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COMPUTING THE AVERAGE MOISTURE CONTENT OF WOOD MATERIALS SUBJECTED TO STEAMING IN AN AUTOCLAVE

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ABSTRACT

An approach for computing the average moisture content of the whole quantity of wood materials in given batch subjected to steaming in an autoclave has been suggested. This value of the wood moisture content is needed for calculation and automatic realization of optimal energy saving regime for autoclave steaming of the materials. The approach is based on two own 2D mathematical models: one of the temperature distribution in non-frozen prismatic wood materials during their steaming and other – of the heat balance of the autoclave. The calculated by the models increase in the steaming medium temperature in the beginning of basic regime is compared with the real increase of that temperature, which is measured with a sensor in the automatic control system. After proper processing of the obtained differences between measured and calculated temperatures with the software package Table Curve, an equation for calculating the average moisture content of the wood materials in the batch loaded in an autoclave is derived. The application of the suggested approach for the cases of autoclave steaming of beech prisms in the production of veneer is presented.

Key words: wooden prisms, average moisture content, autoclave steaming, mathematical models, veneer production.

INTRODUCTION

It is well known that during the process of veneer cutting, the wood should be in good plasticizing condition. For heating in order to plasticize wood materials in the production of veneer and plywood, the wooden prisms are very often subjected to steaming in pits, chambers or autoclaves (Chudinov 1968, Lawniczak 1995, Trebula and Klement 2003, Pervan 2009).

The plasticizing of wood materials under increased pressure and temperature of the steaming medium in autoclaves is used in many applications due to its greater energy efficiency and shorter duration in comparison with the plasticizing at atmospheric pressure (Shubin 1990, Deliiski 2003, 2011, Videlov 2003, Sokolovski et al. 2007, Deliiski and Dzurenda 2010).

To calculate and implement optimal for duration and energy consumption regimes for autoclave steaming of wood materials in modern systems for model-based automatic control, it is necessary to have information about the average moisture content of the total amount of materials for each batch loaded for steaming in an autoclave.

As is known, obtaining information on the average wood moisture content of in a batch cannot be done by direct measurement with sensors in the automatic control system.

In the specialized literature sources (Chudinov 1966, Shubin 1990, Hadjiski et al. 2020, 2021) completely lack any information about approaches and/or algorithms for determining the average moisture content in a certain amount of wood or other capillary-porous materials.

That is why this article considers an approach for computing the average moisture content of the whole quantity of wood materials in given batch subjected to steaming in an autoclave.

COMPUTING THE 2D UNSTEADY TEMPERATURE DISTRIBUTION IN NON-FROZEN WOODEN PRISMS SUBJECTED TO STEAMING

When the length of the prisms, *l*, is larger than their thickness, *d*, at liest more 4 ÷ 5 times, and simultaneously with this the width, *b*, does not exceed the thickness more than 3 times, for computing the temperature field 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 or air medium the following 2D mathematical model can be used (Deliiski 2003):

$$
\begin{aligned}
& c_{\mathrm{w}}\left(T,u,u_{\mathrm{fsp}}\right)\cdot \rho_{\mathrm{w}}(\rho_{\mathrm{b}},u)\frac{\partial T(x,y,\tau)}{\partial \tau}= \\
& =\frac{\partial}{\partial x}\left[\lambda_{\mathrm{w\text{-}cr}}\left(T,u,\rho_{\mathrm{b}},u_{\mathrm{fsp}}\right)\frac{\partial T(x,y,\tau)}{\partial x}\right]+\frac{\partial}{\partial y}\left[\lambda_{\mathrm{w\text{-}cr}}\left(T,u,\rho_{\mathrm{b}},u_{\mathrm{fsp}}\right)\frac{\partial T(x,y,\tau)}{\partial y}\right]
\end{aligned}
\tag{1}
$$

at

$$T(x,y,0)=T_{\mathrm{w0}} \tag{2}$$

and boundary conditions:

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

where c_{w} is the specific heat capacity of the non-frozen wooden prisms, J·kg^{-1}·K^{-1}; ρ_{b} – basic density of the wood, kg·m^{-3}; ρ_{w} – wood density, kg·m^{-3}; *u* – wood moisture content, kg·kg^{-1}; u_{fsp} – fiber saturation point of the wood species, kg·kg^{-1}; $\lambda_{\mathrm{w\text{-}cr}}$ – thermal conductivity of the non-frozen wood cross sectional to the fibers, W·m^{-1}·K^{-1}; *x* – coordinate along the prism's thickness of the separate points of the calculation mesh for numerical solving of the model: $0 \le x \le d$, m; *d* – thickness of the prism, m; *y* – coordinate along the prism's width of the separate points of the calculation mesh: $0 \le y \le b$, m; *b* – width of the prism, m; τ – time, s; *T* – temperature, K; T_{w0} – initial average mass temperature of the prism subjected to steaming, K; T_{m} – processing medium temperature during the steaming of the prisms, K.

Mathematical descriptions of the specific heat capacity, c_{w}, density, ρ_{w}, and thermal conductivity, $\lambda_{\mathrm{w\text{-}cr}}$, of the non-frozen wood as a function of *T*, *u*, and u_{fsp} have been suggested in (Deliiski 2003, 2011, 2013).

MATHEMATICAL MODEL OF THE HEAT ENERGY CONSUMPTION OF REGIMES FOR STEAMING PRISMS IN AUTOCLAVE

The non-stationary heat balance of the steaming autoclave is mathematically presented by the following model, which has been experimentally verified in (Deliiski 2003):

$$Q_{\mathrm{a}}^{n}=Q_{\mathrm{w}}^{n}+Q_{\mathrm{mb}}^{n}+Q_{\mathrm{il}}^{n}+Q_{\mathrm{e}}^{n}+Q_{\mathrm{fv}}^{n}+Q_{\mathrm{cw}}^{n}, \tag{4}$$

where Q_{a}^{n} is the specific (for 1 m^3 wood materials) heat energy, which is supplied into the autoclave by the introduced in it water steam, kWh·m^{-3}.

The meaning of the indices of the variables in Equation (4) is, as follows: a – autoclave; w – wood of the prisms; mb – metal body of the autoclave; il – insulating layer of the autoclave; e – heat emission of the autoclave; fv – free (unoccupied by prisms) volume; cw – condense water; n – current number of the step along the time coordinate, $\Delta\tau$, with the help of which the joint solving of the models is carried out: $n = 0, 1, 2, 3, \ldots$.

Dependences of all components of the heat balance in Equation (4) on the influencing factors have been given in (Deliiski 2003, Deliiski and Dzurenda 2010, Deliiski et al. 2019, 2021).

RESULTS AND DISCUSSION

Using own software package for joint solving of the models (1) – (3) and (4) in the calculation environment of Visual FORTRAN, simulations were made to compute the change in the temperature of the steaming medium in the autoclave, T_m, taking into account the methodology given in Hadjiski et al. (2021). During simulations the following values of the parameters influencing T_m were set:

1. Initial value of t_m: $t_{m0} = 0^oC$.
2. Maximal value of the temperature of the basic steaming regime: $t_{m1} = 130^oC$.
3. Dimensions of the square cross section of prisms subjected to steaming: 0.4 × 0.4 m.
4. Initial temperature t_{w0} of the beech prisms subjected to autoclave steaming: 0^oC.
5. Moisture content u of the prisms for computing the basic steaming regime: $0.6\ kg{\cdot}kg^{-1}$.
6. Moisture content of other studied steaming regimes: 0.4, 0.5, 0.7, and $0.8\ kg{\cdot}kg^{-1}$.
7. Basic density of $560\ kg{\cdot}m^{-3}$ for the beech wood.
8. Inner diameter of 2.4 m and length of 9.0 m of the steaming autoclave.
9. Loading level γ of the autoclave with filled in wooden prisms for steaming: $\gamma = 50\%$.
10. Heat power $q_{source} = 500$ kW of the steam generator, which feeds the autoclave.

On Fig. 1 the calculated change in t_m in the beginning of the steaming regimes depending on u and τ is presented. On Fig. 2 the differences Δt_m between t_m at $u = 0.4, 0.5, 0.7$, and $0.8\ kg{\cdot}kg^{-1}$ and t_m at basic value of $u = 0.6\ kg{\cdot}kg^{-1}$ is shown for 3 values of the time interval, $\Delta\tau$, from the beginning of the steaming regimes, as follows: $\Delta\tau = 0.6$ h, $\Delta\tau = 1.2$ h, and $\Delta\tau = 1.8$ h.

The dependences of Δt_m on u shown in Fig. 2 were approximated using the Internet-available Table Curve software package. The resulting equation has the following general form:

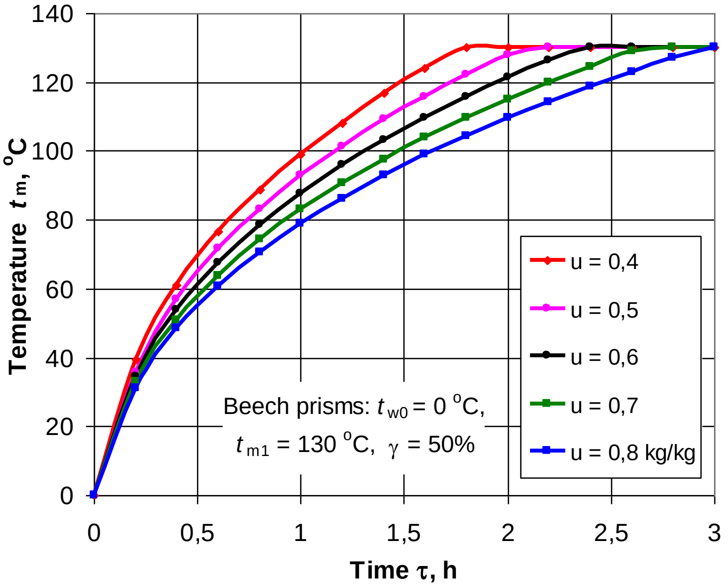

Figure 1: Change in t_m in the beginning of the steaming regimes, depending on *u* and τ

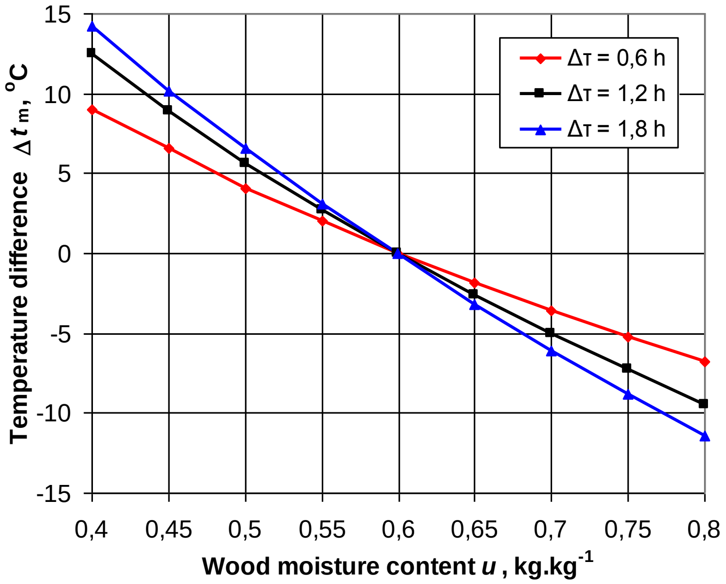

Figure 2: Change in the differences Δt_m between t_m at *u* = var and *u* = 0.6 kg.kg^{-1}, depending on *u* and time interval Δτ

$$\Delta t_m = a + b \cdot u. \tag{5}$$

Table 1 shows the coefficients *a* and *b* in eq. (5) obtained by Table Curve for the most common in the practice range $0.6 \le u \le 0.8$ kg·kg^{-1} of steamed prisms in the production of veneer.

Table 1: Change in *a* and *b* of eq. (5) for $0.6 \le u \le 0.8$ kg·kg^{-1}

№	Duration of the increase of t_m, h	*a*	*b*
1.	0.6	20.32	–34.0
2.	1.2	28.30	–47.4
3.	1.8	33.86	–56.8

After approximation with Table Curve 2D (http://www.sigmaplot.co.uk/products/tablecurve2d/tablecurve2d.php) of the data in Table 1, the following equation was obtained for Δt_m as a function of both τ and u with a correlation coefficient of 0.99 and root mean square error of less than 3% (Figure 3 and Figure 4):

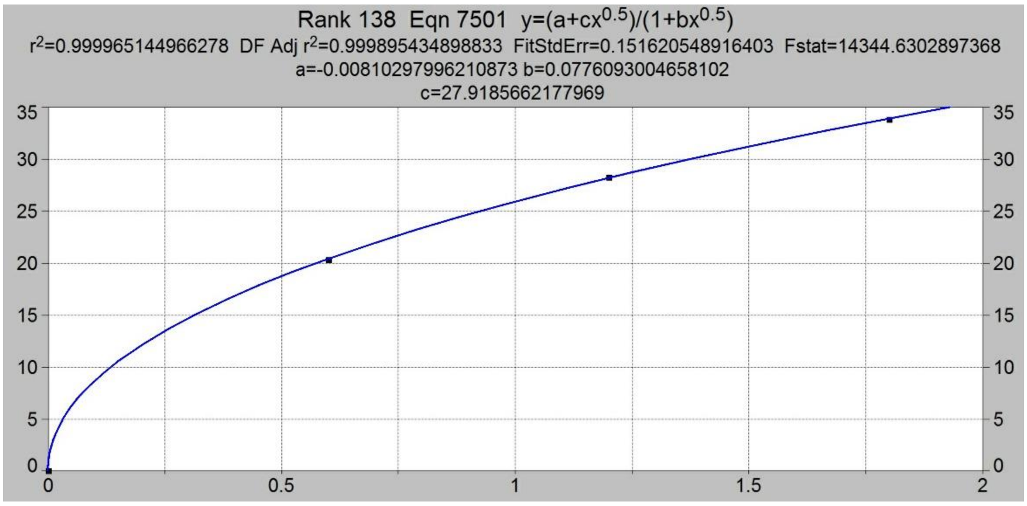

Figure 3: Approximation with Table Curve 2D the coefficients *a* in Table 1 as a function of τ and *u*

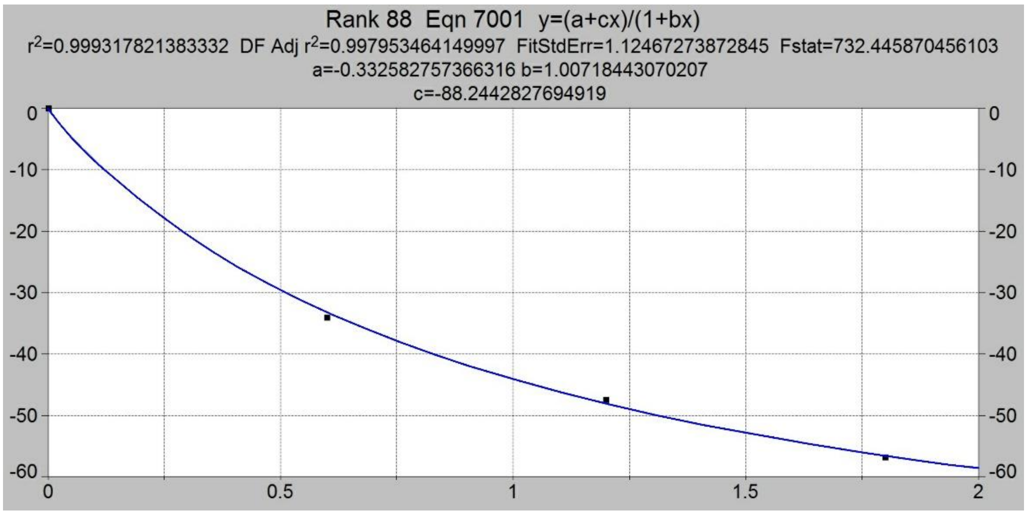

Figure 4: Approximation with Table Curve 2D the coefficients *b* in Table 1 as a function of τ and *u*

$$\Delta t_m = \frac{27.92 \cdot \tau^{0.5}}{1 + 0.08 \cdot \tau^{0.5}} - \frac{88.24 \cdot \tau}{1 + 1.01 \cdot \tau} \cdot u \qquad \textbf{(6)}$$

From eq. (6) it is possible to directly determine the average wood moisture content u of the batch of subjected to steaming prisms in the autoclave according to the following equation:

$$u = \frac{\dfrac{27.92 \cdot \tau^{0.5}}{1 + 0.08 \cdot \tau^{0.5}} - \Delta t_m(\tau) \text{ at } u_b}{\dfrac{88.24 \cdot \tau}{1 + 1.01 \cdot \tau}}, \qquad \textbf{(7)}$$

where u_b is the wood moisture content used in the initial computation of the basic prisms steaming regime. As stated above, in our case u_b = 0.6 kg.kg^{-1}.

It should be noted that equations (6) and (7) do not contain the coefficients *a* given on

Fig. 3 and Fig. 4 due to their negligible small values.

Using the data for Δt_m between curves of u = 0.8 kg·kg^{-1} and u_b = 0.6 kg·kg^{-1} from Fig. 1, verification calculations of the average wood moisture content of batches with beech prisms according to eq. (7) were performed for 5 different time intervals from the beginning of the steaming regimes. The obtained calculated values of u, u_{calc}, and of the error of the calculated values of u, δ, are presented in Table 2.

Table 2: Change in u_{calc} and δ for u = 0.8 kg.kg^{-1} at u_b = 0.6 kg.kg^{-1}

№	Duration of the increase of t_m, h	Δt_m, °C	u_{calc}, kg.kg^{-1}	δ, %
1.	0.6	6.8	0.824	+3.0
2.	1.0	8.7	0.787	–1.6
2.	1.2	9.5	0.785	–1.9
3.	1.8	11.4	0.802	+0.3
3.	2.0	11.8	0.809	+1.1

The data in Table 2 show that eq. (7) provides an accuracy of determining u within 3%. This accuracy is quite sufficient for the use of eq. (7) in the software of systems for calculation and automatic realization of highly efficient regimes for autoclave steaming of wooden prisms intended for veneer production.

CONCLUSIONS

The present paper describes an approach for computing the average moisture content of wood materials subjected to steaming in an autoclave. The approach is based on the use of two personal mathematical models: 2D non-linear model of the unsteady distribution of the temperature in non-frozen prismatic wood materials subjected to steaming, and model of the non-stationary heat balance of autoclaves for steaming wood materials.

Using simulations with both models in Visual FORTRAN Professional and the Table Curve software package, an equation for calculating the average moisture content of a batch of wooden prisms loaded for steaming in an autoclave at limited power of the heat generator is derived. This equation is obtained by appropriate processing of the differences between the steaming medium temperatures periodically measured with a sensor in the autoclave control system and the medium temperatures calculated in the beginning of the basic steaming regime.

The verification calculations performed with this equation show accuracy in the range of 3% to determine the average moisture content of the prisms in the range $0.6 \leq u \leq 0.8$ kg.kg^{-1}. This accuracy is quite sufficient for the use of the obtained equation in the software of systems for calculation and automatic realization of highly efficient regimes for autoclave steaming of wooden prisms intended for veneer production.

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