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APPLYING THE SOFTWARE PACKAGE TABLE CURVE 2D FOR CALCULATING THE ENERGY REQUIRED FOR MELTING OF FROZEN BOUND WATER IN WOOD

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ABSTRACT

A mathematical description of the energy $Q_{\text{ice-bw}}$ required for melting the temperature dependent part of frozen bound water in wood, using a software package Table Curve 2D v.5.01 has been presented. This package allows for the selection of equations, which provide the best similarity between the calculated with them values of $Q_{\text{ice-bw}}$ during thermal treatment of wood containing ice and the respective numerical data obtained with an adequate temperature-energy model of $Q_{\text{ice-bw}}$. The type and coefficient values of the Table Curve equations for $Q_{\text{ice-bw}}$ in this work have been determined for the case of thermal treatment of frozen beech wood with an initial temperature of −1ºC, −10ºC, −20ºC, −30ºC, −40ºC and moisture content of 0.4 kg·kg^{-1}, 0.6 kg·kg^{-1}, 0.8 kg·kg^{-1}. The equations obtained for $Q_{\text{ice-bw}}$ can be used for development and automatic implementation of scientifically based energy-efficient regimes for steaming or boiling of frozen wood materials with different parameters.

Key words: calculation of energy, wood containing ice, melting frozen bound water, thermal treatment, Table Curve 2D.

INTRODUCTION

In various technological and engineering calculations, it is necessary to determine the energy required to defrost the frozen wood materials. This energy includes the following three components (Chudinov 1968, Shubin 1990, Videlov 2003, Câmpean, 2005, Steinhagen 2005, Deliiski and Dzurenda 2010, Deliiski *et al.* 2023, Niemz *et al.* 2023): energy required for heating of the frozen wood itself to a condition necessary to melt the frozen bound water in it, $Q_{\text{w-fr}}$; energy required to melt the temperature-dependent amount of the ice formed by the freezing of bound water in the wood, $Q_{\text{ice-bw}}$; and energy required to melt the entire amount of frozen free water in the wood, $Q_{\text{ice-fw}}$.

The wide experimental study of the defrosting process of logs from different wood species and various moisture content above the hygroscopic range, which has been carried out in (Tumbarkova 2019), has shown that this process can be separated into two ranges. During the first range a heating of the frozen logs is carried out at temperature $T \leq 272.15$ K (i.e. $t \leq -1$ ºC) until reaching of the state needed for starting and realization of gradually melting of frozen bound water in them. During the second range between –1ºC and 0ºC a further heating of the wood occurs until reaching of the state needed for starting and carrying out of the melting of the all frozen free water in it.

The aim of the present work is to apply the software package Table Curve 2D (http://www.sigmaplot.co.uk/products/tablecurve2d/tablecurve2d.php) for a sufficiently accurate and convenient for practical use mathematical description of the change in the energy $Q_{\text{ice-bw}}$

depending on initial temperature and moisture content of frozen wood subjected to defrosting during its thermal treatment.

MATERIALS AND METHODS

This research was conducted over frozen beech (*Fagus sylvatica* L.) wood, which is very often subjected to thermal treatment for the purpose of being plasticized or ennobled for the production of veneer or furniture details (Kollmann and Côté 1984, Sohor and Kadlec 1990, Lawniczak 1995, Trebula and Klement 2002, Deliiski 2003, 2011, Pervan 2009, Kavalov and Angelski 2014, Dzurenda and Deliiski 2019).

The influence of the initial temperature and moisture content of the wood materials above the hygroscopic range on energy required to melt the ice formed by the freezing of bound water in the wood was investigated. The symbols, units, and values of the parameters of the studied wood materials, which were involved in the equations given below and were used in the computer simulations, are presented in Table 1.

Table 1: Set parameters of frozen beech materials, which were used to create and solve the equations.

№	Parameter name	Symbol	Unit	Value
1.	Moisture content of the wood	u	$kg \cdot kg^{-1}$	0.4, 0.6, 0.8
2.	Density of the ice in the wood	ρ_{ice}	$kg \cdot m^{-3}$	917
3.	Initial temperature of the wood	t_{wo}	ºC	−1, −10, −20, −30, −40
4.	Temperature of complete melting of frozen part of bound water in the wood	$t_{bw\text{-}end}$	ºC	−1 (i.e. 272.15 K)

MATHEMATICAL DESCRIPTION OF THE ENERGY $Q_{ice\text{-}bw}$

When calculating the energy $Q_{ice\text{-}bw}$, it is appropriate to applay the well-known statement from thermodynamics that the specific energy required for the heating of 1 m^3 of a given solid body with an initial temperature T_0 to a temperature T_1 is determined using the equation (Telegin *et al.* 2002)

$$Q = \frac{\rho \cdot c \cdot (T_1 - T_0)}{3.6 \cdot 10^6} \tag{1}$$

where Q is the specific heat energy, $kWh \cdot m^{-3}$; ρ – density of the material of the body, $kg \cdot m^{-3}$; c – specific heat capacity of the material of the body, $J \cdot kg^{-1} \cdot K^{-1}$; T_0 and T_1 – temperatures of the body at the beginning and of the end of the heating process, respectively, K.

Based on equation (1), the energy $Q_{ice\text{-}bw}$ required to melt the ice formed by the freezing of bound water in the wood above the hygroscopic range, can be calculated using the following equation (Deliiski *et al.* 2023):

$$Q_{ice\text{-}bw} = \frac{\rho_{ice} \cdot c_{ice\text{-}bw\text{-}avg}}{3.6 \cdot 10^6} \cdot (272.15 - T_{w0}) \tag{2}$$

$$\text{at} \quad u > u_{fsp(272.15K)} \;\&\; 213.15K \le T_{w0} \le 272.15K$$

where T_{w0} is the initial temperature of the frozen wood subjected to heating, K; $c_{ice\text{-}bw\text{-}avg}$ – average specific heat capacity of the frozen bound water in the range from T_{w0} to 272.15 K, $J\cdot kg^{-1}\cdot K^{-1}$, i.e.

$$c_{ice\text{-}bw\text{-}avg} = \frac{c_{ice\text{-}bw}\,\text{at}\,T_{w0} + c_{ice\text{-}bw}\,\text{at}\,272.15\,\text{K}}{2} \tag{3}$$

ρ_{ice} – density of the frozen bound water, $kg\cdot m^{-3}$; u – wood moisture content, $kg\cdot kg^{-1}$; $u_{fsp(272.15K)}$ – fiber saturation point of the wood species at T = 272.15 K (i.e. $t = -1$ °C), $kg\cdot kg^{-1}$, equal to (Stamm 1964, Deliiski 2011)

$$u_{fsp(272.15K)} = u_{fsp(293.15K)} + 0.021 \tag{4}$$

The variable $u_{fsp(293.15K)}$ in eq. (4) is the available in the literature standardized fiber saturation point of the wood species at T = 293.15 K (i.e. t = 20 °C), $kg\cdot kg^{-1}$.

It must be underlined that at T = 272.15 K (i.e. $t = -1$ °C) the melting of the frozen bound water in the wood is fully completed during the heating of the frozen wood (Deliiski and Tumbarkova 2019, Tumbarkova 2019).

MATHEMATICAL DESCRIPTION OF THE HEAT CAPACITY $c_{ice\text{-}bw}$

According to the suggested in Deliiski (2003, 2011) mathematical descriptions of the effective specific heat capacities of wood during its defrosting, the following equation for the calculations of the specific heat capacitiy of the frozen bound water in wood above the hygroscopic range, $c_{ice\text{-}bw}$, have been given in Deliiski *et al.* (2020):

$$c_{ice\text{-}bw} = 1.8938\cdot10^{4}\left(u_{fsp(272.15K)} - 0.12\right)\cdot\frac{\exp[0.0567(T-272.15)]}{1+u} \tag{5}$$

The number $1.8938\cdot10^4$ in the right part of eq. (5) represents the result from multiplying of the number 0.0567 by $3.34\cdot10^5$, which has been obtained in Deliiski (2011) during the mathematical description of $c_{ice\text{-}bw}$. The eq. (5) is based on the widely accepted assumption that the specific latent heats of meting of both the bound and free water in wood are the same and equal to $L_{f\text{-}bw} = L_{f\text{-}fw} = 3.34\cdot10^5$ $J.kg^{-1}$. The number $3.34\cdot10^5$ is the value of the specific latent heat of the free water in wood, which is needed for the phase transition of 1 kg liquid free water into ice.

New research in Efimov (1985) and Deliiski *et al.* (2020) have shown that the latent heat of frozen bound water in wood is not equal to that of frozen free water, but can be calculated by the following equation:

$$L_{f-bw} = 1.223\cdot10^{3}T + 2.102\cdot10^{3}T\cdot\ln\frac{T}{273.15} \tag{6}$$

Using eq. (6), the following update and more precise version of eq. (5) is obtained:

$$c_{\text{ice-bw}} = \left(69.344T + 119.183T \cdot \ln\frac{T}{273.15}\right) \cdot \left(u_{\text{fsp(272.15K)}} - 0.12\right) \cdot \frac{\exp[0.0567(T - 272.15)]}{1+u} \quad (7)$$
$$\text{at } u > u_{\text{fsp(272.15K)}} \ \& \ 213.15\text{K} \le T \le 272.15\text{K}$$

The expression given in the first brackets in eq. (7) is obtained after multiplying of eq. (6) by the number of 0.0567, which has been also used in the derivation of eq. (5).

Equation (7) was applied in eq. (3) to calculate the average specific heat capacity of the frozen bound water in wood in the studied ranges from T_{w0} to 272.15 K.

USING TABLE CURVE 2D TO CALCULATE AND PLOT $Q_{ice\text{-}bw} = f(T_{w0})$

Our research has shown that the software package Table Curve 2D v.5.01 is particularly suitable for precise mathematical description of the complex dependences of $Q_{ice\text{-}bw}$ on T_{w0} at different values of the wood moisture content u, calculated with eq. (2).

This package is intended for linear and non-linear approximation of different 2D dependences by scientists and engineers. The approximation process is fully automated and it can be realized only in a single operation. Over 3600 equations are introduced in this package. They give to the user the possibility quickly in just seconds to easily find the most precise mathematical description for its 2D data.

The package allows to select an equation, which provides the best match between the calculated data with it and those obtained with equation (2).

RESULTS AND DISCUSSION

Table 2 and Table 3 present the change of the average specific heat capacity $c_{ice\text{-}bw\text{-}avg}$ and energy $Q_{ice\text{-}bw}$, respectively, depending on t_{w0} and u, calculated with equations (3) and (2).

Table 2: Change in the capacity $c_{ice\text{-}bw\text{-}avg}$ (in J·kg^{-1}·K^{-1}) depending on t_{w0} and u.

Initial wood temperature t_{w0}, °C	Wood moisture content u, kg·kg^{-1}		
	0.4	0.6	0.8
-1	2825.5	2473.1	2198.3
-10	2137.4	1867.0	1661.9
-20	1562.1	1365.8	1214.9
-30	1137.2	995.0	885.3
-40	826.4	723.8	643.2

Table 3: Change in the energy $Q_{ice\text{-}bw}$ (in kWh·m^{-3}) depending on t_{w0} and u.

Initial wood temperature t_{w0}, °C	Wood moisture content u, kg·kg^{-1}		
	0.4	0.6	0.8
–1	0	0	0
–10	4.90	4.28	3.81
–20	7.56	6.61	5.88
–30	8.40	7.35	6.54
–40	8.21	7.19	6.39

In Table 2 it is seen that the decrease of t_{w0} causes the following decrease in $c_{ice\text{-}bw\text{-}avg}$:

▪ at u = 0.4 kg.kg^{-1}: from 2825.5 J·kg^{-1}·K^{-1} at $t_{w0} = -1$ °C to 826.4 J·kg^{-1}·K^{-1} at $t_{w0} = -40$ °C;

▪ at u = 0.6 kg.kg^{-1}: from 2473.1 J·kg^{-1}·K^{-1} at $t_{w0} = -1$ °C to 723.8 J·kg^{-1}·K^{-1} at $t_{w0} = -40$ °C;
▪ at u = 0.8 kg.kg^{-1}: from 2198.3 J·kg^{-1}·K^{-1} at $t_{w0} = -1$ °C to 643.2 J·kg^{-1}·K^{-1} at $t_{w0} = -40$ °C.

It can be seen from Table 2 that with the lowering of t_{w0}, the energy $Q_{ice\text{-}bw}$ increases from 0.0 kWh·m^{-3} at $t_{w0} = -1$ °C for all values of the wood moisture content u to 8.21, 7.19 and 6.39 kWh·m^{-3} at $t_{w0} = -40$ °C when u is equal to 0.4, 0.6 and 0.8 kg·kg^{-1}, respectively. The reason for this is the increase in the difference 272.15 – T_{w0} given in parentheses in the right-hand part of eq. (2) with the decrease in temperature T_{w0}.

As an example, Figure 1 shows the dependence $Q_{ice\text{-}bw} = f(t_{w0})$ calculated from data in Table 3 and drawn from Table Curve 2 for the case u = 0.6 kg·kg^{-1}.

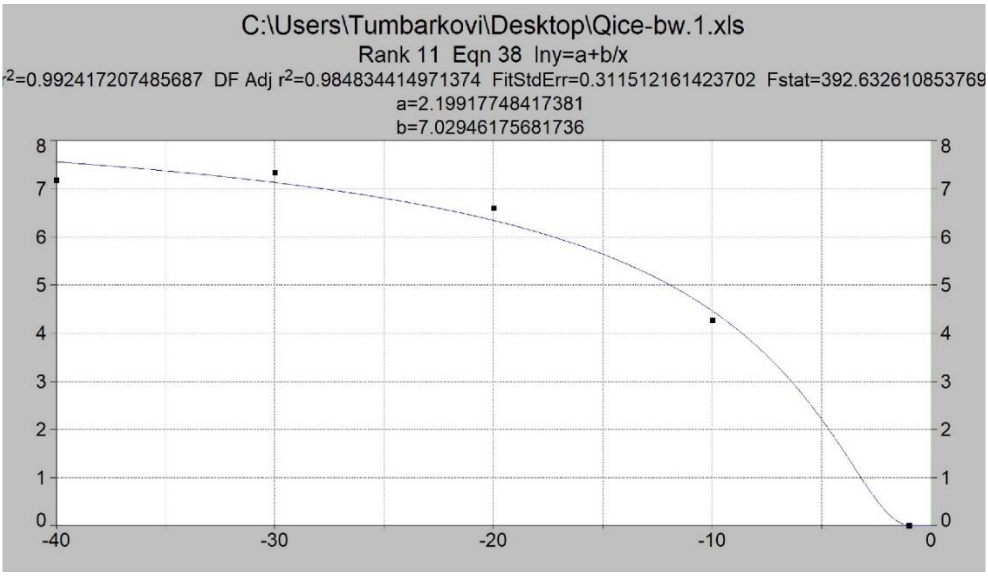

Figure 1: Change in $Q_{ice\text{-}bw}$ depending on t_{w0} at u = 0.6 kg·kg^{-1}calculated and built with Table Curve 2D.

It can be seen frim Fig. 1 that the best fit to the approximated data from Table 2 gives the following logarithmic equation:

$$\ln Q_{\text{ice}-\text{bw}} = a + \frac{b}{t_{\text{w0}}} \qquad (8)$$

From eq. (8) it follows that

$$Q_{\text{ice}-\text{bw}} = 2.7183^{\,a+\frac{b}{t_{\text{w0}}}} \qquad (9)$$

where the number 2.7183 is the base of the natural logarithm written on the left side of eq. (8).

Table 4 shows the values of the coefficients a and b in eq. (8) determined by Table Curve 2 after rounding them to the fourth and third digits after the decimal point, respectively.

Table 4: Values of the coefficients in eq. (8), which approximate the data for $Q_{ice\text{-}bw}$.

Wood moisture content *u*, kg·kg^{-1}	Coefficients' indication	
	a	***b***
0.4	2.3315	6.997
0.6	2.1992	7.029
0.8	2.0814	7.014

After entering these coefficients into eq. (9), the following equations are obtained for calculating the energy $Q_{ice\text{-}bw}$ depending on t_{w0} at the investigated values of u:

$$Q_{ice-bw} = 2.7183^{2.3315+\frac{6.997}{t_{w0}}} \quad \text{at} -1^{o}\text{C} \geq t_{w0} \geq -40^{o}\text{C} \,\&\, u = 0.4 \text{ kg} \cdot \text{kg}^{-1} \tag{10}$$

$$Q_{ice-bw} = 2.7183^{2.1992+\frac{7.029}{t_{w0}}} \quad \text{at} -1^{o}\text{C} \geq t_{w0} \geq -40^{o}\text{C} \,\&\, u = 0.6 \text{ kg} \cdot \text{kg}^{-1} \tag{11}$$

$$Q_{ice-bw} = 2.7183^{2.0814+\frac{7.014}{t_{w0}}} \quad \text{at} -1^{o}\text{C} \geq t_{w0} \geq -40^{o}\text{C} \,\&\, u = 0.8 \text{ kg} \cdot \text{kg}^{-1} \tag{12}$$

Table 5 gives the statistics of the logarithmic curves that approximate the data for $Q_{ice\text{-}bw} = f(t_{w0})$ from Table 3.

Table 5: Statistical parameters of the approximation of $Q_{ice\text{-}bw}$ by equations (10), (11), and (12).

Wood moisture content *u*, kg·kg^{-1}	Parameter name	
	Correlation coefficient, *r*	***RMSE*, ºC**
0.4	0.9961	0.36
0.6	0.9962	0.32
0.8	0.9961	0.28

The correlation coefficient r in Table 4 is equal to the square root of the data for r^2 given in the upper left corner of Fig. 1 and its analogous figures for u = 0.4 kg·kg^{-1} and 0.8 kg·kg^{-1}. The *RMSE* (Root Mean Squared Error) values are taken from those for FitStdErr at the top of Fig. 1 and its analogous two figures.

From the analysis of the data in Fig. 1 and Table 4, it can be seen that the equations (10), (11), and (12) selected using the Table Curve software provide a very good approximation accuracy of the change in $Q_{ice\text{-}bw}$ presented in Table 2 depending on t_{w0} and u.

CONCLUSIONS

The present work presents the use of the Table Curve 2D v.5.01 software package for selecting of equations, which with a high degree of compliance approximate data calculated with our own temperature-energy model for the change in energy $Q_{ice\text{-}bw}$ required to melt the frozen bound water in the wood. The selected equations describe the change of $Q_{ice\text{-}bw}$ depending on the initial temperature of the frozen wood at a given value of its moisture content above the hygroscopic range.

Using the Table Curve 2D package, logarithmic equations were chosen to describe the change in energy $Q_{\text{ice-bw}}$ for beech wood with a moisture content u equal to 0.4 kg·kg^{-1}, 0.6 kg·kg^{-1}, and 0.8 kg·kg^{-1} and an initial temperature t_{w0} in the range from −1ºC to −40ºC. The type of the chosen equations is the same for the three investigated values of u, and only the values of its two coefficients are different.

The obtained numerical, statistical and graphical results testify to the existence of a very good agreement between the approximated and calculated with the selected equation values of the energy $Q_{\text{ice-bw}}$. The regression standard error of approximation (the root mean squared error) ranges from 0.28°C to 0.36°C, and the correlation coefficient is practically the same for the dependence $Q_{\text{ice-bw}} = f\,(t_{w0})$ for all three investigated values of u and is equal to 0.996.

The results obtained in the present work can be used in the development and automatic implementation of scientifically based energy-efficient regimes and technologies for steaming or boiling of frozen wood materials with different parameters and purposes.

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CONTENTS