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AN APPROACH AND AN ALGORITHM FOR COMPUTATION OF THE UNSTEADY ICING DEGREES OF LOGS SUBJECTED TO FREEZING

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ABSTRACT

An approach and an algorithm for the computation of three types of unsteady icing degrees of logs during their cooling until reaching of temperatures, at which the freezing of the free water, and after that the freezing of the bound water in them occurs, have been suggested in the present paper.

The approach and the algorithm are based on the use of numerical solutions of own 2D non-stationary mathematical model of the logs' freezing process. The equations, which realise the suggested algorithm, are introduced in this model. Using these equations, the current values of the following types of unsteady icing degrees of subjected to freezing logs above the hygroscopic range are computed: icing degree, which is caused only by the freezing of free water; icing degree, which is caused only by the freezing of bound water; and total icing degree, which takes into account and mixes the current values of the first two types of the icing degree. For the solution and verification of the model and for the calculation of the logs' icing degrees according to the suggested approach and algorithm, a software program has been prepared in Visual Fortran Professional.

With the help of the program calculations have been carried out for the determination of the unsteady icing degrees of poplar logs during their 50 h freezing at –30 °C. The information about the logs' icing degrees is needed for the computation of the energy consumption of the freezing and also of the subsequent defrosting processes of logs aimed at their plasticizing in the production of veneer.

Key words: logs, modeling, freezing, free water, bound water, total icing degree.

INTRODUCTION

It is known that the duration of the thermal treatment of the frozen logs in the winter aimed at their plasticizing for the production of veneer and also the energy consumption needed for this treatment depend on the degree of the logs' icing (CUDINOV 1966, 1968, SHUBIN 1990, TREBULA – KLEMENT 2002, VIDELOV 2003, PERVAN 2009, DELIISKI – DZURENDA 2010). In the specialized literature there are limited reports about the temperature distribution in subjected to defrosting frozen logs (STEINHAGEN 1986, 1991, STEINHAGEN – LEE 1988, STEINHAGEN *et al.* 1987, KHATTABI – STEINHAGEN 1992, 1993, 1995, DELIISKI 2004, 2005, 2009, DELIISKI – DZURENDA 2010, DELIISKI *et al.* 2015a, HADJISKI – DELIISKI 2015, 2016) and there is only one piece of information about research of the temperature distribution in logs during their freezing

(DELIISKI – TUMBARKOVA 2016a). That is why the modeling and the multi-parameter study of the freezing process of logs are of considerable scientific and practical interest.

For different engineering calculations it is needed to be able to determine the icing degree of the wood materials depending on the temperature of the influencing on them gas or liquid medium and on the duration of their staying in this medium. Such calculations are carried out using mathematical models, which describe adequately the complex processes of the freezing of both the free and bound water in the wood. The computer solutions of these models give the non-stationary distribution of the temperature in the materials during their cooling below temperatures, at which a freezing of the whole amount of the free water and a freezing of respective, depending on the temperature, part of the bound water in the wood occurs (DELIISKI *et al.* 2014).

The aim of the present paper is to suggest a numerical approach and an algorithm for the computation and estimation of three types of unsteady icing degree of logs, which are caused by the freezing of the both free and bound water in them.

MATERIAL AND METHODS

Mathematical model of the 2D heat distribution in logs during their freezing

The mechanism of the heat distribution in logs during their cooling and freezing can be described by the equation of the heat conduction. When the length of the logs does not exceed their diameter by at least 3 ÷ 4 times, then the heat transfer through the frontal sides of the logs can not be neglected, because it influences the change in temperature of their cross sections, which are equally distant from the frontal sides (CHUDINOV 1968, SHUBIN 1990, DELIISKI 2011). In such cases, for the calculation of the change in the temperature in the longitudinal sections of the logs (i.e. along the coordinates r and z of these sections, refer to Fig. 1) during their freezing in air medium the following 2D model can be used:

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

$$\lambda_{\mathrm{wz}}\frac{\partial^2 T(r,z,\tau)}{\partial z^2}+\frac{\partial\lambda_{\mathrm{wz}}}{\partial T}\left[\frac{\partial T(r,z,\tau)}{\partial z}\right]^2+q_{\mathrm{v}}$$

(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 freezing process (see Fig. 1):

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

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

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

where c_{we} is the effective specific heat capacity of the wood in respective temperature ranges, in which the free and the bound water crystallize (CHUDINOV 1966, DELIISKI 2009, 2011, 2013b, DELIISKI – TUMBARKOVA 2016a), $J \cdot kg^{-1} \cdot K^{-1}$;

λ_{wr} and λ_{wp} – thermal conductivity of the wood in radial and longitudinal direction respectively, $W \cdot m^{-1} \cdot K^{-1}$;

ρ_w – wood density, $kg \cdot m^{-3}$;

r – coordinate of the separate points along the log's radius, m;

z – coordinate of the separate points along the log's length, m;

τ – time, s;

T – temperature, K;

T_0 – initial mass temperature of the subjected to freezing log, K;

$T(r,z,0)$ – temperature of all points in the log's volume in the beginning of the freezing, K;

$T(r,0,\tau)$ – temperature of all points on the log's frontal surface, K;

$T(0,z,\tau)$ – temperature of all points on log's cylindrical surface, K;

$T_{m\text{-}fr}$ – temperature of the surrounding air environment during the log's freezing, K;

q_v – internal heat source, $J \cdot m^{-3}$;

$\alpha_{r\text{-}fr}$ and $\alpha_{p\text{-}fr}$ – convective heat transfer coefficients between the log's surfaces and the surrounding air environment in radial and longitudinal direction respectively, $W \cdot m^{-2} \cdot K^{-1}$.

The internal heat source, q_v, takes into account the influence on the logs' freezing process of the latent heat of the water, which is released during its crystallization (PAHI 2010). This heat source can be determined with the help of the following equation:

$$q_v = \rho_w L_{cr-ice} \frac{\partial \Psi_{ice}}{\partial \tau}, \tag{5}$$

where L_{cr-ice} is the latent heat of the solid phase of water in the wood during the logs' freezing: $L_{cr-ice} = 3.34 \cdot 10^5$ $J \cdot kg^{-1}$ (CUDINOV 1966, PAHI 2010);

Ψ_{ice} – current value of the icing degree of the logs during their freezing.

The mathematical model of the logs' freezing process, which consists of eqs. (1) ÷ (5) can be solved without any simplification with the help of an explicit form of the finite-difference method (DELIISKI 2004, 2005, 2011). For this purpose the calculation mesh can be 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 (Fig. 1).

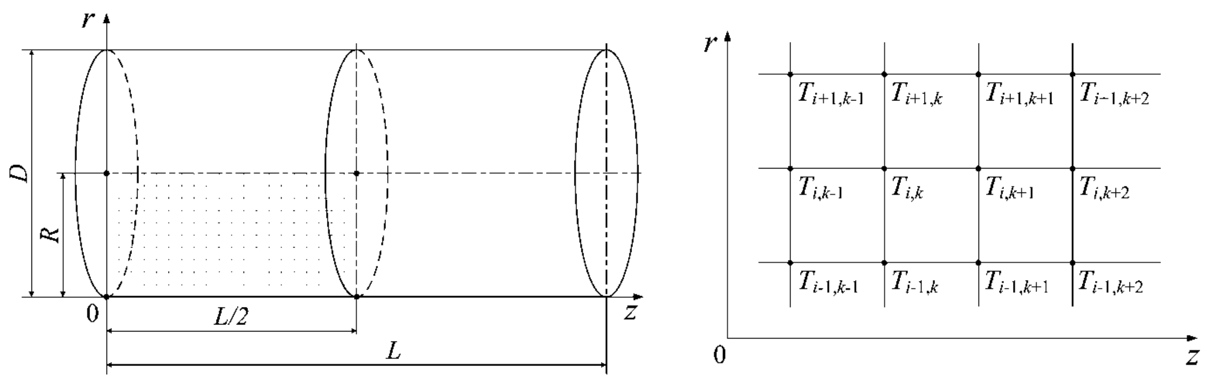

Fig. 1 Positioning of the knots of the calculation mesh on ¼ of the longitudinal section of a log subjected to freezing.

Mathematical description of the unsteady icing degree of logs, caused by the freezing of the free water in the wood

For the calculation of the current value of internal heat source q_v in eq. (5) during the solving of the mathematical model (1) ÷ (5) it is needed to be able to calculate the unsteady icing degrees of logs, which are caused by the freezing separately of the free and of the bound water in them.

The icing degree of logs, which is caused by the freezing only of the free water in them, Ψ^n_{ice-fw}, can be calculated for each moment $n\Delta\tau$ of the freezing process according to the equation

$$\Psi^n_{ice-fw} = \frac{S^n_{ice-fw}}{S_w}, \tag{6}$$

where S^n_{ice-fw} is that part of the ¼ of the log's longitudinal section area, in which up to the present moment $n\cdot\Delta\tau$ the free water crystallizes, m^2;

S_w – area of the entire ¼ of log's longitudinal section (refer to Fig. 1), m^2;

$\Delta\tau$ – step along the time coordinate, by which the mathematical model is solving, s;

n – time level during the solving of the model: n = 0, 1, 2, 3, ……

For the use of equation (6) it is needed for each moment $n\cdot\Delta\tau$ of the log's freezing process to know the current value of S^n_{ice-fw}. Unfortunately, there are no instrumental methods for measurement of this area. Therefore, the only possible way to estimate S^n_{ice-fw} is to use the current solution of the mathematical model of the log's freezing process.

The solution of the model gives the non-stationary distribution of the temperature field in the knots of the calculation mesh (see Fig. 1). The model solutions are obtained for any point in time, which is a multiple of the step $\Delta\tau$. It is not difficult to put a logical condition in the software for the model's solution, which registers and records the moments when the temperature of each of the knots decreases below 273.15 K (i.e. below 0 °C) and then temperature conditions for crystallization of the free water separately for each knot arise (DELIISKI –TUMBARKOVA 2016a).

This means that synchronously with the obtaining of the temperature distribution it is possible to determine the current number of the knots, N^n_{ice-fw}, in which the free water already "crystallizes". The relationship between N^n_{ice-fw} and the total number of knots of the entire calculation mesh, N_{total}, can be used for estimation of the current icing degree of logs, which occurs by the freezing of the free water in them up to the present moment $n\cdot\Delta\tau$, i.e.

$$\Psi^n_{ice-fw} = \frac{N^n_{ice-fw}}{N_{total}}. \tag{7}$$

Mathematical description of the icing degree of logs, caused by the freezing of the bound water in the wood

The results from our experimental research of the freezing process of logs from some wood species at different moisture contents show that the free water in the wood freezes in the temperature range between 273.15 K and 272.15 K (i.e. between 0 °C and –1 °C) (DELIISKI – TUMBARKOVA 2016). After the freezing of the entire amount of free water in the wood, a freezing of the bound water in the wood starts. The quantity of frozen bound water increases with the decrease in temperature, but even during extremely small climatic temperatures on earth, a definite part of it remains in a non-frozen state (CHUDINOV 1968, TOPGAARD – SÖDERMAN 2002).

The icing degree of logs, which is caused by the freezing only of the bound water in them, $\Psi^{n}_{\text{ice-bw}}$, can be calculated according to the equation (DELIISKI 2013b)

$$\Psi_{\text{ice-bw}} = \frac{m_{\text{ice-bw}}}{m_{\text{ice-bw}} + m_{\text{nfw}}} = \frac{u_{\text{fsp}}^{272.15} - u_{\text{nfw}}}{u_{\text{fsp}}^{272.15} - u_{\text{nfw}} + u_{\text{nfw}}} = 1 - \frac{u_{\text{nfw}}}{u_{\text{fsp}}^{272.15}}, \qquad (8)$$

where

$m_{\text{ice-bw}}$ is the weight of the ice in 1 kg wood, which is formed from the freezing of the bound water, kg;

m_{nfw} – weight of non-frozen water in 1 kg wood at a given temperature $T < 272.15$ K, kg;

u_{nfw} – amount of the non-frozen water in the wood at a given temperature $T < 272.15$ K, which can be calculated according to the following equation (DELIISKI 2011, 2013b):

$$u_{\text{nfw}} = 0.12 + \left(u_{\text{fsp}}^{272.15} - 0.12\right) \cdot \exp\left[0.0567\left(T - 272.15\right)\right], \qquad (9)$$

where $u_{\text{fsp}}^{272.15}$ is the fiber saturation point of the wood specie at T = 272.15 K, i.e at t = –1 °C. At this temperature the freezing of the whole amount of the free water has been completed and the freezing of the bound water in the wood starts (DELIISKI – TUMBARKOVA 2016).

Using experimental data of STAMM (1964), DELIISKI (2013b) has been suggested the following equation for the calculation of the fiber saturation point of the wood species, depending on T:

$$u_{\text{fsp}} = u_{\text{fsp}}^{293.15} - 0.001(T - 293.15), \qquad (10)$$

where $u_{\text{fsp}}^{293.15}$ is the standardized fiber saturation point at T = 293.15 K, i.e. at t = 20 °C.

According to eq. (10), the fiber saturation point of the wood specie at T = 272.15 K is equal to

$$u_{\text{fsp}}^{272.15} = u_{\text{fsp}}^{293.15} - 0.001(272.15 - 293.15) = u_{\text{fsp}}^{293.15} + 0.021\,. \qquad (11)$$

Using eq. (8), it is possible to calculate only the icing degree $\Psi^{n}_{\text{ice-bw}}$ separately for each knot of the calculation mesh because of the fact that u_{nfw} changes continuously with the temperature (see eq. (9)). This means that for the assessment of the icing state of the entire log's volume, it would be correct to use the average value of $\Psi^{n}_{\text{ice-bw}}$.

The current value of the average log's icing degree, $\psi^{n}_{\text{ice-bw-avg}}$, can be calculated for each moment $n \cdot \Delta\tau$ of the model solving after integration of $\Psi^{n}_{\text{ice-bw}}$ in all knots according to the following equation:

$$\psi^{n}_{\text{ice-bw-avg}} = \frac{u_{\text{fsp}}^{272.15} - u_{\text{nfw}} @ T^{n}_{i,k}}{u_{\text{fsp}}^{272.15}} =$$

$$\frac{1}{S_{\text{w}}} \iint\limits_{S_{\text{w}}} \frac{u_{\text{fsp}}^{272.15} - \left\{0.12 + (u_{\text{fsp}}^{272.15} - 0.12) \cdot \exp[0.0567\,(T^{n}_{i,k} - 272.15)]\right\}}{u_{\text{fsp}}^{272.15}} \mathrm{d}S_{\text{w}}, \qquad (12)$$

$$@ \;\; T_{\text{w-fre-avg}} \le T^{n}_{i,k} \le 272.15 \;\; \text{K}$$

where $T_{i,k}^{n}$ is the current temperature in the knot with coordinates *i* along *r* and *k* along *z*, K.

The symbol @ in eq. (12) means "at", i.e. that the calculation of u_{nfw} is carried out at temperature $T_{i,k}^{n}$.

Mathematical description of the total icing degree of logs

The total icing degree of the wood, $\Psi_{\text{ice-total}}$, can be expressed as a relationship between the weight of the ice in 1 kg wood and the total weight of the ice and the non-frozen water in 1 kg wood, i.e.

$$\Psi_{\text{ice-total}} = \frac{m_{\text{ice}}}{m_{\text{ice}} + m_{\text{nfw}}} = \frac{u - u_{\text{nfw}}}{u - u_{\text{nfw}} + u_{\text{nfw}}} = 1 - \frac{u_{\text{nfw}}}{u}, \tag{13}$$

where m_{ice} is the weight of the ice in 1 kg wood, kg;

m_{nfw} – weight of the non-frozen water in 1 kg wood, kg;

u – moisture content of the wood, kg.kg^{-1}.

According to eq. (13) we can calculate the icing degree of logs caused by the freezing of the entire amount of the free water and of that part of the bound water, which is in a frozen state at a given $T < 272.15$ K.

For example, if the log presented below on Fig. 2 is subjected to freezing until reaching of average mass temperature $T = 258.15$ K (i.e. $t = -15$ °C), the calculated according to eq. (9) at $u_{\text{fsp}}^{272.15} = 0.371$ kg·kg^{-1} amount of non-frozen water at $T = 258.15$ K is equal to $u_{\text{nfw}} = 0.2335$ kg·kg^{-1}. Then the total icing degree of the log with wood moisture content $u = 1.63$ kg·kg^{-1} according to eq. (13) is equal to $\Psi_{\text{ice-total}} = 1 - \frac{u_{\text{nfw}}}{u} = 1 - \frac{0.2335}{1.63} = 0.857$.

In the practice, during the freezing of the logs, in their peripheral layers the free water can be partly or fully in a frozen state, but the bound water would be partly in a liquid and partly in a frozen state. At the same time, in their central layers both the free and the bound water could be still in a liquid state. This means that $\Psi_{\text{ice-fw}}$ and $\Psi_{\text{ice-bw}}$ have different values at each moment of the freezing process.

That is why the determination of the current value of the total icing degree of logs, $\Psi_{\text{ice-total}}$, during the freezing process, which can not be calculated with the help of eq. (13), is of considerable scientific and practical interest.

The current value of the icing degree $\Psi_{\text{ice-total}}$ of subjected to freezing logs can be calculated according to the following algorithm, using the already computed current values of $\Psi_{\text{ice-fw}}$ and $\Psi_{\text{ice-bw}}$:

1. Using eq. (9), the amount of the non-frozen water in the wood is calculated at a temperature T_{cfre}, which has been reached in the log's center at the end of its freezing during the experiments, or which is desired to be reached during the computer simulations i.e.

$$u_{\text{nfw}}^{T_{\text{cfre}}} = 0.12 + (u_{\text{fsp}}^{272.15} - 0.12) \cdot \exp[0.0567 \cdot (T_{\text{cfre}} - 272.15)]. \tag{14}$$

2. Using eq. (8), the icing degree of the log caused by the freezing of the bound water in it at a temperature $T = T_{\text{cfre}}$ is calculated, i.e.

$$\Psi_{\text{bw-Tcfre}} = 1 - \frac{u_{\text{nfw}}^{T_{\text{cfre}}}}{u_{\text{fsp}}^{272.15}}. \tag{15}$$

3. Using eq. (13), the total icing degree of the log is calculated, which is reached at a temperature T_{cfre}, i.e.

$$\Psi_{\text{total-Tcfre}} = 1 - \frac{u_{\text{nfw}}^{T_{\text{cfre}}}}{u}. \tag{16}$$

4. The total amount of both the frozen free and bound water in the log at a temperature T_{cfre} is calculated according to the following equation:

$$u_{\text{fr-total}} = u_{\text{fr-fw}} + u_{\text{fr-bw}}, \tag{17}$$

where

$$u_{\text{fr-fw}} = u - u_{\text{fsp}}^{272.15}, \tag{18}$$

$$u_{\text{fr-bw}} = u_{\text{fsp}}^{272.15} - u_{\text{nfw}}^{T_{\text{cfre}}}. \tag{19}$$

5. The relative share of the frozen free water at a temperature T_{cfre} in the already determined value of the total log's icing degree at this temperature, $\Psi_{\text{total-Tcfre}}$, is calculated according to the equation:

$$\Psi_{\text{fw}} = \frac{u_{\text{fr-fw}}}{u_{\text{fr-total}}} \cdot \Psi_{\text{total-Tcfre}}. \tag{20}$$

6. The relative share of the frozen bound water at a temperature T_{cfre} in $\Psi_{\text{total-Tcfre}}$ is calculated according to the equation:

$$\Psi_{\text{bw}} = \frac{u_{\text{fr-bw}}}{u_{\text{fr-total}}} \cdot \Psi_{\text{total-Tcfre}}. \tag{21}$$

7. The relative share of Ψ_{fw} and of the current value of the icing degree caused by the freezing of the free water, $\Psi_{\text{ice-fw}}^{n}$, in the current value of the total icing degree, $\Psi_{\text{ice-total}}^{n}$, is calculated, using eq. (7):

$$\Psi_{\text{fw-total}}^{n} = \Psi_{\text{fw}} \cdot \Psi_{\text{ice-fw}}^{n} = \Psi_{\text{total-Tsfre}} \cdot \frac{u_{\text{fr-fw}}}{u_{\text{fr-total}}} \cdot \frac{N_{\text{ice-fw}}^{n}}{N_{\text{total}}}. \tag{22}$$

8. The relative share of Ψ_{bw} and of the current value of the icing degree caused by the freezing of the bound water, $\Psi_{\text{ice-bw-avg}}^{n}$, in the current value of the total icing degree, $\Psi_{\text{ice-total}}^{n}$, is calculated:

$$\Psi_{\text{bw-total}}^{n} = \Psi_{\text{bw}} \cdot \frac{\Psi_{\text{ice-bw-avg}}^{n}}{\Psi_{\text{bw-Tcfre}}} = \frac{\Psi_{\text{total-Tsfre}}}{\Psi_{\text{bw-Tcfre}}} \cdot \frac{u_{\text{fr-bw}}}{u_{\text{fr-total}}} \cdot \Psi_{\text{ice-bw-avg}}^{n}. \tag{23}$$

9. The current value of the total icing degree, $\Psi_{\text{ice-total}}^{n}$, as a sum of $\Psi_{\text{fw-total}}^{n}$ and $\Psi_{\text{bw-total}}^{n}$ is calculated:

$$\Psi_{\text{ice-total}}^{n} = \Psi_{\text{fw-total}}^{n} + \Psi_{\text{bw-total}}^{n}. \tag{24}$$

Experimental research of the logs' freezing process

For application and verification of the suggested above approach and algorithm we needed experimentally obtained data about the change in the temperature field in logs during their freezing. That is why we carried out such experiments.

The logs subjected to experimental research were with a diameter D = 240 mm and a length L = 480 mm. They were produced from the sap-wood of freshly felled poplar trunk (*Populus nigra* L.). Before the experiments, 4 holes with diameters of 6 mm and different lengths were drilled in each log. Sensors with long metal casing were positioned in these 4 holes for the measurement of the wood temperature during the experiments. The coordinates of the points 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 coordinates of the characteristic points allow covering the impact of the heat fluxes simultaneously in radial and longitudinal directions on the temperature distribution in logs during their freezing. For the freezing of the logs a horizontal freezer was used with length of 1.1 m, width of 0.8 m, depth of 0.6 m and an adjustable temperature range from –1 °C to –30 °C (DELIISKI – TUMBARKOVA 2016).

The automatic measurement and record of the temperature and humidity of the air processing medium in the freezer and also of the temperature in the 4 points in logs during the experiments was carried out with the help of Data Logger type HygroLog NT3 produced by the Swiss firm ROTRONIC AG (http:/www.rotronic.com/humidity-measurement-feuchtemessung-temperaturmessung-data-loggers-datenlogger/hygrolog-hl-nt3.html).

On Fig. 2, as an example, the change in the temperature of the processing air medium, t_m and in its humidity, φ_m, and also in the temperature in 4 characteristic points of a poplar log with moisture content u = 1.63 kg·kg^{-1} and basic density ρ_b = 361 kg·m^{-3} during its 50 h freezing is presented. The record of all data was made automatically by Data Logger with intervals of 5 min.

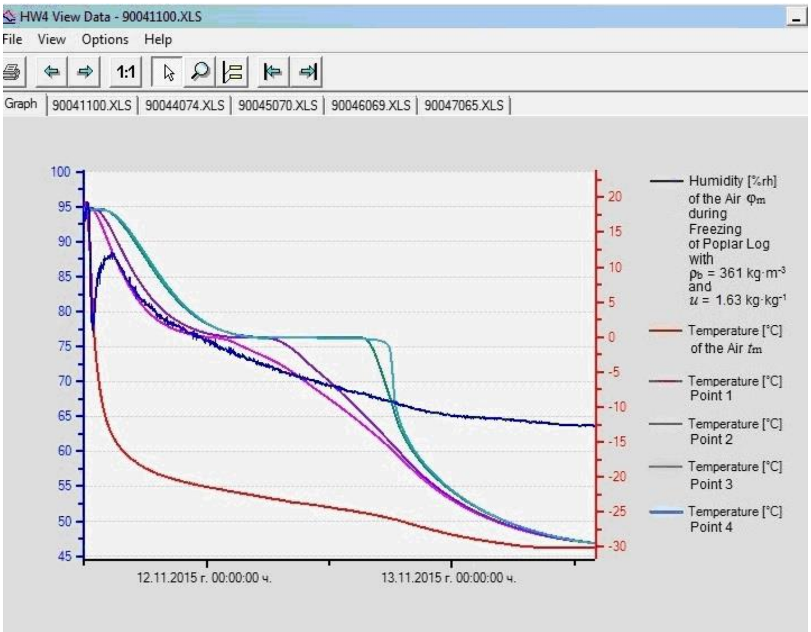

Fig. 2 Experimentally determined change in t_{m}, φ_{m}, and t in 4 points of poplar log with D = 0.24 m, L = 0.48 m, u = 1.63 kg·kg^{-1}, ρ_{b} = 361 kg·m^{-3} (i.e. ρ_{w} = 949 kg·m^{-3}), and t_{0} = 18.3 °C during its 50 h freezing.

RESULTS AND DISCUSSION

For the numerical solution of the above presented mathematical model (1) ÷ (24), a software program was prepared in FORTRAN in the calculation environment of Visual Fortran Professional.

With the help of the program, as an example, computations were made for the determination of the 2D non-stationary change of the temperature in ¼ of the longitudinal section of the poplar log, whose experimentally determined temperature distribution is shown on Fig. 2. The model was solved with step $\Delta r = \Delta z$ = 6 mm along the coordinates r and z (refere to Fig. 1) and with the same initial and boundary conditions, as they were during the experimental research.

During the solving of the model, the mathematical descriptions of the thermo-physical characteristics of poplar wood with $u_{\mathrm{fsp}}^{293.15} = 0.35\ \mathrm{kg \cdot kg^{-1}}$ were used, which have been presented in (DELIISKI 2011, 2013a, 2013b, DELIISKI *et al.* 2015b).

The curvilinear change in the shown on Fig. 2 freezing air medium temperature, $T_{\mathrm{m-fr}}$, with very high accuracy (correlation 0.99 and Root Square Mean Error 0.75 °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 following equation (DELIISKI – TUMBARKOVA 2016b):

$$T_{\mathrm{m-fr}} = \frac{a_{\mathrm{fr}} + c_{\mathrm{fr}}\tau + e_{\mathrm{fr}}\tau^{2} + g_{\mathrm{fr}}\tau^{3}}{1 + b_{\mathrm{fr}}\tau + d_{\mathrm{fr}}\tau^{2} + f_{\mathrm{fr}}\tau^{3} + h_{\mathrm{fr}}\tau^{4}}, \qquad (25)$$

whose coefficients are equal to: a_{fr} = 300.4588131, b_{fr} = 0.000349959, c_{fr}= 0.086418722, $d_{\mathrm{fr}} = -4.3949 \cdot 10^{-9}$, $e_{\mathrm{fr}} = -1.092 \cdot 10^{-6}$, $f_{\mathrm{fr}} = 1.65897 \cdot 10^{-14}$, $g_{\mathrm{fr}} = 4.12511 \cdot 10^{-12}$, $h_{\mathrm{fr}} = 2.8847 \cdot 10^{-22}$.

Equation (25) was used for the solving of eqs. (3) and (4) of the model.

Figure 3 presents the change in $t_{\mathrm{m-fr}}$, log's surface temperature t_{s}, and t of 4 points of the studied poplar log, which have the same coordinates, as during the experimental research.

The comparison to each other of the analogical curves on Fig. 2 and Fig. 3 shows good qualitative and quantitative conformity between the calculated and experimentally determined changes in the temperature field of the log during its freezing. It was calculated that the average Root Square Mean Error for all studied 4 points in the log is σ_{avg} = 2.43 °C.

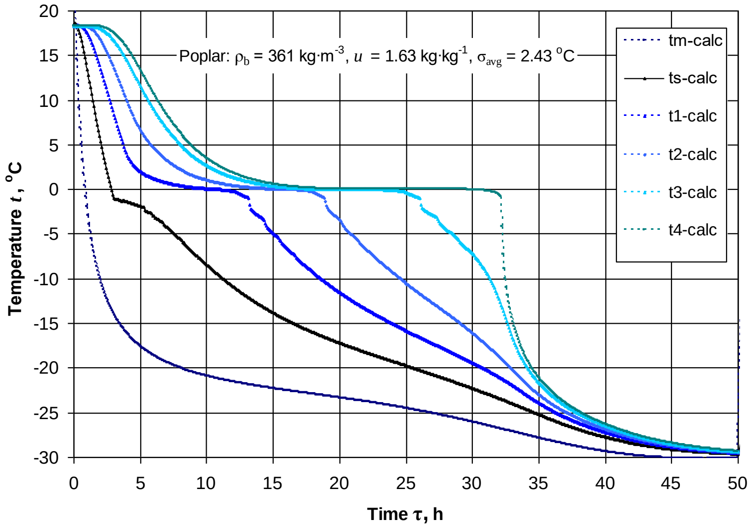

Fig. 3 Calculated with the model change in $t_{m\text{-}fr}$, t_s, and t of 4 points of the studied poplar log during its 50 h freezing.

Figures 4, 5, and 6 present the calculated change of the log's icing degrees Ψ^n_{ice-fw}, $\Psi^n_{ice-bw\text{-}avg}$, and $\Psi^n_{ice-total}$ during the 50 h freezing process of the studied poplar log. The graphs show that the change of all icing degrees is happening according to complex dependences on the freezing time.

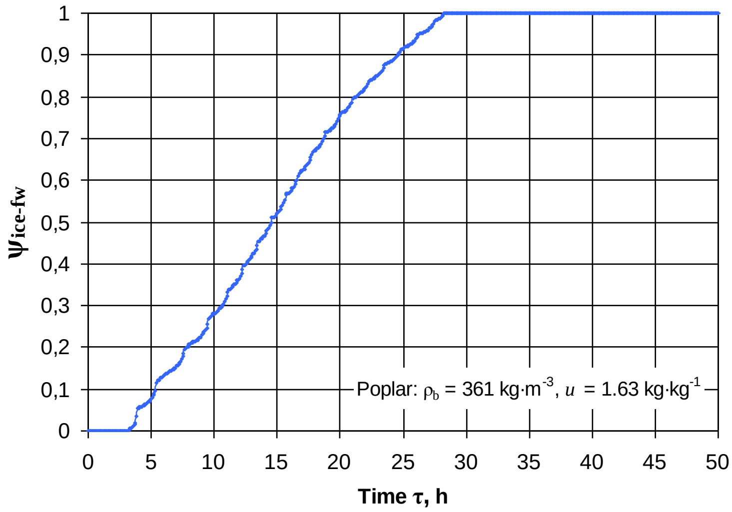

Fig. 4 Change in Ψ_{ice-fw} during the freezing of the studied poplar log.

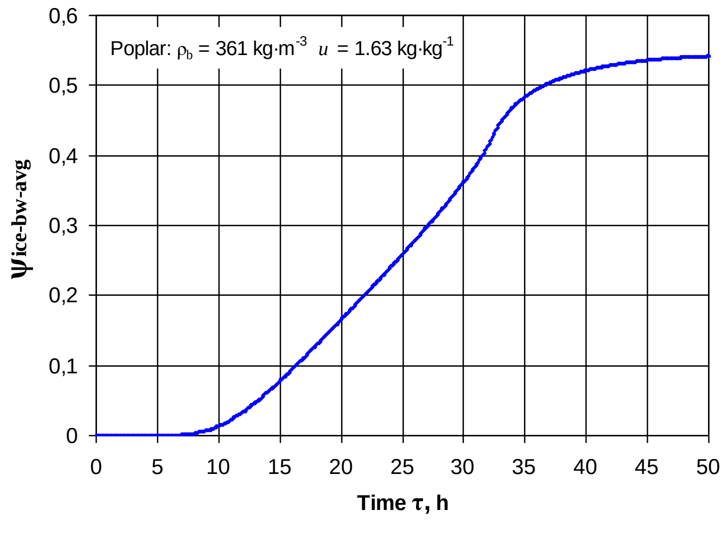

Fig. 5 Change in $\Psi_{ice\text{-}bw\text{-}avg}$ during the freezing of the studied poplar log.

The icing degree Ψ_{ice-fw} varies from 0 to 1 (Fig. 4). It has a value of 0 during the first 2.92 hours of the log' staying in the freezer while the whole amount of the water in the wood is in a liquid state. This icing degree becomes equal to 1 after 28.25 h of the log's staying in the freezer when the freezing of the free water has been fully completed.

The icing degree $\Psi_{ice-bw\text{-}avg}$ varies from 0 to 0.542 (Fig. 5). It has a value of 0 during the first 5.08 hours of the log's staying 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 0.542 at the end of the 50 h log's staying in the freezer. Then the average log's mass temperature is equal to –29.46 °C (i.e. 243.69 K) and the calculated according to eq. (9) amount of the non-frozen water u_{nfw} is equal to 0.170 kg·kg^{-1}. This value of u_{nfw} and the value $u_{fsp}^{272.15} = 0.35 + 0.021 = 0.371$ kg · kg^{-1} (see eq. 11) ensure a value of $\Psi_{ice-bw\text{-}avg}$ = 0.542 (see eq. (8)). This means that 1 – 0.542 = 0.458 relative parts (i.e. 45.8%) of the bound water in the wood remains in a liquid state in cell walls at the end of 50 h of log's freezing when the temperature in the freezer becomes equal to –30.14 °C and the average log's mass temperature is equal to –29.46 °C (see Fig. 2 and Fig. 3).

The icing degree $\Psi_{ice-total}$ changes in the range from 0 to 0.896. It is equal to 0 during the first 2.92 h of the log's cooling while the free water in the peripheral layers has still not cristalized. After that this icing degree starts to increase simultaneously with the increase of Ψ_{ice-fw} and $\Psi_{ice-bw\text{-}avg}$ and reaches a value of 0.896 at the end of the 50 h of the log's freezing. This means that 1 – 0.896 = 0.104 relative parts (i.e. 10.4%) of the whole amount of the water in the studied log remains in a liquid state at the end of the freezing.

This result coincides entirely with the value of $\Psi_{ice-total}$, which can be calculated for the fifteenth hour of the freezing according to eq. (13) with u = 1.63 kg·kg^{-1} and u_{nfw} = 0.170 kg·kg^{-1}. Such a value of u_{nfw} we receive according to eq. (9) after setting in it the average log's mass temperature T = 243.69 K (i.e. –29.46 °C) at the end of the freezing. All this confirms completely the correctness of the suggested above algorithm for the computation of $\Psi_{ice\text{-}total}$.

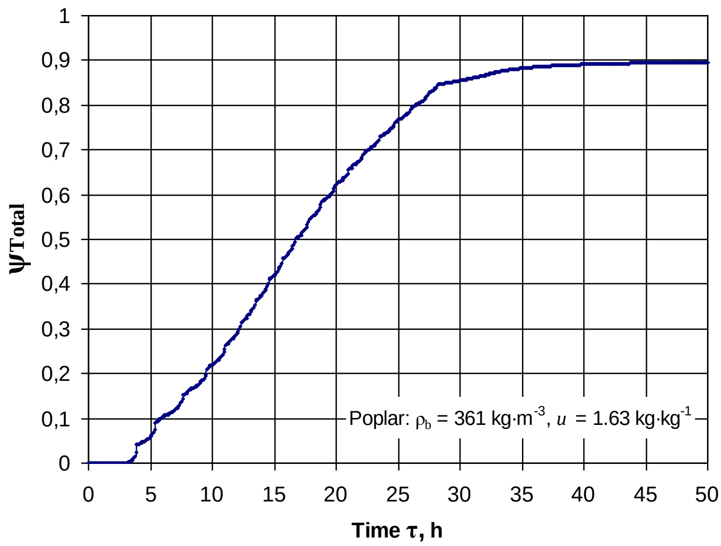

Fig. 6 Change in $\Psi_{ice-total}$ during the freezing of the studied poplar log.

CONCLUSIONS

The present paper describes the suggested for the first time by the authors an approach and an algorithm for the computation of three types of unsteady icing degree of logs during their cooling until reaching of temperatures, at which the freezing of the free water, and after that the freezing of a part of the bound water in them occurs. The approach and the algorithm are based on the use of the numerical solutions of own 2D non-linear mathematical model of the logs' freezing process.

For the solution of the model and practical application of the suggested approach and algorithm, a software program was prepared in the calculation environment of Visual Fortran Professional. The paper shows and analyses, as an example, diagrams of the change in the icing degrees for poplar log with a diameter of 0.24 m, length of 0.48 m, initial temperature of 18.3 ^{o}C, basic density of 361 kg·m^{-3}, and moisture content of 1.63 kg·kg^{-1} during its 50 h freezing in a freezer at –30 ^{o}C. All diagrams are drawn using the results calculated by the model.

It has been determined, that the values of the unsteady icing degrees of the studied log change according to complex relationships in the following ranges:

• the log's icing degree, which is caused by the freezing of only the free water in the wood, Ψ_{ice-fw}, changes from 0 to 1 during the time from 2.92nd h to 28.25th h of the freezing process;

• the average log's icing degree, which is caused by the freezing of a portion of the bound water in the wood, $\Psi_{ice-bw\text{-}avg}$, changes from 0 to 0.542 during the time from 5.08th h to the end of the freezing;

• the log's total icing degree, which is caused be the freezing of both the free and bound water in the wood, $\Psi_{ice-total}$, changes from 0 to 0.896 also from 2.92nd h to the end of the freezing process.

The approach and the algorithm that are suggested in the present paper for the computation of the unsteady logs' icing degrees could be further applied in the development of analogous models, for example, for the calculation of the temperature fields and the energy consumption during freezing of different wooden and other capillary-porous materials.

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