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COMPUTING THE 2D TEMPERATURE DISTRIBUTION IN LOGS STORED FOR A LONG TIME IN AN OPEN WAREHOUSE IN WINTER AND DURING SUBSEQUENT AUTOCLAVE STEAMING

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ABSTRACT

An approach to computing and research on the 2D non-stationary temperature distribution in horizontally situated logs in an open warehouse under the influence of periodically changing atmospheric temperature in winter and during their subsequent steaming in autoclaves is described in the paper. Mathematical descriptions of the changing atmospheric temperature and also of the temperature of the steaming medium in the autoclaves and of the conditioning air medium after steaming are introduced as boundary conditions in own mutually connected 2D non-linear mathematical models of the log freezing and defrosting processes. Numerical solutions of the coupled models in the calculation environment of Visual FORTRAN Professional are given as an application of the suggested approach. The results from a simulative investigation of the change in the 2D temperature field and average mass temperature of beech (*Fagus sylvatica* L.) logs with a diameter of 0.4 m, length of 0.8 m, and moisture content of 0.6 kg·kg^{-1} during their 5 day- and night-long continuous alternating freezing and defrosting at sinusoidal change of the air temperature with different initial values below and equal to 0 °C and with different amplitudes, and also during steaming of such frozen logs with different initial temperature in an autoclave and their subsequent conditioning are graphically presented and analysed.

Key words: autoclave steaming, beech logs, 2D coupled models, atmospheric temperature, freezing, defrosting, model based control.

INTRODUCTION

It is known that different layered items are subjected to steaming or heating in agitated water for plasticization of the logs and other kinds of wood materials in the production of veneer (CHUDINOV 1966, SHUBIN 1990, STEINHAGEN 1986, 1991, TREBULA – KLEMENT 2002, VIDELOV 2003, DELIISKI 2003, 2009, 2011, PERVAN 2009, DELIISKI – DZURENDA 2010), etc.

Steaming in autoclaves is one of the most intensive and energy effective processes for plasticization of the wood materials (RIEHL *et al.* 2002, DELIISKI 2003, 2004, SOKOLOVSKI *et al.* 2007, DELIISKI *et al.* 2015).

For the development and automatic achieving of energy saving and regimes with an optimal duration for autoclave steaming of logs, it is very important to know the initial temperature of the materials of each batch subjected to the thermal treatment.

The initial temperature of the separate batches depends on the duration of log storing in an open warehouse at periodically changing air temperature (DELISKI *et al*. 2020a, 2020b). The influence of this temperature in winter on the temperature field and on the average mass temperature of the logs is of considerable scientific and practical interest.

The aim of the paper is to suggest an approach to computing the 2D temperature distribution in logs at periodically changing atmospheric temperature during many days and nights in winter and to study the influence of the computed average mass temperature of such logs on the duration of the regimes for their steaming in autoclaves.

MATERIAL AND METHODS

Mathematical models of the 2D temperature distribution in logs during their alternating freezing and defrosting in the air environment

In (DELIISKI and TUMBARKOVA 2019, TUMBARKOVA 2019), the following coupled models describing the 2D non-stationary temperature distribution in logs situated in the air environment subjected to freezing and subsequent defrosting horizontally were created, solved, and verified:

a) During the log freezing process:

$$c_{\text{eff-fr}} \cdot \rho \frac{\partial T(r,z,\tau)}{\partial \tau} = \lambda_{\text{r-eff-fr}} \left[\frac{\partial^2 T(r,z,\tau)}{\partial r^2} + \frac{1}{r} . \frac{\partial T(r,z,\tau)}{\partial r} \right] + \frac{\partial \lambda_{\text{r-eff-fr}}}{\partial T} \left[\frac{\partial T(r,z,\tau)}{\partial r} \right]^2 + \\ + \lambda_{\text{p-eff-fr}} \frac{\partial^2 T(r,z,\tau)}{\partial z^2} + \frac{\partial \lambda_{\text{p-eff-fr}}}{\partial T} \left[\frac{\partial T(r,z,\tau)}{\partial z} \right]^2 + q_{\text{v}} \tag{1}$$

under an initial condition:

$$T(r,z,0) = T_{01} \tag{2}$$

and the following boundary conditions:

• Along the radial coordinate *r* on the log frontal surface:

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

• Along the longitudinal coordinate *z* on the log cylindrical surface:

$$\frac{T(0,z,\tau)}{\partial z} = -\frac{\alpha_{\text{r-fr}}(0,z,\tau)}{\lambda_{\text{r-eff-fr}}(0,z,\tau)} \left[T(0,z,\tau) - T_{\text{air-fr}}(\tau) \right]. \tag{4}$$

b) During the log defrosting process:

$$c_{\text{eff-dfr}} \cdot \rho \frac{\partial T(r,z,\tau)}{\partial \tau} = \lambda_{\text{r-eff-dfr}} \left[\frac{\partial^2 T(r,z,\tau)}{\partial r^2} + \frac{1}{r} . \frac{\partial T(r,z,\tau)}{\partial r} \right] + \frac{\partial \lambda_{\text{r-eff-dfr}}}{\partial T} \left[\frac{\partial T(r,z,\tau)}{\partial r} \right]^2 + \\ + \lambda_{\text{p-eff-dfr}} \frac{\partial^2 T(r,z,\tau)}{\partial z^2} + \frac{\partial \lambda_{\text{p-eff-dfr}}}{\partial T} \left[\frac{\partial T(r,z,\tau)}{\partial z} \right]^2 \tag{5}$$

under an initial condition

$$T(r,z,0) = T(r,z,\tau_{\text{fre}}) \tag{6}$$

and boundary conditions

• Along the radial coordinate r:

$$\frac{\partial T(r,0,\tau)}{\partial r} = -\frac{\alpha_{\text{p-dfr}}(r,0,\tau)}{\lambda_{\text{p-eff-dfr}}(r,0,\tau)}\left[T(r,0,\tau) - T_{\text{air-dfr}}(\tau)\right], \tag{7}$$

• Along the longitudinal coordinate z:

$$\frac{\partial T(0,z,\tau)}{\partial z} = -\frac{\alpha_{\text{r-dfr}}(0,z,\tau)}{\lambda_{\text{r-eff-dfr}}(0,z,\tau)}\left[T(0,z,\tau) - T_{\text{air-dfr}}(\tau)\right]. \tag{8}$$

where $c_{\text{eff-fr}}$ and $c_{\text{eff-dfr}}$ are the effective specific heat capacities of the wood during the freezing and defrosting of logs in temperatures when the free and the bound water crystallizes or melts (DELIISKI and TUMBARKOVA 2017), $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$; $\lambda_{\text{r-eff-fr}}$ and $\lambda_{\text{p-eff-fr}}$ – effective thermal conductivities of the wood in radial and longitudinal direction during the separate stages of the log freezing process, $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$; $\lambda_{\text{r-eff-dfr}}$ and $\lambda_{\text{p-eff-dfr}}$ – effective thermal conductivities of the wood in radial and longitudinal direction during the separate stages of the log defrosting process, $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$; ρ_{w} – wood density, $\text{kg}\cdot\text{m}^{-3}$; r – coordinate of the separate points along the log radius: $0 \le r \le R$, m; R – radius of the log, m; z – coordinate of the separate points along the log length: $0 \le z \le L/2$, m (Fig. 1); L – length of the log, m; τ – time, s; τ_{fre} – terminal time of the freezing process and the time when the coupled defrosting process begins, s; T – temperature, K; T_{01} – initial average mass temperature of the log subjected to freezing, K; $T(r,z,0)$ – temperature of all points in the log volume at the beginning of the freezing or defrosting process, K; $T(r,0,\tau)$ – temperature of all points on the log frontal surface during the freezing or defrosting process, K; $T(0,z,\tau)$ – temperature of all points on log cylindrical surface during the freezing or defrosting process, K; $T_{\text{air-fr}}$ and $T_{\text{air-dfr}}$ – temperature of the ambient air environment during the log freezing and defrosting processes, K; q_{v} – internal heat source in the log volume caused by the release of the latent heat of both the free and bound water in the wood during their crystallization (DELIISKI and TUMBARKOVA 2017, 2019), $\text{W}\cdot\text{m}^{-3}$; $\alpha_{\text{r-fr}}$ and $\alpha_{\text{p-fr}}$ – convective heat transfer coefficients between the log surfaces and ambient air environment in radial and longitudinal direction during the freezing process respectively, $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$; $\alpha_{\text{r-dfr}}$ and $\alpha_{\text{p-dfr}}$ – convective heat transfer coefficients between the log surfaces and ambient air in radial and longitudinal direction respectively during the thawing process,$\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$.

The models (1) to (8) can be used for the calculation of the 2D temperature distribution in logs, which length, L, is larger than their diameter, D, not more than 3 ÷ 4 times.

Modelling of the 2D temperature distribution in frozen logs during their steaming in an autoclave and subsequent cooling in an air medium

The mechanism of 2D change in the temperature in the longitudinal sections of frozen logs during their steaming and subsequent conditioning is mathematically described by eq. (5) (DELIISKI 2003) under an initial condition (DELIISKI *et al.* 2020b)

$$T(r,z,0) = T_{02} \tag{9}$$

where T_{02} is an initial average mass temperature of the log subjected to steaming, K and the following boundary conditions:

• During the steaming process – at a prescribed temperature of the steaming medium:

$$T(r,0,\tau) = T(0,z,\tau) = T_{\mathrm{m}}(\tau) \tag{10}$$

where T_m is the temperature of the steaming medium in the autoclave, K.

• During the cooling the steamed logs in an air environment – under convective boundary conditions, which are presented above by eqs. (7) and (8).

Equations (1) to (10) represent a common form of the coupled mathematical models of 2D heat distribution in logs subjected to alternating freezing and defrosting in an air environment and after that to steaming and subsequent cooling in an air medium.

The positioning of the coordinate axis *r* and *z*, and also of 4 representative knots of the calculation mesh is shown in Fig. 1. Subsequently, it was used for the numerical solving the coupled models containing the eqs. (1) to (10).

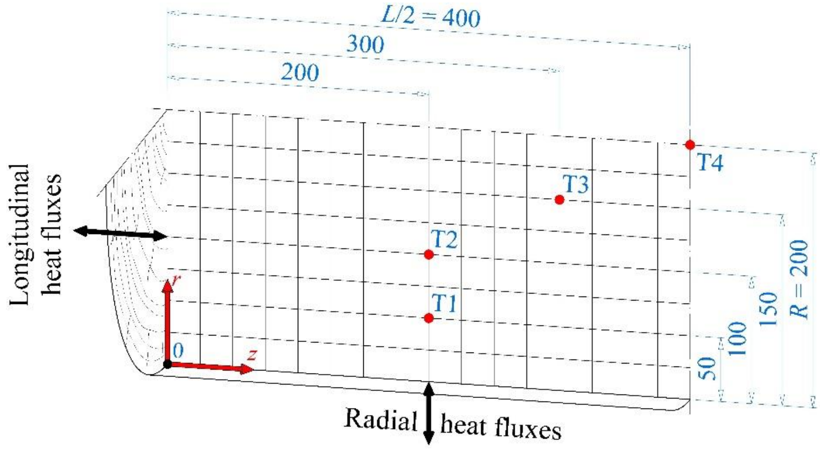

Fig. 1 Positioning of the coordinate axes and the knots of the calculation mesh with representative points T1, T2, T3, and T4 on ¼ of the longitudinal section of log subjected to freezing, defrosting, and autoclave steaming.

Mathematical description of the thermo-physical properties and icing degree of the logs

Mathematical descriptions of the effective specific heat capacities of the wood during its freezing and defrosting, $c_{\text{eff-fr}}$ and $c_{\text{eff-dfr}}$, respectively, and also of the effective thermal conductivities of the wood in radial and longitudinal direction during its freezing and defrosting, $\lambda_{\text{r-eff-fr}}$, $\lambda_{\text{p-eff-fr}}$, and $\lambda_{\text{r-eff-dfr}}$, $\lambda_{\text{p-eff-dfr}}$ respectively, were suggested in DELIISKI (2003, 2004, 2009, 2011, 2013a, 2013b, DELIISKI – DZURENDA 2010, DELIISKI *et al.* 2010, 2019, 2020b) based on the experiments mentioned in the dissertations of CHUDINOV (1966) and KANTER (1955) related to the change in *c* and λ as a function of *t* and *u*.

These relations are used in both the European (CHUDINOV 1968, SHUBIN 1990, POŽGAJ *et al*. 1997, TREBULA and KLEMENT 2002, VIDELOV 2003, PERVAN 2009, HRČKA and BABIAK 2017) and the American professional literature (STEINHAGEN 1986, 1991, STEINHAGEN and LEE 1988, KHATTABI and STEINHAGEN 1992, 1993, 1995) when calculating various processes of wood thermal treatment.

Mathematical descriptions of the effective specific heat capacities of the logs during their freezing and defrosting, $c_{\text{eff-fr}}$ and $c_{\text{eff-dfr}}$ respectively, which participate in eqs. (1) and (5) respectively, were given in (DELIISKI and TUMBARKOVA 2019, TUMBARKOVA 2019, TUMBARKOVA *et al.* 2018). Mathematical descriptions of the wood density above the hygroscopic range, ρ, and of the internal heat source in the log volume, q_v, are also given in the literature.

For the calculation of the heat transfer coefficients of the horizontally situated beech logs during their freezing and defrosting at the free convection of the periodically changing ambient air temperature, the following experimentally verified equations (3), (4), (7), and (8) (TELEGIN *et al.* 2002, TUMBARKOVA 2019, DELIISKI *et al.* 2020c) were used:

• In the radial direction on the cylindrical surface of the logs:

$$\alpha_{\text{r-fr}} = 1.123\left[T(0,z,\tau) - T_{\text{m-fr}}(\tau)\right]^{0.46}, \tag{11}$$

$$\alpha_{\text{r-dfr}} = 1.123\left[T(0,z,\tau) - T_{\text{m-dfr}}(\tau)\right]^{0.26}. \tag{12}$$

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

$$\alpha_{\text{p-fr}} = 2.56\left[T(r,0,\tau) - T_{\text{m-fr}}(\tau)\right]^{0.46}, \tag{13}$$

$$\alpha_{\text{p-dfr}} = 2.56\left[T(r,0,\tau) - T_{\text{m-dfr}}(\tau)\right]^{0.26}. \tag{14}$$

The heat transfer coefficients $\alpha_{\text{r-cond}} = \alpha_{\text{r-dfr}}$ in eq. (8) and $\alpha_{\text{p-cond}} = \alpha_{\text{p-dfr}}$ in eq. (7) of the beech logs subjected to the air conditioning immediately after their autoclave steaming are equal to (DELIISKI 2003, 2013b)

$$\alpha_{\text{r-cond}} = 0.380 \cdot 1.026^{\left|T(0,z,\tau_{\text{reg}}) - T_{\text{air}}(\tau)\right|} \cdot \left[T(0,z,\tau_{\text{reg}}) - T_{\text{air}}(\tau)\right], \tag{15}$$

$$\alpha_{\text{p-cond}} = 0.676 \cdot 1.026^{\left|T(r,0,\tau_{\text{reg}}) - T_{\text{air}}(\tau)\right|} \cdot \left[T(r,0,\tau_{\text{reg}}) - T_{\text{air}}(\tau)\right], \tag{16}$$

where T_{air} is the value of the surrounding air environment during the log conditioning, K; τ_{reg} – duration of the steaming regime, s.

Mathematical description of the periodically changing atmospheric temperature

Mathematical description of the change in the atmospheric temperature, T_{air}, near the logs stored many days and nights in an open warehouse in winter is needed for the numerical solution of the coupled mathematical models (1) to (8).

The periodic change of the atmospheric temperature T_{air} during a long time when its maximum value $T_{\text{air-max}}$ remains constant can be described using the following equation (GUZENDA and GANOWICZ 1986, DELIISKI 1988, OLEK and GUZENDA 1995):

$$T_{\text{air}} = T_{\text{air0}} + (T_{\text{air-max}} - T_{\text{air0}}) \cdot \sin(\omega \cdot \tau) \tag{17}$$

where T_{air0} is the initial value of T_{air}, K; $T_{\text{air-max}}$ – maximal value of T_{air} during its sinusoidal change, K; ω – angular frequency of T_{air}, s^{-1}; τ – time, s.

The angular frequency of T_{air} in eq. (17) is equal to

$$\omega = \frac{2\pi}{\tau_0} \tag{18}$$

where τ_0 is the period of change in T_{air}, s.

It is needed to use π = 3.14159 for the precise solution of the tasks with the participation of eqs. (17) and (18).

For a periodic change of the air temperature during one day and night, i.e. at τ_0 = 1 d = 24 h = 86,400 s, according to eq. (18) it is obtained that

$$\omega = \frac{2\pi}{\tau_0} = \frac{2 \cdot 3.14159}{86400} = 7.2722 \cdot 10^{-5}\ \text{s}^{-1}$$

When T_{air0} and $T_{air\text{-}max}$ gradually increase or decrease during the time compared to their initial values, $T_{air0\text{-}in}$ and $T_{air\text{-}max\text{-}in}$ respectively, the temperature T_{air} can be calculated according to the equation

$$T_{air} = T_{air0\text{-}in} \cdot (1 \pm K_{air0} \cdot \tau) + [(T_{air\text{-}max\text{-}in} - T_{air0\text{-}in}) \cdot (1 \pm K_{air\text{-}a} \cdot \tau)] \cdot \sin(\omega \cdot \tau) \quad (19)$$

where K_{air0} and $K_{air\text{-}a}$ (in s^{-1}) are coefficients determining how much the change in T_{air0} and in the amplitude of T_{air} equal to $T_{air\text{-}a} = T_{air\text{-}max\text{-}in} - T_{air0\text{-}in}$, respectively, is over a period of time. These coefficients can be calculated according to following equations (DELIISKI *et al.* 2020a):

$$K_{air0} = \frac{\dfrac{\Delta T_{air0\text{-}\tau_0}}{T_{air0\text{-}in}}}{\tau_0} \quad (20)$$

$$K_{air\text{-}a} = \frac{\dfrac{\Delta T_{air\text{-}max\text{-}\tau_0}}{T_{air\text{-}max\text{-}in} - T_{air0\text{-}in}}}{\tau_0} \quad (21)$$

where $\Delta T_{air0-\tau_0}$ is the change in T_{air0} during the time interval equal to τ_0, K; $\Delta T_{air\text{-}max-\tau_0}$ – change in $T_{air\text{-}max}$ during one period of τ_0, K; $T_{air0\text{-}in}$ – initial value of the periodically changing temperature T_{air}, K; $T_{air\text{-}max\text{-}in}$ – initial value of $T_{air\text{-}max}$, K.

The signs "+" and "–" on the right side of eq. (19) are used when T_{air0} and $T_{air\text{-}max}$ increase or decrease respectively during the periodical change in T_m.

For the purpose of the analysis of the current log temperature condition at the initial temperature of the logs before their steaming, synchronously with solving the models (1) to (8), the average mass temperature of the logs, T_{avg}, for each moment of their alternating freezing and defrosting is calculated according to the equation

$$T_{avg} = \frac{1}{S} \iint_S T_{i,k}^n \mathrm{d}S \quad (22)$$

where the area of ¼ of the log longitudinal section, S, is equal to

$$S = R \cdot \frac{L}{2} \quad (23)$$

RESULTS AND DISCUSSION

The mathematical descriptions of the thermo-physical representatives of non-frozen logs considered above, and also of the periodically changing atmospheric temperature were introduced in the mathematical models (1) to (8).

For numerical solution of the models aimed at computing the 2D temperature fields in logs, a software program was prepared. It was an input in the calculation environment of Visual FORTRAN Professional. An explicit form of the finite-difference method were used for transformation of the models in a form suitable for programming (DELIISKI 2003, 2011, 2013b, DELIISKI and TUMBARKOVA 2019). The calculation mesh was built on ¼ of the longitudinal section of the logs due to the circumstance that this ¼ is mirror symmetrical towards the remaining ¾ of the same section (refer to Fig. 1).

Using the program, computations were made to determine the 2D non-stationary temperature distribution in the longitudinal sections of beech logs under different boundary conditions given below.

During the solution of the models, the mathematical descriptions of the thermo-physical characteristics of non-frozen and frozen beech logs with industrial dimensions (diameter D = 0.4 m and length L = 0.8 m), basic density $\rho_b = 560\ \mathrm{kg \cdot m^{-3}}$ (DELIISKI and DZURENDA 2010), moisture content of $0.6\ \mathrm{kg \cdot kg^{-1}}$, and standardized fibre saturation point at 293.15 K (i.e. at 20 °C), $u_{\mathrm{fsp}}^{293.15} = 0.31\ \mathrm{kg \cdot kg^{-1}}$, were used.

The change in the following parameters during the alternating atmospheric freezing and defrosting or autoclave steaming of the logs were studied in this work: temperature of the processing mediums t_{air} during storing the logs in an open warehouse and t_{m} during their steaming in an autoclave, log surface and average mass temperatures, t_{s} and t_{avg} respectively, and also t of 4 representative points in the logs.

The coordinates of the four representative points in the longitudinal section of the logs were equal to: Point 1 with temperature t_1: $r = R/4$ = 50 mm and $z = L/4$ = 200 mm; Point 2 with t_2: $r = R/2$ = 100 mm and $z = L/4$ = 200 mm; Point 3 with t_3: $r = 3R/4$ = 150 mm and $z = 3L/8$ = 300 mm; Point 4 with t_4: $r = R$ = 200 mm and $z = L/2$ = 400 mm. These coordinates of the points allow the determination and analysis of the 2D temperature distribution in logs during their storing for a long time in an open warehouse and during their subsequent autoclave steaming and conditioning.

Computation of 2D temperature field in logs at changing atmospheric temperature

Three options of 120 h (i.e. 5 d) continuous periodic freezing and defrosting of beech logs with an initial temperature t_{01} = 0 °C (refer to eq. (2)) were studied as follows:

- for Log 1: at a constant values of the initial air temperature T_{air0} = 268.15 K (i.e. t_{air0} = –5 °C) and of the maximum value of the sinusoidal changing air temperature $T_{\mathrm{air\text{-}max}}$ = 288.15 K (i.e. at the amplitude value of the air temperature $t_{\mathrm{air\text{-}a}} = T_{\mathrm{air\text{-}max}} - T_{\mathrm{air0}}$ = 20 °C);
- for Log 2: at a constant value of t_{air0} = –5 °C and gradual decrease in the value of $t_{\mathrm{air\text{-}a\text{-}in}}$ = 20 °C by 2 °C/d;
- for Log 3: at a gradual decrease in the initial values of $t_{\mathrm{air0\text{-}in}}$ = –5 °C and $t_{\mathrm{air\text{-}a\text{-}in}}$ = 20 °C by 2 °C/d.

To provide a decrease in $t_{\mathrm{air0\text{-}in}}$ = 20 °C and $t_{\mathrm{air\text{-}a\text{-}in}}$ by 2 °C/d, the following values of the coefficients K_{air0} and $K_{\mathrm{air\text{-}a}}$ according to eqs. (20) and (21) were used: $K_{\mathrm{air0}} = -8.6325 \cdot 10^{-8}\ \mathrm{s^{-1}}$ and $K_{\mathrm{air\text{-}a}} = -1.15741 \cdot 10^{-6}\ \mathrm{s^{-1}}$.

Fig. 2, Fig. 3, and Fig. 4 present the calculated change in t_{air}, t_{s}, t_{avg}, and t of 4 representative points in Log 1, Log 2, and Log 3 during their continuous 5 day- and night-long (i.e. 120 h) periodic freezing and defrosting under the described conditions of the atmospheric temperature influence.

It can be seen that during the second period of the change in t_{air} (i.e. between 24$^{\mathrm{th}}$ and 48$^{\mathrm{th}}$ hour) the temperature in all points of the studied logs drops below 0 °C. It means that there are conditions for water crystalizing in the entire volume of the logs. The temperature in the central point, t_4, changes the least. It remains very long in the range from 0 °C and –1 °C, in which the free water in the wood freezes (DELIISKI and TUMBARKOVA 2017). Only in the 81$^{\mathrm{st}}$ h for Log 1, in the 91$^{\mathrm{st}}$ h for Log 2, and in the 71$^{\mathrm{st}}$ h for Log 3 t_4 drops to –1 °C and the freezing process of the whole amount of the free water in the log centre ends and then the freezing of the bound water begins (TUMBARKOVA 2019).

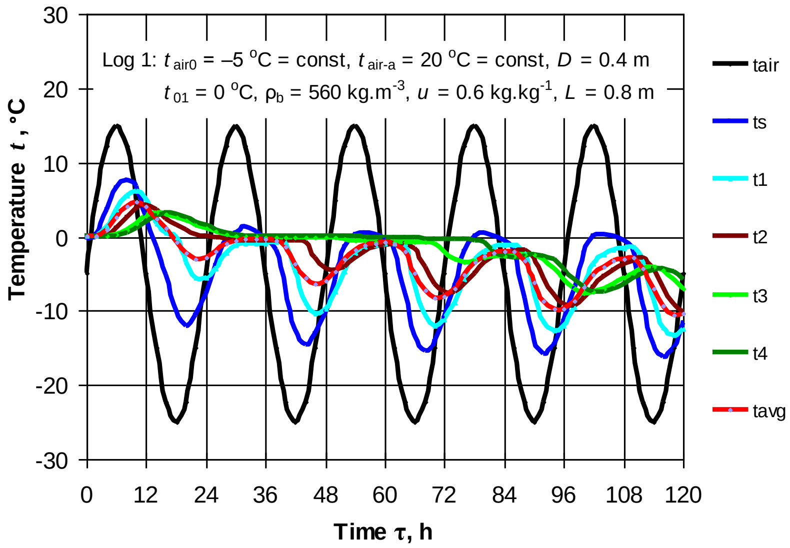

Fig. 2 Change in t_{air}, t_s, t_{avg}, and t of 4 representative points of the Log 1 during its 120 h periodical freezing and defrosting at constant values of t_{air0} and t_{air-a}.

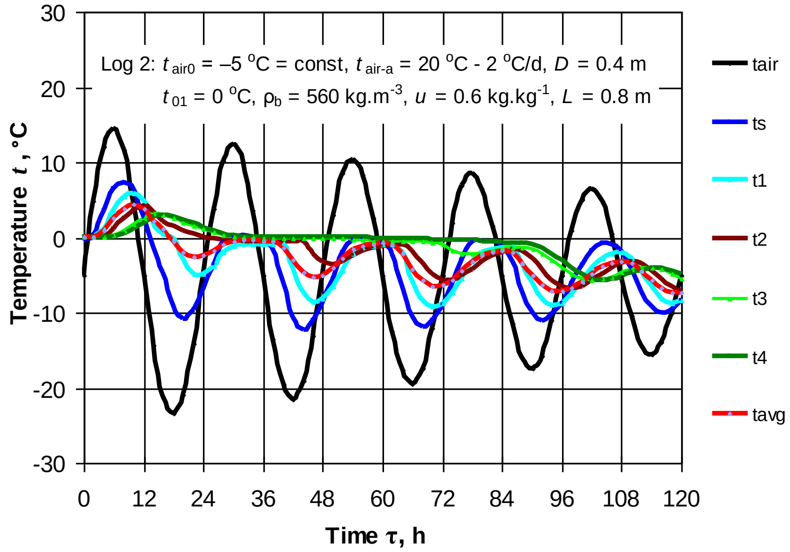

Fig. 3 Change in t_{air}, t_s, t_{avg}, and t of 4 representative points of the Log 2 during its 120 h periodical freezing and defrosting at constant value of t_{air0} and decreasing value of t_{air-a}.

In Fig. 2 it is seen that at the constant values of t_{air0} = –5 °C and t_{air-a} = 20 °C after 96th h, i.e. after the 4th period of t_{air}, a periodical change in the log temperature with practically constant amplitudes for the separate points comes. The further is distance of the point from the log surfaces, the smaller is the amplitude of the periodic change in the temperature in that point. The amplitudes of t_{air}, t_s, t_{avg}, and t in the separate representative points after the 4th period are equal to: t_{air-a} = 20.0 °C, t_{s-a} = 8.4 °C, t_{1a} = 6.4 °C, t_{2a} = 4.3 °C, t_{3a} = 2.0 °C, t_{4a} = 1.6 °C, and t_{avg-a} = 4.1 °C.

When t_{air0} = –5 °C remains constant and the initial value of t_{air-a} = 20 °C decreases by 2 °C/d (Fig. 3) or when both mentioned initial values of t_{air0} and t_{air-a} decrease by 2 °C/d (Fig. 4) during the time, the amplitudes of the temperature in the separate points gradually decrease and during the second half of the last 5th period of t_{air} they are equal to: t_{air-a} = 10.0 °C, t_{sa} = 5.0 °C, t_{1a} = 3.6 °C, t_{2a} = 2.4 °C, t_{3a} = 1.2 °C, and t_{4a} = 1.0 °C.

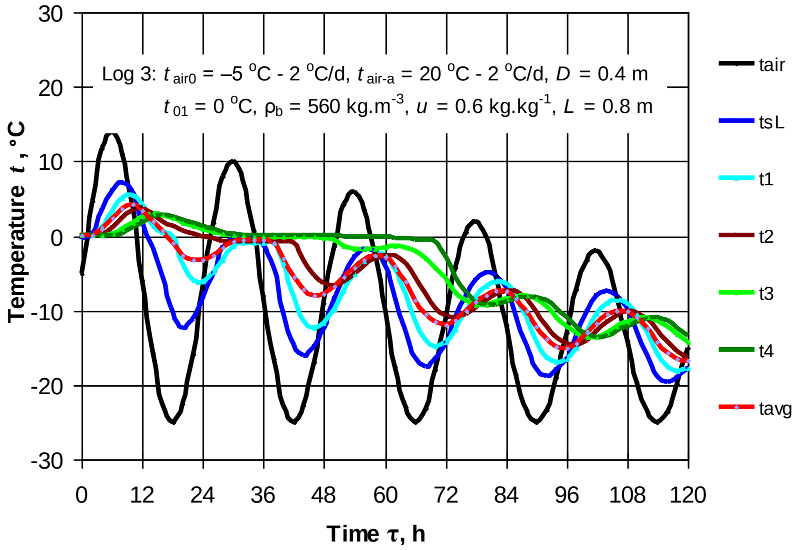

Fig. 4 Change in t_{air}, t_s, t_{avg}, and t of 4 representative points of the Log 3 during its 120 h periodical freezing and defrosting at decreasing values of t_{air0} and t_{air-a}.

The average mass temperature of the logs, t_{avg} strongly affecting the duration and energy consumption of the regimes for autoclave steaming of frozen logs (DELIISKI 2013b) is equal to the following values:

▪ at 24th h: –2.8 °C for Log1, –2.5 °C for Log2, and –3.2 °C for Log3;
▪ at 48th h: –6.0 °C for Log1, –5.0 °C for Log2, and –7.8 °C for Log3;
▪ at 72nd h: –8.2 °C for Log1, –6.4 °C for Log2, and –11.9 °C for Log3;
▪ at 96th h: –9.8 °C for Log1, –7.2 °C for Log2, and –15.1 °C for Log3;
▪ at 120th h: –10.4 °C for Log1, –7.4 °C for Log2, and –16.7 °C for Log3.

Computation of 2D temperature field in logs during their steaming in an autoclave

Two options of autoclave steaming and subsequent conditioning of the frozen beech logs (named as Log 4 and Log 5) were studied:

• Log 4 was with an initial temperature t_{02} = –1 °C (refer to eq. (9));
• Log 5 was with an initial temperature t_{02} = –20 °C.

At the beginning of the steaming process, the Log 4 contains only frozen free water in it, but the Log 5 apart from this contains significant amount of frozen bound water.

During solving the equation (5) under an initial condition (9) and boundary conditions (10), 3-stage regimes for autoclave steaming of the logs were used. The typical temperature time profile of the processing medium temperature t_m in a steaming autoclave and of the air medium for the consequent conditioning of the heated wood materials is shown in (DELIISKI 2003, DELIISKI and DZURENDA 2010, DELIISKI *et al.* 2020b).

In Fig. 5 and Fig. 6, the calculated change in t_m, t_s, and t of 4 representative points of the Log 4 and Log 5 during their autoclave steaming and subsequent conditioning at t_m = 20 °C is presented.

One of the aims of this study was to determine how the average mass temperature of the logs at the beginning of the steaming process influences the duration of the steaming regime. That is why the initial temperature of Log 4 and Log 5, t_{02}, which in the practice is equal to t_{avg} of the logs after their storing in an open warehouse, were assumed to be too different from each other and equal to t_{02} = –1 °C and t_{02} = –20 °C respectively, during the simulations with the model (5) ÷ (8), using eqs. (15) and (16).

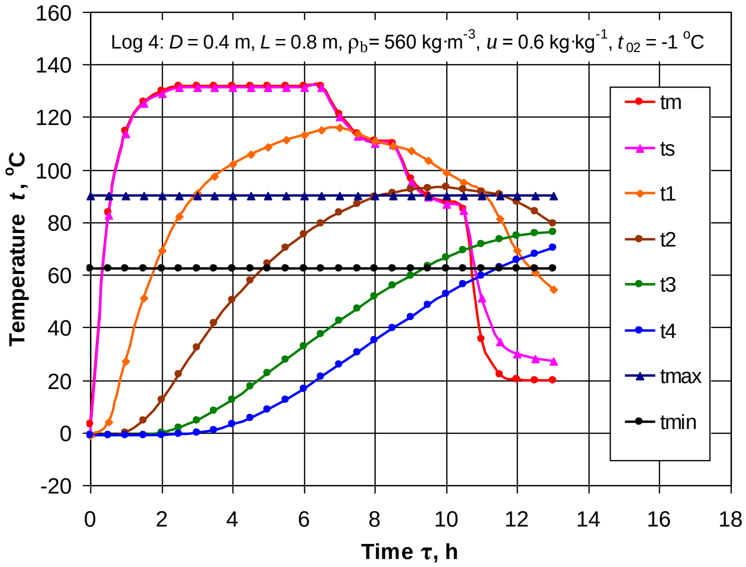

Fig. 5 Change in t_m, t_s, and t in 4 representative points of the Log 4 with t_{02} = –1 °C during its steaming in an autoclave and its subsequent conditioning at t_{air} = 20 °C.

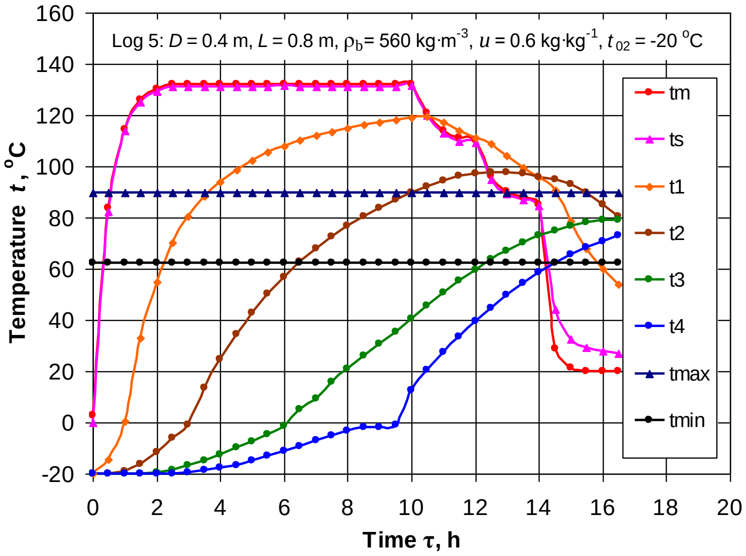

Fig. 6 Change in t_m, t_s, and t in 4 representative points of the Log 5 with t_{02} = –20 °C during its steaming in an autoclave and its subsequent conditioning at t_{air} = 20 °C.

In Fig. 5 and Fig. 6, the minimum and maximum values of the temperature, t_{min} = 62 °C and t_{max} = 90 °C, are also shown. It is well known that the temperature of all representative points of the logs during the veneer cutting process between these optimum values of t_{min} and t_{max} is needed to obtain the quality veneer from plasticized beech wood (DELIISKI 2003, DELIISKI and DZURENDA 2010).

The temperature fields in the logs was computed for the processes of their steaming in an autoclave and their subsequent conditioning in an air environment.

This means that the calculation of the non-stationary 2D change in the temperatures in the longitudinal sections of the logs during the time of their conditioning begins from the already reached temperature during the time of calculations distribution of temperature at the end of the steaming regime. Based on the calculations, the time of reaching the temperature in the entire volume of the heated logs needed for cutting the veneer can be determined (between t_{min} and t_{max} in Fig. 5 and Fig. 6).

Fig. 5 and Fig. 6 show that temperatures of all representative points enter between t_{min} = 62 °C and t_{max} = 90 °C after conditioning of the heated logs in an air environment equal to approximately 60 min for Log 4 and 90 min for Log 5.

The analysis of Fig. 5 and Fig. 6 shows that the duration of the steaming regimes of the studied logs is equal to τ_{reg} = 10.5 h for Log 4 and to τ_{reg} = 14.0 h for Log 5. It means that a decrease in the initial log temperature t_{02} from –1 °C to –20 °C (i.e. by 19 °C causes a decrease in τ_{reg} by 3.5 h, i.e. each decrease in t_{02} by 1 °C in our case causes an increase in τ_{reg} by approximately 11 min.

The comparison of the obtained results with the results in (DELIISKI *et al.* 2020b) show that a decrease in the initial temperature of the logs from 0 °C to –1 °C when the whole amount of the free water is fully crystallized and there is still no frozen bound water in the wood causes elongation of the regime for the autoclave steaming by 30 min.

CONCLUSIONS

An approach to mathematical modelling and research on the 2D non-stationary temperature distribution in logs stored for a long time in an open warehouse in winter under the influence of periodically changing atmospheric temperature and during their subsequent steaming in autoclaves was described in the paper.

Mathematical descriptions of the periodically changing atmospheric temperature, of the temperature of the autoclave steaming regimes of the logs, and also of their subsequent conditioning in an air environment were presented. These descriptions were introduced as boundary conditions in our own 2D non-linear coupled mathematical models of the 2D temperature distribution in logs during their freezing and defrosting.

A software program for solving the models and computing the 2D temperature field of logs during the processes were prepared in the calculation environment of Visual FORTRAN Professional. The paper showed and analysed, e.g. the application of the suggested approach, diagrams of the change in t_m, t_s, t_{avg}, and 2D temperature distribution in beech logs with industrial dimensions (diameter of 0.4 m and length of 0.8 m), basic density of 560 $kg \cdot m^{-3}$, and moisture content of 0.6 $kg \cdot kg^{-1}$ in the following two cases:

• during 5 day-long (i.e. 120 h) continuous alternating freezing and defrosting of logs with an initial temperature of 0 °C under the influence of periodically changing atmospheric temperature at its constant initial value t_{air0} = –5 °C and constant amplitude t_{air-a} = 20 °C (Log 1); at a constant value of t_{air0} = –5 °C and gradual decrease in $t_{air-a-in}$ = 20 °C by 2 °C/d (Log 2) and at gradual decrease in both initial values of $t_{air0-in}$ = –5 °C and $t_{air-a-in}$ = 20 °C by 2 °C/d. It was computed that at the end of 120 h periodically freezing and defrosting of the studied logs their average mass temperature was equal to –10.4 °C for Log 1, to –7.4 °C for Log 2, and to –16.7 °C for Log 3;

• during 3-stage regimes for autoclave steaming of two logs with an initial temperature of –1 °C (Log 4) and –20 °C (Log 5) and during 2.5 h of their subsequent conditioning (cooling) at the air temperature of 20 °C. It was determined that the duration of the steaming regimes of the studied logs was equal to τ_{reg} = 10.5 h for Log 4 and to τ_{reg} = 14.0 h for Log 5. It means that each decrease in the initial log temperature by 1 °C in the considered temperature range causes an increase in τ_{reg} by approximately 11 min.

Comparing these data with previous results of the authors it was determined that a decrease in the initial temperature of the logs from 0 °C to –1 °C when the whole amount of the free water is fully crystallized and there is still no frozen bound water in the wood causes elongation of the regime for autoclave steaming by 30 min.

The presented approach to the computing the 2D temperature field in logs and their average mass temperature at periodically changing atmospheric temperature can help to determine accurately the initial temperature of the logs before steaming, depending on the duration of the log storing in an open warehouse during all seasons. This creates a basis for the development of energy saving steaming regimes with an optimal duration depending on the initial temperature of the frozen and non-frozen logs of each batch subjected to thermal treatment.

The suggested approach and the results from the solutions of the coupled two models can be used for development and implementation of advanced systems for model-based automatic control (DELIISKI 2004, 2011, HADJISKI and DELIISKI 2016, HADJISKI *et al.* 2019) of different thermal treatment processes of logs and other wood materials.

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