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# Computing the Icing States of Logs Subjected to Freezing

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***Key Words:*** *Modeling; logs; freezing; free water; bound water; total icing degree.*

***Abstract.*** *An approach and an algorithm for computing the three types of icing degrees of logs during their freezing have been suggested. The approach and the algorithm are based on the use of numerical solutions of own 2D non-linear mathematical model of the logs' freezing process at convective boundary conditions. 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 icing degrees of pine logs during their 30 h freezing at approximately –30 °C. The information about the logs' icing degrees is needed for the computation of the duration and energy consumption of the thermal treatment process of frozen logs aimed at their plasticizing in the production of rotary cutting veneer.*

## 1. Introduction

It is known that the duration and the energy consumption of the thermal treatment of frozen logs, aimed at their plasticizing for the production of veneer, depend on the immeasurable by sensors degree of the logs' icing [1-4, 6, 13, 15-19, 24-26, 28].

In the specialized literature there are limited reports about the temperature distribution in subjected to thawing frozen logs [5, 7, 9, 11-14, 21-23] and there is very scarce information about research of the temperature distribution in logs during their freezing [8, 26, 27]. 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 could be 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 can 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 low temperature, part of the bound water in the wood occurs.

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

Based on the suggested approach, this paper presents and visualizes the results from simulative investigation of the 2D non-stationary temperature distribution and icing degrees of pine logs with a diameter of 0.24 m, length of 0.48 m, and moisture content above the hygroscopic range during their 30 h freezing at approximately –30 °C.

## 2. Mathematical model of the 2D temperature distribution in logs during their freezing

When the length of the logs, $L$, is larger than their diameter, $D$, by not more than 3 ÷ 4 times, for the calculation of the change in the temperature in the longitudinal sections of horizontally situated logs (i.e., along the coordinates $r$ and $z$ of these sections) during their freezing in air medium the following 2D mathematical model can be used [27]:

$$c_{\mathrm{we-fr}}\rho_{\mathrm{w}}\frac{\partial T_{\mathrm{w}}(r,\ z,\ \tau)}{\partial \tau}= \\ =\mathrm{div}(\lambda_{\mathrm{w-fr}}\mathrm{grad}\ T_{\mathrm{w}})+q_{\mathrm{v}} \qquad (1)$$

with an initial condition

$$(2) \quad T(r,\ z,\ 0) = T_{w_0}$$

and boundary conditions for convective heat transfer:

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

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

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

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

Equations (1) ÷ (4) represent a common form of a mathematical model of the freezing process of the logs, i.e., of the 2D temperature distribution in logs subjected to freezing.

The internal heat source, $q_v$, takes into account in Eq. (1) the influence on the logs' freezing process of the latent heat of the water, which is released during its crystallization [10, 27]. This heat source can be determined with the help of the following equation:

$$(5) \quad q_v = \rho_w L_{\text{cr-ice}} \frac{\partial \Psi_{\text{ice}}}{\partial \tau}.$$

For the purpose of analysis of the logs' icing degrees below, synchronously with the solving of the model, the average mass temperature of the logs, $T_{\text{w-avg}}$, for each moment of their freezing is calculated according to the equation

$$(6) \quad T_{\text{w-avg}} = \frac{1}{S_w}\iint_{S_w} T_{i,k}^n \, dS_w,$$

where the area of ¼ of the log's longitudinal section, $S_w$, on which the calculation mesh for solving of the model is built, is equal to

$$(7) \quad S_w = \frac{DL}{4}.$$

# 3. Mathematical description of the icing degree of logs, caused by the freezing of the free water in them

For the calculation of the current value of internal heat source $q_v$ in Eq. (5) during the solving of the mathematical model (1) ÷ (4) it is needed to be able to calculate the 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, $\Psi_{\text{ice-fw}}^n$, can be calculated for each moment $n\cdot\Delta\tau$ of the freezing according to the equation

$$(8) \quad \Psi_{\text{ice-fw}}^n = \frac{S_{\text{ice-fw}}^n}{S_w}.$$

For the use of Eq. (8) it is needed for each moment $n\cdot\Delta\tau$ of the log's freezing process to know the current value of $S_{\text{ice-fw}}^n$. Unfortunately, there are no instrumental methods for measurement of this area. Therefore, the only possible way to estimate $S_{\text{ice-fw}}^n$ is to use the current solution of the mathematical model of the logs' freezing process.

The solution of the model gives the non-stationary distribution of the temperature field in the knots of the calculation mesh. The model solutions are obtained for any point in time, which is a multiple of the step Δτ. It is not difficult to put a logical condition in the software for the model's solving, 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 [8, 27]. This means that synchronously with the obtaining of the temperature distribution it is possible to determine the current number of the knots, $N_{\text{ice-fw}}^n$, in which the free water already "crystallizes". The relationship between $N_{\text{ice-fw}}^n$ and the total number of knots of the entire calculation mesh, $N_{\text{total}}$, can be used for estimation of the current icing degree of logs, which occurs from the freezing only of the free water in them up to the present moment $n\cdot\Delta\tau$, i.e.,

$$(9) \quad \Psi_{\text{ice-fw}}^n = \frac{N_{\text{ice-fw}}^n}{N_{\text{total}}}.$$

## 4. Mathematical description of the icing degree of logs, caused by the freezing of the bound water in them

The results from wide 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) [8, 27].

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 [1].

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 [4]:

$$\Psi_{\text{ice-bw}} = \frac{m_{\text{ice-bw}}}{m_{\text{ice-bw}} + m_{\text{nfw}}} = $$

$$(10)\quad = \frac{u_{\text{fsp}}^{272.15} - u_{\text{nfw}}}{u_{\text{fsp}}^{272.15} - u_{\text{nfw}} + u_{\text{nfw}}} = \quad ,$$

$$= 1 - \frac{u_{\text{nfw}}}{u_{\text{fsp}}^{272.15}}$$

where the amount of the non-frozen water in the wood, $u_{\text{nfw}}$, at a given temperature $T$ < 272.15 K, and the fiber saturation point of the wood species at $T$ = 272.15 K (i.e., at $t$ = –1 °C), $u_{\text{fsp}}^{272.15}$, are equal to [4, 5, 20]:

$$(11)\quad \begin{aligned} u_{\text{nfw}} &= 0.12 + \left(u_{\text{fsp}}^{272.15} - 0.12\right)\times \\ &\times exp\left[0.0567\left(T - 272.15\right)\right] \end{aligned} ,$$

$$(12)\quad u_{\text{fsp}}^{272.15} = u_{\text{fsp}}^{293.15} + 0.021.$$

Using Eq. (10), 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 $u_{\text{nfw}}$ changes continuously with the temperature (see Eq. (11)). 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:

$$(13)\quad \Psi^n_{\text{ice-bw-avg}} = \frac{u_{\text{fsp}}^{272.15} - u_{\text{nfw}} @ T^n_{i,k}}{u_{\text{fsp}}^{272.15}} =$$

$$\frac{1}{S_{\text{w}}} \iint_{S_{\text{w}}} \frac{u_{\text{fsp}}^{272.15} - \left\{ \begin{matrix} 0.12 + (u_{\text{fsp}}^{272.15} - 0.12)\cdot \\ \exp[0.0567(T^n_{i,k} - 272.15)] \end{matrix} \right\}}{u_{\text{fsp}}^{272.15}} \mathrm{d}S_{\text{w}}$$

at $T^n_{i,k} \le 272.15$ K.

## 5. Algorithm for computing the total icing degree of logs, caused by the freezing of both the free and bound water in them

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

$$\Psi_{\text{ice-total}} = \frac{m_{\text{ice}}}{m_{\text{ice}} + m_{\text{nfw}}} =$$

$$(14)\quad = \frac{u - u_{\text{nfw}}}{u - u_{\text{nfw}} + u_{\text{nfw}}} = \quad .$$

$$= 1 - \frac{u_{\text{nfw}}}{u}$$

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 the icing degrees $\Psi^n_{\text{ice-fw}}$ and $\Psi^n_{\text{ice-bw}}$ 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, $\Psi^n_{\text{ice-total}}$, during the freezing process, which can not be calculated with the help of Eq. (14), is of considerable scientific and practical interest.

The current value of the icing degree $\Psi^n_{\text{ice-total}}$ of subjected to freezing logs can be calculated according to the following algorithm, using the already computed current values of $\Psi^n_{\text{ice-fw}}$ and $\Psi^n_{\text{ice-bw}} = \psi^n_{\text{ice-bw-avg}}$ (refer to Eqs. (9) and (13)):

1. Using Eq. (11), the amount of the non-frozen water in the wood is calculated at temperature $T_{\text{w-avg-min}}$, which has been reached at the end of the log's freezing process during the experiments, or which is desired to be reached during the computer simulations, i.e.,

$$(15)\quad \begin{aligned} u_{\text{nfw}}^{T_{\text{w-avg-min}}} &= 0.12 + \left(u_{\text{fsp}}^{272.15} - 0.12\right) \times \\ &\times exp\left[0.0567(T_{\text{w-avg-min}} - 272.15)\right] \end{aligned}.$$

2. Using Eq. (10), the icing degree of the log caused by the freezing of only the bound water in it at $T = T_{\text{w-avg-min}}$ is calculated, i.e.,

$$(16)\quad \Psi_{\text{bw-Tw-avg-min}} = 1 - \frac{u_{\text{nfw}}^{T_{\text{w-avg-min}}}}{u_{\text{fsp}}^{272.15}}.$$

3. Using Eq. (14), the total icing degree of the log is calculated, which is reached at temperature $T_{\text{w-avg-min}}$:

$$(17)\quad \Psi_{\text{total-Tw-avg-min}} = 1 - \frac{u_{\text{nfw}}^{T_{\text{w-avg-min}}}}{u}.$$

4. The total amount of both the frozen free and bound water in the log at a temperature $T_{\text{w-avg-min}}$ is equal to

$$(18)\quad u_{\text{fr-total}} = u_{\text{fr-fw}} + u_{\text{fr-bw}},$$

where

$$(19)\quad u_{\text{fr-fw}} = u - u_{\text{fsp}}^{272.15},$$

$$(20)\quad u_{\text{fr-bw}} = u_{\text{fsp}}^{272.15} - u_{\text{nfw}}^{T_{\text{w-avg-min}}}.$$

5. The relative share of the frozen free water at temperature $T_{\text{w-avg-min}}$ in the already determined value of the total log's icing degree at this temperature, $\Psi_{\text{total-Tw-avg-min}}$, is equal to

$$(21)\quad \Psi_{\text{fw}} = \frac{u_{\text{fr-fw}}}{u_{\text{fr-total}}} \Psi_{\text{total-Tw-avg-min}}.$$

6. The relative share of the frozen bound water at temperature $T_{\text{w-avg-min}}$ in $\Psi_{\text{total-Tw-avg-min}}$ is equal to

$$(22)\quad \Psi_{\text{bw}} = \frac{u_{\text{fr-bw}}}{u_{\text{fr-total}}} \Psi_{\text{total-Tw-avg-min}}.$$

7. The relative share of $\Psi_{\text{fw}}$ 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. (9):

$$(23)\quad \begin{aligned} \Psi_{\text{fw-total}}^{n} &= \Psi_{\text{fw}} \Psi_{\text{ice-fw}}^{n} = \\ &= \Psi_{\text{total-Tw-avg-min}} \frac{u_{\text{fr-fw}}}{u_{\text{fr-total}}} \frac{N_{\text{ice-fw}}^{n}}{N_{\text{total}}} \end{aligned}.$$

8. The relative share of $\Psi_{\text{bw}}$ 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 according to the equation

$$(24)\quad \begin{aligned} \Psi_{\text{bw-total}}^{n} &= \Psi_{\text{bw}} \frac{\Psi_{\text{ice-bw-avg}}^{n}}{\Psi_{\text{bw-Tcfre}}} = \\ &= \frac{\Psi_{\text{total-Tw-avg-min}}}{\Psi_{\text{bw-Tw-avg-min}}} \frac{u_{\text{fr-bw}}}{u_{\text{fr-total}}} \Psi_{\text{ice-bw-avg}}^{n} \end{aligned}.$$

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

$$(25)\quad \Psi_{\text{ice-total}}^{n} = \Psi_{\text{fw-total}}^{n} + \Psi_{\text{bw-total}}^{n}.$$

# 6. Solving of the mathematical model

The above created mathematical descriptions of the three types of icing degrees of logs, and also the earlier suggested mathematical descriptions of the thermo-physical characteristics of frozen and non-frozen wood [4-6] are introduced in the mathematical model of the logs' freezing process, which consists of Eqs. (1) to (5).

The model has been solved with the help of explicit schemes of the finite difference method in the calculation environment of Visual FORTRAN Professional. r 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.

The model was solved with a step $\Delta r = \Delta z = 0.006$ m along the coordinates $r$ and $z$. This means that the number of the steps along $r$ was 20 and along $z$ it was 40, i.e., the total number of the knots in the logs' longitudinal section was equal to $N_{\text{total}} = 20 \times 40 = 800$. The interval between the time levels, $\Delta\tau$, (i.e., the value of the step along the time coordinate during the solving of the models), has been determined by the software according to the condition of stability for explicit schemes of the finite difference method [4, 6] and in our case it was equal to 6 s.

The heat transfer coefficients of the logs, which participate in the boundary conditions of the model, have been calculated according to the following equations [24]:

• in the radial direction on the cylindrical surface of the horizontally situated logs:

$$(26)\quad \alpha_{\text{wr-fr}} = 1.123\left[T(0,z,\tau) - T_{\text{m-fr}}(\tau)\right]^{E_{\text{fr}}};$$

• in the longitudinal direction on the frontal surface of the logs:

$$(27)\quad \alpha_{\text{wp-fr}} = 2.56\left[T(r,0,\tau) - T_{\text{m-fr}}(\tau)\right]^{E_{\text{fr}}},$$

where $E_{\text{fr}}$ and $E_{\text{dfr}}$ are exponents, whose values are determined during the solving and verification of the model through minimization of the root square mean error (RSME) between the calculated by the model and experimentally obtained results about the change of the temperature field in subjected to freezing logs.

## 6.1. Computing the 2D temperature distribution in pine logs during their freezing

*Figures 1* and *2* present the calculated 2D and experimentally determined in [27] change in $t_{\text{m-fr}}$ and also in logs' surface temperature $t_{\text{s}}$ and $t$ of 4 characteristic points of two pine logs (Log 1 and Log 2) subjected to separately 30 h freezing in a freezer. The studied logs have the following basic density $\rho_b$ and moisture content $u$: $\rho_b$ = 470 kg·m$^{-3}$ and $u$ = 0.33 kg·kg$^{-1}$ for Log 1 and $\rho_b$ = 423 kg·m$^{-3}$ and $u$ = 0.42 kg·kg$^{-1}$ for Log 2.

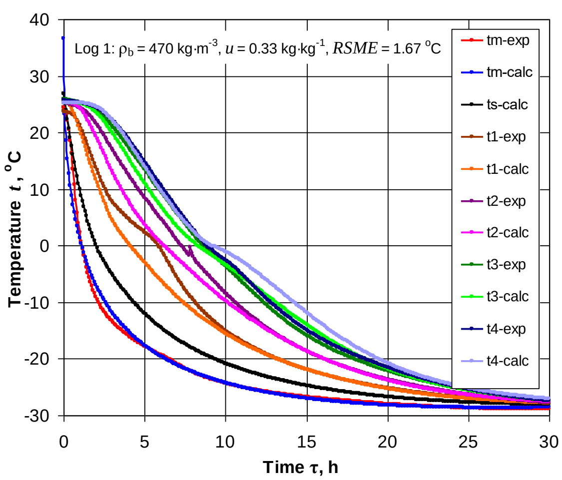


**Figure 1.** Calculated and experimentally determined change in $t_{\text{m}}$, $t_{\text{s}}$, and $t$ in 4 points of the Log 1 during its 30 h freezing

The coordinates of the points in the logs are, as follows: Point 1 with temperature $t_1$: along the radius $r$ = 30 mm and along the length $z$ = 120 mm; Point 2 with $t_2$: $r$ = 60 mm and $z$ = 120 mm; Point 3 with $t_3$: $r$ = 90 mm and $z$ = 180 mm and Point 4 with $t_4$: $r$ = 120 mm and $z$ = 240 mm (center of the logs). These coordinates of the points allow covering the impact of the heat fluxes simultaneously in radial and longitudinal directions on the temperature distribution in logs during their freezing. The comparison to each other of the analogical curves on *figures 1* and *2* show good conformity between the calculated and experimentally determined changes in the very complicated temperature field of the studied logs.

During our wide simulations with the mathematical model, we observed good compliance between computed and experimentally established temperature fields of logs from various wood species with different moisture content.

The overall *RSME* for the studied 4 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 [27].

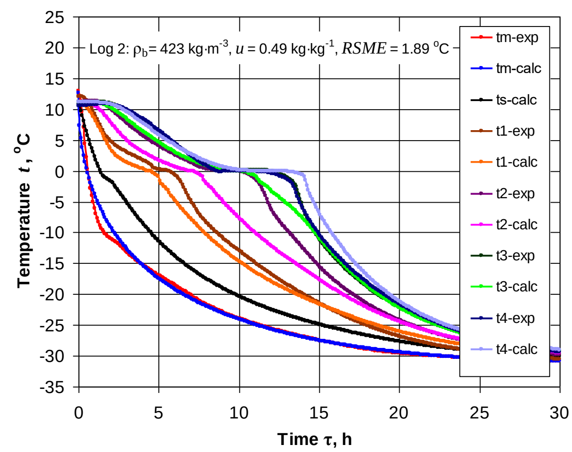


**Figure 2.** Calculated and experimentally determined change in $t_{\text{m}}$, $t_{\text{s}}$, and $t$ in 4 points of the Log 2 during its 30 h freezing

## 6.2. Computing the icing degrees of logs during their freezing

*Figures 3, 4,* and *5* present the calculated change of the log's icing degrees $\Psi^{n}_{\text{ice-fw}}$, $\Psi^{n}_{\text{ice-bw-avg}}$, and $\Psi^{n}_{\text{ice-total}}$ during the 30 h freezing process of the studied logs. The graphs show that the change of all icing degrees is happening according to complex dependences on the freezing time.

The icing degree $\Psi_{\text{ice-fw}}$ varies from 0 to 1 (*figure 3*). It has a value of 0 during the first 1.50 and 2.25 hours of the staying of Log 1 and Log 2 respectively 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 9.25 h and 11.75 h of the logs' staying in the freezer when the freezing of the free water has been fully completed.

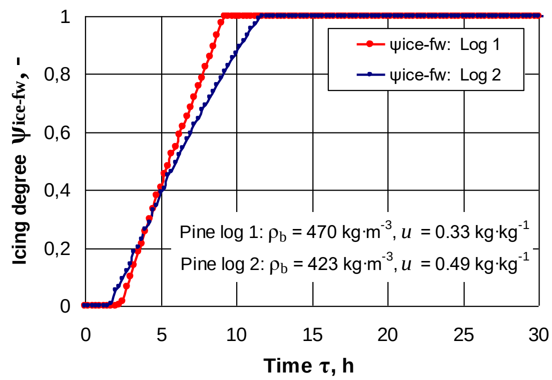


**Figure 3.** Change in $\Psi_{\text{ice-fw}}$ during the freezing of the studied pine logs

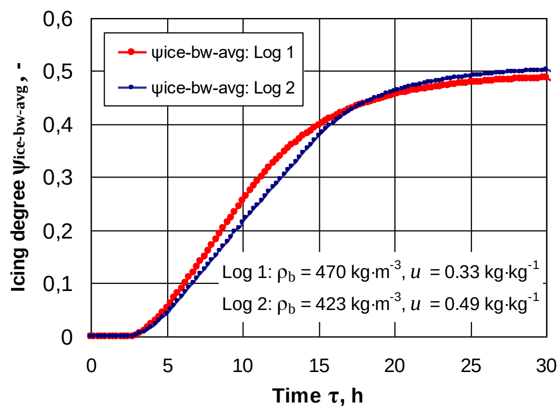


**Figure 4.** Change in $\Psi_{\text{ice-bw-avg}}$ during the freezing of the studied pine logs

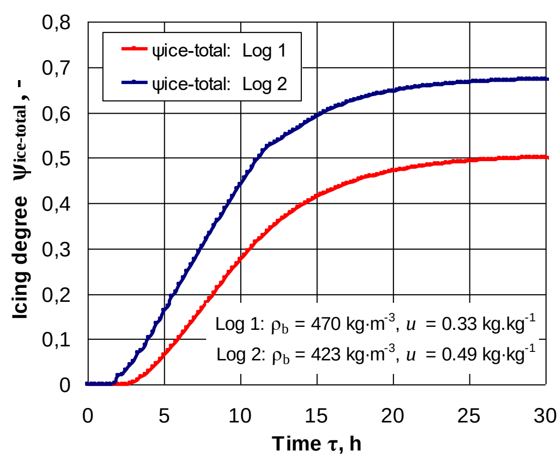


**Figure 5.** Change in $\Psi_{\text{ice-total}}$ during the freezing of the studied pine logs

The icing degree $\Psi_{\text{ice-bw-avg}}$ varies from 0 to 0.488 for Log 1 and to 0.502 for Log 2 (*figure 4*). It has a value of 0 during the first 2.25 and 2.00 hours of the staying of Log 1 and Log 2 respectively in the freezer, while the temperature of the peripheral layers of the logs decreases below –1 °C and the freezing of the bound water in these layers starts [8].

This icing degree becomes equal to 0.488 for Log 1 and to 0.502 for Log 2 at the end of the 30 h logs' staying in the freezer, when the average logs' mass temperature is equal to –27.59 °C (i.e., 245.56 K) for Log 1 and to –29.59 °C (i.e., 243.56 K) for Log 2. Then the calculated according to Eq. (11) amount of the non-frozen water $u_{\text{nfw}}$ is equal to 0.1645 kg·kg$^{-1}$ for Log 1 and to 0.1597 kg·kg$^{-1}$ for Log 2 because of the circumstance that at the standardized value of $u_{\text{fsp}}^{293.15} = 0.30$ kg·kg$^{-1}$ for the pine wood [6, 15] it is obtained according to Eq. (12) that $u_{\text{fsp}}^{272.15} = 0.321$ kg·kg$^{-1}$.

These values of $u_{\text{nfw}}$ and of $u_{\text{fsp}}^{272.15}$ ensure according to Eq. (10) the following values of the icing degree $\Psi_{\text{ice-bw-avg}}$ : $\Psi_{\text{ice-bw-avg}}$ = 0.488 for Log 1 and $\Psi_{\text{ice-bw-avg}}$ = 0.502 for Log 2.

This means that 1 – 0.488 = 0.512 relative parts (i.e., 51.2%) for Log 1 and 1 – 0.502 = 0.498 relative parts (i.e., 49.8%) for Log 2 of the bound water in the wood remains in a liquid state in cell walls at the end of 30 h of the logs' freezing, when the temperature in the freezer becomes equal to –28.58 °C for Log 1 and to –30.86 °C for Log 2 (see *figure 1* and *figure 2*).

The icing degree $\Psi_{\text{ice-total}}$ changes in the range from 0 to 0.501 for Log 1 and to 0.674 for Log 2. It is equal to 0 during the first 1.50 and 2.25 hours of the logs' cooling while the free water in the peripheral layers has still not crystallized. After that this icing degree starts to increase simultaneously with the increase of $\Psi_{\text{ice-fw}}$ and $\Psi_{\text{ice-bw-avg}}$ and reaches values of 0.501 for Log 1 and to 0.674 for Log 2 at the end of the 30 h of the logs' freezing.

This means that 1 – 0.501 = 0.499 relative parts (i.e., 49.9% ) for Log 1 and that 1 – 0.674 = 0.326 relative parts (i.e., 32.6% ) for Log 3 of the whole amount of the water in the studied logs remains in a liquid state at the end of the freezing.

These results coincide entirely with the values of $\Psi_{\text{ice-total}}$, which can be calculated for the 30th hour of the freezing according to Eq. (14) with $u$ = 0.33 kg·kg$^{-1}$ and $u_{\text{nfw}}$ = 0.1645 kg·kg$^{-1}$ for Log 1 and with $u$ = 0.49 kg·kg$^{-1}$ and $u_{\text{nfw}}$ = 0.1597 kg·kg$^{-1}$ for Log 2.

All this confirms completely the correctness of the described above algorithm for computing the icing degree $\Psi_{\text{ice-total}}$.

# 7. Conclusions

This work presents an approach and algorithm for computing the three types of icing degree of logs during their cooling until reaching of temperatures, at which the freezing of the free water and 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.

This work shows and analyzes, as an example, diagrams of the change in the icing degrees for two pine logs with a diameter of 0.24 m, length of 0.48 m, and different initial temperature, density and moisture content during their 30 h freezing in a freezer at approximately –30 °C. All diagrams are drawn using the results calculated by the model. It has been determined, that the values of the icing degrees of the studied logs 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, changes from 0 to 1 during the freezing process;

• the average logs' icing degree, which is caused by the freezing of a portion of the bound water in the wood changes from 0 to 0.488 for Log 1 and to 0.502 for Log 2 at the end of 30 h freezing process;

• the logs' total icing degree, which is caused be the freezing of both the free and bound water in the wood, changes from 0 to 0.501 for Log 1 and to 0.674 for Log 2 at the end of the considered freezing process.

The approach and the algorithm that are described in this work for computing the icing degrees of logs 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.

The results from the solutions of the model presented above can be used for the development of scientifically based energy saving optimized regimes for thermal treatment of frozen logs with consideration of their specific icing degree and also in the software of systems for model predictive automatic control [9, 11, 12] of that treatment.

## Symbols

| | | |
|---|---|---|
| $c$ | = | specific heat capacity (J·kg$^{-1}$·K$^{-1}$) |
| $D$ | = | diameter (m) |
| $E$ | = | exponent (-) |
| $L$ | = | latent heat (J·kg$^{-1}$) or length (m) |
| $N$ | = | number of knots of the calculation mesh (-) |
| $q$ | = | internal heat source (W·m$^{-3}$) |
| $R$ | = | radius (m): $R = D/2$ |
| $r$ | = | radial coordinate: $0 \le r \le R$ (m) |
| $S$ | = | area (m$^2$) |
| $t$ | = | temperature (°C): $t = T - 273.15$ |
| $T$ | = | temperature (K): $T = t + 273.15$ |
| $u$ | = | moisture content (kg·kg$^{-1}$) = %/100 |
| $z$ | = | longitudinal coordinate: $0 \le z \le L/2$ (m) |
| $\alpha$ | = | neat transfer coefficients between log's surfaces and ambient air medium (W·m$^{-2}$·K$^{-1}$) |
| $\lambda$ | = | thermal conductivity (W·m$^{-1}$·K$^{-1}$) |
| $\rho$ | = | density (kg·m$^{-3}$) |
| $\tau$ | = | time (s) |
| $\Delta r$ | = | step along the coordinates $r$ and $z$ for solving of the model (m) |
| $\Delta\tau$ | = | step along the time coordinate for solving of the model (s) |
| $\psi$ | = | relative icing degree (-) |

## Subscripts

| | | |
|---|---|---|
| avg | = | average (for wood mass temperature or for icing degree caused by bound water) |
| b | = | basic (for wood density, based on dry mass divided to green volume) |
| bw | = | bound water |
| cr | = | crystallization |
| fr | = | freezing |
| fre | = | end of freezing |
| fsp | = | fiber saturation point |
| fw | = | free water |
| $i$ | = | knot of the calculation mesh in the direction along the logs' radius: $i$ = 1, 2, 3, …, 21 |
| $k$ | = | knot of the calculation mesh in longitudinal direction of the logs: $k$ = 1, 2, 3, …, 41 |
| ice | = | ice |
| m | = | medium (for the air near logs during their freezing) |
| min | = | minimal (for value of the average mass temperature |
| nfw | = | non-frozen water |
| p | = | parallel to the wood fibers |
| r | = | radial direction |
| s | = | surface |
| v | = | volume |
| w | = | wood |
| we | = | wood effective (for specific heat capacity) |
| 0 | = | initial |

### Superscripts

$n$ = current number of the step $\Delta\tau$ along the time coordinate for model's solving: $n = 0, 1, 2, \ldots$

272.15 = at 272.15 K, i.e., at –1 °C

293.15 = at 293.15 K, i.e., at 20 °C

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