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COMPUTATION OF THE 2-DIMENTIONAL TRANSIENT TEMPERATURE DISTRIBUTION AND HEAT ENERGY CONSUMPTION OF FROZEN AND NON-FROZEN LOGS

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ABSTRACT

A summarized 2-dimensional mathematical model has been created, solved, and verified for the transient non-linear heat conduction and energy consumption in frozen and non-frozen logs at arbitrary, encountered in the practice initial and boundary conditions. The model takes into account for the first time the fiber saturation point of each wood specie and the specific heat capacity of the wood itself and the ice contained in it, which has been formed from the freezing of the free, as well as of the hygroscopically bounded to it, water. It has been solved with the usage of an explicit form of the finite-difference method, where the distribution of the temperature field in all points of the volume of the log is calculated for the first time only with one system of equations.

The paper presents solutions of the model, which prove the applicability of Fourier's criterion for similarity from the theory of heat transfer for the calculation of the heating of the logs. At different diameters of the logs and identical relations of their lengths to their diameters, the distribution of the temperature in their volumes and the consumed energy for their heating at given initial and boundary conditions turn out to be identical for one and the same relations of the duration of heating to the logs' diameters.

KEY WORDS: wood logs, modeling, temperature distribution, heat energy, Fourier's criterion for similarity, programmable controller

INTRODUCTION

For the optimization of the control of the heating process of logs in veneer/plywood and waferboard/ flakeboard mills, it is required that the distribution of the temperature field in the logs and the consumed energy for their heating at every moment of the process are known. The intensity of heating and the consumption of energy depend on the dimensions and the initial temperature of the logs, on the texture and micro-structural features of the wood species, on the anisotropy of the wood and on the content and aggregate condition of the water in it, on the law of change and the values of the temperature of the heating medium (the steam or hot water), etc. (Trebula and

Klement 2002, Videlov 2003). There are many publications, which are dedicated to the distribution of the temperature in the logs at different initial and boundary conditions of the process and there are practically none that present the influence of various factors on the non-stationary change of the heat energy, which is needed for the heating of frozen and non-frozen logs.

Considerate contribution to the calculation of the non-stationary distribution of the temperature in frozen and non-frozen logs and to the duration of their heating has been made by Steinhagen. For this purpose, he, alone, (Steinhagen 1986, 1991) or with co-authoring (Steinhagen et al. 1987), (Steinhagen and Lee 1988) has created and solved a 1-dimensional, and later a 2-dimensional (Khattabi and Steinhagen 1992, 1993, 1995) mathematical model, whose application is limited only for $u \geq 0,3$ kg.kg^{-1}. The development of these models is dominated by the usage of the method of enthalpy, which is rather more complicated than its competing temperature method. The models contain two systems of equations, one of which is used for the calculation of the change in temperature at the axis of the log, and the other – for the calculation of the temperature distribution in the remaining points of its volume. The heat energy, which is needed for the melting of the ice, which has been formed from the freezing of the hygroscopically bounded water in the wood, although the specific heat capacity of that ice is comparable by value to the capacity of the frozen wood itself (Chudinov 1968), has not been taken into account in the models.

These models assume that the fiber saturation point is identical for all wood species and that the melting of the ice, formed by the free water in the wood, which is found in the inter-cellular areas, occurs at 0°C. However, it is known that there are significant differences between the fiber saturation point of the separate wood species and that the dependent on this point quantity of ice, from the free water in the wood, thaws at a temperature in the range between -2°C and -1°C (Chudinov 1966, 1984).

This paper presents the creation, solutions, and verification of the summarized 2-dimensional mathematical model of the transient non-linear heat conduction and energy consumption in frozen and non-frozen logs, where the indicated complications and incompleteness in existing analogous models have been overcome. The solutions include the non-stationary temperature distribution in the volume of the logs, as well as the specific energy consumption at every moment of the heating for each $u \geq 0$ kg.kg^{-1}. They prove the applicability of Fourier's criterion for similarity from the theory of heat transfer for the calculation of the heating of the logs. For different diameters of the logs and identical relations of their lengths to their diameters, the distribution of the temperature in their volumes and the consumed energy for their heating at given initial and boundary conditions turn out to be identical for one and the same relations of the duration of heating to the logs' diameters.

Mathematical model for the non-stationay heating of logs

During the heating of the wood materials along with the purely thermal processes, a mass-exchange occurs between the heating medium and the wood. The values of the moisture diffusion of the different wood species in the radial direction of their fibers are hundreds of times smaller than the values of their temperature conductivity. In a longitudinal to the fibers direction, the temperature conductivity exceeds the moisture diffusion by more than a hundred times. These facts determine a not so big change in the content of water in the materials during their thermal treatment, which lags significantly from the distribution of heat in them. This allows during the creation of a mathematical model to disregard the exchange of mass between the wood and the heating medium and the change in temperature in the materials to be viewed as a result of a purely thermo-exchange process, where the heat in them is distributed only through thermo-conductivity.

Consequently, the process of heat transfer in the logs can be described by a non-linear differential equation of the thermo-conductivity, which in polar coordinates takes the following form (Deliiski 1979):

$$\rho_w c_{we} \frac{\partial T(r,z,\tau)}{\partial \tau} = \lambda_{wr}\left[\frac{\partial^2 T(r,z,\tau)}{\partial r^2} + \frac{1}{r}.\frac{\partial T(r,z,\tau)}{\partial r}\right] + \frac{\partial \lambda_{wr}}{\partial T}\left[\frac{\partial T(r,z,\tau)}{\partial r}\right]^2 + \lambda_{wz}\frac{\partial^2 T(r,z,\tau)}{\partial z^2} + \frac{\partial \lambda_{wz}}{\partial T}\left[\frac{\partial T(r,z,\tau)}{\partial z}\right]^2 \quad (1)$$

with an initial condition

$$T_w(r,z,0) = T_{w0}, \quad (2)$$

and a boundary condition

$$T_w(0,z,\tau) = T_w(r,0,\tau) = T_m(\tau). \quad (3)$$

For the solution of the system of equations (1) – (3), a mathematical description of the participant in it thermo-physical characteristics of the wood, c_{we}, λ_{wr}, λ_{wz}, and of its density, ρ_w, is needed. For the ensuring of a possibly best accuracy of the results from the calculations of the temperature distribution in the logs and the consumed energy during their heating, a mathematical description of c_{we}, λ_{wr}, λ_{wz} must be expressed as a function of the absolute temperature. We have prepared this description with the usage of experimental data for the thermal characteristics of the wood, obtained by Kanter (1955) and Chudinov (1966, 1968, 1984) during the development of their dissertations. A part of this data, which concerns the characteristics of the non-frozen wood only, has been presented graphically and described mathematically for $0 \le u \le 1{,}3$ kg.kg^{-1} by us (Deliiski 1977) for a function of T, which has been expressed there in °C, and not in K. This mathematical description has been used by us for the calculation of temperature distribution in the volume of intended for the production of veneer prismatic materials of different wood species with $u \ge u_{fsp}$, and also for the calculation of the change in T in wood beams with $u < u_{fsp}$ (Deliiski 1988) and (Olek and Guzenda 1995).

The same experimental results obtained by Kanter (1955) and Chudinov (1968) are mathematically described by Steinhagen and Lee (1988) only for the interval $0{,}3 \le u \le 1{,}3$ kg.kg^{-1} and with the mathematical description of the latent heat of the thawing of frozen free water in the wood have been used by Khattabi and Steinhagen (1992, 1993, 1995) for the calculation of the distribution of T in logs.

Equations in (Deliiski 1990, 2003a, 2004) present a mathematical description of the effective specific heat capacity coefficient, c_{we}, of the wood as a sum of the capacities of the wood itself, c_w, and the created in it ice from the freezing of the free water, c_{fw}, and of the hygroscopically bounded water, c_{bw}.

Equations in (Deliiski 1994, 2003a) present a mathematical description of the density of the wood, ρ_w, and of its thermal conductivity λ_w in different anatomical directions. In the description of λ_w, as well as in that of c_{we}, the moisture content u_{fsp} has been introduced for the first time as an independent variable for different wood species, instead of the ordinarily used averaged value of u_{fsp} = 0,3 kg.kg^{-1} for all wood species.

The mathematical description of c_w (Deliiski 1990) and λ_w (Deliisky, 1994) has been used for the computer-aided estimation of thermal conductivity of Scots pine wood (Olek et al. 2000).

Symbols:

a - temperature conductivity [$m^2.s^{-1}$],
c - specific heat capacity [$W.kg^{-1}.K^{-1}$],
D - diameter [m],
e - exponent
L - length [m],
Q - specific heat energy [$kWh.m^{-3}$],
r - radial coordinate: $0 \le r \le R$ [m],
R - radius [m],
S - area [m^2],
T - temperature [K],
u - moisture content [$kg.kg^{-1}$ = %/100],
z - longitudinal coordinate: $0 \le z \le L/2$ [m],
λ - thermal conductivity [$W.m^{-1}.K^{-1}$],
ρ - density [$kg.m^{-3}$],
τ - time [s],
Δr - distance between mesh points in space coordinates [m],
$\Delta\tau$ - interval between time levels [s].

Subscripts:

a - anatomical direction
avg - average
b - basic (for density, based on dry mass, divided to green volume)
bw - bound water
c - center (of logs)
fsp - fiber saturation point
fw - free water
i - nodal point in radial direction: 1, 2, 3, …, $(R/\Delta r)$+1
k - nodal point in longitudinal direction: 1, 2, 3, …, $(L/2\Delta r)$+1
m - medium
0 - initial (at 0°C for λ)
p - parallel to the fibers
pr - parallel to the radial
r - radial direction (radial to the fibers)
w - wood
we - wood effective (for specific heat capacity)
z - longitudinal direction

Superscript:

n - time level 0, 1, 2, …

RESULTS AND DISCUSSION

The following system of equations has been derived by passing to final increases in equation (1) with the usage of the same, as well as by the described by us (Deliiski, 1977, 2003a) explicit form of the finite-difference method and taking into account the mathematical description of the thermal conductivity λ_w in different anatomical directions:

$$T_{i,k}^{n+1} = T_{i,k}^{n} + \frac{\Delta\tau b\lambda_{\mathrm{w0r}}}{\rho_{\mathrm{w}} c_{\mathrm{we}} \Delta r^2} \left\{ \begin{array}{l} \left[1+\beta\left(T_{i,k}^{n} - 273{,}15\right)\right] \left[\begin{array}{l} T_{i-1,k}^{n} + T_{i+1,k}^{n} + K_{\mathrm{wpr}}\left(T_{i,k-1}^{n} + T_{i,k+1}^{n}\right) - \\ \left(2+2K_{\mathrm{wpr}}\right)T_{i,k}^{n} + \frac{1}{i-1}\left(T_{i-1,k}^{n} - T_{i,k}^{n}\right) \end{array} \right] + \\ + \beta\left[\left(T_{i-1,k}^{n} - T_{i,k}^{n}\right)^2 + K_{\mathrm{wpr}}\left(T_{i,k-1}^{n} - T_{i,k}^{n}\right)^2\right] \end{array} \right\} \tag{4}$$

with an initial condition

$$T_{i,k}^{0} = T_{\mathrm{w0}}, \tag{5}$$

and a boundary condition

$$T_{0,k}^{n} = T_{i,0}^{n} = T_{\mathrm{m}}(\tau)\ . \tag{6}$$

The value of the interval between time levels $\Delta\tau$ is determined from the condition of stability, needed for the solution of the system of equations (4) (Deliiski 1977).

Wide experimental studies have been performed by us for the determination of a 1- and 2-dimensional distribution of the temperature in the volume of frozen and non-frozen logs of pine (*Pinus silvestris* L.), beech (*Fagus silvatica* L.), and poplar (*Populus nigra* L.), which have been heated at different temperatures of the steaming medium. The values of the coefficient $K_{\mathrm{wpr}} = \frac{\lambda_{\mathrm{w0p}}}{\lambda_{\mathrm{w0r}}}$ in equation (4) have been determined through the solution of the model with the same initial and boundary conditions for the reaching of a maximum conformity between the calculated and experimental results, i.e. through the solution of the inverse problem of the field theory (Lukov 1978).

It has been determined, that the coefficient K_{wr}, which takes into account the influence of the microstructure of the wood on the thermal conductivity in its radial direction in the presence, as well as in the absence of ice in it, has the following values: for pine K_{wr} = 1,25, for beech K_{wr} = 1,35, and for poplar wood K_{wr} = 1,48. The coefficient K_{wpr} has the following values: for pine K_{wpr} = 2,37, for beech K_{wpr} = 1,78, and for poplar K_{wpr} = 1,96. After the application of an analogous approach, Khattabi and Steinhagen (1995) found out that K_{wpr} = 2,50 for both *Pinus canariensis* and *Pinus maritima*, which is very close to the value of K_{wpr} = 2,37 for the wood of *Pinus silvestris*, determined by us.

Computation of the specific consumption of energy during the heating of logs

The average temperature of the log in any moment of the heating is calculated with the following equation, which incorporates numerical integration with the help of the Simpson method (Dorn and McCracken 1972) of the obtained as a result of the solution of the model non-stationary distribution of T in the log:

$$T_{\mathrm{wavg}}^{n} = \frac{1}{S_{\mathrm{w}}} \iint\limits_{(S_{\mathrm{w}})} T(r, z, n.\Delta\tau)\, dS_{\mathrm{w}}\ , \tag{7}$$

where

$$S_w = \frac{L.D}{4}. \tag{8}$$

The distribution of T in the volume of the log and the calculation of T_{wavg} are obtained from the solution of the model with an interval between time levels $\triangle\tau$, when the instantaneous values for the boundary conditions and the thermo-physical characteristics of the wood during heating are taken into consideration. Synchronously with this, a calculation is performed of the specific consumption of thermal energy, which is used for the heating of the wood until moment $n.\triangle\tau$, according to equation

$$Q_w^n = \frac{\rho_w}{3{,}6.10^6 S_w}\left\{\iint_{(S_w)}[T(r,z,n.\Delta\tau) - T(r,z,0)]\frac{c_{we}(r,z,n.\Delta\tau) + c_{we}(r,z,0)}{2}dS_w\right\} \tag{9}$$

In the software, which we prepared in the calculation environment of VISUAL FORTRAN PROFESSIONAL, created by Microsoft, for the solution of the model, during the computation of Q_w the average arithmetical values of c_{we} on the right side of equation (9) are calculated at every interval of $\triangle\tau$ separately for the interval $T_{w0} \leq T \leq 271{,}15\ ^0$K in the presence of ice in the wood and separately for the entire interval $T \geq T_{w0}$ in the absence of ice in it, depending on the instantaneous value of T in every node of the calculation network.

Resuls from experimental and simulation studies

With the help of the model, the changes in T and Q_w are studied for situated in a geometrical likeliness frozen and non-frozen logs with D = 0,08; 0,16; 0,32; 0,40, and 0,80 m and relations L / D = 0,5; 1,0; 1,5; 2,0; 4,0; 5,0, and 10 during their heating at different T_m. The values of D have been so selected, as to include almost all encountered in the practice diapasons of their change, and besides this, the second, third, fourth, and fifth from the indicated values for D are respectively 2, 4, 5, and 10 times larger than the first value for D = 0,08 m.

According to Fourier's criterion of likeliness (Lukov 1978), the distribution of T in geometrically alike bodies must be the same after a duration of the heating, equal in our case to τ / D. The applicability of this postulate from the theory of heat transfer and the possibility for it to be used for the determining of thermal energy consumption Q_w, have been verified with a part of the studies.

Change in *T* in the volume of logs

The change in T_c and T_{wavg} of beech logs with T_{w0} = -20°C and L / D = 4 depending on the relation τ / D and on u during their heating at T_m = 80°C is shown on Fig. 1. Since u_{fsp} = 0,31 kg.kg^{-1} for beech wood, then the curves on Fig. 1 show the heating of absolutely dry wood (u = 0 kg.kg^{-1}), as well as of wood, that contains ice from the free and bounded water ($u \geq$ 0,4 kg.kg^{-1}), or only from the bounded water in the wood (u = 0,3 kg.kg^{-1}).

The change in T_c is shown on Fig. 2 for beech logs with T_{w0} = -20°C and u = 0,6 kg.kg^{-1} during their heating at T_m = 80°C depending on the relations τ / D and L / D. The change in the defrosted part of D in the central cross section of the beech materials with T_{w0} = -20°C and L / D = 4, heated at T_m = 80°C, depending on τ / D and on $u \geq u_{fsp}$, is shown on Fig. 3.

The obtained results lead to the following conclusions:

1. The applicability of Fourier's criterion of likeliness is proven for the determining of the change in T of the subjected to heating logs. For logs of given wood specie with different D and the same L / D, the distribution of T in their volume is identical for the same relations τ / D and given values of T_{w0}, T_m and u.

2. At points, situated in the interior of the logs, which contain ice from the free water in the wood, a characteristic section for the delay of the increase in T is observed in the range between -2 and −1°C, while the thawing of that ice lasts. Such a section has been determined also in all studies with the participation of H.P.Steinhagen, which are cited in the references. The duration of the thawing of the ice increases with the distancing of the point from the surface of the log to a direction of its center and from its frontal sides to a distance, equal to $L / D = 2K_{wpr}$.

3. The decrease of T_m and the increase of u and ρ_b cause a delaying in the heating of the logs, mainly because of a decrease in a_w in a function of u and ρ_b and an increase in a_w depending on T. The delay is particularly long for logs that contain ice from the free water in them. From the studied wood species the poplar is heated the fastest, having ρ_b = 355 kg.m^{-3} and K_{wr} = 1,48; after it is the beech with ρ_b = 560 kg.m^{-3} and K_{wr} = 1,35, and the pine logs warming up the slowest with ρ_b = 430 kg.m^{-3} and K_{wr} = 1,25.

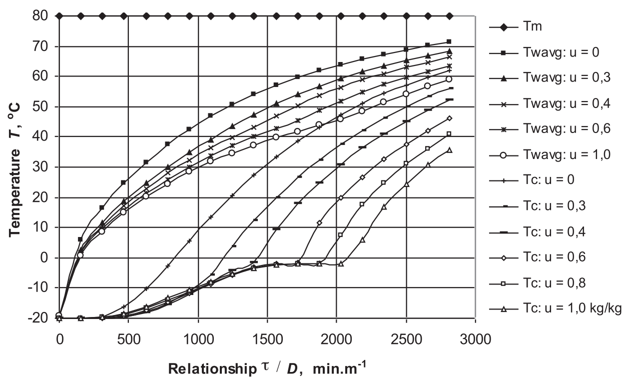

Fig.1: Change in T_c and T_{wav} of beech logs with T_{w0} = -20°C and L / D = 4 at T_m = 80°C depending on τ / D and on u

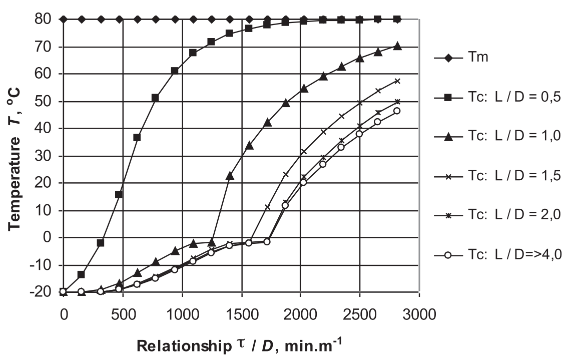

Fig. 2: Change in T_c of beech logs with T_{w0} = -20°C and u = 0,6 kg.kg^{-1} at T_m = 80°C depending on τ / D and on L / D

4. The increase of the defrosted part from the diameter of logs at $u \geq u_{fsp}$ occurs according to an exponential dependence on τ / D, which turns into a linear one at τ / D > 500 min.m^{-1}. The steepness of this dependency decreases with an increase of u.

5. The increase of T_{wavg} during the heating of the logs occurs at an exponent, which begins at T_{w0} and asymptotically aims at T_m, as its steepness is proportional to T_m. The shown in point 2 delay in the change in T in the interior of the logs, containing ice from the free water in the wood, causes a small curving in the exponential change of T_{wavg}. The duration of the concave section is proportional to the difference $u - u_{fsp}$.

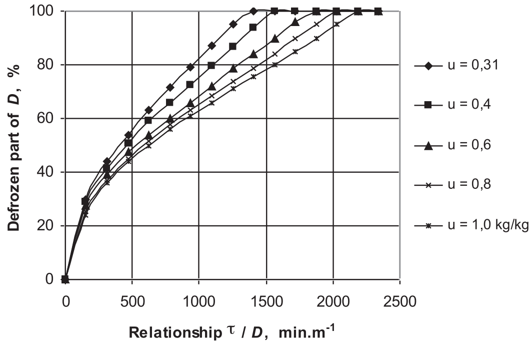

Fig. 3: Change in the defrosted part of D in the central cross-section of beech logs with T_{w0} = -20°C and L / D = 4 at T_m = 80°C depending on τ / D and on $u \geq u_{fsp}$

Change in the specific consumption of heat energy Q_w

The change in the specific heat energy Q_w, which is consumed by beech logs with T_{w0} = -20°C and L/D = 4 during their heating at T_m = 80°C depending on the relation τ/D and on u, is shown on Fig. 4.

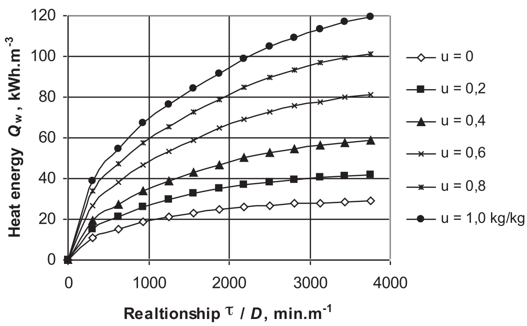

Fig. 4: Change in Q_w of beech logs with T_{w0} = -20°C and L / D = 4 at T_m = 80°C depending on τ / D and on u

The change of the maximum value Q_w^{max} of Q_w, which is reached at an equalizing of T_{wavg} with T_m during the heating of beech logs with L/D = 4 and u = 0,6 kg.kg^{-1} depending on T_{w0} and on T_m, is shown on Fig. 5. The change of the maximum value Q_w^{max} of Q_w, which is reached during the heating at T_m = 80°C of beech logs and L/D = 4 depending on T_{w0} and on u, is shown on Fig. 6. The change of Q_w of beech logs with T_{w0} = -20°C and u = 0,6 kg.kg^{-1}, heated at T_m = 80°C, depending on the relations τ/D and L/D, is shown on Fig. 7.

The obtained results lead to the following conclusions:

1. The applicability of Fourier's criterion of likeliness is proven for the determining of the consumption of specific thermal energy Q_w, which is needed for the heating of the logs. For logs of a given wood specie with different D and the same L / D, the energy Q_w is identical for the same relations τ / D and for given values of T_{w0}, T_m and u.

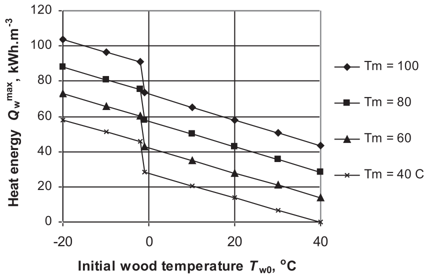

Fig. 5: Change in Q_w^{max} of beech logs with L / D = 4 and u = 0,6 kg.kg^{-1} depending on T_{w0} and on T_m

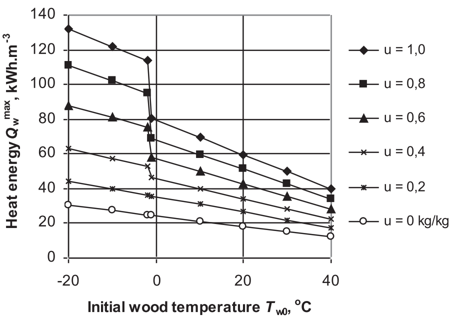

Fig. 6: Change in Q_w^{max} of beech logs with L / D = 4 at T_m = 80°C depending on T_{w0} and on u

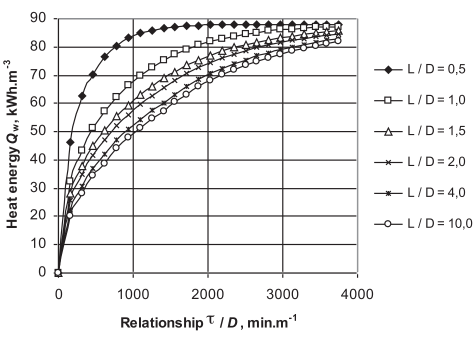

Fig. 7: Change in Q_w of beech logs with T_{w0} = -20°C and u = 0,6 kg.kg^{-1} at T_m = 80°C depending on τ / D and on L / D

2. The increase of Q_w during the heating occurs at exponents, which begin at 0 and asymptotically approach the maximum values Q_w^{max}, depending increasingly on T_m, ρ_b, and u and decreasingly on T_{w0}. The steepness of these exponents depends decreasingly on T_{w0} and increasingly on T_m, ρ_b, u

and on the quantity of ice in the wood. The values of Q_w^{max} are reached at $T_{wavg} = T_m$.

3. The increase of T_{w0} causes a proportional decrease of Q_w^{max} with a slope, which is practically identical for both the frozen and the non-frozen wood. This slope decreases insufficiently with the decrease of T_m and increases with the increase of ρ_b and u.

4. When $T_{w0} \leq 2°C$ and $u > u_{fsp}$, a jump in the change of Q_w^{max} between -2^0C and -1^0C is observed, which is caused by the need for additional energy for the thawing of the ice, formed from the free water in the wood. This jump increases with an increase in the difference $u - u_{fsp}$.

5. The differences between u_{fsp} of the different wood species influence significantly (up to 40% and more) the consumption of thermal energy, which is needed for the thawing of the ice from the free water in the wood with a large u. This confirms the expediency from the including for the first time of u_{fsp} as an independent variable in the mathematical model.

6. The increase in the relation L / D of the logs causes a delay in the increase of Q_w and at the moment of reaching Q_w^{max} during the heating, as Q_w^{max} does not depend on L / D. This delay practically ends at $L / D \geq 10$.

CONCLUSIONS

The present paper describes the creation, solution, and verification of a summarized 2-dimensional mathematical model for the non-stationary heating of frozen and non-frozen logs. The model takes into account the physics of the process and allows the calculation of the temperature distribution in the volume of subjected to heating logs of different wood species, and also of the specific consumption of thermal energy by the wood during the heating. The developed for the solution of the model software allows for the computations to be done almost for any encountered in the practice initial and boundary conditions for the heating of the logs.

An analogous 3-dimentional summarized model for the non-stationary heating of frozen and non-frozen prismatic wood materials is created, solved and verified by us (Deliiski 2003a).

Fig. 8: Controllers for automatic computation and regulation of the steaming process of logs and prismatic wood materials (on the left and on the right) and for the leading away of the condensed water from the steaming equipment (center)

The development of the models and algorithms and software for their solution is consistent with the possibility of their usage in automatic systems with a model predicting control (Hadjiyski 2003) of different technological processes for wood thermal treatment. At this stage the obtained with personal computer solutions of the models are processed in an appropriate way and are input in a computing and controlling algorithm of programmable logic controllers (Deliiski 2003b).

The displays of the controllers (Fig. 8) show a few input, calculated, currently measured, and also technologically or emergency signaled parameters of the controlled process. The information for the most important of them is output constantly, while for the others the operator needs to press certain buttons on the front panels of the controllers. During an unregulated power outage the controllers keep in their memory the up-to-date values of the measured and controlled parameters and when the power is restored the controllers scan the actual condition of the process and continue its operation.

The individualization of the regimes for thermal treatment for each share of wood materials with the help of the controllers ensures the carrying out of practically flawless steaming or boiling of the materials.

In result to the adoption of the controllers for the automatic computation, regulation and optimization of the steaming or boiling process of wood materials in pits, chambers and autoclaves, the quality and quantity of veneer and lumber output have been improved and the specific heat energy consumption has been significantly decreased.

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