ACTA FACULTATIS XYLOLOGIAE ZVOLEN, 62(2): 47−59, 2020
Zvolen, Technická univerzita vo Zvolene
DOI: 10.17423/afx.2020.62.2.05

COMPUTING THE 2D TEMPERATURE FIELD IN NON-FROZEN LOGS AT CHANGING ATMOSPHERIC TEMPERATURE AND DURING THEIR SUBSEQUENT AUTOCLAVE STEAMING

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ABSTRACT

An approach for mathematical modelling and research into the 2D non-stationary temperature distribution in logs under an influence of periodically changing atmospheric temperature near them and during their subsequent steaming in autoclaves is described in the paper. Mathematical descriptions of the periodically changing atmospheric temperature and also of the temperature of the steaming medium in the autoclaves and of the conditioning air medium is introduced as boundary conditions in our own 2D non-linear mathematical model of the 2D temperature distribution in non-frozen logs during their heating and cooling. Numerical solutions of the model in calculation environment of Visual FORTRAN Professional are given as an application of the suggested approach. The results from a simulative investigation into 2D non-stationary temperature distribution in non-frozen beech (*Fagus sylvatica* L.) logs during their 5 day and night heating and cooling at sinusoidal change of the air temperature with different initial values above 0 °C and different amplitudes, and also during steaming of the logs in autoclave and their subsequent conditioning are graphically presented and analysed. The obtained results can be used for development of energy saving steaming regimes with an optimal duration depending on the precise determining the initial temperature of the logs of each batch subjected to thermal treatment. They can be used also for the creation of a system for optimized model predictive automatic control of the steaming process of logs.

Key words: autoclave steaming, beech logs, 2D model, atmospheric temperature, heating, cooling, model based control.

INTRODUCTION

It is known that the steaming of wood materials with different shape is an important part of the technological processes in the production of veneer, plywood, parquet, layered articles (CHUDINOV 1966, SHUBIN 1990, STEINHAGEN 1991, BURTIN *et al.* 2000, BEKHTA – NIEMZ 2003, DELIISKI 2003, 2009, 2011a, DAGBRO *et al.* 2010, DELIISKI – DZURENDA 2010, DZURENDA 2014), etc.

Logs from various tree species are subjected to steaming with the aim of plasticization in the production of veneer, plywood, and other items (CHUDINOV 1968, TREBULA – KLEMENT 2002, VIDELOV 2003, PERVAN 2009, DELIISKI *et al.* 2010). The higher temperature of the steaming medium and the good heat insulation of the autoclaves allow the significant reduction of the duration and the specific energy consumption of the process in comparison with the traditional technologies for steaming wood materials under atmospheric pressure (RIEHL *et al.* 2002, DELIISKI 2003, 2009, SOKOLOVSKI *et al.* 2007, DELIISKI *et al.* 2013, 2015).

For the development and automatic realizing of energy saving steaming regimes with an optimal duration, and also for ensuring an optimal performance of the autoclaves it is very important to know the initial temperature of the logs of each batch subjected to steaming. The initial temperature of the separate batches depends on the duration of the log storing in an open warehouse at periodically changing air temperature.

The aim of the present work is to suggest an approach to computing the temperature field in logs at periodically changing atmospheric temperature during many days and nights and to study the influence of the computed average mass temperature of such non-frozen logs on the duration of the regimes for their autoclave steaming.

MATERIAL AND METHODS

Modelling of the 2D temperature distribution in non-frozen logs subjected to influence of periodically changing atmospheric temperature during days and nights

When the length of the logs, *L*, is larger than their diameter, *D*, not more than 3 ÷ 4 times, for the calculation of the temperature changes in the logs' longitudinal sections (i.e. along the coordinates *r* and *z* of these sections) during their heating or cooling in air medium the following 2D mathematical model can be used (DELIISKI – TUMBARKOVA 2019):

$$c \cdot \rho \frac{\partial T(r,z,\tau)}{\partial \tau} = \lambda_{\mathrm{r}} \left[\frac{\partial^2 T(r,z,\tau)}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial T(r,z,\tau)}{\partial r} \right] + \frac{\partial \lambda_{\mathrm{r}}}{\partial T} \left[\frac{\partial T(r,z,\tau)}{\partial r} \right]^2 + \\ + \lambda_{\mathrm{p}} \frac{\partial^2 T(r,z,\tau)}{\partial z^2} + \frac{\partial \lambda_{\mathrm{p}}}{\partial T} \left[\frac{\partial T(r,z,\tau)}{\partial z} \right]^2 \qquad (1)$$

with an initial condition:

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

and the following boundary conditions:

- along the radial coordinate *r* on the logs' frontal surface:

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

- along the longitudinal coordinate *z* on the logs' cylindrical surface:

$$\frac{\partial T(0,z,\tau)}{\partial z} = -\frac{\alpha_{\mathrm{r}}(0,z,\tau)}{\lambda_{\mathrm{r}}(0,z,\tau)} \left[T(0,z,\tau) - T_{\mathrm{air}}(\tau) \right] \qquad (4)$$

Equations (1) to (4) represent a common form of a mathematical model of 2D heat distribution in non-frozen logs subjected to influence of periodically changing atmospheric temperature.

Modelling of the 2D temperature distribution in non-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 logs during their steaming and subsequent conditioning is mathematically described by eq. (1) (DELIISKI 2003) with an initial condition

$$T(r, z, 0) = T_{02} \tag{5}$$

and the following boundary conditions:

• during the steaming process – at prescribed temperature of the steaming medium:

$$T(r, 0, \tau) = T(0, z, \tau) = T_{\mathrm{m}}(\tau) \tag{6}$$

• during the cooling of the steamed logs in air environment – at convective boundary conditions, which are presented above by eqs. (3) and (4).

Equations (1), (5), (6), (3), and (4) represent a common form of a mathematical model of 2D heat distribution in non-frozen logs subjected to steaming and subsequent cooling in air medium.

Mathematical description of the thermo-physical characteristics of the non-frozen logs

For solving and practical use of eq. (1) it is necessary to have mathematical descriptions of the radial and longitudinal thermal conductivity of the non-frozen wood, λ_{r} and λ_{p} respectively, the specific heat capacity of the non-frozen wood, *c*, and the wood density above the hygroscopic range (i.e. when $u > u_{\mathrm{fsp}}$), ρ.

Mathematical descriptions of the thermal conductivity and the specific heat capacity of non-frozen wood have been suggested by DELIISKI (1990, 1994, 2003, 2013a, 2013b) using the data for their change as a function of *t* and *u* experimentally determined in the dissertations by KANTER (1955) and CHUDINOV (1966, 1968). This data find a wide use in both the European (SHUBIN 1990, POŽGAJ *et al*. 1997, TREBULA – KLEMENT 2002, VIDELOV 2003, PERVAN 2009) and the American specialized literature (STEINHAGEN 1986, 1991, STEINHAGEN – LEE 1988, KHATTABI – STEINHAGEN 1992, 1993) when calculating various processes of the wood thermal treatment.

According to the mathematical description suggested in DELIISKI (1994, 2003, 2013a), the thermal conductivity of the non-frozen wood can be calculated using the following equations for $\lambda(T, u, \rho_{\mathrm{b}})$ above the hygroscopic range:

$$\lambda = \lambda_0 \cdot \left[1 + \beta \cdot (T - 273.15)\right] \tag{7}$$

$$\lambda_0 = K_{\text{ad-}\lambda} \cdot \nu \cdot [0.165 + (1.39 + 3.8u) \cdot (3.3 \cdot 10^{-7} \rho_{\mathrm{b}}^2 + 1.015 \cdot 10^{-3} \rho_{\mathrm{b}})] \tag{8}$$

$$\beta = 3.65 \left(\frac{579}{\rho_{\mathrm{b}}} - 0.124 \right) \cdot 10^{-3} \tag{9}$$

$$v = 0.1284 - 0.013u \tag{10}$$

The precise values of the coefficient $K_{\text{ad-}\lambda}$ in eq. (8) for various tree species have been determined by DELIISKI (2003, 2013b). For beech (*Fagus sylvatica* L.) wood, the following values of the coefficient $K_{\text{ad-}\lambda}$ in eq. (8) were obtained: in radial direction $K_{\text{r-}\lambda} = 1.35$ and in longitudinal direction $K_{\text{r-}\lambda} = 2.40$.

According to the mathematical description suggested by DELIISKI (1990, 2003, 2011b, 2013b), the specific heat capacity of the non-frozen wood above the hygroscopic range can be calculated using the following equation:

$$c = \frac{1}{1+u}(2862u + 2.95T + 5.49u \cdot T + 0.0036T^2 + 555) \quad (11)$$

The wood density ρ, which participates in eq. (1), is determined above the hygroscopic range according to the equation (CHUDINOV 1968, PERVAN 2009, DELIISKI 2011b, DELIISKI *et al*. 2015, HRČKA 2017, HRČKA – BABIAK 2017)

$$\rho = \rho_b \cdot (1+u) \quad (12)$$

The heat transfer coefficients α_r in eq. (4) and α_p in eq. (3) of the horizontally situated logs subjected to heating or cooling at free convection of the periodically changing air near them is equal to (TELEGIN *at al.* 2002, TUMBARKOVA 2019)

$$\alpha_r = 1.123 \cdot \left[\left|T(0,z,\tau) - T_{air}(\tau)\right|\right]^{0.26} \quad (13)$$

$$\alpha_p = 2.560 \cdot \left[\left|T(r,0,\tau) - T_{air}(\tau)\right|\right]^{0.26} \quad (14)$$

The heat transfer coefficients α_r in eq. (4) and α_p in eq. (3) of the beech logs subjected to air cooling after their autoclave steaming is equal to (DELIISKI 2003b, 2013b)

$$\alpha_r = 0.380 \cdot 1.026^{\left[T(0,z,\tau_{reg}) - T_{air}(\tau)\right]} \cdot \left[T(0,z,\tau_{reg}) - T_{air}(\tau)\right] \quad (15)$$

$$\alpha_p = 0.676 \cdot 1.026^{\left[T(r,0,\tau_{reg}) - T_{air}(\tau)\right]} \cdot \left[T(r,0,\tau_{reg}) - T_{air}(\tau)\right] \quad (16)$$

Mathematical description of the periodically changing atmospheric temperature

For the numerical solving of the mathematical model (1) ÷ (4), a mathematical description of the change in the atmospheric temperature near the logs during many days and nights, T_{air} is needed.

The periodic change of the atmospheric temperature T_{air} during the time at a constant value of its amplitude $T_{air\text{-}a}$ can be described by the following equation (DELIISKI 1988):

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

where T_{air0} is the initial value of T_{air}, K; $T_{air\text{-}a}$ – amplitude value of T_{air}, K; ω – angular frequency of T_{air}, s^{-1}; τ – time, s.

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

$$\omega = \frac{2\pi}{\tau_0} \quad (18)$$

where τ_0 is the period of change in T_m, s. For the precise solving of tasks with the participation of eqs. (17) and (18) it is needed to use π = 3.14159.

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

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

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

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

where K_{air0} and $K_{air\text{-}a}$ are coefficients determining how much the change in T_{air0} and $T_{air\text{-}a}$ (in K) is over a period.

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

For the purpose of analysis of the current log temperature condition at the initial temperature of the logs before their steaming, synchronously with the solving of the model (1) to (4), the average mass temperature of the logs, T_{avg}, for each moment of their periodically heating and cooling is calculated according to the equation

$$T_{avg} = \frac{1}{S_w} \iint_{S_w} T_{i,k}^{n} \mathrm{d}S_w \tag{20}$$

RESULTS AND DISCUSSION

The mathematical descriptions of the thermo-physical characteristics of non-frozen logs considered above, and also of the periodically changing atmospheric temperature were introduced in the mathematical models (1) to (6).

For numerical solution of the models aimed at computation of 2D temperature fields in logs, a software package was prepared, which was an input in the calculation environment of Visual FORTRAN Professional developed by Microsoft. For transformation of the models in a form suitable for programming an explicit form, the finite-difference method has been used (DELIISKI 2011b, 2013b). The calculation mesh was built on ¼ of the longitudinal section of the logs due to the circumstance that this ¼ was mirror symmetrical towards the remaining ¾ of the same section.

Using that package, computations were made for the determination of the 2D non-stationary temperature distribution in the longitudinal sections of non-frozen beech logs with different dimensions and initial temperatures.

The change in temperature of the processing air medium, t_m, log surface and average mass temperature, t_s and t_{avg}, respectively, and also t of 4 characteristic points in the logs subjected to atmospheric temperature influence or to autoclave steaming were studied in this work.

The coordinates of the four characteristic points in the longitudinal section of the logs were equal to: Point 1: $r = R/4$ and $z = L/4$; Point 2: $r = R/2$ and $z = L/4$; Point 3: $r = 3R/4$ and $z = 3L/8$; Point 4: $r = R$ and $z = L/2$. These coordinates of the points allow the determination and analysing the 2D temperature distribution in logs during their heating and cooling.

During the solution of the models, the above presented descriptions of the thermo-physical characteristics of non-frozen beech wood with the moisture content of 0.6 kg·kg^{-1} and basic density $\rho_b = 560$ kg·m^{-3} (DELIISKI – DZURENDA 2010) were used.

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

Three options of 120 h (i.e. 5 d) continuous periodic heating and cooling of non-frozen beech logs with a diameter $D = 0.24$ m, length $L = 0.48$ m, moisture content $u = 0.6$ kg·kg^{-1}, and initial temperature $t_{01} = 10$ °C (refer to eq. (2)) were studied as follows:

• for Log 1: at constant values of $t_{air0} = 20$ °C and $t_{air\text{-}a} = 20$ °C;

• for Log 2: at gradual increasing of $t_{m0\text{-}in} = 20$ °C by 2 °C/d and synchronously with this gradual decreasing of $t_{air\text{-}a\text{-}in} = 20$ °C by 4 °C/d.

• for Log 3: at gradual decreasing of $t_{air0\text{-}in}$ = 20 °C by 2 °C/d and synchronously with this gradual decreasing of $t_{air\text{-}a\text{-}in}$ = 20 °C by 4 °C/d.

To provide a change of t_{air0} by 2 °C/d and of $t_{air\text{-}a}$ by 4 °C/d the following values of the coefficients K_{air0} and $K_{air\text{-}a}$ in eq. (19) were used: $K_{air0} = 7.89635\cdot10^{-8}$ and $K_{air\text{-}a} = 2.3148\cdot10^{-6}$.

Fig. 1, Fig. 2 and Fig. 3 present the calculated change in t_m, t_s, t_{avg}, and t of 4 characteristic points in Log 1, Log 2 and Log 3 during their continuous 5 day and night (i.e. 120 h) periodic heating and cooling under the described above conditions of the atmospheric temperature influence.

The coordinates of the characteristic points were as follows: Point 1 with the temperature t_1: $r = R/4 = 30$ mm and $z = L/4 = 120$ mm; Point 2 with t_2: $r = R/2 = 60$ mm and $z = L/4 = 120$ mm; Point 3 with t_3: $r = 3R/4 = 90$ mm and $z = 3L/8 = 180$ mm; Point 4 with t_4: $r = R = 120$ mm and $z = L/2 = 240$ mm.

In Fig. 1 it is seen that at constant values of t_{air0} and $t_{air\text{-}a}$ after 48th h, i.e. after the 2nd period of t_{air}, a periodical change in the log temperature with practically constant amplitudes for the separate points is coming. As far as the point is distanced from the log surfaces that much smaller is the amplitude of the periodic change of the temperature in that point.

The amplitudes of t_{air}, t_{avg}, and t in the separate characteristic points after the 2nd period are equal to as follows: $t_{air\text{-}a}$ = 20.0 °C, $t_{s\text{-}a}$ = 11.4 °C, t_{1a} = 10.9 °C, t_{2a} = 9.7 °C, t_{3a} = 8.8 °C, t_{4a} = 8.6 °C, and $t_{avg\text{-}a}$ = 9.6 °C. The average mass temperature of the Log 1, t_{avg}, at 120th h reaches a value equal to 11.2 °C.

When t_{air0} increases and $t_{air\text{-}a}$ decreases during the time, the amplitudes of t in the separate points and also of t_{avg} gradually decrease but the minimal values of t_{avg} gradually increase from period to period (see Fig. 2). At 120th h the amplitudes of all log points become equal to 0 when t_{air0} = 20 °C + 2 °C/d and $t_{air\text{-}a}$ = 20 °C – 4 °C/d, and then t_{avg} of Log 2 reaches a value, equal to 29.0 °C.

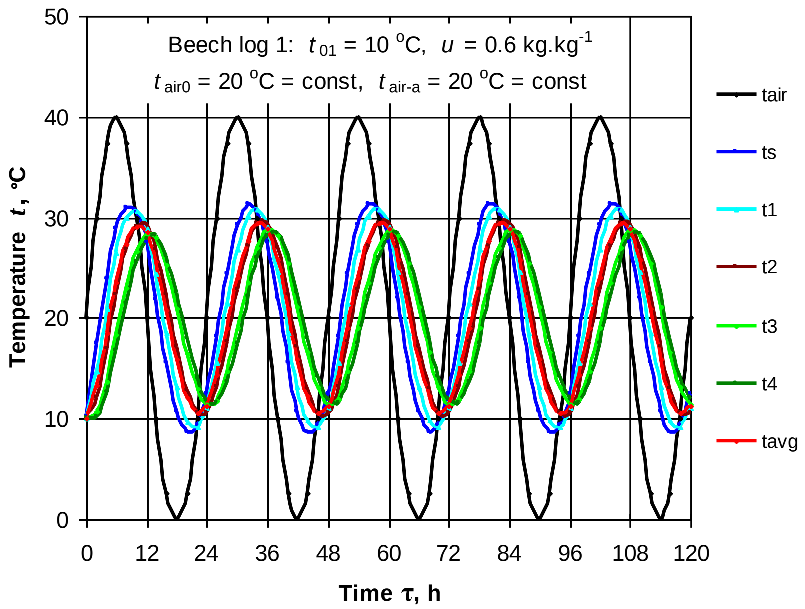

Fig. 1 Change in t_{air}, t_s, t_{avg}, and t of 4 characteristic points of the Log 1 during its 120 h periodical heating and cooling at constant values of t_{air0} and $t_{air\text{-}a}$.

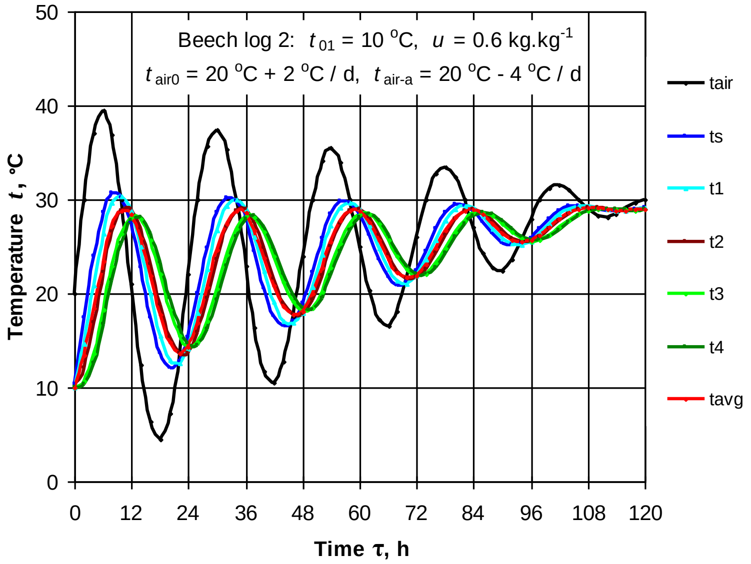

Fig. 2 Change in t_{air}, t_s, t_{avg}, and t of 4 characteristic points of the Log 2 during its 120 h periodical heating and cooling at increasing values of t_{air0} and decreasing values of t_{air-a}.

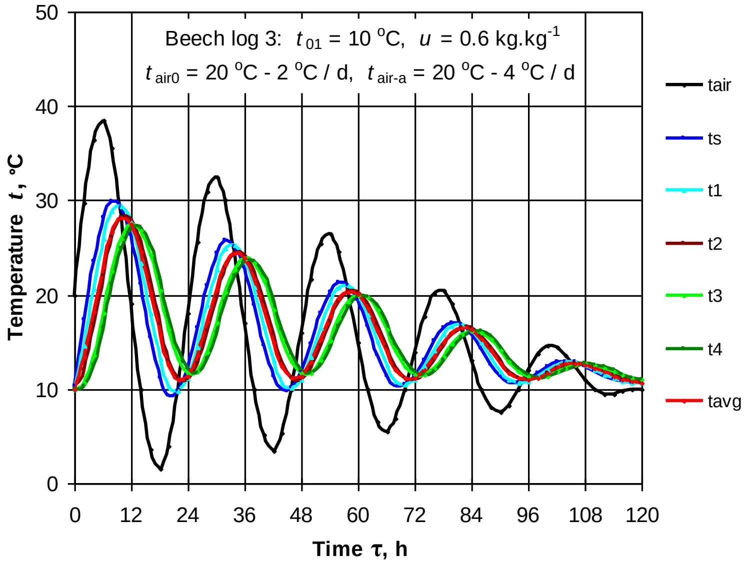

Fig. 3 Change in t_{air}, t_s, t_{avg}, and t of 4 characteristic points of the Log 3 during its 120 h periodical heating and cooling at decreasing values of t_{air0} and t_{air-a}.

When t_{air0} and t_{air-a} decrease during the time, the amplitudes of t in the separate points and also of t_{avg} gradually decrease but the maximum values of t_{avg} gradually decrease from period to period (see Fig. 3). At 120th h the amplitudes of all the log's points become equal to 0 when t_{air0} = 20 °C – 2 °C/d and t_{air-a} = 20 °C – 4 °C/d, and then t_{avg} of Log 3 reaches a value, equal to 10.7 °C.

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

Two options of autoclave steaming and subsequent conditioning of non-frozen beech logs (named as Log 4 and Log 5) with a diameter D = 0.4 m, length L = 0. 8 m, and the moisture content 0.6 kg·kg^{-1} were studied as follows:

- Log 4 was with initial temperature t_{02} = 0 °C (refer to eq. (5));
- Log 5 was with initial temperature t_{02} = 20 °C.

During the solving the mathematical model, 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 the air medium for the consequent conditioning of the heated wood materials is shown in (DELIISKI 2003, DELIISKI – DZURENDA 2010).

During the first stage of the steaming regimes input of water steam is accomplished in the autoclave, with logs situated inside, until the temperature of the processing medium t_m = 132 °C at the steam pressure of 0.2 MPa was reached. After reaching t_m = 132 °C, this temperature was maintained unchanged by reducing the input of steam flux inside the autoclave until the calculated by the model average mass temperature of the wood, t_{avg}, reaches a value of 90 °C.

After reaching t_{avg} = 90 °C the input of steam in the autoclave was terminated and the second stage of the steaming regime began. During this stage, by using the accumulated heat in the autoclave, the further heating and plasticizing of the logs was accomplished, thus resulting in gradual reduction of the temperature t_m for about 2 hours down to around 110 °C.

Afterwards, the cranes directing the steam and condensed water out of the autoclave were opened, which initiates the third stage of the steaming regime. This stage ended after about 2 hours, when t_m reached approximate value of around 85 °C. After that, a conditioning of the logs under external aerial medium was conducted. During the time of conditioning of the heated logs a redistribution and equalization of the temperature in their volume took place, which was especially appropriate for the obtaining of quality veneer.

In Fig. 4 and Fig. 5 the calculated change in t_m, t_s, and t of 4 characteristic points of the Log 4 and Log 5 during their autoclave steaming and subsequent conditioning at t_m = 20 °C is presented. The coordinates of the characteristic points of Logs 1 and 2 correspond according to the theory of similarity to the coordinates of the characteristic points in Logs 1 to 3, as follows: 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.

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 during the simulations with the model, 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 staying in an open warehouse before steaming, were assumed to be equal to t_{02} = 0 °C and t_{02} = 20 °C respectively.

In Fig. 4 and Fig. 5 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 for obtaining the quality veneer from plasticized beech wood it is needed that the temperature of all characteristic points of the logs during the veneer cutting process stays between these optimum values of t_{min} and t_{max} (DELIISKI 2003, DELIISKI – DZURENDA 2010).

The computation of the temperature fields in the logs was done interconnectedly for the processes of their heating in an autoclave and their subsequent conditioning in an air environment. This means that the calculation of the non-stationary 2D change in temperatures in the longitudinal sections of the logs during the time of their conditioning begins from the already reached during the time of calculations distribution of temperature at the end of the heating. Based on the calculations it can be determined when the moment of reaching in the entire volume of the heated logs occurred for the necessary ideal temperatures (between t_{min} and t_{max} on Fig. 4 and Fig. 5) needed for cutting the veneer.

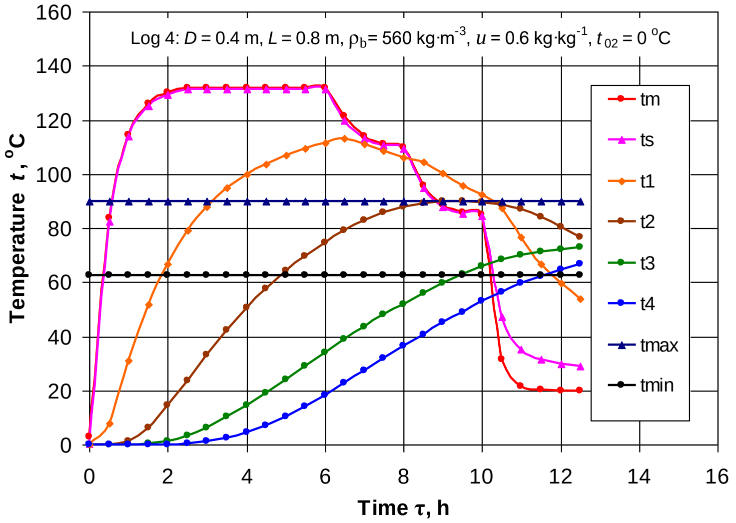

Fig. 4 Change in t_m, t_s, and t in 4 characteristic points of the Log 4 with t_{02} = 0 °C during its steaming in an autoclave and its subsequent conditioning at t_{air} = 20 °C.

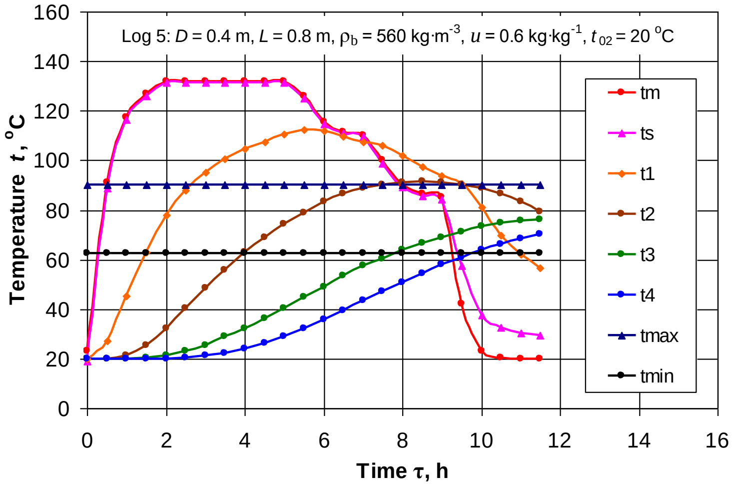

Fig. 5 Change in t_m, t_s, and t in 4 characteristic points of the Log 5 with t_{02} = 20 °C during its steaming in an autoclave and its subsequent conditioning at t_{air} = 20 °C.

It can be seen in Fig. 4 and Fig. 5 that temperatures of all characteristics enter between t_{min} = 62 °C and t_{max} = 90 °C after the following duration of the conditioning process of the logs at the air environment: 90 min for Log 4 and 60 min for Log 5.

The analysis of Fig. 4 and Fig. 5 showed that the duration of the steaming regimes of the studied logs was equal to τ_{reg} = 10 h for Log 4 and to τ_{reg} = 9 h for Log 5. This means that an increase in the initial log temperature t_{02} by 20 °C caused a decrease in τ_{reg} by 1 h, i.e. each increase in t_{02} by 1 °C in our case causes a decrease in τ_{reg} by approximately 3 min.

CONCLUSIONS

This paper describes an approach to mathematical modelling and research into the 2D non-stationary temperature distribution in non-frozen logs under influence of periodically changing atmospheric temperature and during their subsequent steaming in autoclaves.

Mathematical descriptions of the periodically changing atmospheric temperature and of the temperature of the log steaming regimes and of their subsequent conditioning in an air environment were carried out. These descriptions are introduced as boundary conditions in our own 2D non-linear mathematical model of the 2D temperature distribution in non-frozen logs during their heating and cooling.

A software package for solving the model and computing the 2D temperature field of logs during considered processes were prepared in FORTRAN, which was input in the calculation environment of Visual FORTRAN Professional. The paper shows and analyses, e.g. for the application of the suggested approach, diagrams of the change in t_{m}, t_{s}, t_{avg}, and 2D temperature distribution in non-frozen beech logs with basic density of 560 kg·m^{-3} and moisture content of 0.6 kg·kg^{-1} for the following two cases:

• during 5 days (i.e. 120 h) of continuous heating and cooling of logs with D = 0.24 m and L = 0.48 m under an influence of periodically changing atmospheric temperature at the constant values of t_{air0} = 20 °C and $t_{\mathrm{air\text{-}a}}$ = 20 °C (Log 1); at gradual increasing of $t_{\mathrm{m0\text{-}in}}$ = 20 °C by 2 °C/d and synchronously with this gradual decrease in $t_{\mathrm{air\text{-}a\text{-}in}}$ = 20 °C by 4 °C/d (Log 2) and at gradual decrease in $t_{\mathrm{air0\text{-}in}}$ = 20 °C by 2 °C/d and synchronously with this gradual decrease in $t_{\mathrm{air\text{-}a\text{-}in}}$ = 20 °C by 4 °C/d (Log 3). It was calculated that at the end of 120 h periodically heating and cooling of the studied logs their average mass temperature was equal to 11.2 °C for Log 1, to 29.0 °C for Log 2, and to 10.7 °C for Log 3;

• during 3-stage regimes for autoclave steaming of two logs with D = 0.4 m, L = 0.8 m, and an initial temperature of 0 °C and 20 °C and during the time of their subsequent conditioning 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 h for Log 4 and to τ_{reg} = 9 h for Log 5, which means that each increase in the initial log temperature by 1 °C in the considered case caused a decrease of τ_{reg} by approximately 3 min.

The obtained results can be used for the development of energy saving steaming regimes with an optimum duration depending on the initial temperature of the logs of each batch subjected to thermal treatment. This will ensure optimal productivity of the autoclaves.

The presented approach to the computing the 2D temperature field in logs and their average mass temperature at periodically changing atmospheric temperature can help the accurate determination of the initial temperature of the logs before steaming, depending on the duration of the log storing in an open warehouse. This approach can be used also for the creation of a system for optimized model predictive automatic control (DELIISKI 2004, 2011a, HADJISKI – DELIISKI 2016) of the steaming process of logs and other wood materials.

Symbols

c – specific heat capacity, J·kg^{-1}·K^{-1}
d – day and night, 1 d = 24 h = 86,400 s
D – diameter, m
L – length, m
R – radius, m: $R = D/2$
r – radial coordinate: $0 \leq r \leq R$, m
S – aria (for longitudinal section of the logs), m^2
T – temperature, K: $T = t + 273.15$
t – temperature, °C: $t = T - 273.15$
u – moisture content, kg·kg^{-1} = %/100
z – longitudinal coordinate: $0 \leq z \leq L/2$, m
α – heat transfer coefficients between log's surfaces and the surrounding air medium, W·m^{-2}·K^{-1}

λ – thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
ρ – density, $kg \cdot m^{-3}$
τ – time, s
ω – angular frequency, s^{-1}
d – day and night: d = 24 h = 86,400 s

Subscripts:

a – amplitude
ad – anatomical direction
air – air
avg – average (for wood mass temperature)
b – basic (for wood density, based on dry mass divided to green volume)
fsp – fiber saturation point
i – knot of the calculation mesh in the direction along the logs' radius: $i = 1, 2, 3, \ldots, 21$
k – knot of the calculation mesh in longitudinal direction of the logs: $k = 1, 2, 3, \ldots, 41$
in – initial
m – medium (for temperature of the steaming medium)
max – maximal
min – minimal
p – parallel to the wood fibres
r – radial direction
reg – regime (for duration of the steaming regimes)
s – surface
w – wood
0 – period of the change in the atmospheric temperature, or at 0 °C (for λ)
01, 02 – initial (for temperature of logs in the beginning of their thermal treatment)

Superscripts:

n – current number of the step along the time coordinate: $n = 0, 1, 2, \ldots$

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ACKNOWLEDGEMENTS

This document was supported by the APVV Grant Agency as part of the project: APVV-17-0456 as a result of work of authors and the considerable assistance of the APVV agency.

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