh·t^{-1}·K^{-1} at u = 0.8 kg·kg^{-1};
- 0.5788 kWh·t^{-1}·K^{-1} at u = 1.0 kg·kg^{-1}.

CONCLUSIONS

The present paper describes the suggested by the authors' mathematical model and an engineering approach for the calculation of the specific mass energy consumption $q_{\text{fr-bwm}}^{\text{m/t}}$, which is needed for the heating of the wood chips until melting of the frozen bound water in it during defrosting of the chips with moisture content above the hygroscopic range. The model reflects the influence of the initial temperature, the wood moisture content, and the fiber saturation point of each wood specie on $q_{\text{fr-bwm}}^{\text{m/t}}$ during defrosting and also the influence of the temperature on the fiber saturation point of the frozen wood.

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

For the calculation of $q_{\text{fr-bwm}}^{\text{m/t}}$ 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 $q_{\text{fr-bwm}}^{\text{m/t}}$ 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 $^{\text{o}}$C to t_0 = –2 $^{\text{o}}$C because of the fact that at t_0 = –2 $^{\text{o}}$C the melting ot the frozen bound water in the wood chips has been completed.

The obtained results show that $q_{\text{fr-bwm}}^{\text{m/t}}$ increases almost linearly 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 $q_{\text{fr-bwm}}^{\text{m/t}}$ increases from 4.99 kWh·t^{-1} to 5.21 kWh·t^{-1} at $t_0 = -10$ $^{\text{o}}$C and from 20.35 kWh·t^{-1} to 21.94 kWh·t^{-1} at $t_0 = -40$ $^{\text{o}}$C. The values of $q_{\text{fr-bwm}}^{\text{m/t}}$ at a given value of u are proportionally dependent on the fiber saturation point $u_{\text{fsp}}^{293.15}$ of the chips' wood specie. Each increase in $u_{\text{fsp}}^{293.15}$ by 0.01 kg·kg^{-1} causes an increase in $q_{\text{fr-bwm}}^{\text{m/t}}$ by approximately 0.03 kWh·t^{-1} at $t_0 = -10^{\text{o}}$C, 0.05 kWh·t^{-1} at $t_0 = -20^{\text{o}}$C, 0.07 kWh·t^{-1} at $t_0 = -30^{\text{o}}$C and 0.09 kWh·t^{-1} at $t_0 = -40^{\text{o}}$C.

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

The obtained results can be used for a science-based determination of the energy consumption, which is needed for the heating 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 (Deliiski 2003, Hadjiiski 2003, Deliiski and Dzurenda 2010) of the chips' defrosting, heating and drying processes.

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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 ($^{\text{o}}$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:

b = basic (for density, based on dry mass divided to green volume)
c = specific heat capacity
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 $kWh \cdot t^{-1}$)
nfw = non-frozen water in the wood
v/m3 = volume (for the specific volume energy consumption in $kWh \cdot m^{-3}$)
0 = initial (for the average mass t of the frozen chips at the beginning of its heating)
1 = final (for the average mass temperature of the chips at the end of its heating)
271.15 = at 271.15 K, (for the fiber saturation point of the wood or for the temperature, at which the melting of the frozen bound water in the chips has complited)
293.15 = at 293.15 K, i.e. at 20 °C (for the temperature of the standard values of the wood fiber saturation point)

REFERENCES

1. CHUDINOV, B. S., 1966: Theoretical research of thermo physical properties and thermal treatment of wood. Dissertation for DSc., SibLTI, Krasnoyarsk, USSR (In Russian).
2. DELIISKI, N., 2003: Modelling and technologies for steaming wood materials in autoclaves. Dissertation for DSc., University of Forestry, Sofia (in Bulgarian).
3. DELIISKI, N., 2013a: 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 2. Calculation of the specific heat energy needed for heating of frozen wood until melting of the ice, which is created in it from the hygroscopically bounded water. Annals of Warsaw University of Life Sciences, Forestry and Wood Technology, No 82, c.178-184, ISSN 1898-5912.
4. DELIISKI, N., 2013b: Modelling of the energy needed for heating of capillary porous bodies in frozen and non-frozen states. ISBN 978-3-639-70036-7, Lambert Academic Publishing, Scholars' Press, Saarbruecken, Germany, 116 p. http://www. scholars-press.com//system/covergenerator/build/1060.
5. DELIISKI, N., DZURENDA, L., 2010: Modelling of the thermal processes in the technologies for wood thermal treatment. TU Zvolen, Slovakia (in Russian).
6. HADJIISKI, M., 2003: Mathematical models in advanced technological control systems. Automatic & Informatics, 37 (3): 7-12 (in Bulgarian).
7. KANTER, K. R., 1955: Investigation of the thermal properties of wood. PhD thesis, MLTI, Moscow, USSR (In Russian).
8. NIKOLOV, S., VIDELOV, H., 1987: Handbook for wood drying. Publishing Company "Zemizdat", Sofia (in Bulgarian).
9. STAMM, A. J., 1964: Wood and cellulose science. Ronald Press, New York.
10. TREBULA, P., KLEMENT, I., 2002: Drying and hydrothermal treatment of wood, TU Zvolen, Slovakia (in Slovakian).

11. VIDELOV, H., 2003: Drying and thermal treatment of wood, University of Forestry in Sofia, Bulgaria (in Bulgarian).
12. YOSIFOV, N., 2005: Briquettes and pellets from plant biomass. University “St. Kliment Ohridski”, Sofia (in Bulgarian).