Computing the heat flux required for warming up of frozen wooden prisms for veneer production in the beginning of their autoclave steaming

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Abstract. An approach for computing the heat flux required for warming up of frozen wooden prisms in the regimes for their autoclave steaming at limited heat power of the steam generator, depending on the dimensions of the prisms cross section, wood moisture content, and loading level of the autoclave has been suggested. The approach is based on the use of two personal mathematical models: 2D non-linear model of the temperature distribution in subjected to steaming frozen wooden prisms and model of the non-stationary heat balance of autoclaves for steaming wood materials. For numerical solving of the models and practical application of the suggested approach, a software program was prepared in the calculation environment of Visual FORTRAN Professional developed by Microsoft. Using this program computation and research of the non-stationary change of the processing medium temperature and heat fluxes in an autoclave with a diameter of 2.4 m, length of 9.0 m and loading level of 50% at a limited heat power of the steam generator, equal to 500 kW during the initial part of the steaming in it of frozen beech prisms with different moisture content have been carried out. The suggested approach can be used for computing and model based automatic realization of energy efficient optimized regimes for autoclave steaming of different wood materials.

1. Introduction

For plasticizing of prismatic wood materials in the production of veneer and plywood the materials are usually subjected to steaming in different types of equipment [1, 3, 10, 12, 14]. The steaming of wood materials under increased pressure of the processing medium in autoclaves is used in many applications due to its higher energy efficiency and lower duration in comparison with the steaming at atmospheric pressure [2, 11, 13].

Information about the duration and energy consumption of steaming wood materials in atmospheric or increased pressure for the cases of unlimited generator power has been given in [4, 5, 6, 7, 12, 14]. For medium and small enterprises, steaming regimes for wood materials at limited power of the steam generator is of considerable interest.

The aim of the present work is to suggest an approach for the computation and research of the processing medium temperature and largest for the whole steaming process heat fluxes in the beginning of regimes for autoclave steaming of frozen wooden prisms for veneer production at limited power of the heat generator, depending on the dimensions of the prisms cross section, wood moisture content, and loading level of the autoclave with prisms subjected to steaming.
2. Material and methods

2.1. Modeling of the 2D temperature distribution in frozen wooden prisms subjected to steaming

When the length of the prisms, L, is larger than their thickness, d, at least 4 ÷ 5 times, and simultaneously with this the width, b, does not exceed the thickness more than 3 times, for the calculation of the change in the temperature in the prism’s cross section, which is equally distant from the frontal sides (i.e. along the coordinates x and y of this section) during heating and cooling in steaming medium the following 2D mathematical model can be used [2, 5]:

\[ ε_{w-eff} \cdot ρ_w \frac{∂T}{∂τ} = \text{div} \left( \lambda_{w-eff} \text{grad} \ T \right) \]

with an initial condition:

\[ T(x, y, 0) = T_{w0} \]

and following boundary condition:

\[ T(x, y, 0) = T(0, y, τ) = T_m(τ) \]

where \( ε_{w-eff} \) is the effective specific heat capacity of the frozen and non-frozen wood during its heating, \( J\cdot kg^{-1} \cdot K^{-1} \); \( λ_{w-eff} \) – effective thermal conductivity of the frozen and non-frozen wood cross sectional to the fibers, \( W\cdot m^{-1} \cdot K^{-1} \); \( ρ_w \) – wood density, \( kg\cdot m^{-3} \); \( x \) – coordinate along the prism’s thickness of the separate points of the calculation mesh for numerical solving of the model: \( 0 ≤ x ≤ d/2 \); \( m \) – thickness of the prism; \( y \) – coordinate along the prism’s width of the separate points of the calculation mesh: \( 0 ≤ y ≤ b/2 \); \( m \) – width of the prism; \( τ \) – time, s; \( T \) – temperature, K; \( T_{w0} \) – initial average mass temperature of the prism. K; \( T_m \) – processing medium temperature, K; \( T(x, y, 0) \) – temperature of all points in the prism in the beginning of the steaming, K; \( T(x, 0, τ) \) – temperature of all points on the surface of the prism parallel to its thickness during the steaming process, K; \( T(0, y, τ) \) – temperature of all points on the surface of the prism parallel to its width during the steaming.

Mathematical descriptions of the effective specific heat capacities of the frozen and non-frozen wood during its heating, \( c_{w-eff} \), and also of the effective thermal conductivities of the wood in different anatomical directions during its heating, \( λ_{w-eff} \), have been suggested in [2, 3, 4] based on the experimentally determined in the dissertations of Chudinov [1] and Kanter [9] relations for the change in \( c \) and \( λ \) of frozen and non-frozen wood as a function of the temperature, \( t \), and wood moisture content, \( u \).

2.2. Modeling of the heat balance of the steaming autoclave

The non-stationary heat balance of the autoclave for each moment \( n \cdot Δτ \) of the steaming process can be described by the following mathematical model [2]:

\[ Q_{ha}^n = Q_{hw}^n + Q_{hf}^n + Q_{hil}^n + Q_{hec}^n + Q_{hfv}^n + Q_{hcv}^n \]

where \( Q_{ha} \) is the specific (for 1 m³ wood) heat energy, which is supplied into the autoclave by the introduced in it water steam, kWh·m⁻³; \( Q_{hw} \) – energy used for heating of the subjected to steaming wood materials, kWh·m⁻³; \( Q_{hf} \) – energy used for heating of the body of the autoclave and of the situated in it metal trolleys for positioning of the wood materials, kWh·m⁻³; \( Q_{hil} \) – energy used for heating of the insulating layer of the autoclave, kWh·m⁻³; \( Q_{hec} \) – energy used for covering of the heat emission from the autoclave in the surrounding air, kWh·m⁻³; \( Q_{hfv} \) – energy used for filling in with steam the free (unoccupied by wood materials) part of the working volume of the autoclave, kWh·m⁻³; \( Q_{hcv} \) – energy, which is accumulated in the gathered in the lower part of the autoclave condense water, kWh·m⁻³; \( n \) – current number of the step along the time coordinate, \( Δτ \), with the help of which the solving of the model is carried out: \( n = 0, 1, 2, 3, … \)
The whole mathematical model (4) with descriptions of all components in it, depending on the influencing factors, has been given in [2, 5].

The specific heat flux 

\[ q_{hw}^n = \frac{dQ_{hw}^n}{d\tau} \]

which provides the energy required for warming up of 1 m\(^3\) wooden prisms for any moment \(n\cdot\Delta\tau\) of the steaming process is equal to (in kW\(\cdot\)m\(^3\))

\[ q_{hw}^n \approx \frac{3600\Delta Q_{hw}^n}{\Delta\tau} \quad (5) \]

The specific heat flux 

\[ q_{hw}^n = \frac{dQ_{hw}^n}{d\tau} \]

which provides the whole energy \(Q_{hw}^n\) during the heating of 1 m\(^3\) of prisms for any moment \(n\cdot\Delta\tau\) of the steaming process is equal to

\[ q_{hw}^n \approx \frac{3600\Delta Q_{hw}^n}{\Delta\tau} \quad (6) \]

3. Results and discussion

For numerical solving of the above considered 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 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 [8].

The increase of the processing medium temperature, \(T_m\), in the beginning of the steaming regimes is calculated according to the approach given in [6] by taking in mind the available heat power of the steam generator. During simulations the heat power of the steam generator \(q_{source} = 500\) kW was used. With the help of the software package computations were made for the determination of \(T_m\) and also of the 2D non-stationary change of the temperature in 4 representative points of \(\frac{1}{4}\) 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, length of \(L = 9.0\) m, and working volume \(V_a = 48\) m\(^3\) [5, 13].

Simultaneously with this, calculations for determination of the average mass temperature \(T_{avg}\) of the prisms, energy end heat flux consumed by the autoclave, \(Q_a\) and \(q_a\), respectively, and also the heat energy consumption, \(Q_w\), and the heat flux, \(q_w\), required for the warming up of the prisms themselves, have been carried out according to approaches given in [2, 5].

![Figure 1. Change in \(T_m\) in the beginning of the steaming regime of frozen beech prisms with \(d \times b = 0.4 \times 0.4\) m and \(\gamma = 50\%\), depending on \(u\)](image-url)
During the solving of the models, the presented in [2, 3] mathematical descriptions of the thermophysical properties of beech wood with basic density $\rho_b = 560$ kg·m\(^{-3}\) and standardized (at 20 °C) fiber saturation point $u_{fsp} = 0.31$ kg·kg\(^{-1}\) were used. The initial and the maximal values of the steaming medium temperature were equal to $t_{m0} = -20$ °C and $t_{m1} = 130$ °C respectively. During simulations the initial temperature of the frozen prisms $t_{w0} = -20$ °C and the following values of the factors influencing the duration $\tau$ of the initial part of the steaming regimes were set: dimensions of the square cross section of beech prisms with thickness $d$ and width $b$: $0.4 \times 0.4$ m; moisture content $u$ of the prisms subjected to steaming: 0.4 kg·kg\(^{-1}\), 0.6 kg·kg\(^{-1}\), and 0.8 kg·kg\(^{-1}\); loading level $\gamma$ of the autoclave with filled in prisms for steaming: 0.5 m\(^3\)·m\(^{-3}\) (i.e. $\gamma = 50\%$).

On Figure 1 the calculated change in the duration of the initial part of the steaming regimes for beech prisms, $\tau_1$, in an autoclave with $D = 2.4$ m and $L = 9.0$ m, depending on the studied influencing factors:

1. By increasing the heating time $\tau$, the temperature of the processing medium $t_m$ increases curvilinear until reaching its largest value $t_{m1}$ after time interval, which depends on the investigated factors. The lack of smoothness of the dependences $t_m = f(\tau)$ is caused by the uneven melting of the frozen free water in the separate points of the wooden prisms. The more points at which the ice melts at a given moment of the steaming process, the more this dependence is deformed.

2. The increase of the prisms moisture content $u$ from 0.4 to 0.8 kg·kg\(^{-1}\) at given values of $d \times b$ and $\gamma$ causes non-linear increase of $\tau_1$. When $d \times b = 0.4 \times 0.4$ m and $\gamma = 50\%$ the duration $\tau_1$ at $t_{m1} = 130$ °C and $q_{source} = 500$ kW is equal as follow: $\tau_1 = 2.2$ h for $u = 0.4$ kg·kg\(^{-1}\), $\tau_1 = 2.6$ h for $u = 0.6$ kg·kg\(^{-1}\), and $\tau_1 = 3.2$ h for $u = 0.8$ kg·kg\(^{-1}\).

The reason for this influence of $u$ is that the larger $u$ means there is a presence of more heat capacity of the wet wood in the autoclave [2, 3, and 4]. Because of this, the larger part of the constant flux $q_a$ is needed for warming up of the prisms with larger $u$, while the remaining smaller part from it leads to a smaller increase in $t_m$ during any next step $\Delta \tau$ when solving the mathematical model.

![Figure 2](image_url)

**Figure 2.** Change in $q_a$ and $q_w$ for beech prisms with $d \times b = 0.4 \times 0.4$ m at $\gamma = 50\%$, depending on $u$

On Figures 2 the calculated change in the specific heat fluxes $q_a$ and $q_w$ in the beginning of the autoclave steaming regimes of the studied beech prisms for veneer production is presented.

The constant value of $q_a = 20.83$ kW·m\(^{-3}\) during the increasing of $t_m$ from $t_{m0} = -20$ °C to $t_{m1} = 130$ °C in the beginning of the steaming regimes is determined as follows: By multiplying the autoclave working volume $V_a = 48.0$ m\(^3\) by $\gamma = 50\%$ the volume of the prisms subjected to steaming $V_u = 24.0$ m\(^3\) is obtained. After dividing the value of the limited heat power of the steam generator $q_{source} = 500$ kW by $V_u = 24.0$ the shown on Fig. 2 value of the specific heat flux $q_a = 20.83$ kW·m\(^{-3}\) is obtained.
The obtained results show that the dependencies \( q_w = f(t) \) reach their maximal values, which are very close to \( q_u \), as follow: at \( t = 0.75 \) h for \( u = 0.4 \) kg·kg\(^{-1}\); at \( t = 0.90 \) h for \( u = 0.6 \) kg·kg\(^{-1}\), and at \( t = 1.05 \) h for \( u = 0.8 \) kg·kg\(^{-1}\). These maximum values of \( q_w \) are caused by the largest numbers of points in the frozen prisms, in which the ice melts in the specified moments of the steaming regimes.

After reaching of \( t_{m1} = 130 \) °C at \( t = t_1 \) a significant decrease in \( q_w \) and \( q_u \) is observed. The lack of smoothness of the dependences \( q_w = f(t) \) and \( q_u = f(t) \) then is caused by the continuing uneven melting of the frozen free water in the separate points of the prisms.

It can be noted that the difference between fluxes \( q_u \) and \( q_w \) is equal to the sum of the heat fluxes, which ensure the energy consumptions needed for the last five members in the right side of eq. (4).

4. Conclusions

The present paper describes an approach for computing and research of the processing medium temperature, \( t_m \), and largest for the whole steaming process heat fluxes, \( q_w \) (required for warming up of the wood) and \( q_u \) (consumed by the autoclave), in the beginning of regimes for autoclave steaming of frozen prismatic wood materials at limited power of the steam generator, depending on dimensions of the prisms cross section, \( d \times b \), wood moisture content \( u \), and loading level of the autoclave with wood materials subjected to steaming, \( \gamma \).

The paper presents and analyses diagrams of the non-stationary change in \( t_m \), \( q_w \), and \( q_u \) in an autoclave with a diameter of 2.4 m, length of 9.0 m and loading level of 50\% at a limited heat power of the steam generator, equal to 500 kW during autoclave steaming process of frozen beech prisms with initial temperature of \( -20 \) °C, basic density of 560 kg·m\(^{-3}\), cross-section dimensions \( d \times b = 0.4 \times 0.4 \) m, moisture content \( u = 0.4, 0.6, \) and 0.8 kg·kg\(^{-1}\). All diagrams are drawn using the results obtained in the calculation environment of Visual FORTRAN by two personal mathematical models. It has been determined, that the increase of the wood moisture content at given values of \( d \times b \) and \( \gamma \) causes non-linear change in \( t_m \) and \( q_w \) during the time interval \( 0 - t_1 \) in-between \( t_m \) increases from its initial value of \( t_m = -20 \) °C to the maximal steaming regime temperature \( t_{m1} = 130 \) °C. The reasons for these changes have been explained in the paper.

The suggested approach and the obtained results can be used for the computation and model based automatic realization of energy efficient optimized regimes for autoclave steaming of different wood materials at limited heat power of the steam generator [7, 8].

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