# APPLYING THE SOFTWARE PACKAGE TABLE CURVE 2D FOR COMPUTATION OF PROCESSING AIR MEDIUM TEMPERATURE DURING FREEZING IN A FREEZER AND DEFROSRING OF LOGS

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## ABSTRACT

A mathematical description of the change in the processing air medium temperature $T_m$ during freezing in a freezer and subsequent defrosting of logs using a software package Table Curve 2D v.5.01 has been suggested. This package allows for the selection of equations, which provides the best similarity between the calculated with them values of $T_m$ during the log's freezing and defrosting processes and the respective experimentally established data for $T_m$. The values of the coefficients in the selected equations have been determined in the work for the cases of decreasing in $T_m$ in the range from about 20 ºC to about –30 ºC during separately 30 h freezing and of the following increasing in $T_m$ up to about 20 ºC during the subsequent 30 h or 50 h defrosting of 6 pine logs with diameter of 240 mm and length of 480 mm.

**Key words:** : temperature, processing air medium, freezing, defrosting, pine logs, Table Curve.

## INTRODUCTION

During the winter the prepared for the veneer production logs are subjected to freezing and defrosting in natural air conditions. It is known that the duration of the thermal treatment of the frozen logs aimed at their plasticizing and also the energy consumption needed for this treatment depends on the degree of the logs'icing. It is well known that the degree of icing of the logs depends on the changes in the temperature of the influencing on them air environment and on the duration of their stay in this environment (Sergovsky 1975, Shubin 1990, Trebula and Klement 2002, Videlov 2003, Deliiski 2004).

The degree of the logs' icing can be computed with the help of mathematical models, which take into account a lot of peculiarities of the complex processes of the freezing and defrosting of both the free and bound water in the wood (Khattabi and Steinhagen 1992, 1993, 1995, Deliiski 2004, 2005, 2011, Deliiski and Dzurenda 2010). In the boundary conditions of such models the temperature of the influencing on the logs air environment, $T_m$, participates. For the solution of the models it is necessary to have a mathematical description of $T_m$.

The aim of the present paper is to apply the software package Table Curve 2D for precise mathematical description of the complex change in $T_m$ during the experimental research of the freezing process of pine logs in a freezer and during the subsequent defrosting of the frozen logs.

## MECHANISM OF THE HEAT DISTRIBUTION IN LOGS DURING THEIR FREEZING AND SUBSEQUENT DEFROSTING IN AIR ENVIRONMENT

The mechanism of the heat distribution in logs during their freezing and defrosting can be described by the equation of heat conduction (Shubin 1990, Deliiski 2004). When the length of the logs does not exceed their diameter by at least 2 ÷ 3 times, then the heat transfer through the frontal sides of the logs can not be neglected, because it influences the change in the temperature of their cross sections, which are equally distant from the frontal sides. In such cases, for the computation of the change in the temperature in the longitudinal sections of the logs (i.e. along the coordinates $r$ and $z$ of these sections) during their freezing and the subsequent defrosting the following 2D model can be used (Deliiski 2011):

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

with an initial condition

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

and boundary conditions for convective heat transfer at free air convection:

- along the radial coordinate $r$ on the logs' frontal surface during the freezing and defrosting processes:

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

$$\frac{\partial T(r,0,\tau)}{\partial r}=-\frac{\alpha_{\mathrm{p\text{-}dfr}}(r,0,\tau)}{\lambda_{\mathrm{wp}}(r,0,\tau)}\left[T(r,0,\tau)-T_{\mathrm{m\text{-}dfr}}(\tau)\right]. \tag{4}$$

- along the longitudinal coordinate $z$ on the logs' cylindrical surface during the freezing and defrosting processes:

$$\frac{\partial T(0,z,\tau)}{\partial z}=-\frac{\alpha_{\mathrm{r\text{-}fr}}(0,z,\tau)}{\lambda_{\mathrm{wr}}(0,z,\tau)}\left[T(0,z,\tau)-T_{\mathrm{m\text{-}fr}}(\tau)\right], \tag{5}$$

$$\frac{\partial T(0,z,\tau)}{\partial z}=-\frac{\alpha_{\mathrm{r\text{-}dfr}}(0,z,\tau)}{\lambda_{\mathrm{wr}}(0,z,\tau)}\left[T(0,z,\tau)-T_{\mathrm{m\text{-}dfr}}(\tau)\right]. \tag{6}$$

It must be noted that the effective specific heat capacity $c_{\mathrm{we}}$ in eq. (1) during the freezing of the logs is equal to $c_{\mathrm{we\text{-}fr}}$ and during the defrosting of the logs it is equal to $c_{\mathrm{we\text{-}dfr}}$. Besides this, during the logs' defrosting the internal volume heat source $q_{\mathrm{v}}$ in eq. (1) is equal to zero.

## METHODOLOGY FOR USE OF TABLE CURVE 2D FOR MATHEMATICAL DESCRIPTION OF $T_{\mathrm{m\text{-}fr}}$ AND $T_{\mathrm{m\text{-}dfr}}$

For the solution of the mathematical model (1) ÷ (6) it is necessary to have a mathematical description of the change in the processing air medium temperatures $T_{\mathrm{m\text{-}fr}}$ and $T_{\mathrm{m\text{-}dfr}}$ during the log's freezing and defrosting processes. It is seen from above that $T_{\mathrm{m\text{-}fr}}$ participates in eqs. (3) and (5) and $T_{\mathrm{m\text{-}dfr}}$ participates in eqs. (4) and (6).

Our research shows that the software package Table Curve 2D v.5.01 (http://www.sigmaplot. co.uk/products/tablecurve2d/tablecurve2d.php;http://www.bioprocessonline.com/doc/automated-curve-fitting-software-tablecurve-2-0001) is particularly suitable for precise mathematical description of the complex curves of $T_{\mathrm{m\text{-}fr}}$ and $T_{\mathrm{m\text{-}dfr}}$ during the logs' freezing and defrosting. This package is intended for linear and non-linear approximation of different 2D dependences by scientists and engineers. The approximation process is fully automated and it can be realized only in a single operation.

Over 3600 equations are introduced in this package. They give to the user the possibility quickly in just seconds to easily find the most precise mathematical description for its 2D data. The package allows to select an equation, which provides the best match between the calculated and experimentally established data. It calculates and draws (Fig. 1) a curve, which most approximates the 2D experimental data. So it helps to quickly solve different scientific and engineering problems.

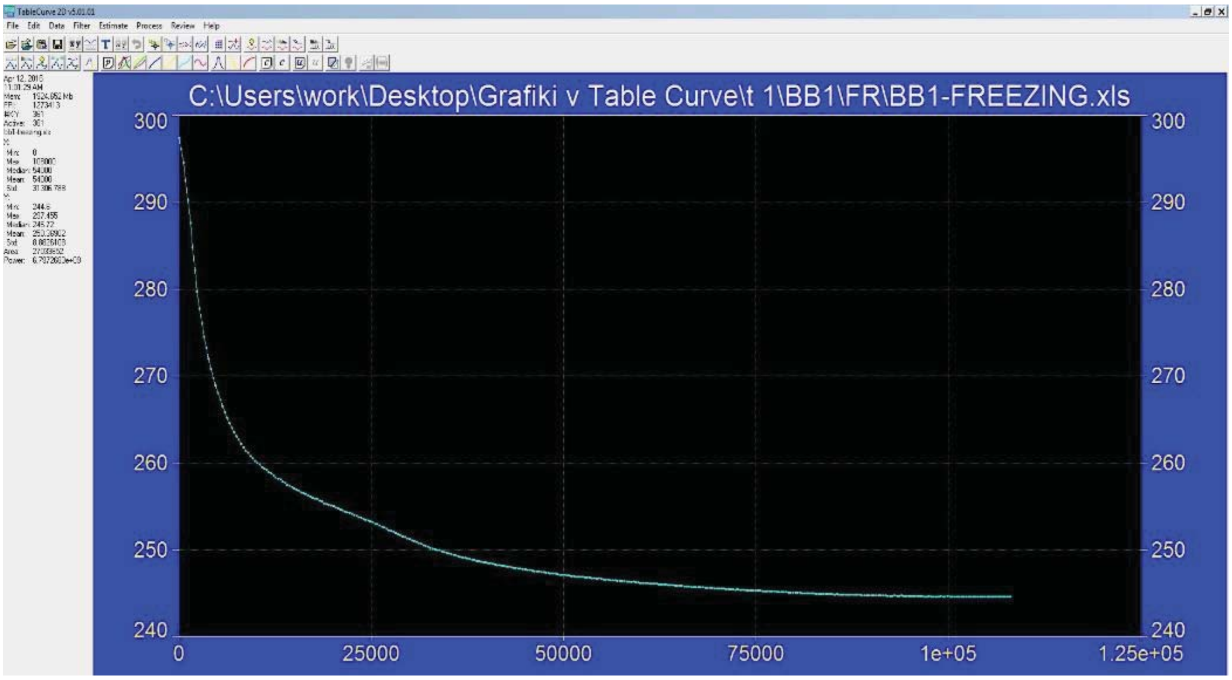


**Figure 1: 2D curve calculated and built by usage of Table Curve 2D**

The experiments, which we carried out aimed at research of the temperature distribution in the longitudinal sections of 6 pine logs with a diameter of 240 mm and a length of 480 mm during their 30 h freezing in freezer and during their subsequent 30 or 50 h defrosting show that $T_{\text{m-fr}}$ and $T_{\text{m-dfr}}$ change according to very complex curves. The automatic measurement and record of $T_{\text{m-fr}}$ in the closed operating freezer and immediately after that in $T_{\text{m-dfr}}$ in the open not operating freezer, and also of the temperature in 4 characteristic 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).The data for the change in $T_{\text{m-fr}}$ and $T_{\text{m-dfr}}$ during the experiments are received in .xls files. This data is introduced easily in the calculation environment of Table Curve 2D. After clicking on the function "Curve – Fit All Equations" the software suggests a set of equations for the approximation of the experimental data and builds the curves on the monitor separately for $T_{\text{m-fr}}$ and $T_{\text{m-dfr}}$ (Fig. 2).

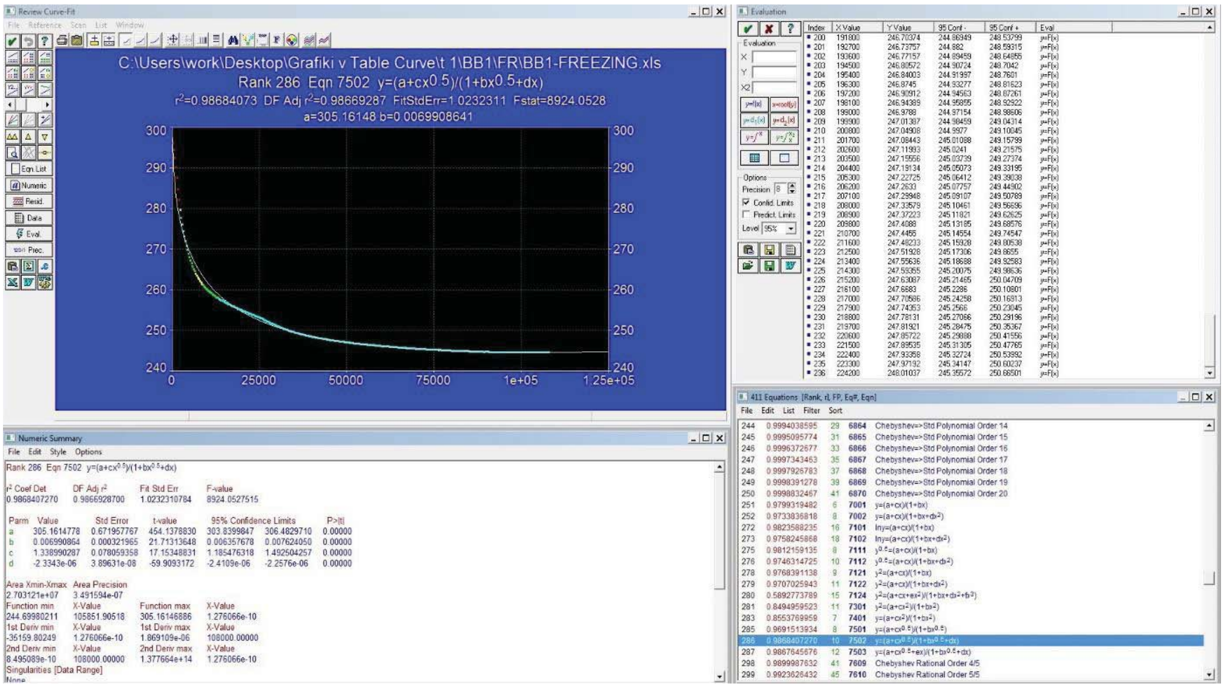


**Figure 2: Dialog windows of the software Table Curve 2D**

The dialog windows on Fig. 2 show, as follows:

- the chosen equation for approximation of the experimental data (bottom right);
- the curve, which approximates the experimental data according to chosen equation (top left);
- the calculated coefficients and the statistical parameters of the chosen equation (bottom left);
- the coordinates and the values of the calculated curve's points (top right).

## RESULTS AND DISCUSSION

With the help of Table Curve 2D approximating equations for the change in $T_{\text{m-fr}}$ and $T_{\text{m-dfr}}$ during separately freezing in a freezer and subsequent defrosting of 6 pine logs with a diameter of 240 mm, a length of 480 mm, and different moisture contents have been selected. The duration of the log's freezing process was equal to 30 h and the duration of their subsequent defrosting was equal to 30 h or 50 h depending on the wood moisture content.

The software suggested the following types of equations, which provide the best match between the calculated and experimentally established values of $T_{\text{m-fr}}$ and in $T_{\text{m-dfr}}$:

- for the calculation of $T_{\text{m-fr}}$ for all studied pine logs, which are named below as Log P1, Log P2, Log P3, Log P4, Log P5, and Log P6:

$$T_{\text{m-fr}} = \frac{a_{\text{fr}} + c_{\text{fr}}\tau^{0.5}}{1 + b_{\text{fr}}\tau^{0.5} + d_{\text{fr}}\tau}, \qquad (7)$$

- for the calculation of $T_{\text{m-dfr}}$ for Log P1, Log P2, Log P3, Log P4, and Log P6:

$$T_{\text{m-dfr}} = \frac{a_{\text{dfr}} + c_{\text{dfr}}\tau^{0.5}}{1 + b_{\text{dfr}}\tau^{0.5} + d_{\text{dfr}}\tau}, \qquad (8)$$

- for the calculation of $T_{\text{m-dfr}}$ only for Log P5:

$$T_{\text{m-dfr}} = \frac{a_{\text{dfr}} + c_{\text{dfr}}\tau^{0.5} + e_{\text{dfr}}\tau + g_{\text{dfr}}\tau^{1.5} + i_{\text{dfr}}\tau^{2} + k_{\text{dfr}}\tau^{2.5}}{1 + b_{\text{dfr}}\tau^{0.5} + d_{\text{dfr}}\tau + f_{\text{dfr}}\tau^{1.5} + h_{\text{dfr}}\tau^{2} + j_{\text{dfr}}\tau^{2.5}}, \qquad (9)$$

where the values of the calculated by Table Curve 2D coefficients from $a_{fr}$ to $d_{fr}$ are given in Table 1 and the values of the coefficients from $a_{dfr}$ to $k_{dfr}$ are given in Table 2.

In Table 3 and Table 4 the initial and the final experimentally determined and the calculated values of $T_{m\text{-}fr}$ and in $T_{m\text{-}dfr}$ are presented respectively, and the statistical parameters Root Mean Squared Error (*RMSE*) and cross-correlation coefficient $r$ are given too.

**Table 1: Values of the coefficients in eq. (7), which approximate the experimental data for $T_{m\text{-}fr}$**

| Log's name | Coefficients' indication | | | |
|---|---|---|---|---|
| | $a_{fr}$ | $b_{fr}$ | $c_{fr}$ | $d_{fr}$ |
| Log P1 | 304.1666690 | 0.004135171 | 0.631367662 | $-2.4658\cdot10^{-6}$ |
| Log P2 | 309.7863391 | 0.007125039 | 1.321533597 | $-2.7691\cdot10^{-6}$ |
| Log P3 | 305.1614778 | 0.006990864 | 1.338990287 | $-2.3343\cdot10^{-6}$ |
| Log P4 | 291.7654640 | 0.001896762 | 0.156947633 | $-1.9849\cdot10^{-6}$ |
| Log P5 | 283.6020907 | 0.000243475 | –0.18928061 | $-1.5132\cdot10^{-6}$ |
| Log P6 | 285.7898447 | 0.001571322 | 0.123970584 | $-1.5621\cdot10^{-6}$ |

**Table 2: Values of the coefficients in eqs. (8) and (9), which approximate the experimental data for $T_{m\text{-}dfr}$**

| Log's name | Coefficients' indication | | | |
|---|---|---|---|---|
| | $a_{dfr}$ | $b_{dfr}$ | $c_{dfr}$ | $d_{dfr}$ |
| Log P1 | 292.4561739 | –0.00314829 | –0.90308452 | $1.60806\cdot10^{-7}$ |
| Log P2 | 302.7370809 | –0.00307055 | –0.93514109 | $-8.5495\cdot10^{-8}$ |
| Log P3 | 304.2995595 | –0.00308265 | –0.94314500 | $-8.4804\cdot10^{-8}$ |
| Log P4 | 303.4590302 | –0.00307175 | –0.94227471 | $-1.4379\cdot10^{-7}$ |
| Log P5 | 290.3411665 | –0.01209208 | –3.50998655 | $5.80966\cdot10^{-5}$ |
| Log P6 | 283.6489249 | –0.00315220 | –0.87304134 | $2.0934\cdot10^{-7}$ |

**Note:** The values of the remaining coefficients in eq. (9) for $T_{m\text{-}dfr}$ of Log P5, which are not presented in Table 2, are: $e_{dfr} = 0.016860786$, $f_{dfr} = -1.3865\cdot10^{-7}$, $g_{dfr} = -4.0233\cdot10^{-5}$, $h_{dfr} = 1.64359\cdot10^{-10}$, $i_{dfr} = 4.76899\cdot10^{-8}$, $j_{dfr} = -7.7438\cdot10^{-14}$, $k_{dfr} = -2.2468\cdot10^{-11}$.

**Table 3: Initial and final experimentally determined and calculated values of $T_{m\text{-}fr}$, and statistical parameters of the approximation of $T_{m\text{-}fr}$ by equation (7)**

| Log's name | Experimental values of $T_{m\text{-}fr}$ during the logs' freezing process, K | | Calculated values of $T_{m\text{-}fr}$ during the logs' freezing process, K | | Correlation coefficient, $r_{fr}$ | $RMSE_{fr}$, K |
|---|---|---|---|---|---|---|
| | initial | final | initial | final | | |
| Log P1 | 296.69 | 244.33 | 304.17 | 244.50 | 0.989001 | 1.451735 |
| Log P2 | 297.51 | 244.34 | 309.79 | 244.57 | 0.990854 | 1.280417 |
| Log P3 | 297.46 | 244.63 | 305.16 | 244.70 | 0.993399 | 1.023231 |
| Log P4 | 289.55 | 243.51 | 291.77 | 243.68 | 0.992633 | 1.054287 |
| Log P5 | 287.56 | 241.35 | 283.60 | 241.55 | 0.991615 | 1.099593 |
| Log P6 | 286.04 | 242.27 | 285.79 | 242.29 | 0.994627 | 0.841933 |

**Table 4: Initial and final experimentally determined and calculated values of $T_{m\text{-}dfr}$, and statistical parameters of the approximation of $T_{m\text{-}dfr}$ by equations (8) and (9)**

| Log's name | Experimental values of $T_{m\text{-}dfr}$ during the logs' defrosting process, K | | Calculated values of $T_{m\text{-}dfr}$ during the logs' defrosting process, K | | Correlation coefficient, $r_{dfr}$ | $RMSE_{dfr}$, K |
|---|---|---|---|---|---|---|
| | initial | final | initial | final | | |
| Log P1 | 244.33 | 296.42 | 244.50 | 297.02 | 0.989196 | 0.999824 |
| Log P2 | 244.34 | 295.78 | 244.57 | 296.00 | 0.991066 | 0.920995 |
| Log P3 | 244.63 | 296.95 | 244.70 | 297.19 | 0.996485 | 1.111108 |
| Log P4 | 243.51 | 292.99 | 243.68 | 293.12 | 0.970816 | 1.301726 |
| Log P5 | 241.35 | 291.35 | 241.55 | 291.44 | 0.998615 | 0.308300 |
| Log P6 | 242.27 | 290.24 | 242.29 | 290.87 | 0.991850 | 0.787781 |

On Fig. 3 and Fig. 4 the experimentally established and the calculated curves of $T_{m\text{-}fr}$ and $T_{m\text{-}dfr}$ according to above given equations for Log P5 and Log P6 are presented, respectively.

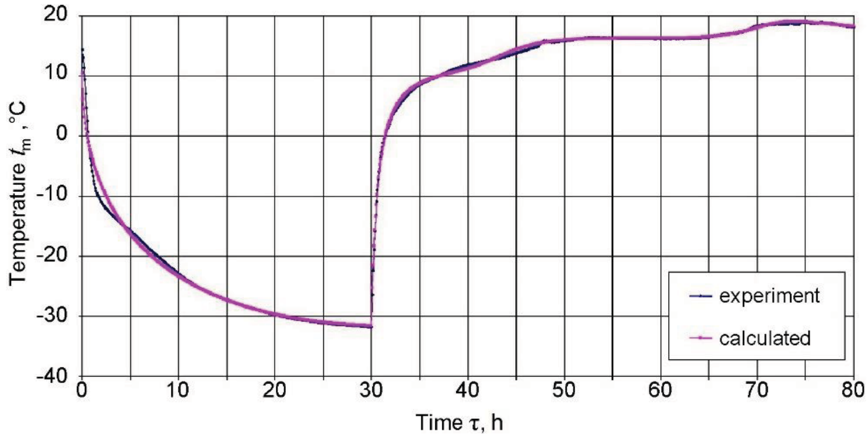


**Figure 3: Change in the experimentally determined and calculated values of $t_{m\text{-}fr}$ and $t_{m\text{-}dfr}$ during 30 h freezing in a freezer and 50 h subsequent defrosting of log P5**

It can be seen from Table 3, Table 4, Fig. 3, and Fig. 4 that the chosen equations (7), (8), and (9), whose coefficients are given in Table 1 and in and Table 2, provide a very good match between the calculated and experimentally established data for both $T_{m\text{-}fr}$ and in $T_{m\text{-}dfr}$.

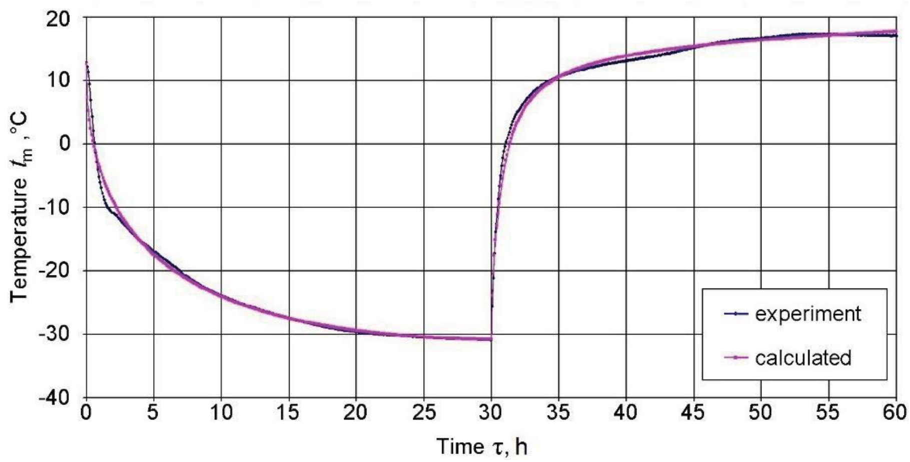


**Figure 4: Change in the experimentally determined and calculated values of $t_{m\text{-}fr}$ and $t_{m\text{-}dfr}$ during 30 h freezing in a freezer and 30 h subsequent defrosting of pine Log P6**

## CONCLUSIONS

The applying of the software package Table Curve 2D v.5.01 for the mathematical description of the temperature of the processing air medium temperature during freezing in a freezer and subsequent defrosting of logs has been presented in this paper. This package allows for the selection of equations, which provide the best similarity between the calculated with them values and the respective experimentally established 2D data.

With the help of Table Curve 2D one algebraic equation for mathematical description of the decreasing in the temperature $T_{m\text{-}fr}$ in the range from about 20 ºC to about –30 ºC during separately 30 h freezing in a freezer of 6 pine logs with diameter of 240 mm, length of 480 mm, and different moisture content was selected and its coefficients were determined.

With the help of the same software two types of algebraic equations for the mathematical description of the increasing in the temperature $T_{m\text{-}dfr}$ in the range from about –30 °C to about 20 °C during subsequent 30 h or 50 h defrosting of the frozen pine logs were selected and their coefficients were determined.

The obtained numerical, statistical, and graphical results show that the selected equations from the menu of Table Curve provide an extremely good match between the calculated and respective experimentally established data for both $T_{m\text{-}fr}$ and in $T_{m\text{-}dfr}$.

The Root Mean Squared Error is in the range from 0.31 K to 1.45 K and the cross-correlation coefficient is more than 0.97 for $T_{m\text{-}fr}$ and for $T_{m\text{-}dfr}$ of all studied 6 pine logs.

The equations selected with the help of Table Curve will be used in the boundary conditions of 2D mathematical model (1) ÷ (6) of the pine logs' freezing and defrosting processes during its solution and verification at concrete values of the processing air medium's temperatures.

**Symbols**

$c$ = specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)
$q$ = internal heat source ($J \cdot m^{-3}$)
$r$ = radial coordinate: $0 \leq r \leq R$, or correlation coefficient
$R$ = radius, m
$RMSE$ = Root Mean Squared Error
$t$ = temperature (°C): $t = T - 273.15$
$T$ = temperature (K): $T = t + 273.15$
$z$ = longitudinal coordinate or correlation coefficient
$\alpha$ = heat transfer coefficient between the logs' surface and the environment ($W \cdot m^{-2} \cdot K^{-1}$)
$\lambda$ = thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
$\rho$ = density ($kg \cdot m^{-3}$)
$\tau$ = time (s)

**Subscripts and superscripts:**

dfr = defrosting
e = effective (for the specific heat capacity of the frozen and non-frozen wood)
fr = freezing
m = medium (for the temperature of the freezing or defrosting air environment)
p = longitudinal direction (parallel to the wood fibers)
r = radial direction
v = volume (for the internal heat source)
w = wood
0 = initial (for the average mass temperature of the logs in the beginning of their freezing)

**REFFERENCES**

DELIISKI, N. 2004. Modelling and automatic control of heat energy consumption required for thermal treatment of logs. Drvna Industria, Volume 55, № 4: 181–199.

DELIISKI, N. 2005. Modelling and automatic control of the process of thermal treatment of logs. Information Technologies and Control, UAI, Sofia, Year 3, № 2: 9–14.

DELIISKI, N. 2011. Transient heat conduction in capillary porous bodies. In: Convection and Conduction Heat Transfer. In Tech Publishing House, Rieka, 149–176 p. http://dx.doi.org/10.5772/21424

DELIISKI, N., DZURENDA, L. 2010. Modelling of the thermal processes in the technologies for wood thermal treatment. TU Zvolen, Slovakia, 224 p. (in Russian).

KHATTABI, A., STEINHAGEN, H. P. 1992. Numerical solution to two-dimensional heating of logs. Holz als Roh- und Werkstoff, 50, 308–312, http://dx.doi.org/ 10.1007/BF02615359.

KHATTABI, A., STEINHAGEN, H. P. 1993. Analysis of transient nonlinear heat conduction in wood using finite-difference solutions. Holz als Roh- und Werkstoff, 51, 272–278, http://dx.doi.org/10.1007/BF02629373.

KHATTABI, A., STEINHAGEN, H. P. 1995. Update of "Numerical solution to two-dimensional heating of logs". Holz als Roh- und Werkstoff, 53, 93–94, http://dx.doi.org/10.1007/BF02716399.

SERGOVSKY, P. S. 1975. Hydro-thermal Treatment and Conserving of Wood. Lesnaya Promyshlennost, Moscow, URSS, 400 p. (in Russian).

SHUBIN, G. S. 1990. Drying and Thermal Treatment of Wood. Lesnaya Promyshlennost, Moscow, URSS, 337 p. (in Russian).

TREBULA, P., KLEMENT. I. 2002. Drying and hydrothermal treatment of wood. Technical University in Zvolen, Slovakia, 449 p. (in Slovak).

VIDELOV, H. 2003. Drying and thermal treatment of wood, University of Forestry, Sofia, 335 p. (in Bulgarian).

http:/www.rotronic.com

http://www.sigmaplot.co.uk/products/tablecurve2d/tablecurve2d.php

http://www.bioprocessonline.com/doc/automated-curve-fitting-software-tablecurve-2-0001

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