ACTA FACULTATIS XYLOLOGIAE ZVOLEN, 60(1): 101−112, 2018
Zvolen, Technická univerzita vo Zvolene
DOI: 10.17423/afx.2018.60.1.11

AN APPROACH TO COMPUTING REGIMES OF AUTOCLAVE STEAMING THE PRISMS FOR VENEER PRODUCTION WITH A LIMITED POWER OF THE HEAT GENERATOR

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ABSTRACT

An approach to computing the medium temperature of steaming the prisms for veneer production in an autoclave depending on the available limited power of the heat generator is suggested. The approach is based on the use of the optimized method called "variable return step", together with the method created by the first co-author previously. 2-dimensional mathematical model for the transient non-linear heat conduction and energy consumption in frozen and non-frozen prismatic wood materials at arbitrary are summarized. An application of the suggested approach is shown in the paper for the case of scientifically based regimes of computation of the autoclave steaming of non-frozen and frozen beech prisms with various cross-section dimensions and moisture content of 0.6 $kg \cdot kg^{-1}$ aimed at plasticizing in the veneer production, when the power of the available steam generator is limited and equal to 500 kW. The obtained results can be used for creating the system for optimized model based on automatic control of the time and energy consumption of the steaming process of wood materials.

Key words: autoclave steaming, wood materials, limited power, heat generator, optimization.

INTRODUCTION

The steaming of wood materials is an important part of the technological processes in the production of veneer, plywood, parquet, layered articles, (SHUBIN 1990, STEINHAGEN 1991, BURTIN *et al.* 2000, BEKHTA – NIEMZ 2003, DELIISKI – DZURENDA 2007, DAGBRO *et al.* 2010, DELIISKI 2013), etc.

The wood materials with prismatic shape are subjected to steaming with the aim of plasticization in the production of veneer, as well as when have to receive bent parts in the production of chairs and sporting equipment (CHUDINOV 1968, TREBULA – KLEMENT 2002, VIDELOV 2003, PERVAN 2009, DELIISKI *et al.* 2010). This is determined by the circumstance that the heated moist wood has an increased deformation capability and is susceptible to cutting and spatial configuration.

Traditionally, for many past decades applied without changes, equipment and technologies for steaming wood materials are characterized by long durability (till some days) and extremely low energy efficiency. During the last couple of decades the utilization of intensive steaming of wood materials under increased pressure of the steam in encapsulated autoclaves started (RIEHL *et al.* 2002, DELIISKI 2003, VIDELOV 2003, DELIISKI – SOKOLOVSKI 2007, SOKOLOVSKI *et al.* 2007). The higher temperature of the steaming medium on one side, and the good heat insulation of the autoclaves on the other side, allow the reduction by several times of the duration and the specific energy consumption of the process by comparison with the traditional technologies for steaming wood materials under atmospheric pressure (Riehl *et al.* 2002, Videlov 2003, Deliiski 2004, 2009, Deliiski *et al.* 2013a, 2013b).

The aim of the present work is to suggest an approach and an algorithm for the computation of the processing medium temperature of the steaming process of prisms for veneer production in an autoclave, depending on their parameters and on the available limited power of the available heat generator.

MATERIAL AND METHODS

Modelling of the 2D heat distribution in the wood prisms during their steaming

Mathematical model of the heating processes of prismatic wood materials during their steaming at atmospheric and increased pressure are created, solved and verified earlier by the first co-author (Deliiski 2011b, 2003b). The 2D heat distribution mechanism in subjected to steaming prismatic wood materials during their steaming is described by the following system of equations above the hygroscopic range:

$$c_{\mathrm{e}}\left(T,u,u_{\mathrm{fsp}}\right)\rho(\rho_{\mathrm{b}},u)\frac{\partial T(x,y,\tau)}{\partial \tau}=\frac{\partial}{\partial x}\left[\lambda_{\mathrm{r}}(T,u,\rho_{\mathrm{b}})\frac{\partial T(x,y,\tau)}{\partial x}\right]+\frac{\partial}{\partial y}\left[\lambda_{\mathrm{t}}(T,u,\rho_{\mathrm{b}})\frac{\partial T(x,y,\tau)}{\partial y}\right], \qquad (1)$$

with an initial condition:

$$T(x,y,0)=T_0 \qquad (2)$$

and the following boundary conditions:

$$T(0,y,\tau)=T(x,0,\tau)=T_{\mathrm{m}}(\tau), \qquad (3)$$

where T is the wood temperature, K;

T_0 – initial temperature of the subjected to steaming wood materials, K;

T_{m} – temperature of the steaming medium in the autoclave, K;

c_{e} – effective specific heat capacity of the wood, $\mathrm{J\cdot kg^{-1}\cdot K^{-1}}$;

ρ – wood density, $\mathrm{kg\cdot m^{-3}}$;

ρ_{b} – basic density of the wood, $\mathrm{kg\cdot m^{-3}}$;

u – wood moisture content, $\mathrm{kg\cdot kg^{-1}}$;

u_{fsp} – fiber saturation point of the wood specie, $\mathrm{kg\cdot kg^{-1}}$;

λ_{r} – thermal conductivity of the wood in radial direction, $\mathrm{W\cdot m^{-1}\cdot K^{-1}}$;

λ_{t} – thermal conductivity of the wood in tangential direction, $\mathrm{W\cdot m^{-1}\cdot K^{-1}}$;

x – coordinate on the thickness of subjected to steaming prismatic materials, m: $0 \le x \le d$;

d – thickness of the wooden prism, m;

y – coordinate on the width of subjected to steaming prismatic materials, m: $0 \le y \le b$;

b – width of the wooden prism, m;

τ – time, s.

The thermo-physical characteristics of the wood, which participate in eq. (1) are mathematically described in (Deliiski 2009, 2011b, 2013a, 2013b, Deliiski – Dzurenda 2010, Deliiski *et al.* 2015).

Modeling of the energy consumption of the autoclave

The heat energy Q_{ha}, which is supplied into the autoclave by the introduced in it water steam is consumed for (Fig. 1):

- heating the subjected to steaming wood materials (Q_{hw});
- heating of the body of the autoclave and of the situated in it metal trolleys for positioning of the wood materials (Q_{hf});
- heating of the heat insulating layer of the autoclave (Q_{hil});
- covering of the heat emission from the autoclave in the surrounding aerial space Q_{he});
- filling in with steam the free (unoccupied by wood materials) part of the working volume of the autoclave (Q_{hfv});
- accumulating heat in the gathered in the lower part of the autoclave condensed water (Q_{hcw}).

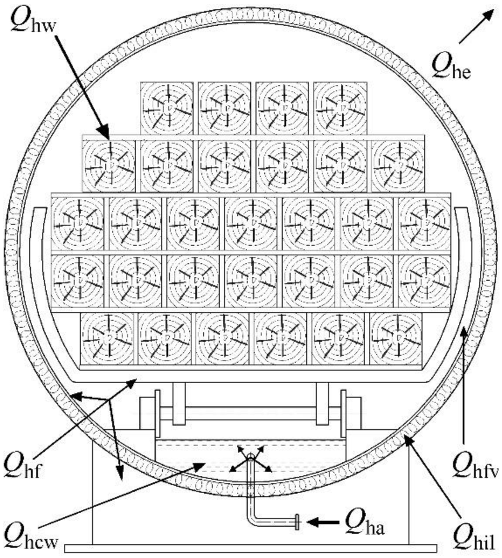

Fig. 1 Structural model of the heat distribution in an autoclave for steaming wood materials.

On the grounds of the performed analyses, a structural model of distribution of the heat in the autoclaves for steaming of wood materials is suggested. By using this model, a mathematical description of the heat energy consumption and its equivalent of water steam are made, and also a mathematical description of the heat balance and its corresponding steam balance of the autoclaves (DELIISKI 2013b, DELIISKI – DZURENDA 2010).

Heat balance of the autoclave

The total specific heat energy needed for steaming of 1 m^3 wood materials in autoclave for any moment $n\cdot\Delta\tau$ of the thermal treatment, Q_{ha}^{n} (in kWh·m^{-3}), is equal to (see Fig. 1):

$$Q_{\mathrm{ha}}^{n} = Q_{\mathrm{hw}}^{n} + Q_{\mathrm{hf}}^{n} + Q_{\mathrm{hil}}^{n} + Q_{\mathrm{he}}^{n} + Q_{\mathrm{hfv}}^{n} + Q_{\mathrm{hcw}}^{n}, \tag{4}$$

where $\Delta\tau$ is the step along the time coordinate, by which the mathematical model is solving, s;

n – time level during the solving of the model: n = 0, 1, 2, 3, ……

The total specific heat flux $q_{\mathrm{ha}}^{n} = \dfrac{dQ_{\mathrm{ha}}^{n}}{d\tau}$, which provides the energy Q_{ha}^{n} for any moment $n\cdot\Delta\tau$ of the steaming process can be determined (in kW) according to the following equation:

$$q_{\mathrm{ha}}^{n} = \frac{dQ_{\mathrm{ha}}^{n}}{d\tau} \approx \frac{3600 \Delta Q_{\mathrm{ha}}^{n}}{\Delta\tau} . \tag{5}$$

Calculation of the temperature of the steaming medium in the autoclave when the heat generator has a limited power

For the realization of automatic control of the wood steaming process with limited power of the heat generator, q_{source} (in kW), the following problem occurs: depending on the present limited heat power it is needed to determine the real law of increase in the temperature of the heating medium T_{m} in the autoclave during the initial part of the thermal treatment processing (TTP) of the wood materials.

For the solution of such problem, an approach for the calculation of the change in T_{m} after submission of the limited heat power to autoclave at the beginning of TTP until reaching of the technological acceptable maximal value of $T_{\mathrm{m}}^{\max}$ is needed.

It is known that at the beginning of TTP the temperature T_{m} increases to curvilinear dependence. The separate sections of this dependence can be approximated by a part of exponent with respective time constant τ_{e} for each step $\Delta\tau$ of the steaming process. This allows describing the increase of T_{m} during the initial part of TTP by the following equation:

$$T_{\mathrm{m}}^{n} = T_{\mathrm{m}}^{\max} - \left(T_{\mathrm{m}}^{\max} - T_{\mathrm{m}0}\right) \exp\left(-\frac{\tau}{\tau_{\mathrm{e}}}\right), \tag{6}$$

where T_{m}^{n} is the current value of the processing medium temperature in the autoclave for each moment $n \cdot \Delta\tau$ of TTP, K, and:

$T_{\mathrm{m}0}$ – initial medium temperature in the autoclave, K;

$T_{\mathrm{m}}^{\max}$ – maximal technologically allowable medium temperature in the autoclave, K;

τ – current time of TTP, equal to $n \cdot \Delta\tau$, s;

τ_{e} – time constant of the exponential increase of separate sections of T_{m} during the initial part of TTP, s.

For determination of τ_{e} and computation of $T_{\mathrm{m}}^{\max}$ for each moment $n \cdot \Delta\tau$ of the initial part of TTP the method for optimization with variable reverse step (STOYANOV 1983) is suitable for use. For this purpose the following optimization criteria can be used:

$$q_{\mathrm{source}} - \partial_{\mathrm{h}} \leq \frac{dQ_{\mathrm{ha}}^{n}}{d\tau} \leq q_{\mathrm{source}} + \partial_{\mathrm{h}} , \tag{7}$$

where by ∂_{h} (in kW) the setting of the limits of localization of $\frac{dQ_{\mathrm{ha}}^{n}}{d\tau}$ is carried out.

For the determination of the time constant τ_{e} in eq. (6), an algorithm and a subroutine to the software package were created. Depending on the limited power of the heat generator, q_{source}, they realize the optimization procedures for the calculation of T_{m}^{n} during the initial part of TTP.

When the condition (7) is satisfied that means that during the next step $\Delta\tau$ of TTP the energy $\Delta\tau \cdot q_{\mathrm{ha}}$, which with the determined true value of T_{m}^{n} is calculated will be equal to the energy $\Delta\tau \cdot q_{\mathrm{source}}$.

RESULTS AND DISCUSSION

For numerical solution of the above mentioned mathematical models aimed at usage of the suggested approach for the calculation of T_m during the initial part of TTP a software package was prepared in FORTRAN, which was input in the calculation environment of Visual Fortran Professional. For the preparation of the models for programming an explicit form of the finite-difference method has been used, which allows for the exclusion of any simplifications in the models (DELIISKI 2011b, 2013b).

With the help of the software package, as an example, computations were made for the determination of T_m and also of the 2D non-stationary change of the temperature in 4 characteristic points of ¼ of the square cross section of beech prisms with thickness *d* and width *b* respectively, during their steaming in an autoclave with a diameter $D = 2.4$ m and length of its cylindrical part $L = 9.0$ m (DELIISKI – SOKOLOVSKI 2007, DELIISKI – DZURENDA 2010). The dimensions of the prisms' cross sections were equal to 0.3 × 0.3 m, 0.4 × 0.4 m, 0.5 × 0.5 m, and the coordinates of their characteristic points were, as follow: Point 1: d/8, b/8; Point 2: d/4, b/4; Point 3: d/2, b/4; and Point 4: d/2, b/2. During the solving of the models, the mathematical descriptions of the thermo-physical characteristics of beech wood (*Fagus Sylvatica* L.) with basic density 560 $\text{kg}\cdot\text{m}^{-3}$ and fiber saturation point 0.31 $\text{kg}\cdot\text{kg}^{-1}$) were used, which have been presented in (DELIISKI 2009, 2011b, 2013a, 2013b). The initial temperature and the moisture content of the prisms were equal to 0 °C or –20 °C and 0.6 $\text{kg}\cdot\text{kg}^{-1}$ respectively.

During the numerical simulations 3-stage regimes for autoclave steaming of the prisms (see Fig. 2, 3, 4 below) were used (DELIISKI 2013b).

During the first stage of the TTP regime input of water steam is accomplished in the autoclave, with situated inside wooden materials, until the temperature $t_m = 130$ °C is reached. The time for increasing t_m up to $t_m = 130$ °C depends on the heat power of the steam generator. As higher this heat power is as fast is the increasing of t_m. This assures less duration of the TTP regimes and increased production capacity of the autoclave.

After reaching $t_m = 130$ °C, this temperature is 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. The TTP at $t_m = 130$ °C does not cause thermal destruction in wood, which ensures keeping its mechanical characteristics.

After reaching $t_{avg} = 90$ °C the input of steam in the autoclave is terminated and the second stage of the steaming regime begins. During this stage, by using the accumulated heat in the autoclave, the further heating and plasticizing of the prisms is accomplished, thus resulting in gradual reduction of the temperature t_m for about 2 hours down to around 115 °C.

Afterwards, the cranes directing the steam and condensed water out of the autoclave are opened, which initiates the third stage of the steaming regime. This stage ends after about an hour and a half, when t_m reaches approximate value of around 80 °C.

The end of the third stage defines the finish of the whole steaming regime and then the plasticized prisms are taken out of the autoclave. At the end of the third regime stage the temperature at the characteristic points of the cross section of the prisms falls entirely in the range of the optimum temperatures from 55 °C to 90 °C, needed upon cutting of veneer made of plasticized beech wooden prisms (DELIISKI – DZURENDA 2010).

After taking the heated and plasticized prisms out of the autoclave, their air-conditioning (cooling) is executed at factory premises temperature during a certain period before cutting the veneer out them. During the air-conditioning additional homogenization of the temperature field occurs in the prisms volume, which ensures better quality veneer production.

The increase of t_m at the beginning of the steaming regime is calculated by taking in mind the available heat power of the generator that produces steam. During simulations we have set limited power of the generator $q_{source} = 500$ kW. Two loading levels of the autoclave with filled in beech prisms for steaming, γ, have been investigated: $\gamma = 0.4\ m^3 \cdot m^{-3}$ and $\gamma = 0.5\ m^3 \cdot m^{-3}$ (i.e. $\gamma = 40\%$ and $\gamma = 50\%$) and their influence over the change of t_m during the initial part of TTP, as well as over the entire duration of the prisms steaming regimes have been followed and analysed.

On Fig. 2, as an example, the calculated change in the temperature of the processing steaming medium, t_m and also in the temperature in 4 characteristic points of 2 beech prisms with cross-section dimensions $d \times b = 0.4 \times 0.4$ m, initial temperature $t_0 = 0$ °C and $t_0 = -20$ °C during their TTP in an autoclave with loading level $\gamma = 40$ % is presented. The coordinates of the separate characteristic points are given in the legend of the figure.

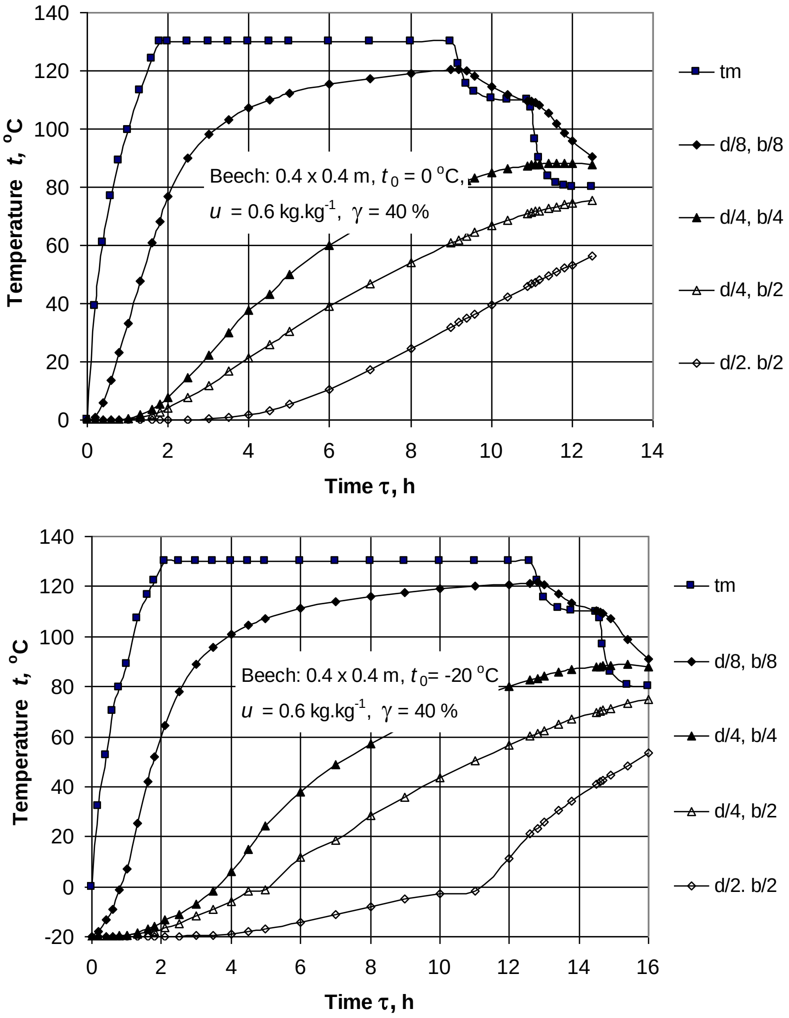

Fig. 2 Change in t_m and t in 4 characteristic points of beech prisms with cross-section dimensions $d \times b$ = 0.4 × 0.4 m, t_0 = 0 °C (above), and t_0 = –20 °C (below) during their TTP in an autoclave at a loading of 40%.

Figures 3 and 4 present the calculated change in t_m during TTP of the studied beech prisms in an autoclave at $\gamma = 40\%$ and $\gamma = 50\%$, respectively.

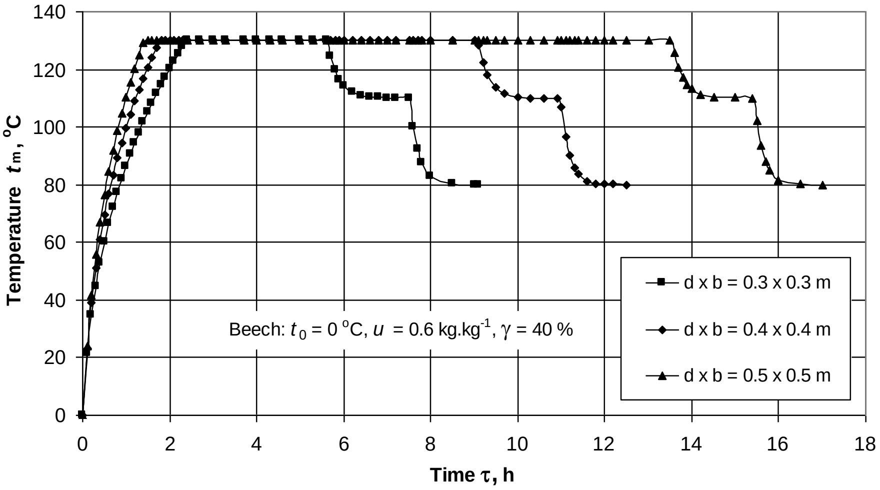

Fig. 3 Regimes for TTP of beech prisms with t_0 = 0 °C in an autoclave at γ = 40%, depending on their cross-section dimensions.

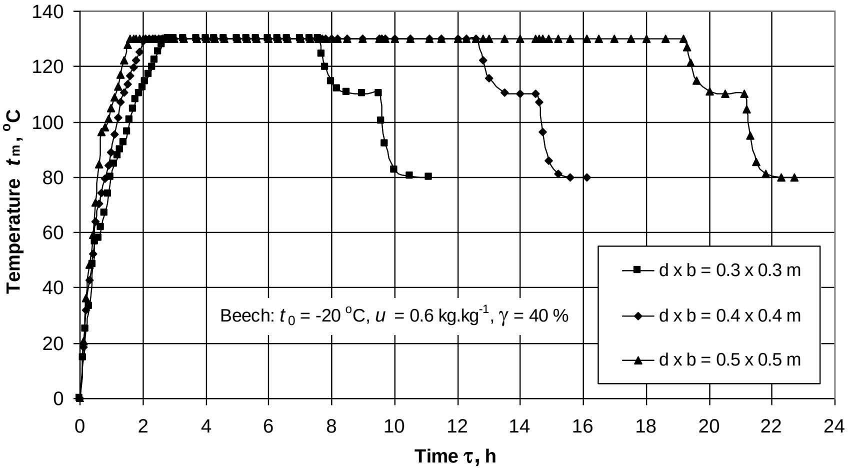

Fig. 4 Regimes for TTP of beech prisms with t_0 = –20 °C in an autoclave at γ = 40%, depending on their cross-section dimensions.

Figures 5 and 6 present the calculated change in the heat fluxes of the autoclave, $q_{ha} = dQ_{ha}/d\tau$, which are needed for the realization of the regimes shown on Fig. 3 and Fig. 4, respectively.

The analysis of the obtained simulation results, part of which are presented on Fig. 2 to Fig. 6 lead to the following conclusions:

1. The main consumer of the heat energy in TTP are the wood prisms in the autoclave. That is why during the optimization procedure for the determination of the time constant τ_e in eq. (6) the current value of the total energy of the autoclave $\Delta\tau \cdot q_{ha}$ is most impacted by the change of the current value of the heat consumption of the wood $\Delta\tau \cdot q_{hw}$.

2. As the thickness and width of the wood materials, *d* and *b*, increase, the heat in the wood materials is distributed slower. This means that with an increase of *d* and *b,* a larger increase in t_m during any next step Δτ until warming up of the surface layers of the wood materials and reaching of the equality $\Delta\tau \cdot q_{ha} = \Delta\tau \cdot q_{source}$ is needed. This provides for a faster increase in t_m with an increase of *d* and *b* during the initial part of TTP.

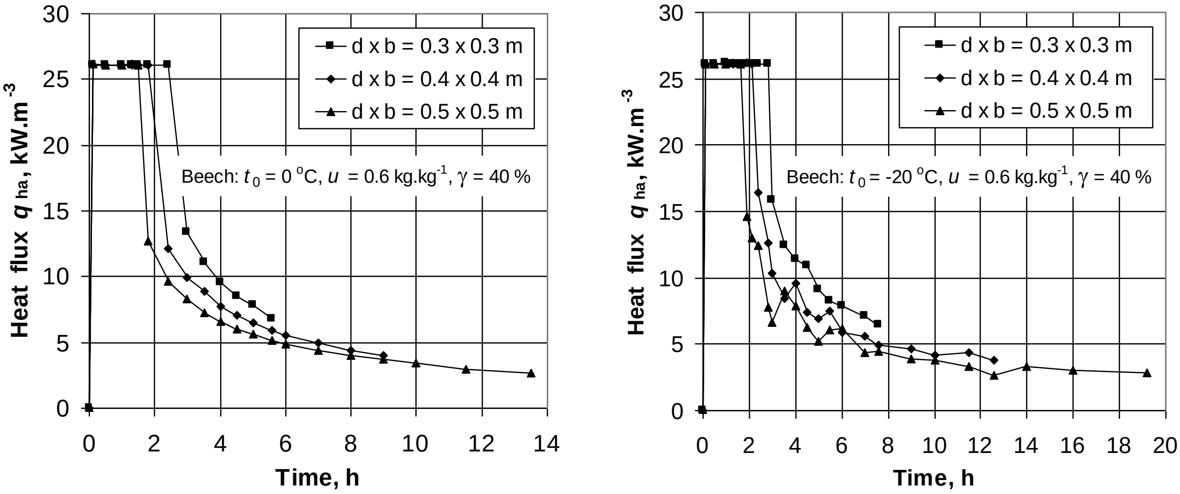

Fig. 5 Change in q_{ha} during TTP of beech prisms with t_0 = 0 °C (left) and t_0 = –20 °C (right) in an autoclave at γ = 40%, depending on their cross-section dimensions.

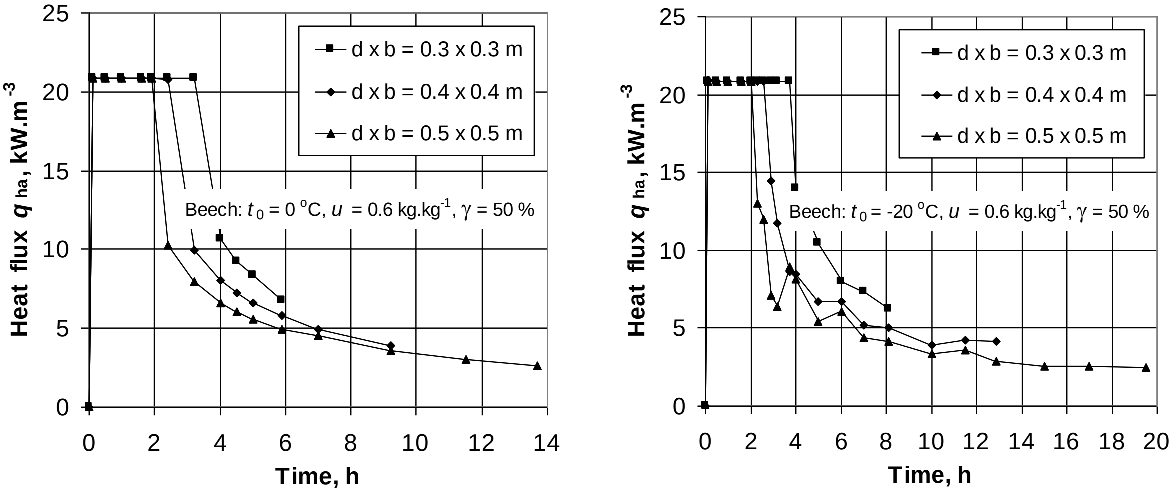

Fig. 6 Change in q_{ha} during TTP of beech prisms with t_0 = 0 °C (left) and t_0 = –20 °C (right) in an autoclave at γ = 50%, depending on their cross-section dimensions.

3. The larger loading of the autoclave means there is a presence of more heat capacity of the wood in the autoclave. This means that a smaller increase in t_m during any next step Δτ until reaching of the equality $\Delta\tau \cdot q_{ha} = \Delta\tau \cdot q_{source}$ in these cases is needed. This provides a slower increase in calculated according to eq. (6) values of t_m at the beginning of TTP with an increase of the autoclave's loading.

The presented on Fig. 3 and Fig. 4 durations of the increase of t_m from 0 °C to 130 °C at the beginning of TTP are in accordance with the conclusions given above. These durations are equal to, as follow:

• at autoclave's loading γ = 40%:

- •• at t_0 = 0 °C: 1.5 h, 1.8 h, and 2.4 h for prisms with $d \times b = 0.5 \times 0.5$ m, $d \times b = 0.4 \times 0.4$ m, and $d \times b = 0.3 \times 0.3$ m respectively;
- •• at t_0 = –20 °C: 1.6 h, 2.1 h, and 2.8 h for prisms with $d \times b = 0.5 \times 0.5$ m, $d \times b = 0.4 \times 0.4$ m, and $d \times b = 0.3 \times 0.3$ m respectively;

- at autoclave’s loading $\gamma = 50\%$:
  - at t_0 = 0 °C: 1.9 h, 2.4 h, and 3.2 h for prisms with $d \times b = 0.5 \times 0.5$ m, $d \times b = 0.4 \times 0.4$ m, and $d \times b = 0.3 \times 0.3$ m respectively;
  - at t_0 = –20 °C: 2.0 h, 2.6 h, and 3.7 h for prisms with $d \times b = 0.5 \times 0.5$ m, $d \times b = 0.4 \times 0.4$ m, and $d \times b = 0.3 \times 0.3$ m respectively;

4. The duration of the TTP regimes increases nonlinearly depending on the cross-section dimensions of the wooden prisms. The duration of the first stage of the TTP regime, upon which time the autoclave is filled in with water steam until reaching average mass temperature of the beech prisms of 90 °C, is equal to:

- at autoclave’s loading $\gamma = 40\%$:
  - at t_0 = 0 °C: 5.6 h, 9.0 h, and 13.5 h for prisms with $d \times b = 0.3 \times 0.3$ m, $d \times b = 0.4 \times 0.4$ m, and $d \times b = 0.5 \times 0.5$ m respectively;
  - at t_0 = –20 °C: 7.6 h, 12.6 h, and 19.2 h for prisms with $d \times b = 0.3 \times 0.3$ m, $d \times b = 0.4 \times 0.4$ m, and $d \times b = 0.5 \times 0.5$ m respectively;
- at autoclave’s loading $\gamma = 50\%$:
  - at t_0 = 0 °C: 5.9 h, 9.2 h, and 13.7 h for prisms with $d \times b = 0.3 \times 0.3$ m, $d \times b = 0.4 \times 0.4$ m, and $d \times b = 0.5 \times 0.5$ m respectively;
  - at t_0 = –20 °C: 8.1 h, 12.9 h, and 19.5 h for prisms with $d \times b = 0.3 \times 0.3$ m, $d \times b = 0.4 \times 0.4$ m, and $d \times b = 0.5 \times 0.5$ m respectively;

The total duration of the investigated 3-stage TTP regimes, by the end of which the temperature at the characteristic points of the cross section of the beech prisms falls in the range of the optimum temperatures from 55 °C to 90 °C, which assures maximum plasticizing upon further veneer cutting, is equal to:

- at autoclave’s loading $\gamma = 40\%$:
  - at t_0 = 0 °C: 9.1 h, 12.5 h, and 17.0 h for prisms with $d \times b = 0.3 \times 0.3$ m, $d \times b = 0.4 \times 0.4$ m, and $d \times b = 0.5 \times 0.5$ m respectively;
  - at t_0 = –20 °C: 11.1 h, 16.1 h, and 22.7 h for prisms with $d \times b = 0.3 \times 0.3$ m, $d \times b = 0.4 \times 0.4$ m, and $d \times b = 0.5 \times 0.5$ m respectively;
- at autoclave’s loading $\gamma = 50\%$:
  - at t_0 = 0 °C: 9.4 h, 12.7 h, and 17.2 h for prisms with $d \times b = 0.3 \times 0.3$ m, $d \times b = 0.4 \times 0.4$ m, and $d \times b = 0.5 \times 0.5$ m respectively;
  - at t_0 = –20 °C: 11.6 h, 16.4 h, and 23.1 h for prisms with $d \times b = 0.3 \times 0.3$ m, $d \times b = 0.4 \times 0.4$ m, and $d \times b = 0.5 \times 0.5$ m respectively;

5. During the initial part of TTP when the heat power of the steam generator is limited at q_{source} = 500 kW, the specific heat fluxes q_{ha} are constant and equal to 26.07 kW.m^{-3} at $\gamma = 40\%$ (Fig. 5) and to 20.85 kW.m^{-3} at $\gamma = 50\%$ (Fig. 6).

These values of q_{ha} are received by the following way depending on these variables: generator power q_{source}, volume of the empty autoclave V_{a} and level of the autoclave’s loading with wooden materials γ. By autoclave dimensions D = 2.4 m and L = 9.0 m its inside volume is equal to V_{a} = 47.95 m^3. The multiplied volume V_{a} by γ results in the wooden materials volume V_{w}, at the respective level of loading: in our case V_{w} = 19.18 m^3 at $\gamma = 40\%$ and V_{w} = 23.98 m^3 at $\gamma = 50\%$. In the analysed example after dividing the generator power q_{source} = 500 kW by V_{w}, we get the presented in figures 5 and 6 constant values for heat fluxes q_{ha} = 26.07 kW·m^{-3} at $\gamma = 40\%$ and q_{ha} = 20.85 kW·m^{-3} at $\gamma = 50\%$ during the increase of t_{m} in the autoclave.

After reaching t_{m} = 130 °C in the autoclave in the beginning of TTP, the heat fluxes q_{ha} decrease considerably – initially at a faster speed, then gradually slowing down.

Due to strongly expressed non-linearity of the process of thawing of the frozen free water in the wood materials during their heating (refer to Fig.2-below), the decrease of the fluxes q_{ha}

at t_0 = –20 °C occurs according to broken lines (see the right sides of Fig. 5 and Fig. 6). However, at t_0 = 0 °C the decrease of the fluxes q_{ha} occurs according to smooth curved lines depending on the steaming time, since in this case there is a lack of phase transition of the water in the wood during the heating of the materials.

At the end of the first stage of TTP regimes the decrease of the heat fluxes q_{ha} reach the following values:

• at autoclave's loading γ = 40%:

- •• at t_0 = 0 °C: 6.82 kW·m^{-3}, 4.03 kW·m^{-3}, and 2.71 kW·m^{-3} for prisms with $d \times b$ = 0.3 × 0.3 m, $d \times b$ = 0.4 × 0.4 m, and $d \times b$ = 0.5 × 0.5 m respectively;
- •• at t_0 = –20 °C: 6.47 kW·m^{-3}, 3.82 kW·m^{-3}, and 2.89 kW·m^{-3} for prisms with $d \times b$ = 0.3 × 0.3 m, $d \times b$ = 0.4 × 0.4 m, and $d \times b$ = 0.5 × 0.5 m respectively;

• at autoclave's loading γ = 50%:

- •• at t_0 = 0 °C: 6.76 kW·m^{-3}, 3.88 kW·m^{-3}, and 2.63 kW·m^{-3} for prisms with $d \times b$ = 0.3 × 0.3 m, $d \times b$ = 0.4 × 0.4 m, and $d \times b$ = 0.5 × 0.5 m respectively;
- •• at t_0 = –20 °C: 6.23 kW·m^{-3}, 4.15 kW·m^{-3}, and 2.47 kW·m^{-3} for prisms with $d \times b$ = 0.3 × 0.3 m, $d \times b$ = 0.4 × 0.4 m, and $d \times b$ = 0.5 × 0.5 m respectively.

CONCLUSIONS

The present paper describes the suggested by the authors approach for the computation of the temperature increase of the steaming environment, t_m, in the beginning of TTP of wooden materials at limited heat power of the steam generator. The approach is based on the use of the numerical solutions of personal 2D non-linear mathematical model of the steaming process of prismatic wood materials. For computation of t_m for each moment of the initial part of TTP the method for optimization with variable reverse step is used.

For the solution of the model and practical application of the suggested approach, a software program was prepared in the calculation environment of Visual Fortran Professional.

The paper shows and analyses, as an example, diagrams of the change in t_m and 2D temperature distribution in beech prisms with cross-section dimensions 0.3 × 0.3 m, 0.4 × 0.4 m, and 0.5 × 0.5 m, initial temperatures of 0 °C and –20 °C, basic density of 560 kg·m^{-3}, and moisture content of 0.6 kg·kg^{-1} during their steaming in an autoclave with a diameter of 2. 4 m, length of 9.0 m and loading with wood materials 40% and 50%, until reaching of average wood mass temperature of 90 °C at a limited heat power of the steam generator, equal to 500 kW. All diagrams are drawn using the results calculated by the model.

It has been determined, that the increase of the cross-section dimensions of the prisms causes faster increase in t_m during the initial part of TTP. The duration of the regimes for TTP increases non-linear with the increase of the prisms' dimensions. This duration practically almost does not depend on the loading of the autoclave with subjected to TTP prisms at given their cross-section dimensions.

The obtained results can be used for the creation of a system for optimized model based automatic control (DELIISKI 2011a, HADJISKI – DELIISKI 2015, 2016) of the duration and energy consumption of the steaming process of wood materials.

The approach that was suggested in the present paper for the computation of the increase in t_m during the initial part of TTP and also of the total duration of the regimes for TTP at limited power of the heat generator could be further applied in the development of analogous models, for example, for the computation of the temperature fields and the energy consumption during

TTP of different wooden and other capillary-porous materials in non-frozen and frozen state, and also for optimization and model based control of these processes.

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ACKNOWLEDGEMENTS

This document was supported by the grant No BG05M2OP001-2.009-0034-C01 "Support for the Development of Scientific Capacity in the University of Forestry", financed by the Science and Education for Smart Growth Operational Program (2014–2020) and co-financed by the European Union through the European structural and investment funds.
This document was also supported by the VEGA-SR Grant Agency as part of the project VEGA SR project No. 1/0563/16 Study of phenomena modifying wood colour in the process of thermal treatment of wood by saturated water vapour.

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