An Approach for Computing the Heat Sources in Logs Subjected to Freezing

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Abstract – This study suggests an approach for computing the specific energies of the internal heat sources in logs subjected to freezing. The approach maximally considers the physics of the freezing processes of both the free and the bound water in wood. It reflects the influence on the mentioned energies of the wood density above and below the hygroscopic range. It also considers the icing degrees formed separately by both the free and bound water in the logs, as well as the influence of the fiber saturation point of each wood species on its respective amount of non-frozen water depending on temperatures below 272.15 K. Mathematical descriptions of the specific heat energies $Q_{v\text{-fw}}$ and $Q_{v\text{-bw}}$ released in logs during free water freezing in the range from 0 $^{\mathrm{o}}$C to –1 $^{\mathrm{o}}$C and of the bound water below –1 $^{\mathrm{o}}$C, respectively, have been executed. These descriptions are introduced in own 2D non-linear mathematical model of the freezing process of logs. For the solution of the model and computation of the energies $Q_{v\text{-fw}}$ and $Q_{v\text{-bw}}$, a software program based on the suggested approach and mathematical descriptions was prepared in FORTRAN, which was input into the calculation environment of Visual Fortran. With the aid of the program, computations were completed to determine the energies $Q_{v\text{-fw}}$ and $Q_{v\text{-bw}}$ and their sum, $Q_{v\text{-total}}$ of a beech log subjected to freezing. The beech log had a diameter of 0.24 m, a length of 0.48 m, an initial temperature of 20.5 $^{\mathrm{o}}$C, a basic density of 683 kg·m^{-3}, and a moisture content of 0.48 kg·kg^{-1} during its 30 hours in a freezer at approximately –30 $^{\mathrm{o}}$C.

internal heat sources / latent heat / free water / bound water / freezing / logs

Kivonat – Egy módszer a fagyásnak kitett farönk belső hőmérlegének számítására. A jelen tanulmány egy olyan módszert ír le, amellyel fagyásnak kitett farönkök belső hőforrásainak fajlagos energiái becsülhetők. A módszer teljes mértékben figyelembe veszi a szabad- és kötött víztartalom fagyási folyamatainak fizikai vonatkozásait valamint tükrözi a fa sűrűségének hatását az említett energiákra a rosttelítettségi tartomány alatt és felett. Emellett számol a szabad- és a kötött víz által okozott jegesedés mértékével, valamint a rosttelítettségi pontnak a nem-fagyott víz mennyiségére gyakorolt hatásával 272,15 K hőmérséklet alatt. Módszerünkkel matematikai becslést adunk a farönkökben fagyás során felszabaduló fajlagos energiákra ($Q_{v\text{-fw}}$ and $Q_{v\text{-bw}}$) a szabad víz esetében a 0 $^{\mathrm{o}}$C és –1 $^{\mathrm{o}}$C közötti hőmérséklet tartományra, kötött víz esetében –1 $^{\mathrm{o}}$C alatti körülményekre. A számítások eredményeit integráltuk a farönkök fagyási folyamatait modellező saját fejlesztésű 2 dimenziós nemlineáris modellünkbe. A közölt matemaikai eljárások és módszerek alapján egy FORTRAN szoftver került kifejlesztésre, mellyel a $Q_{v\text{-fw}}$ and $Q_{v\text{-bw}}$ energiák értékei számíthatók és a modell megoldható. A fejlesztett szoftvert Visual Fortran környezetbe adaptáltunk. A program segítségével egy fagyásnak kitett bükk rönk esetében kiszámoltuk a $Q_{v\text{-fw}}$ and $Q_{v\text{-bw}}$ energiákat, valamint ezek összegét, $Q_{v\text{-total}}$-t. A vizsgált bükk törzs 0,24 m átmérőjű, 0,48 m hosszú volt. A kb. –30 $^{\mathrm{o}}$C-on végzett fagyasztás megkezdése előtt a rönk kezdeti hőmérséklete 20,5 $^{\mathrm{o}}$C, sűrűsége 683 kg·m^{-3}, nedvesség tartalma pedig 0.48 kg·kg^{-1} volt.

belső hő források / látens hő / szabad víz / kötött víz / fagyás / farönk

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1 INTRODUCTION

The duration and energy consumption of thermally treating frozen logs in the winter to plasticize the wood for veneer production depend on the degree of icing (Chudinov 1966, 1968, Shubin 1990, Požgaj et al. 1997, Trebula – Klement 2002, Videlov 2003, Pervan 2009, Deliiski – Dzurenda 2010, Deliiski 2011, 2013b). Reports about the temperature distribution in frozen logs subjected to defrosting are limited in the accessible specialized literature (Steinhagen 1986, 1991, Steinhagen – Lee 1988, Khattabi – Steinhagen 1992, 1993, 1995, Deliiski 2004, 2009, 2011, Deliiski – Dzurenda 2010, Deliiski et al. 2015a, Hadjiski – Deliiski 2015, 2016). In addition, research into the temperature distribution in logs during the freezing process has been limited (Deliiski – Tumbarkova 2016, 2017). Thus, there is considerable scientific and practical interest in the modeling and the multi-parameter study of the freezing process of logs.

Different engineering and technological calculations require the determination of the non-stationary temperature field in logs depending on the temperature of the gaseous or liquid medium influencing them. These calculations also require information concerning the duration of logs remaining in this medium. Such calculations are completed using mathematical models that adequately describe the complex freezing processes of both the free and bound water in wood. The internal sources of latent heat of the water, which are released within the wood during water crystallization and influence the duration and energy consumption of a log's freezing process, are an important component of these models (Deliiski – Tumbarkova 2017). No information about the approaches for quantitative determination of the internal heat sources during wood freezing exists in the available literature regarding the hydrothermal treatment of frozen wood materials.

The present paper aims to suggest an approach to compute the specific energies of internal heat sources in logs subjected to freezing; the approach takes into account, to a maximum degree, the physics of the freezing processes of both the free and bound water in wood.

Symbols:
c – specific heat capacity (J·kg^{-1}·K^{-1}),
D – diameter (m),
L – specific latent heat (J·kg^{-1}) or length (m),
N – number of the knots of the calculation mesh, (-),
Q – internal heat source (J·m^{-3}) or specific heat energy (Wh·m^{-3}),
R – radius (m),
r – radial coordinate: $0 \leq r \leq R$ (m),
S – shrinkage (%),
T – temperature (K): $T = t + 273.15$,
t – temperature ($^\circ$C): $t = T - 273.15$,
u – moisture content (kg.kg^{-1} = %/100),
z – longitudinal coordinate: $0 \leq z \leq L/2$ (m),
α – heat transfer coefficients between log surfaces and the surrounding air medium (W·m^{-2}·K^{-1}),
λ – thermal conductivity (W·m^{-1}·K^{-1}),
ρ – density (kg·m^{-3}),
σ – root square mean error ($^\circ$C),
τ – time (s),
Ψ – relative icing degree of logs or relative degree of solidification of the metal (-).

Subscripts:

avg   – average (for root square mean error of calculated values of the temperature),
b   – basic (for wood density, based on dry mass divided to green volume),
cr   – crystallization,
dfr   – defrosting,
fr   – freezing,
fsp   – fiber saturation point,
ice   – ice (for logs' icing degrees or for numbers of knots of the calculation mesh),
m   – medium,
M   – metal,
Ms   – metal in solid state,
nfw   – non-frozen water,
0   – initial,
p   – parallel to the wood fibers,
r   – radial direction,
total   – total (for the whole amount of knots of the calculation mesh or for energy of the latent heat sources),
v   – volume,
vM   – volume of the metal,
w   – wood,
we   – wood effective (for specific heat capacity of the wood),
wL   – wood with liquid water in it,
wS   – wood with solid state of water (ice) in it,
wUfsp   – wood at fsp,
wUnfw   – wood at nfw.

Superscripts:
272.15 – at 272.15 K, i.e. at –1 °C,
293.15 – at 293.15 K, i.e. at 20 °C.

2   MATERIALS AND METHODS

Mathematical model of the 2D heat distribution in logs subjected to freezing

The heat conduction equation can describe the distribution mechanism in logs subjected to freezing. When log length does not exceed log diameter by more than 3 – 4 times, the heat transfer through the frontal sides of the logs cannot be neglected because it influences the temperature change of the log cross sections, which are equally distant from the frontal sides (Chudinov 1966, 1968, Shubin 1990, Deliiski 2011). In such cases, the following 2D model for the calculation of the temperature change in the longitudinal sections of the logs (i.e. along the coordinates r and z of these sections) during their freezing in an air medium can be used (Deliiski – Tumbarkova 2017):

$$c_{we}\rho_w \frac{\partial T(r,z,\tau)}{\partial \tau} = \lambda_{wr}\left[\frac{\partial^2 T(r,z,\tau)}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial T(r,z,\tau)}{\partial r}\right] + \frac{\partial \lambda_{wr}}{\partial T}\left[\frac{\partial T(r,z,\tau)}{\partial r}\right]^2 +$$

$$+ \lambda_{wp}\frac{\partial^2 T(r,z,\tau)}{\partial z^2} + \frac{\partial \lambda_{wp}}{\partial T}\left[\frac{\partial T(r,z,\tau)}{\partial z}\right]^2 + Q_v \tag{1}$$

with an initial condition

$$T(r,z,0) = T_0 \tag{2}$$

and boundary conditions for convective heat transfer:

- along the radial coordinate r on the logs' frontal surface during the freezing process:

$$\frac{dT(r,0,\tau)}{dr} = -\frac{\alpha_{p\text{-fr}}(r,0,\tau)}{\lambda_{wp}(r,0,\tau)}\left[T(r,0,\tau) - T_{m\text{-fr}}(\tau)\right] \tag{3}$$

- along the longitudinal coordinate z on the logs' cylindrical surface during the freezing:

$$\frac{dT(0,z,\tau)}{dz} = -\frac{\alpha_{r\text{-fr}}(0,z,\tau)}{\lambda_{wr}(0,z,\tau)}\left[T(0,z,\tau) - T_{m\text{-fr}}(\tau)\right]. \tag{4}$$

Equations (1) to (4) represent a common form of a mathematical model of 2D heat distribution in logs subjected to freezing.

Mathematical description of the internal heat sources in logs subjected to freezing

The internal heat source in logs, Q_v, in eq. (1) reflects the influence of the latent heat of the water in the wood on the logs' freezing process. As mentioned above, no information on the approaches of the quantitative determination of the heat source Q_v could be found in the available literature for hydrothermal treatment of frozen wood materials. That is why, as a methodology for the determination of Q_v during the freezing of logs, the present paper applies a perspective that has been applied for the determination of the internal heat source Q_{vM} during the solidification process of melted metal (Salcudean – Abdullah 1988, Dantzig 1989, Hu – Argyropoulos 1996, Mihailov – Petkov 2010). According to this methodology, the heat source Q_{vM} is equal to

$$Q_{vM} = \rho_{MS}L_{crM}\frac{\partial\psi_{MS}}{\partial\tau}. \tag{5}$$

Based on the physics of the log freezing process, for the density of the wood, ρ_w, during its freezing, it could be written that

$$\rho_w = \rho_{wL} + \rho_{wS}, \tag{6}$$

$$\rho_{wS} = \rho_w - \rho_{wL} \tag{7}$$

For the numerical solution of eq. (1) it is suitable to present eq. (7) in the following form:

$$\rho_{wS} = (\rho_w - \rho_{wL})\cdot\frac{\rho_w}{\rho_w}. \tag{8}$$

Using eq. (8), analogously to eq. (5), for the internal heat source in the wood it is obtained that

$$Q_v = \rho_{wS}\cdot L_{cr-ice}\frac{\partial\Psi_{ice}}{\partial\tau} = \rho_w\cdot\left(\frac{\rho_w - \rho_{wL}}{\rho_w}\right)\cdot L_{cr-ice}\frac{\partial\psi_{ice}}{\partial\tau}, \tag{9}$$

where L_{cr-ice} is the specific latent heat of the water, also known as the "heat of crystallization". This heat is released in the wood during the water freezing process and is equal   to $L_{cr-ice} = 3.34\cdot10^5$ J·kg^{-1} (Chudinov 1966, 1968, Efimov 1985, Pahi 2010, Deliiski – Tumbakova 2016).

Based on the data in the references cited above, the value of $3.34\cdot10^5$ J·kg^{-1} as constant for the specific latent heat for both the free and the bound water in the wood materials has been accepted in the present paper. Our wide experiments with different wood species showed

that the free water freezing occurs in the small range from 0 °C to –1 °C (Deliiski – Tumbarkova 2016). This means that the acceptance of the non-temperature dependent constant value of $3.34 \cdot 10^5$ J·kg^{-1} as a specific latent heat of the free water is correct.

We did not find data in the accessible specialized literature that reflects the temperature dependence of the specific latent heat of bound water in the wood. Rogers – Yau 1989 contains data for the specific latent heat of the sublimation and deposition from and into ice in the range from –40 °C to 0 °C (in J·g^{-1}), which can be approximated by the following equation: $L_{\text{ice}} = 2834.2 - 0.29T - 0.004T^2$. Deposition is a thermodynamic process – a phase transition in which gas (or water steam) solidifies without passing through the liquid phase. The reverse of deposition is sublimation.

Calculation of L_{ice} with the equation given above at $T = 243.15$ K (i.e. at $t = -30$ °C, which is the lowest T reached during our experiment described below), and at $T = 272.15$ K (i.e. at $t = -1$ °C) show that the obtained results differ from each other by only 2.7%. Because liquid water is a far more stable substance compared to steam, it can be surmised that the specific latent heat of the bound water at $t = -30$ °C differs negligibly from its value at $t = -1$ °C. This allowed us to accept a constant value of the specific latent heat of the bound water during log freezing equal to $3.34 \cdot 10^5$ J·kg^{-1}.

Designating the expression in the brackets from eq. (9) with K_{ψ}, i.e.

$$K_{\psi} = \frac{\rho_w - \rho_{wL}}{\rho_w} \tag{10}$$

and substituting eq. (10) into eq. (9), the following final expression for Q_v is obtained:

$$Q_v = K_{\psi} \cdot \rho_w \cdot L_{\text{cr-ice}} \frac{\partial \psi_{\text{ice}}}{\partial \tau} . \tag{11}$$

Mathematical description of the internal heat source in logs during freezing of the free water

According to eq. (11), during the free water freezing process in wood, the consequent formed source of latent heat $Q_{\text{v-fw}}$ is equal to

$$Q_{\text{v-fw}} = K_{\psi-\text{fw}} \cdot \rho_w \cdot L_{\text{cr-ice}} \frac{\partial \psi_{\text{ice-fw}}}{\partial \tau} , \tag{12}$$

where based on the physics of the process and on the form of eq. (10), it is obtained that

$$K_{\psi-\text{fw}} = \frac{\rho_w - \rho_{wU\text{fsp}}}{\rho_w} , \tag{13}$$

given that $\Psi_{\text{ice-fw}}$ is the relative icing degree of the logs, which results from the freezing of the free water in them. An approach and an algorithm for its calculation are given in Deliiski – Tumbarkova (2017).

The difference $\rho_w - \rho_{wU\text{fsp}}$ in the right-hand part of eq. (13) reflects the entire mass of free water (in kg), which is contained in 1 m^3 of the logs.

The wood densities ρ_w and $\rho_{wU\text{fsp}}$, which participate in eq. (13), are determined above the hygroscopic range according to the below equations (Chudinov 1968, Pervan 2009, Deliiski 2011, Deliiski et al. 2015b, Hrčka 2017)

$$\rho_w = \rho_b \cdot (1 + u) , \tag{14}$$

$$\rho_{wU\text{fsp}} = \rho_b \cdot (1 + u_{\text{fsp}}) . \tag{15}$$

Mathematical description of the internal heat source in logs during bound water freezing

Analogously to eq. (11) and eq. (12), during the freezing of the bound water in the wood, the consequently formed source of latent heat in it, $Q_{v\text{-bw}}$, is equal to

$$Q_{v\text{-bw}} = K_{\psi-bw} \cdot \rho_w \cdot L_{cr\text{-ice}} \frac{\partial \psi_{ice\text{-bw}}}{\partial \tau}, \tag{16}$$

where based on the physics of the process and on the form of eq. (10), it is obtained that

$$K_{\psi-bw} = \frac{\rho_{wUfsp} - \rho_{wUnfw}}{\rho_w}, \tag{17}$$

given that $\Psi_{ice\text{-bw}}$ is the relative icing degree of the logs, which results from the freezing of the bound water in them. An approach and an algorithm for its calculation are given in Deliiski – Tumbarkova (2017);

ρ_{wUnfw} – density of the wood, determined according to the following equation in relation to the present entirely liquid quantity of water in the wood (kg·m^{-3}), corresponding to the current temperature $T < 272.15$ K (Chudinov 1966, Deliiski 2013b):

$$\rho_{wUnfw} = \rho_b \cdot \frac{1 + u_{nfw}}{1 - \dfrac{S_v}{100}\left(u_{fsp}^{272.15} - u_{nfw}\right)}, \tag{18}$$

$u_{fsp}^{272.15}$ – fiber saturation point of the wood (kg·kg^{-1}) at $T = 272$ K (i.e. at $t = -1\ ^oC$). At this temperature the freezing of the bound water begins in the wood.

While observing the freezing of the logs from various wood species with different moisture contents above the hygroscopic range during our wide experiments, we determined that freezing of the bound water begins at $t = -1\ ^oC$ (Deliiski – Tumbarkova 2016) and not at $t = -2\ ^oC$, which was determined by Chudinov (1966, 1968) and, consequently, was widely accepted in the relevant literature.

The fiber saturation point $u_{fsp}^{272.15}$ can be calculated according to the following equation (Stamm 1964, Deliiski 2013a):

$$u_{fsp}^{272.15} = u_{fsp}^{293.15} + 0.021, \tag{19}$$

where $u_{fsp}^{293.15}$ is the standardized value of the fiber saturation point of the wood (kg·kg^{-1}) at 293.15 K, i.e. at 20 ^oC;

u_{nfw} – non-frozen quantity of bound water in the wood (kg·kg^{-1}) at a given temperature $T < 272.15$ K. It can be calculated according to the equation (Chudinov 1968, Deliiski 2013b):

$$u_{nfw} = 0.12 + \left(u_{fsp}^{272.15} - 0.12\right) \cdot \exp\left[0.0567(T - 272.15)\right] \quad @ \quad 213.15\ \text{K} \le T \le 272.15\ \text{K}. \tag{20}$$

Experimental research of the log freezing process

Experimentally obtained data about the change in the temperature field in logs during their freezing were required for the application and verification of the approach suggested above. Consequently, we carried out such experiments.

The logs subjected to experimental research, produced from the sapwood of freshly felled beech trunks (*Fagus sylvatica* L.), had diameters of $D = 240$ mm, lengths of $L = 480$ mm, and moisture contents above the hygroscopic range.

Before the experiments, four holes, with differing lengths and diameters of 6 mm were drilled into each log. Sensors with long metal casings were positioned in these four holes to measure wood temperature during the experiments. The point coordinates of the logs are as follows:

Point 1: along the radius $r = 30$ mm and along the length $z = 120$ mm;
Point 2: along the radius $r = 60$ mm and along the length $z = 120$ mm;
Point 3: along the radius $r = 90$ mm and along the length $z = 180$ mm;
Point 4: along the radius $r = 120$ mm and along the length $z = 240$ mm.

These characteristic point coordinates make it possible to sense the impact of the heat fluxes simultaneously in radial and longitudinal directions on the temperature distribution in logs during the freezing process.

For log freezing according to the methodology suggested by the authors (Deliiski – Tumbarkova 2016), a horizontal freezer with a fitted with temperature sensors and was horizontally situated on a special stand in the open freezer that was initially at room temperature. The freezer was then closed and switched on to full power; the temperature of the freezing air medium in the freezer, t_m, was lowered gradually until it reached approximately $-30\ ^\circ$C (*Figure 1*).

The automatic measuring and recording of the temperature and humidity of the air processing medium in the freezer and the temperature in the 4 points in the logs during the experiments was implemented with the help of Data Logger type HygroLog NT3 produced by the Swiss firm ROTRONIC AG (http:/www.rotronic.com).

As an example, *Figure 1* presents the change in the temperature of the processing air medium, t_m and in its humidity, φ_m, and also in the temperature in four characteristic points of a beech log with $u = 0.48$ kg·kg^{-1} and $\rho_b = 683$ kg·m^{-3} during 30 h of freezing. The record of all data was made automatically by Data Logger in 5 minute intervals.
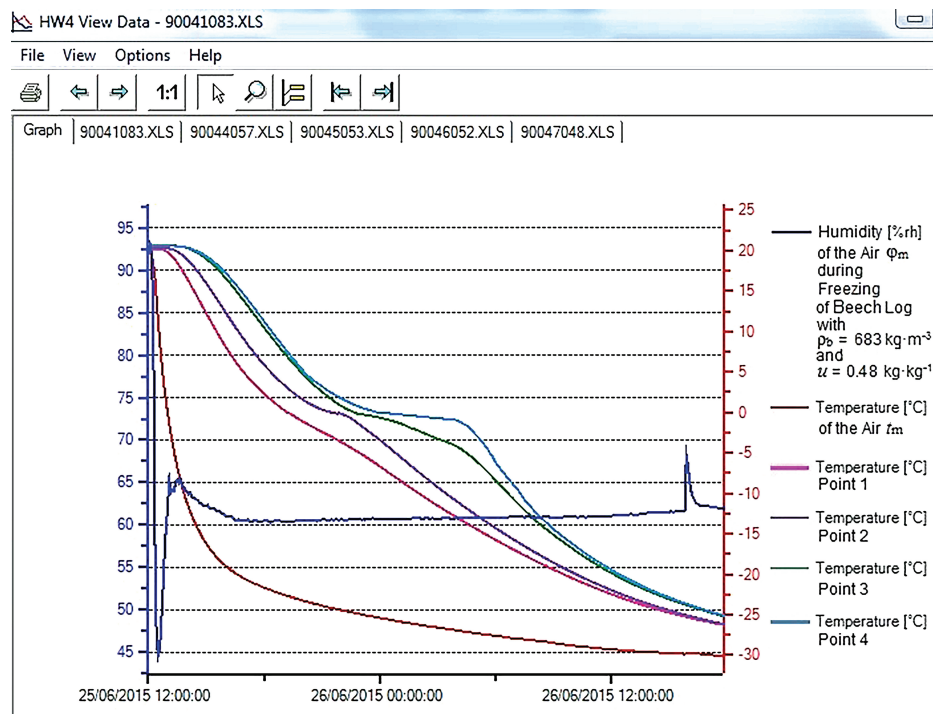

Figure 1. Experimentally determined change in t_m, φ_m, and t in 4 characteristic points of beech log with $D = 0.24$ m, $L = 0.48$ m, $u = 0.48$ kg·kg^{-1}, $\rho_b = 683$ kg·m^{-3} (i.e. $\rho_w = 1010.8$ kg·m^{-3}), and $t_0 = 20.5\ ^\circ$C during its 30 h freezing

3   RESULTS AND DISCUSSION

The mathematical descriptions of the internal heat sources $Q_{v\text{-fw}}$ and $Q_{v\text{-bw}}$ created above and the mathematical descriptions of the thermo-physical characteristics of frozen and non-frozen wood suggested earlier (Deliiski 2004, 2009, 2011, 2013a) are introduced in the mathematical model of the log freezing process, which consists of eqs. (1) – (20). This model has been solved with the help of explicit schemes of the finite difference method, analogous to the one used and described in (Deliiski 1977, 1988, 2009, 2011, Deliiski et al. 2015a) for the solution of a model of the heating process of prismatic and cylindrical wood materials. For this purpose, the calculation mesh has been built on ¼ of the longitudinal section of the log due to the circumstance that this ¼ is mirror symmetrical towards the remaining ¾ of the same section (*Figure 2*).

Computation of 2D non-stationary temperature distribution in logs during their freezing

For the numerical solution of the mathematical model, a software program was prepared in FORTRAN in the calculation environment of Visual Fortran Professional. With the help of the program, computations were made for the determination of the 2D non-stationary change of t in ¼ of the longitudinal section of the beech log whose experimentally determined temperature distribution is shown on *Figure 1* as an example.

The model was solved with step $\Delta r = \Delta z = 6$ mm along the coordinates r and z and with the same initial and boundary conditions, as they were during the experimental research. This means that the calculation mesh consists of 20 x 40 = 800 knots: 20 along r and 40 along z.

The solution of the model gives the non-stationary change of the temperature in calculation mesh knots (*Figure 2*) and of different energy characteristics of logs subjected to freezing.
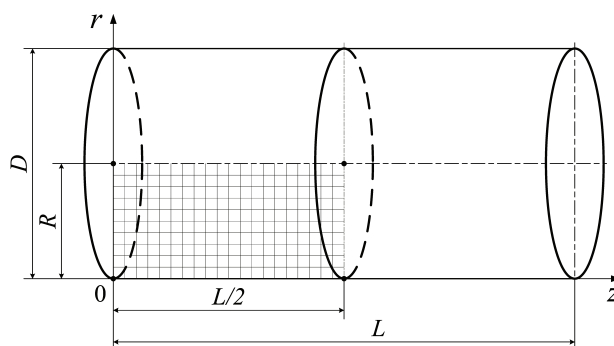

Figure 2. Positioning of the knots of the calculation mesh
on ¼ of the longitudinal section of a log subjected to freezing

During the solving of the model, the mathematical descriptions of the thermo-physical characteristics of beech wood with fiber saturation point $u_{\text{fsp}}^{293.15} = 0.31$ kg·kg^{-1} and volume shrinkage $S_v = 17.3\%$ were used (Nikolov – Videlov 1987).

The curvilinear change shown in *Figure 1* in the freezing air medium temperature, $T_{\text{m-fr}}$, with high accuracy (correlation 0.99 and Root Square Mean Error (*RSME*) 0.14 $^{\circ}$C) has been approximated with the help of the software package Table Curve 2D (http://www.sigmaplot.co.uk/products/tablecurve2d/tablecurve2d.php) by the equation

$$T_{\text{m-fr}} = \frac{a_{\text{fr}} + c_{\text{fr}}\tau^{0.5} + e_{\text{fr}}\tau + g_{\text{fr}}\tau^{1.5}}{1 + b_{\text{fr}}\tau^{0.5} + d_{\text{fr}}\tau + f_{\text{fr}}\tau^{1.5} + h_{\text{fr}}\tau^{2}}, \tag{21}$$

whose coefficients are equal to:

$a_{fr} = 293.0642230$, $b_{fr} = -0.01985592$, $c_{fr} = -5.66878889$, $d_{fr} = -0.000298843$,
$e_{fr} = 0.080801194$, $f_{fr} = -6.7184 \cdot 10^{-7}$, $g_{fr} = -0.00019564$, and $h_{fr} = -1.7404 \cdot 10^{-10}$.

Equation (21) was used for the solving of eqs. (3) and (4) of the model.

Figure 3 presents the change in t_{m-fr} , log surface temperature t_s, and t of 4 points of the studied beech log, which have the same coordinates, as during the experimental research.

The comparisons of the analogical curves in *Figure 1* and *Figure 3* show good qualitative and quantitative conformity between the calculated and experimentally determined changes in the complicated temperature field of the log during its freezing. It was calculated that the *RSME* for all studied four points in the log is $\sigma_{avg} = 1.42$ °C.
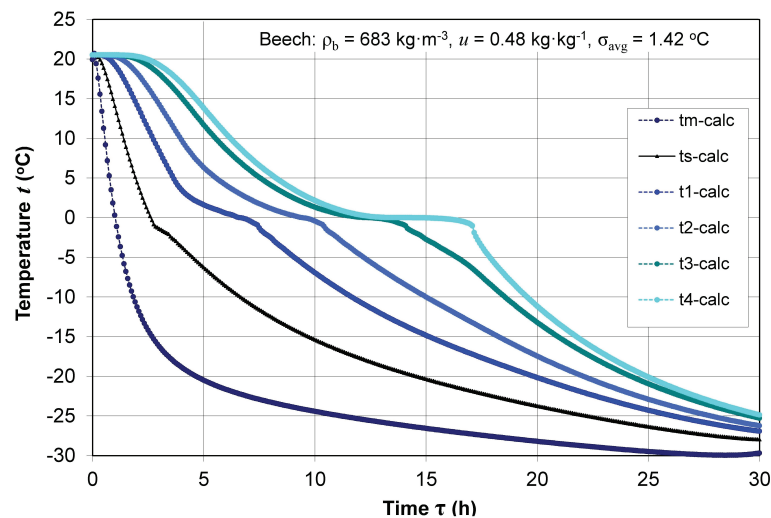

*Figure 3. Calculated with the model change in t_{m-fr} , t_s, and t of
4 characteristic points of the studied beech log during its 30 h freezing*

Change of log icing degrees Ψ_{ice-fw} and Ψ_{ice-bw}

A logical condition in the software for the model's solution that registers and records the moments when the temperature of each knot decreases below 273.15 K (i.e. below 0 °C) and then registers and records temperature conditions for the crystallization of the free water separately for each knot has been introduced earlier (Deliiski – Tumbarkova 2016).

This means that the current number of the knots in which the free water already "crystallizes", N_{ice-fw}, has been constantly determined synchronously with the obtaining of the temperature distribution. The relationship between N_{ice-fw} and the total number of knots of the entire calculation mesh, $N_{ice-total} = 800$, is used for the estimation of the current relative icing degree of logs, Ψ_{ice-fw} , which has happened by the freezing of the free water up to the present moment of log's cooling.

The relative icing degree of logs, which is caused by the freezing of the bound water in them, Ψ_{ice-bw}, has been estimated according to a similar but more complicated approach given in (Deliiski – Tumbarkova 2017). A logical condition to solve the model in the software has also been introduced. This condition registers and records the moments when the temperature of each of the knots decreases below 272.15 K (i.e. below –1 °C) and then temperature conditions for the crystallization of the bound water separately for each knot arise.

Figure 4 presents the calculated change of log icing degrees Ψ_{ice-fw} and Ψ_{ice-bw} during the 30 h freezing process of the studied beech log (Deliiski – Tumbarkova 2017).
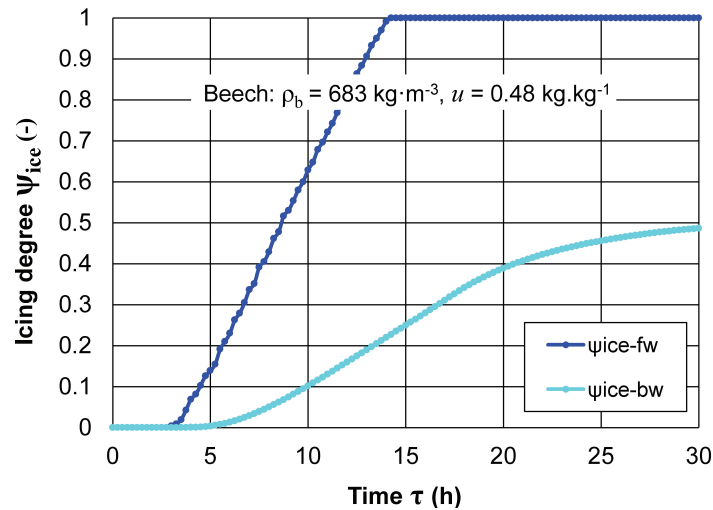
Figure 4. Change in $\Psi_{ice\text{-}fw}$ and $\Psi_{ice\text{-}bw}$ during the freezing of the studied beech log

The icing degree $\Psi_{ice\text{-}fw}$ varies from 0 to 1 (*Figure 4*). It has a value of 0 during the first 2.92 hours the log spends in the freezer when all the water in the wood is in a liquid state. This icing degree becomes equal to 1 after 14.08 h when the free water has frozen completely. The icing degree $\Psi_{ice\text{-}bw}$ varies from 0 to 0.486 (*Figure 4*). It has a value of 0 during the first 3.50 hours the log spends in the freezer, while the temperature of the peripheral layers of the log decreases below –1 °C and the freezing of the bound water in these layers starts. This icing degree becomes equal to 0.486 at the end of the 30 h in the freezer. The calculated average log mass temperature is then equal to –26.38 °C (i.e. 246.77 K) and the calculated according to eq. (21) amount of the non-frozen water u_{nfw} is equal to 0.170 kg·kg^{-1}. This value of u_{nfw} and the value $u_{fsp}^{272.15} = 0.31 + 0.021 = 0.331$ kg·kg^{-1} (see eq. (20)) ensure a

value of $\Psi_{ice\text{-}bw}$ = 0.486 (see equation $\Psi_{ice-bw} = 1 - \dfrac{u_{nfw}}{u_{fsp}^{272.15}}$ given in Deliiski – Tumbarkova

(2017)). This means that 1 – 0.486 = 0.514 relative parts (i.e. 51.4%) of the bound water in the studied beech log remains in a liquid state at the end of 30 h of freezing when the calculated according to eq. (22) temperature in the freezer becomes equal to $t_{m\text{-}fr}$ = –29.69 °C (*Figure 3*) and the average log mass temperature is equal to –26.38 °C.

Change of the specific energies of the internal heat sources $Q_{v\text{-}fw}$ and $Q_{v\text{-}bw}$

Figure 5 presents the calculated change of specific energies of the internal heat sources $Q_{v\text{-}fw}$ and $Q_{v\text{-}bw}$, and their sum $Q_{v\text{-}total} = Q_{v\text{-}fw} + Q_{v\text{-}bw}$ during the 30 h freezing process of the studied beech log. The values of the heat sources are calculated as specific (for 1 m^3 wood) heat energies in Wh·m^{-3} instead of in J·m^{-3}. For this purpose, the values obtained by eqs. (12) and (16) have been divided by 3600.

During the first 17.00 h of the freezing process, the energies $Q_{v\text{-}fw}$ and $Q_{v\text{-}total}$ increase according to three mutually connected almost linear sections. During the first 2.92 h, when the entire amount of the free and bound water in the log is in a liquid state, these energies remain equal to 0. After that they increase rapidly until reaching 52.27 Wh·m^{-3} and 65.34 Wh·m^{-3} respectively at the end of the freezing of the free water in the log, which takes 14.08 h. From the 14.08th h to 17.00th h, the energy $Q_{v\text{-}fw}$ remains constant and equal to 52.27Wh·m^{-3} and the energy $Q_{v\text{-}total}$ increases from 65.34 Wh·m^{-3} to 70.25 Wh·m^{-3}.
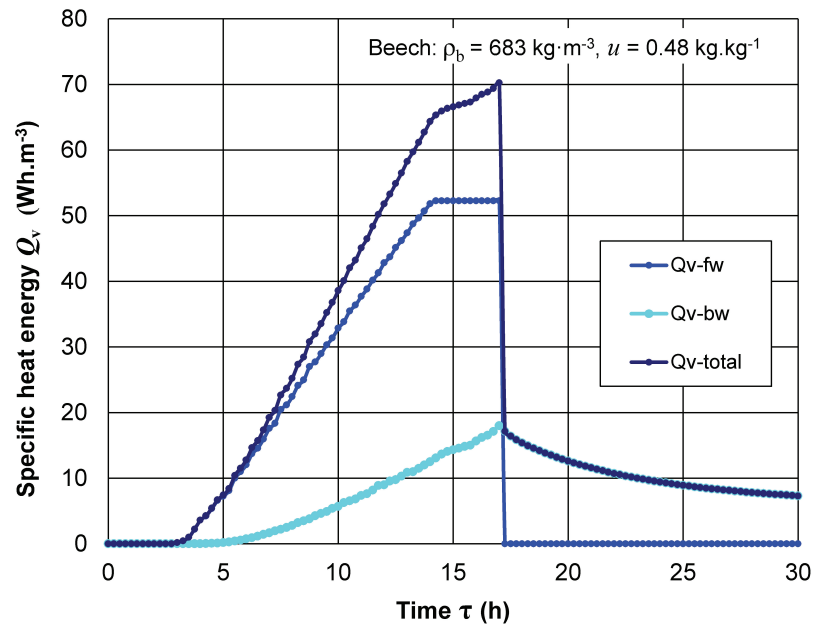
Figure 5. Change in $Q_{v\text{-}fw}$, $Q_{v\text{-}bw}$, and $Q_{v\text{-}total}$ during the freezing of the studied beech log

During the first 3.50 h, when all the bound water in the log is in a liquid state, the energy $Q_{v\text{-}bw}$ remains equal to 0. From 3.50[th] h to 17.00[th] h, when the gradual crystallization of the bound water in all knots of the calculation mesh (incl. in the log center) has begun, the specific energy $Q_{v\text{-}bw}$ increases exponentially from 0 to 17.98 Wh·m^{-3}.

After the 17.00[th] h, the energy $Q_{v\text{-}fw}$ is equal to 0 (all the free water is frozen) and the energy $Q_{v\text{-}bw}$ decreases exponentially; at the end of 30 h of freezing process, it reaches a value of 7.31 Wh·m^{-3}. From the 17.00[th] h to 30.00[th] h of the freezing process, the total energy $Q_{v\text{-}total}$ is equal to $Q_{v\text{-}bw}$. The reason for the decreasing of $Q_{v\text{-}bw}$ during this time interval is the decrease of the first derivative of the icing degree $\Psi_{ice\text{-}bw}$ in eq. (16) due to the decreasing slope of the dependence of this icing degree on the time during this interval in comparison to its slope prior to that (*Figure 4*).

We executed extensive simulations to verify the mathematical model given above and to study the freezing process of logs from various wood species with different moisture contents. By varying the values of the energies $Q_{v\text{-}fw}$ and $Q_{v\text{-}bw}$ we determined that:

- the larger values of $Q_{v\text{-}fw}$ in comparison to those calculated by eq. (12) cause an acceleration of the computed freezing process, i.e. they cause a shortening of the horizontal sections of the temperatures in the log's central layers in the range between 0 °C and –1 °C (*Figure 1* and *Figure 3*). On the contrary, the lower values of $Q_{v\text{-}fw}$ in comparison to those calculated by eq. (12) cause a deceleration of the computed freezing process of the logs;

- the larger values of $Q_{v\text{-}bw}$ in comparison to those calculated by eq. (16) make the curves of the temperature field of the log below –1 °C steeper. On the contrary, the lower values of $Q_{v\text{-}fw}$ in comparison to those calculated by eq. (16) make the mentioned curves more lenient.

During our simulations with the model, using the approach suggested above and the mathematical descriptions of $Q_{v\text{-}fw}$ and $Q_{v\text{-}bw}$, we obtained good qualitative and quantitative conformity between the calculated and experimentally determined temperature distribution in the log's longitudinal section during the whole process of the freezing of both the free and the bound water not only in the studied beech log for the purposes of this paper, but also many other logs above the hygroscopic range (including the poplar logs presented in Deliiski – Tumbarkova (2016, 2017)).

The heat energies for the freezing of the free and bound water are not equal to the specific latent heat of the water. As pointed out in (Deliiski – Tumbarkova 2016), the latent heat is used for description of the thermal energy only, which is needed for the change of the aggregate state of a given substance without changing its temperature.

In (Chudinov 1966, 1968, Deliiski 2004, 2011, 2013b), it has been shown that the energies required for the freezing of the free and bound water (or for the melting of the ice formed by them) in the wood depend mainly on the specific heat capacity of the free water in a frozen state, c_{fw}, and on the specific heat capacity of the bound water in a frozen state, c_{bw}, respectively. Both specific heat capacities depend on the specific latent heat of the water.

In addition, c_{fw} depends on the amount of free water in the wood and does not depend on the temperature because the free water freezes in the small range from 0 °C to –1 °C.

The specific heat capacity c_{bw} depends on the wood moisture content and on the temperature since the bound water freezes gradually in the range from –1 °C to the set or desired end temperature of the freezing, T_{end} (Deliiski 2013b, 2013c). However, even at the lowest climate temperatures on the earth about 0.12 kg·kg^{-1} of the bound water remains in a non-frozen state (Chudinov 1968).

4   CONCLUSIONS

The present paper describes an approach offered by the authors for the computation of the specific energies of the internal heat sources in logs subjected to freezing.

This approach takes into account, to a maximum degree, the physics of the freezing process of both the free and the bound water in the wood. It reflects the influence of the latent heat of the water in the wood on these energies. It also considers the wood density above and below the hygroscopic range, the icing degrees of the logs formed separately by both the free and bound water at each moment of log freezing, and the influence of the fiber saturation point of each wood species on its non-frozen water depending on the current temperature in the logs below 272.15 K.

Mathematical descriptions of the specific heat energies Q_{v-fw} and Q_{v-bw}, released in logs during the freezing of the free water in the range from 0 °C to –1 °C, and of the bound water below –1 °C, respectively, have been carried out. These descriptions are introduced in our own 2D non-linear mathematical model of the freezing process of logs.

A software program for the solution of the model and computation of the energies Q_{v-fw} and Q_{v-bw} according to the suggested approach and mathematical descriptions has been prepared in FORTRAN, which has been input in the calculation environment of Visual Fortran Professional developed by Microsoft.

With the help of the program, computations for the determination of the energies Q_{v-fw} and Q_{v-bw} and their sum, $Q_{v-total}$, have been completed as an example for the case of a beech log with a diameter of 0.24 m, length of 0.48 m, initial temperature of 20.5 °C, basic density of 683 kg·m^{-3}, and moisture content of 0.48 kg·kg^{-1} subjected to 30 h of freezing in a freezer at about –30 °C.

It has been determined that the values of the specific heat energies Q_{v-fw}, Q_{v-bw}, and $Q_{v-total}$ of the studied log change according to complex relationships, as follows:

- the energy Q_{v-fw}, which is released by the freezing of only the free water in the wood, changes from 0 to 52.27 Wh·m^{-3} during the time from 2.92nd h to 14.08th h of the freezing process;
- the energy Q_{v-bw}, which is released by the freezing of a portion of the bound water in the wood, changes from 0 to 17.98 Wh·m^{-3} during the time from 3.50th h to 17.00th h of the freezing process. After the 17.00th h this energy decreases exponentially and at the end of 30 h of freezing process it reaches a value of 7.31 Wh·m^{-3};

- the total energy $Q_{v\text{-total}} = Q_{v\text{-fw}} + Q_{v\text{-bw}}$ changes from 0 to 70.25 Wh·m^{-3} during the time from 2.92nd h to 17.00th h of the freezing process. From the 17.00th h to 30.00th h the energy $Q_{v\text{-total}}$ is equal to $Q_{v\text{-bw}}$.

By applying the suggested approach for the computation of Qv-fw and Qv-bw during our simulations with the mathematical model, we observed good conformity between the calculated and experimentally determined changes in the temperature field during the freezing of logs from different wood species with different moisture contents.

The overall *RSME* for the studied four characteristic points in the logs does not exceed 5% of the temperature ranges between the initial and the end temperatures of the logs subjected to freezing. This proves the suitable adequacy of the model as well as the correctness of the suggested approach.

The validation of the model with curvilinear change in the temperature of the freezing air medium will allow us, in the future, to solve the model (mutually connected with other our model of the logs' defrosting process) with curvilinear changing of the climate temperature (Deliiski 1988) over many winter days and nights. It will also allow for scientific calculations based the temperature distribution, icing degrees, and different energy characteristics of logs for each desired moment.

The approach for the computation of the specific energies of the internal heat sources in logs subjected to freezing suggested in this paper could be further applied in the development of analogous models; for example, for the calculation of the temperature fields and the energy consumption during the freezing of different wooden and other capillary-porous materials.

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