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Computation of the Temperature Field at Cooling of Logs below the Freezing Point of the Moisture

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Key Words: *Beech logs; freezing; ANSYS; temperature field.*

Abstract. *An approach for modeling and computation of the temperature field in subjected to freezing logs with the help of software package ANSYS Workbench 16.0 has been suggested. Numerical results about the transient temperature fields in a beech log with a diameter of 0.24 m, length of 0.48 m, initial temperature of 22.4 °C, and moisture content of 0.63 kg·kg-1 during its 50 h cooling in a freezer at approximately –30 °C are graphically presented and analyzed. The root square mean error between the calculated and experimentally established temperatures of the studied log has been determined in order to validate the mathematical models.*

1. Introduction

The software ANSYS is consisted of packages for numerical analyses based on finite elements and finite volumes methods. It is used successfully for solutions of partial differential equations of the mechanics of solid bodies, fluid dynamics, acoustics, thermodynamics, and coupled field problems. The software is also suitable for optimizations of the design of products.

At studying of the thermal treatment of wood materials, it is necessary to obtain the transient temperature fields in the solid domain at different environmental temperatures and time durations of the process. The aim of the present work is to suggest and demonstrate an approach for numerical simulation of the temperature filed at cooling of logs to temperatures, lower than the freezing point of the moisture in the material by ANSYS Workbench.

2. Numerical Simulation of the Logs' Freezing Process

The computation of the temperature fields at the logs' freezing process is performed at the following steps:

a. Creation of a working project in ANSYS Workbench/Transient Thermal module (*figure 1*).

b. Definition of the thermo-physical characteristics of the materials (density, thermal conductivity, and specific heat capacity) using table mode in **Engineering Data** library (*figure 2*). The values of the thermal conductivity and the specific heat capacity of the materials are input separately for the temperature ranges of the logs' freezing process (see *figure 8*). Details about their determination are given in point 3. The dimensions of all variables are according to system SI.

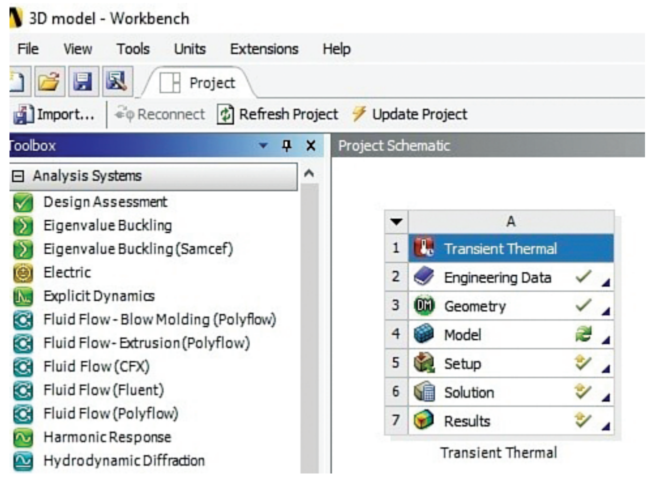

Figure 1. Main dialogue window of ANSYS

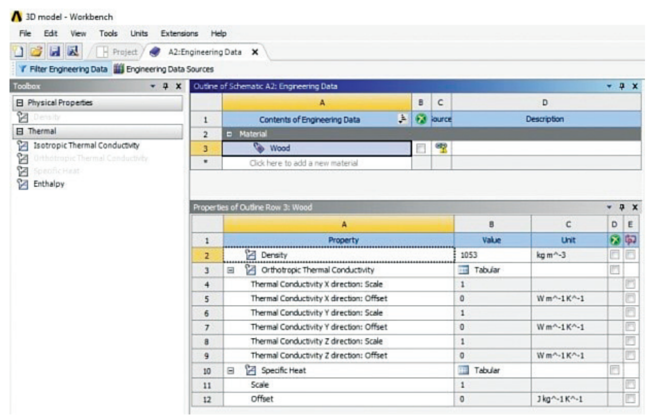

Figure 2. Definition of density, thermal conductivity and specific heat capacity of the wood

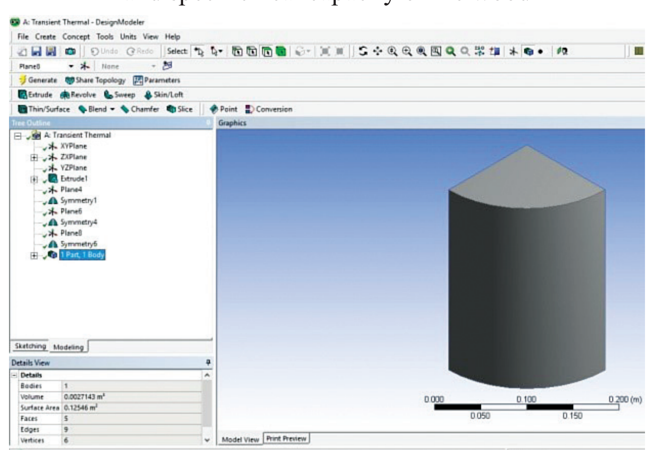

Figure 3. 3D model of the cooled at all surrounding surfaces cylindrical log

c. Creation of a 3D geometrical model of the solid body (*figure 3*). The geometrical model of cylindrical logs can be a ¼ of the longitudinal section if there exists axis symmetry of the temperature fields.

d. Generation of a computation mesh, approximating the geometrical model by **Mesh** module. Sweep method and size control are used (*figure 4*).

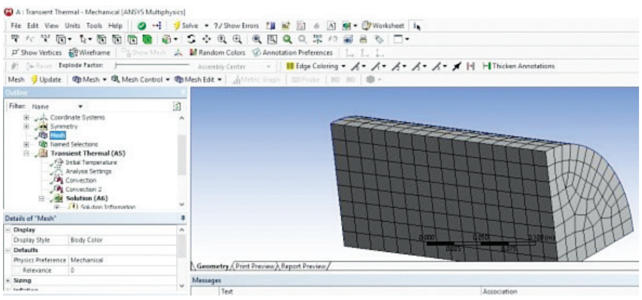

Figure 4. Finite element mesh

e. Definition of boundary, initial conditions and time step control in **Setup** module. Initial temperatures of the log, duration of the freezing process, time steps and time interval for results output are defined (*figures 5* and *6*). Third kind of boundary conditions are used. The heat transfer coefficients at the surfaces of the wood, normal and parallel to the axis respectively α_{wr} and α_{wp}, and the temperature of the freezing air medium Tm as function of the time are defined.

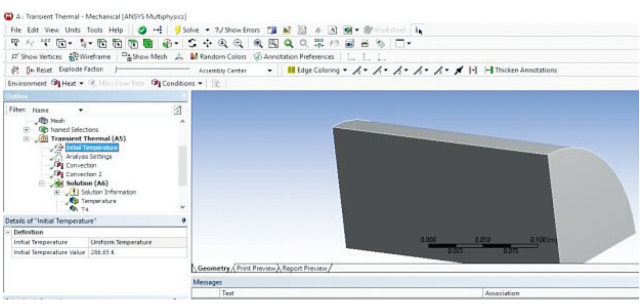

Figure 5. Initial log's temperature

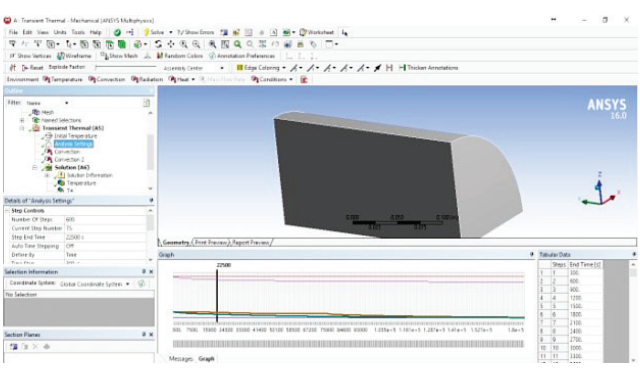

Figure 6. Time step definition

f. Numerical solution of Fourier equation for thermal conduction and computation of the transient temperature distribution in the cooled log (*figure 7*).

g. Post processing of the results by visualization and animation of the temperature fields. Temperature variation in different points during the simulation of the freezing process (see *figure 15*) can be graphed.

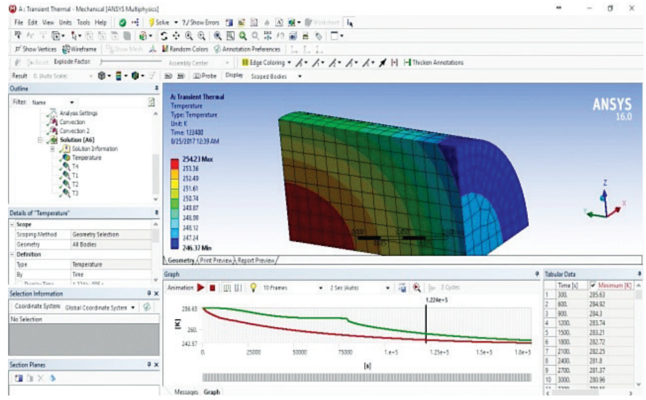

Figure 7. Window with calculated and graphically prezented change in the log's temperature

The computed data can be exported for subsequent numerical analysis in MS Excel.

3. Modeling of the Thermo-Physical Characteristics of the Logs during their Freezing

The thermal conductivity, λ_w, effective specific heat capacity, c_{we}, density ρ_w, and heat transfer coefficients at the logs' surfaces can be obtained for separate ranges of the freezing process. On figure 8 three temperature ranges are shown, at which the process of the logs' freezing above the hygroscopic range can be defragmented.

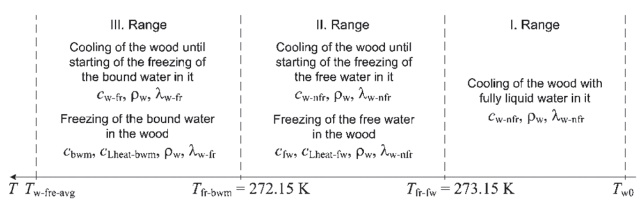

Figure 8. Temperature ranges of the wood cooling process

During the first range a cooling of the logs with fully liquid water in them occurs from the initial logs' temperature T_{w0} to the freezing point $T_{fr\text{-}fw}$.

During the second range between $T_{fr\text{-}fw}$ and $T_{fr\text{-}bwm}$ a further cooling of the logs occurs until reaching of the start of the free water crystallization. The phase change of this water into ice is carried out. The second range is absent when the wood moisture content u is less than fiber saturation point.

In the third range from $T_{fr\text{-}bwm}$ to the average mass temperature at the end of the freezing $T_{w\text{-}fre\text{-}avg}$, a further cooling of the logs is carried out until reaching of start of the bound water crystallization.

3.1. Thermal Conductivity

A mathematical description of the thermal conductivity λ_w of non-frozen and frozen wood as a function of T and

u has been suggested in [3,1,8] on the base of experimentally obtained data. These relations are used in the European [2,4,6,12,15,16] and the American specialized literature [9,10,11,13] at computing of various processes of the thermal treatment of different wood materials.

According to the suggested in [3] mathematical approach the wood thermal conductivity during freezing of the logs with moisture content above the hygroscopic range can be calculated by the following equations:

(1) $$\lambda_{\mathrm{w}} = \lambda_0 \gamma \left[1 + \beta (T - 273.15)\right],$$

(2) $$\lambda_{\mathrm{w0}} = K_{\mathrm{ad}} \cdot v \cdot \left[\begin{array}{l} 0.165 + (1.39 + 3.8u) \cdot \\ \left(3.3 \cdot 10^{-7} \rho_{\mathrm{b}} + 1.015 \cdot 10^{-3} \rho_{\mathrm{b}}\right) \end{array} \right],$$

(3) $$v = 0.1284 - 0.013u \, .$$

Precise empirical values of K_{ad} in eq. (2) for different wood species have been determined in [4] and [6]. Values of K_{ad} have been determined for the investigated in this paper beech wood: $K_r = 1.35$ and $K_p = 2.40$, i.e $K_p / K_r \approx 1.78$.

The coefficients γ and β in eq. (1) are calculated using the next equations.

• Non-frozen wood at $u > u_{fsp}^{272.15}$ and 272.15 K < $T \leq$ 423.15 K

(4) $$\gamma = 1.0 \, ,$$

(5) $$\beta = 3.65 \left(\frac{579}{\rho_{\mathrm{b}}} - 0.124 \right) \cdot 10^{-3} \, .$$

• Frozen wood at $u > u_{fsp}^{272.15}$ and 213.15 K < $T \leq$ 272.15 K:

(6) $$\gamma = 1 + 0.34 [1.15 (u - u_{\mathrm{fsp}})] \, ,$$

(7) $$\beta = 0.002 (u - u_{\mathrm{fsp}}) - 0.0038 \left(\frac{579}{\rho_{\mathrm{b}}} - 0.124 \right),$$

The fiber saturation point of the wood in (6) and (7) is computed according to:

(8) $$u_{\mathrm{fsp}} = u_{\mathrm{fsp}}^{293.15} - 0.001 (T - 293.15) \, ,$$

where $u_{fsp}^{293.15}$ is the standardized fiber saturation point of the wood at T = 293.15 K.

3.2. Density

The wood density of the logs ρ_w above the hygroscopic range is determined according to the following equation [1,3,6,12,13]:

(9) $$\rho_{\mathrm{w}} = \rho_{\mathrm{b}} \cdot (1 + u) \, .$$

3.3. Effective Specific Heat Capacity

The effective specific heat capacities of the logs' wood c_{we} are equal to:

(10) I. Range: $c_{\mathrm{we1}} = c_{\mathrm{w-nfr}}$,

(11) II. Range: $c_{\mathrm{we2}} = c_{\mathrm{w\text{-}nfr}} + c_{\mathrm{fw}} - c_{\mathrm{Lheat-fw}}$,

(12) III. Range: $c_{\mathrm{we3}} = c_{\mathrm{w\text{-}fr}} + c_{\mathrm{bwm}} - c_{\mathrm{Lheat-bwm}}$.

The next detail expressions for c_{we1}, c_{we2}, and c_{we3} are obtained according to the approaches in [1,2,3,4,6]

(13)
$$c_{\mathrm{we}} = \left\{ \begin{array}{l} \frac{2862u + 555}{1+u} + \frac{5.49u + 2.95}{1+u} T + \frac{0.0036}{1+u} T^2 \\ @ u > u_{\mathrm{fsp}}^{272.15} \ \& \ 273.15 \ \mathrm{K} \leq T \leq 413.15 \ \mathrm{K} \qquad \text{(I. Range)} \\ \\ \frac{2862u + 555}{1+u} + \frac{5.42u + 2.95}{1+u} T + \frac{0.0036}{1+u} T^2 + \\ + 3.34 \cdot 10^5 \frac{u - u_{\mathrm{fsp}}^{272.15}}{1+u} - 3.34 \cdot 10^5 \frac{\rho_{\mathrm{w}} - \rho_{\mathrm{wUfsp}}}{\rho_{\mathrm{w}} u} \cdot \frac{\partial \Psi_{\mathrm{ice-fw}}}{\partial T} \\ @ u > u_{\mathrm{fsp}}^{272.15} \ \& \ 272.15 \ \mathrm{K} < T < 273.15 \ \mathrm{K} \qquad \text{(II. Range)} \\ \\ \left[1.06 + 0.04u + \frac{0.00075 (T - 272.15)}{u_{\mathrm{fsp}}^{272.15}} \right] \cdot \\ \cdot \frac{526 + 2.95T + 0.0022T^2 + 2261u + 1976u_{\mathrm{fsp}}^{272.15}}{1+u} + \\ + 1.8938 \cdot 10^4 \left(u_{\mathrm{fsp}}^{272.15} - 0.12 \right) \cdot \frac{\exp\left[0.0567 (T - 272.15)\right]}{1+u} - \\ - 3.34 \cdot 10^5 \frac{\rho_{\mathrm{wUfsp}} - \rho_{\mathrm{wUnfw}}}{\rho_w} \cdot \frac{\partial \Psi_{\mathrm{ice-bwm}}}{\partial T} \\ @ u > u_{\mathrm{fsp}}^{272.15} \ \& \ 213.15 \ \mathrm{K} \leq T \leq 272.15 \ \mathrm{K} \qquad \text{(III. Range)} \end{array} \right\}$$

3.4. Heat Transfer Coefficients at the Logs' Surfaces

For the convective boundary conditions of the logs' cooling process the following relations for the heat transfer coefficients are most suitable [14]:

• Cylindrical surface of the horizontally situated logs

(14) $$\alpha_{\mathrm{wr}} = 2.56 \left[T(0, z, \tau) - T_{\mathrm{m-fr}}(\tau) \right]^{E_{\mathrm{fr}}} ;$$

• Frontal surface of the logs

(15) $$\alpha_{\mathrm{wp}} = 1.123 \left[T(r, 0, \tau) - T_{\mathrm{m-fr}}(\tau) \right]^{E_{\mathrm{fr}}} ,$$

where E_{fr} is determined during the validation of the non-linear mathematical model of the process through minimization of the root square mean error (*RSME*) between the computed by the model and experimentally obtained transient temperature fields.

4. Experimental Research of the Temperature Fields in the Logs during the Cooling

Objects of investigations are logs with diameter D = 240 mm and length L = 480 mm. They are made by a freshly felled beech trunk. Before the experiments, 4 holes with diameters of 6 mm and different lengths were drilled in order to reach the characteristic points of the log [5]. The coordinates of the characteristic points of the logs are as follows:

- point 1: r = 30 mm and z = 120 mm;
- point 2: r = 60 mm and z = 120 mm;
- point 3 r = 90 mm and z = 180 mm;
- point 4: r = 120 mm and z = 240 mm (center of the log).

Temperature sensors were positioned in these holes in order to measure the wood temperature during the cooling (*figure 9*).

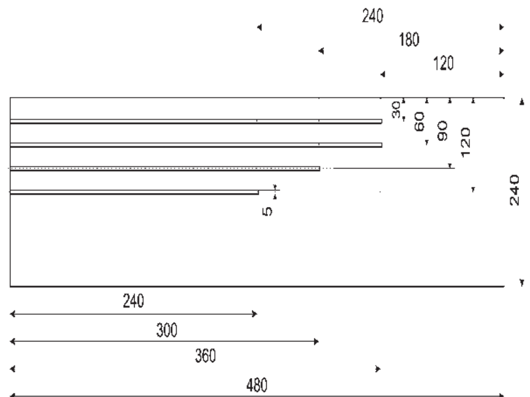

Figure 9. Longitudinal section of the beech log with drilled holes for positioning of temperature sensors

For the cooling of the logs according to the suggested in [5] methodology, a horizontal freezer was used with adjustable temperature range from – 1°C to –30°C. Each log with temperature sensors in it was situated horizontally on a special stand in the freezer. The temperature of the air medium tm in it was lowered gradually until reaching approximately –30°C (*figure 10*).

The automatic record of the temperature, relative humidity of the air medium in the freezer and the temperatures 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 changes of the measured parameters at beech log with moisture content $u = 0.63$ kg·kg^{-1} and basic density ρ_b = 684 kg·m^{-3} during 50 h freezing are presented on *figure 10.*

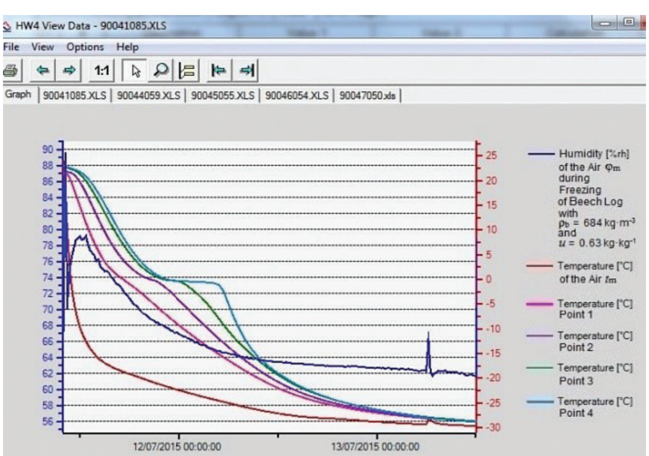

Figure 10. Experimentally obtained change in t_m, φ_m, and t in 4 points of the cooled beech log at time duration of 50 h

5. Modeling Investigation about the Cooling Process

The geometrical model of the log has the same sizes as the real object. It is discretized by a planed mesh (Δl = 15 mm). The cooling was modeled at the following temperature ranges (refer to *figure 8*):

- **I range**: from initial temperature t_{w0} = 22.4°C to reaching of t_w = 0°C (cooling of the studied log with fully liquid water in it);
- **II range**: from t_w = 0°C to t_w = –1°C (freezing of the whole amount of the free water in the log);
- **III range**: from t_w = –1°C to t_w = –28.8°C at the end of the 50 h freezing process (freezing of a part of the bound water in the studied log).

The change of the temperatures in the same four characteristic points as the real object has been graphically presented and analyzed. The aim of the simulations was to assess the degree of the qualitative and quantitative compliance between the experimentally determined and calculated by ANSYS temperatures in the longitudinal section of the log.

The average value of *RSME* σ_{avg} has been used as a criterion for the degree of compliance between the compared temperatures

$$\sigma_{\text{avg}} = \sqrt{\frac{\sum_{n=1}^{N}\sum_{p=1}^{P}\left(t_{p,n}^{\text{calc}} - t_{p,n}^{\text{exp}}\right)^2}{P(N-1)}}, \qquad (16)$$

where $t_{p,n}^{calc}$ and $t_{p,n}^{exp}$ are the calculated and experimentally established temperatures in the characteristic points;

p – number of the characteristic points in the log's longitudinal section: p = 1, 2, 3, 4, i.e. P = 4 is inputted into eq. (16);

n – number of the moments of the freezing process (200 time steps at time duration of 50 h and time step of 900 s).

RSME has been calculated simultaneously for total $(N+1)\cdot P$ = 804 temperature-time points with the help of MS Excel.

5.1. Physical Properties of the Wood and Boundary Conditions of the Cooling Process

The change of thermal conductivities, effective specific heat capacities and heat transfer coefficients during the 50 h log's freezing has been computed by the help of software Visual Fortran.

5.1.1. Thermal Conductivities

The calculated changes of the thermal conductivities in radial and longitudinal directions in the center of the studied beech log are presented on *figure 11*.

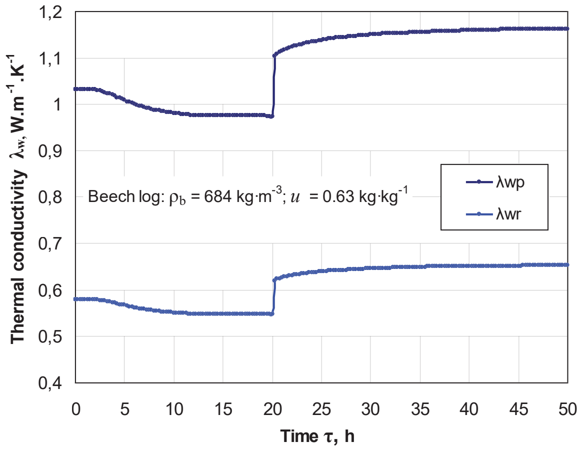

Figure 11. Thermal radial and longitudinal conductivities in center of the studied log during freezing

Using the data from *figure 11*, the following average values of λ_{wr} and λ_{wp} have been determined and used at the modeling investigations:

- $\lambda_{wr1} = 0.560$ W·m^{-1}·K^{-1}, $\lambda_{wp1} = 0.998$ W·m^{-1}·K^{-1};
- $\lambda_{wr2} = 0.548$ W·m^{-1}·K^{-1}, $\lambda_{wp2} = 0.975$ W·m^{-1}·K^{-1};
- $\lambda_{wr3} = 0.646$ W·m^{-1}·K^{-1}, $\lambda_{wp3} = 1.151$ W·m^{-1}·K^{-1}.

5.1.2. Wood Density

According to eq. (9) the wood density of the studied beech log with basic density $\rho_b = 684$ kg·m^{-3} and moisture content u = 0.63 kg·kg^{-1} is equal to 1115 kg·m^{-3}.

5.1.3. Effective Specific Heat Capacities

The change of the specific heat capacities of the wood and the water in the center of the studied log is presented on *figure 12*. The specific heat capacity variation of the frozen free water in the log's center is shown on *figure 13*. According to these variations the average values of c_{we1}, c_{we2}, and c_{we3} have been determined and used at the simulation:

- $c_{we1} = 2744$ J·kg^{-1}·K^{-1};
- $c_{we2} = 2684 + 61267 - 339 = 63612$ J·kg^{-1}·K^{-1};
- $c_{we3} = 2086 + 747 - 60 = 2773$ J·kg^{-1}·K^{-1}.

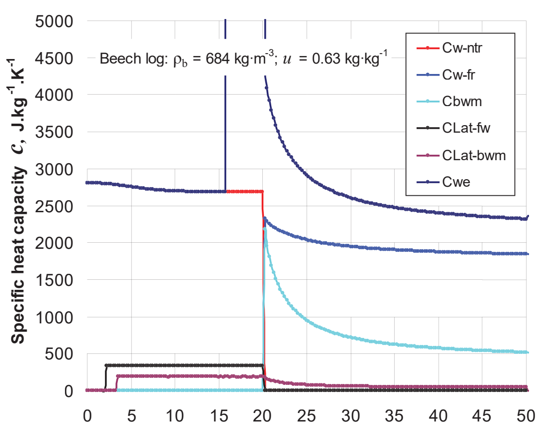

Figure 12. Specific heat capacities in the center of the studied beech log during its cooling

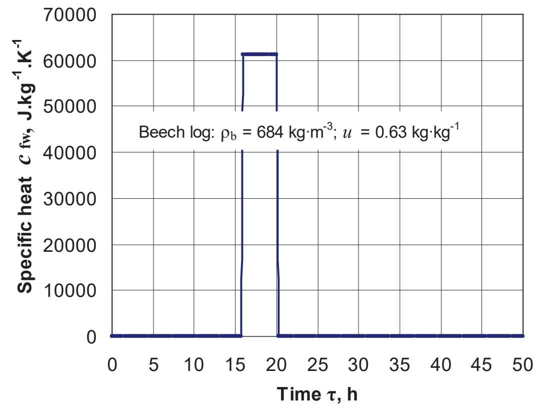

Figure 13. Specific heat capacity of the free water in the center of the studied log during its cooling

5.1.4. Heat Transfer Coefficients

For the computation with ANSYS of the temperature field in subjected to freezing beech log the presented on *figure 14* values of the heat transfer

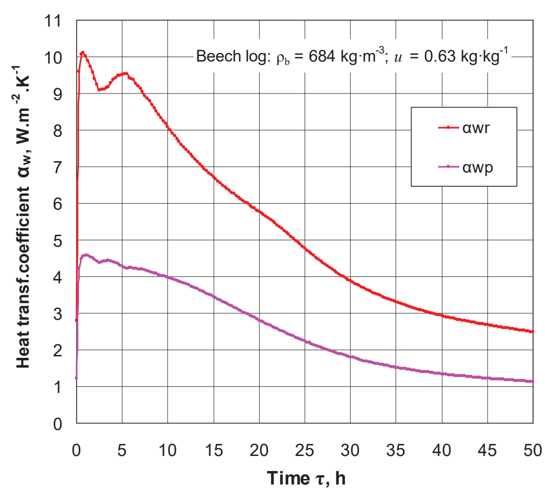

Figure 14. Change of the heat transfer coefficients at different surfaces of the beech log during the cooling

coefficients of the log's surfaces in radial and longitudinal directions have been used as an input data. These values of α_{wr} and α_{wp} have been calculated in Visual Fortran with an interval of 60 s synchronously with the solving of an own non-linear mathematical model of the logs' freezing process

During the freezing, the values of α_{wr} and α_{wp} decrease because they depend on the decreasing with the time difference between the temperature of the air medium, t_m, and temperature on the log's surface, t_s.

5.1.5. Temperature of the Cooling Air

The change of the cooling air temperature T_m, shown on *figure 10*, with high accuracy (correlation of 0.99 and *RSME* of 1.61 °C) has been approximated by software Table Curve 2D [17]:

$$T_m = \frac{a_{fr} + c_{fr}\tau^{0.5}}{1 + b_{fr}\tau^{0.5}}, \quad (17)$$

The coefficients in (17) are: a_{fr} = 294.3352069, b_{fr} = 0.010648218 and c_{fr}= 2.468350514.

The calculated values of Tm according to (17) with a time step $\Delta\tau$ = 60 s have been used as input data in the boundary condition for the computation in ANSYS of the temperature field in subjected to freezing beech log.

6. Numerical Simulation of Temperature Field in the Cooled Beach Log

The finite element mesh on ¼ of the longitudinal section of the subjected to freezing log and the positioning of the four characteristic points T1, T2, T3, and T4 in it are presented on *figure 15*. The numerical simulation of the temperature fields is implemented at duration of the cooling 50 h using different combinations of the input data.

The first simulation has been made with the following combination of the input data:

• average values of the thermal conductivities and effective specific heat capacities of the log, which have been determined above for the separate three ranges of the freezing process (refer to *figure 8*);

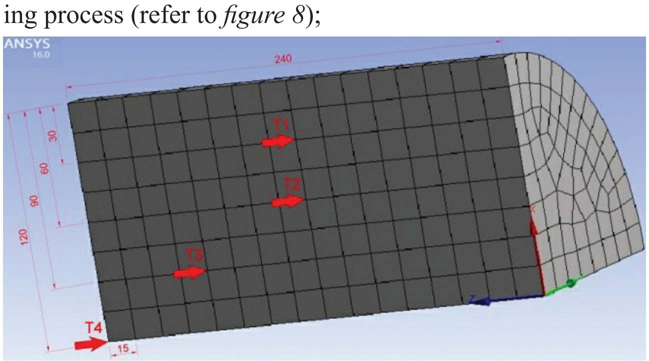

Figure 15. Calculation mesh on ¼ of the longitudinal section of the subjected to freezing log

• constant value of the wood density of 1115 kg·m-3;

• variation of the heat transfer coefficients according to (14) and (15) using an exponent E_{fr} = 0.52 in them at time intervals of 60 (*figure 14*);

• variation of the cooling air temperature according to (17) at time intervals of 60 s.

The temperatures, computed at the above input data, are much slower than the experimentally determined ones, shown on *figure 10*. The calculated value of *RSME* according to (16) was unacceptably large and equal to 12.37 K respectively.

The study has shown that the main reasons for such a large value of *RSME* are the inputted relatively small values of the heat transfer coefficients, especially during the second and the third ranges. That provoke next simulation of the cooling of the log using the maximal values of the heat transfer coefficients α_{wr} = 10.11 $W \cdot m^{-2} \cdot K^{-1}$ and α_{wp} = 4.58 $W \cdot m^{-2} \cdot K^{-1}$ during the freezing process (refer to *figure 14*).

The obtained in this solution, the experimentally established temperatures in the log and log's surface temperature t_s, and t_m are given on *figure 16*. The comparison shows good qualitative and quantitative conformity between the measured and computed temperatures. This is proven by a relatively small value of *RSME* of 1.69 K.

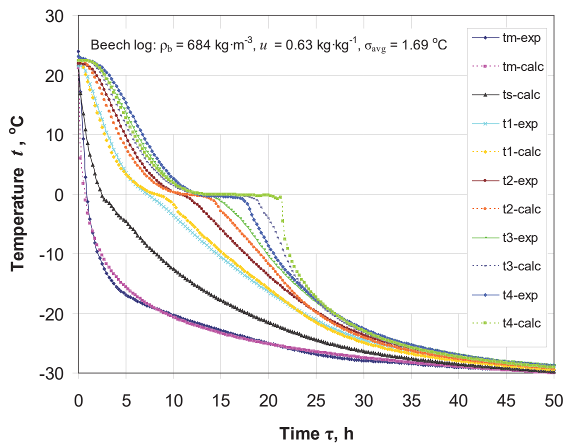

Figure 16. Experimentally determined and calculated temperatures at constant maximal values of the heat transfer coefficients

Lower values of *RSME* also have been obtained at smaller values of the specific heat capacity than c_{we2} = 63612 $J \cdot kg^{-1} \cdot K^{-1}$ and also with 1.5 times larger values of the heat transfer coefficients than their maximal values. For example:

• σ_{avg} = 1.48°C when c_{we2} = 55000 $J \cdot kg^{-1} \cdot K^{-1}$, $\alpha_{wr:1.5max}$ = 15.17 $W \cdot m^{-2} \cdot K^{-1}$ and $\alpha_{wp:1.5max}$ = 6.87 $W \cdot m^{-2} \cdot K^{-1}$;

• $\sigma_{avg-min}$ = 1.27°C when c_{we2} = 45000 $J \cdot kg^{-1} \cdot K^{-1}$, $\alpha_{wr:1.5max}$ = 15.17 $W \cdot m^{-2} \cdot K^{-1}$ and $\alpha_{wp:1.5max}$ = 6.87 $W \cdot m^{-2} \cdot K^{-1}$ (*figure 17*).

The further decreasing of c_{we2} causes an increase of the *RSME* and physically non possible shortening of the freezing process of the free water in the wood.

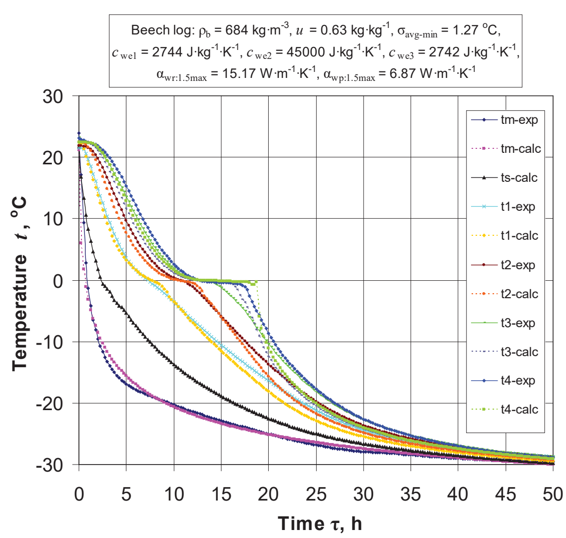

Figure 17. Experimentally determined and calculated temperatures at 1.5 times larger than the maximal values of the heat transfer coefficients and at decreased value of c_{we2} (c_{we2} = 45000 $J \cdot kg^{-1} \cdot$K-1)

7. Conclusions

An approach for modeling and numerical simulation of temperature fields in cooled logs, including the freezing process is suggested. It is used for the computation of the transient temperature distribution in a beach log at cooling to temperature of approximately –30 °C. The cooling process has been divided by three temperature ranges. During the first range only a cooling of the logs with fully liquid water in them occurs. During the second and third stages the phase transitions of the free and the bound water in the wood into ice occurs respectively.

The results of the numerical simulation are used to evaluate the qualitative and quantitative compliance between the experimentally determined and calculated temperatures in the log. The average value of *RSME* for characteristic points in the cooled body has been used as a criterion for the accuracy of the physical and boundary conditions and for their calibration. So the suggested approach can be successfully applied for the computation of the temperature fields in cooled wood bodies at different conditions and subsequent automatic control of thermal treatment of the wood materials [6,7].

It must be noted that such modeling investigations have to be validated by relevant experimental and simulation studies.

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The numerical simulations by software ANSYS are implemented in Center of Mathematical Modeling and Numerical Simulation at University of Chemical Technology and Metallurgy in Sofia.

Symbols

c – specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)
D – diameter (m)
E – exponent in the equations for determining of α (-)
L – length (m) or specific latent heat ($J \cdot kg^{-1}$)
N – amount of knots of the calculation mesh
R – radius (m)
r – radial coordinate: $0 \le r \le R$ (m)
T – temperature (K)
t – temperature (°C)
u – moisture content ($kg.kg^{-1}$)
z – longitudinal coordinate: $0 \le z \le L/2$ (m)
α – heat transfer coefficients between the log’s surfaces and the surrounding air medium ($W \cdot m^{-2} \cdot K^{-1}$)
λ – thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
ρ – density ($kg \cdot m^{-3}$)
φ – relative humidity of the air (%)
σ – root square mean error (°C)
τ – time (s)
Δl – finite element edge lenght (m)

Subscripts and Superscripts

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)
bw – bound water
bwm – maximal possible amount of bound water
calc – calculated
exp – experimental
fr – freezing
fre – end of freezing
fsp – fiber saturation point
fw – free water
Lheat – latent heat
m – medium (for freezing substance) or maximum (for bound water)
n – following number of the separate moments of the freezing process
nfw – non-frozen water
p – parallel to the wood fibers or following number of the characteristic points in the log’s longitudinal section
r – radial direction
w – wood
we – wood effective (for specific heat capacity of the wood)
0 – initial
1 – first (for temperature range of freezing)
2 – second (for temperature range of freezing)
3 – third (for temperature range of freezing)
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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