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MODELLING OF THE ENERGY CONSUMPTION OF THE UNILATERAL CONVECTIVE HEATING PROCESS OF FURNITURE ELEMENTS BEFORE THEIR LACQUER COATING

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ABSTRACT

Two mutually connected 1D linear mathematical models created and solved by the authors earlier, are updated and presented as a nonlinear model. The first of them allows the computation of the non-stationary temperature distribution along the thickness of subjected to unilateral convective heating flat wooden furniture elements before their subsequent lacquer coating. The second one allows the computation of the non-stationary distribution of the temperature along the thickness of the carrying rubber band, on which the non-heated surface of the furniture elements lies. A methodology for the computation of the specific (for 1 m^2) energy consumptions needed for warming up both the furniture elements and the carrying rubber band, and also for covering of the heat emission from the band to the surrounding air are suggested. The methodology is based on the integration of solutions of two mutually connected nonlinear models mentioned above. For the numerical solution of the models with the aim at applying the methodology, a software program as an input in the calculation environment of Visual Fortran Professional was prepared. The computations were carried out to determine the specific energy consumption during the unilateral heating process of flat oak furniture elements with an initial temperature of 20 ^{o}C, moisture content of 8 %, thickness of 16 mm, width of 0.6 m, and length of 0.6 m, 1.2 m, and 1.8 m, during their 10 min convective heating by hot air with the temperature of 100 ^{o}C and velocity of 5 $m \cdot s^{-1}$. At the temperature of the surrounding air of 20 ^{o}C, and the initial temperature of 20 ^{o}C, the thickness of the rubber band was 4 mm, the width was 0.8 m, The obtained results can be used for technological and energy calculations of unilateral heating processes of furniture elements at different boundary conditions, as well as in the software of systems for model based automatic control of these processes aimed at improvement of thermal conditions for the subsequent lacquering of the elements.

Key words: modelling, specific energy, unilateral convective heating, furniture elements, lacquer coating, carrying rubber band, heat emission

INTRODUCTION

The pre-heating of subjected to lacquering furniture elements is done with the aim to speed up the hardening of thin coatings of lacquering systems with organic solvents. During the application of the lacquer coatings onto the heated wood' surfaces, the evaporation of the solvents is speeded up and the air is removed from the pores of the wood (ZHUKOV – ONEGIN 1993, RÜDIGER 1995, JAIĆ – ŽIVANOVIĆ 2000).

Unilateral convective heating used prior to lacquering is mostly applied on flat furniture elements with thickness from 4 to 35 mm and moisture content of 8 ÷ 10 %. The equipment for heating of the furniture elements before their lacquering is formed usually as a tunnel section (Fig. 1), which can be part of an assembly line for protective and decorative film application (SKAKIĆ 1992, KAVALOV – ANGELSKI 2014).

Fig. 1 General view of equipment for unilateral convective heating of furniture elements before their subsequent lacquering.

In the accessible specialized literature there is very limited information about the temperature distribution in wooden elements and details during their unilateral convective heating (DELIISKI *et al.* 2016a, 2016b) and there is no information at all about the energy consumption needed for realizing of such heating. That is why each research in this aria has both a scientific and a practical interest.

The aim of the present paper is to suggest a methodology for mathematical modeling and research of the total specific energy consumption of the unilateral heating process of flat furniture element and of each of its three components: for warming up of the wooden elements; for warming up of the carrying rubber band and for covering of the heat emission from the band to the surrounding air.

MATERIAL AND METHODS

Modelling of the 1D heat distribution in flat furniture elements during their convective heating

The mechanism of the non-stationary heat distribution in wooden furniture elements during their unilateral convective heating can be described by the equation of the heat conduction (CHUDINOV 1968, VIDELOV 2003, SHUBIN 1990, DELIISKI 2013d, DELIISKI *et al.* 2016a).

When the width and length of the furniture elements exceed their thickness by at least 3 and 5 times respectively, then the calculation of the change in the temperature only along the thickness of the elements in the center of their flat side during the unilateral convective heating (i.e. along the coordinate *x*, which coincides with the elements' thickness h_w) can be carried out with the help of the following non-linear 1D mathematical model:

$$c_w(T,u)\rho_w(\rho_b,u,u_{fsp},S_v)\frac{\partial T_w(x,\tau)}{\partial \tau}=\lambda_w(T,u,\rho_b)\frac{\partial^2 T_w(x,\tau)}{\partial x^2}+\frac{\partial \lambda_w(T,u,\rho_b)}{\partial T}\left(\frac{\partial T_w}{\partial x}\right)^2 \quad (1)$$

with an initial condition

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

and following boundary conditions:

• from the side of the elements' heating – at conditions of forced convective heat exchange between the upper surface of the elements and the circulated hot air with temperature T_{ha} and velocity v_{ha} (see Fig. 2 below):

$$\frac{\mathrm{d}T_{\mathrm{w-hs}}(\tau)}{\mathrm{d}x} = -\frac{\alpha_{\mathrm{w\text{-}hs}}(\tau)}{\lambda_{\mathrm{w\text{-}hs}}(T,u,\rho_{\mathrm{b}},\tau)}\left[T_{\mathrm{w-hs}}(\tau) - T_{\mathrm{ha}}(\tau)\right], \tag{3}$$

• from the opposite non-heated surface of the elements – at temperature, which is equal to the temperature $T_{B\text{-}hs}$ of the upper (heated) side of the carrying rubber band, on which the non-heated surface of the elements lies (see Fig. 2 below):

$$T_{\mathrm{w-nhs}}(\tau) = T_{\mathrm{B-hs}}(\tau), \tag{4}$$

where x is the coordinate along the thickness of the elements and the carrying rubber band: $0 \leq x \leq X = h_w + h_B$,m;

h_w – thickness of the elements, m;

h_B – thickness of the rubber band, m;

c_w – specific heat capacity of the wood in the hygroscopic range, J·kg^{-1}·K^{-1};

u – moisture content of the elements' wood, kg·kg^{-1};

u_{fsp} – fiber saturation point of the elements' wood, kg·kg^{-1};

λ_w – thermal conductivity of the wood cross sectional to the fibers in the hygroscopic range, W·m^{-1}·K^{-1};

$\lambda_{w\text{-}hs}$ – thermal conductivity of the wood on the heated elements' surface, W·m^{-1}·K^{-1};

ρ_w – wood density, in kg·m^{-3};

ρ_b – basic density of the elements' wood specie, equal to the dry mass divided by green volume, kg·m^{-3};

τ – time, s;

S_v – volume shrinkage of the elements' wood specie, %;

T – temperature, K;

T_w – temperature of the wood, K;

T_{w0} – initial temperature of the subjected to heating furniture elements, K;

$T_w(x,0)$ – temperature of all points along the elements' thickness at the beginning (i.e. at $\tau = 0$) of the heating process, K;

$T_{w\text{-}hs}$ – temperature of subjected to heating upper surface of the elements, K;

$T_{w\text{-}nhs}$ – temperature of the non-heated bottom surface of the elements, K;

$T_{B\text{-}hs}$ – temperature of the upper (heated) surface of the rubber band, K;

T_{ha} – temperature of the hot air circulating above the upper elements' surface, K;

$\alpha_{w\text{-}hs}$ – convective heat transfer coefficient of the upper elements' surface, W·m^{-2}·K^{-1}. An approach and an algorithm for its calculation are given in DELIISKI *et al.* (2016a, 2016b).

Because of the tight contact between the furniture elements and the thin carrying rubber band on which they lie during the heating process, the temperature of the non-heated lower surface of the elements is assumed in eq. (4) to be equal to the temperature of the band's upper surface.

Modelling of the 1D heat distribution in the carrying rubber band during unilateral convective heating of the furniture elements

The non-stationary change in the temperature along the thickness of the carrying rubber band, on which the non-heated surface of the furniture elements lies during the elements' heating (i.e. along the coordinate x, which coincides with the thicknesses of the elements and of the band – see Figure 2), can be computed using the following 1D mathematical model:

$$\frac{\partial T_B(x,\tau)}{\partial \tau} = a_B(T)\frac{\partial^2 T_B(x,\tau)}{\partial x^2} \tag{5}$$

with an initial condition

$$T_B(x,0) = T_{B0} \tag{6}$$

and following boundary conditions:

• from the upper (heated by the furniture elements) surface of the band – at temperature, which is equal to the temperature of the bottom (non-heated) side of the elements:

$$T_{B-hs}(\tau) = T_{w-nhs}(\tau), \tag{7}$$

• from the bottom (non-heated) surface of the band – at conditions of free convective heat exchange between the band and the surrounding air environment:

$$\frac{dT_{B-nhs}(\tau)}{dx} = -\frac{\alpha_{B\text{-nhs}}(\tau)}{\lambda_{B\text{-nhs}}}\left[T_{B\text{-nhs}}(\tau) - T_{nha}(\tau)\right], \tag{8}$$

where a_B in eq. (5) is the temperature conductivity of the rubber band perpendicular to the textile fibers by which it is reinforced, $m^2 \cdot s^{-1}$. It can be calculated according to the equation (JUMA *et al*. 2000):

$$a_B = 1.4409 \cdot 10^{-7} - 4.14765 \cdot 10^{-10} T + 1.0791 \cdot 10^{-12} T^2, \tag{9}$$

λ_B – thermal conductivity of the rubber band, $W \cdot m^{-1} \cdot K^{-1}$;
$\lambda_{B\text{-nhs}}$ – thermal conductivity of the bottom non-heated surface of the band, $W \cdot m^{-1} \cdot K^{-1}$;
τ – time, s;
T_B – temperature of the rubber band, K;
T_{B0} – initial temperature of the rubber band, K;
$T_B(x,0)$ – temperature of all points along the band's thickness at the beginning of the elements' heating process, K;
$T_{B\text{-hs}}$ – temperature of the upper (heated) surface of the band, K;
$T_{w\text{-nhs}}$ – temperature of the non-heated bottom surface of the elements, K;
$T_{B\text{-nhs}}$ – temperature of the bottom non-heated surface of the band, K;
T_{nha} – temperature of the air near the bottom surface of the band during heating, K;
$\alpha_{B\text{-nhs}}$ – convective heat transfer coefficient of the non-heated band's surface, $W \cdot m^{-2} \cdot K^{-1}$. An approach and an algorithm for the calculation of $\alpha_{B\text{-nhs}}$ are given in DELIISKI *et al.* (2016a, 2016b).

Modeling of the total specific energy needed for unilateral convective heating of the furniture elements

The total specific (for 1 m^2) energy needed for unilateral convective heating of furniture elements, q_{total}, consists of three components:

• energy needed for warming up of the furniture elements, q_w;

• energy needed for warming up of the carrying rubber band, q_B;

• energy needed for covering of the heat emission from the non-heated side of the carrying rubber band to the surrounding air, q_e.

This means that the energy q_{total} can be calculated according to the following equation:

$$q_{total} = q_w + q_B + q_e. \tag{10}$$

Modeling of the specific energy consumption for warming up of the furniture elements

It is known that the specific energy consumption (in $kWh \cdot m^{-3}$) for the heating of 1 m^3 of solid materials with an initial mass temperature T_{w0} to a given average mass temperature $T_{w\text{-}avg}$ is determined using the equation (DELIISKI 2013c, DELIISKI – DZURENDA 2010)

$$q = \frac{c_w(T,u) \cdot \rho_w(\rho_b, u, u_{fsp})}{3.6 \cdot 10^6} \left(T_{w\text{-}avg} - T_{w0}\right). \tag{11}$$

After multiplying the right part of eq. (11) by the element's thickness h_w the following equation for the determination of the specific mass energy consumption (in $kWh.m^{-2}$) needed for warming up of 1 m^2 of the subjected to unilateral heating wooden furniture elements, q_w, is obtained:

$$q_w = \frac{c_w(T,u) \cdot \rho_w(\rho_b, u, u_{fsp}) \cdot h_w}{3.6 \cdot 10^6} \left[T_{w-avg}(\tau) - T_{w0}\right], \tag{12}$$

where

$$T_{w\text{-}avg}(\tau) = \frac{1}{h_w} \int_{(h_w)} T_w(x,\tau) \mathrm{d}x \tag{13}$$

and for the non-frozen wood with moisture content in the hygroscopic range (i.e. when $u < u_{fsp}$) the specific heat capacity c_w (in $J \cdot kg^{-1} \cdot K^{-1}$) and the wood density in the hygroscopic range ρ_w (in $kg \cdot m^{-3}$) are equal to (DELIISKI 2011, 2013c, DELIISKI *et al.* 2015)

$$c_w = \frac{2097u + 826}{1+u} + \frac{9.92u + 2.55}{1+u} T + \frac{0.0002}{1+u} T^2, \tag{14}$$

$$\rho_w = \rho_b \frac{1+u}{1 - \frac{S_v}{100}\left(u_{fsp} - u\right)}, \tag{15}$$

where S_v is the volume shrinkage of the elements' wood specie, %.

The multiplier $3.6 \cdot 10^6$ in the denominator of eq. (12) ensures that the values of q_w are obtained in $kWh \cdot m^{-2}$, instead of in $J \cdot m^{-2}$.

Modeling of the specific energy consumption for warming up of the carrying rubber band

Based on eq. (12), it can be written that the specific mass energy needed for warming up of 1 m^2 of the carrying rubber band, on which the non-heated surface of the furniture elements lies, is equal to

$$q_B = \frac{c_B \cdot \rho_B \cdot h_B}{3.6 \cdot 10^6} \left[T_{B-avg}(\tau) - T_{B0}\right], \tag{16}$$

where

$$T_{B\text{-}avg}(\tau) = \frac{1}{h_B} \int_{(h_B)} T_B(x,\tau) \mathrm{d}x\,. \tag{17}$$

Modeling of the specific energy needed for covering of the heat emission from the non-heated side of the rubber band

The change in the specific energy consumption q_e, which is needed for covering of the heat emission from 1 m^2 of the non-heated side of the rubber band to the surrounding air environment during the time $\Delta\tau$, can be calculated according to the following equation (DELIISKI *et al.* 2016c):

$$\Delta q_{\mathrm{e}} = \frac{\alpha_{\mathrm{B-nhs}}(\tau)\cdot\Delta\tau}{3.6\cdot 10^{6}}\left[T_{\mathrm{B\text{-}nhs}}(\tau) - T_{\mathrm{nha}}\right]. \tag{18}$$

The specific energy needed for the covering of the heat emission from 1 m^2 surface of the rubber band during unilateral convective heating with duration $\tau_p = N\cdot\Delta\tau$ is equal to

$$q_{\mathrm{e}} = \sum_{n=1}^{N}\Delta q_{\mathrm{e}_n} , \tag{19}$$

where $\Delta\tau$ is the value of the step along the time coordinate, by which the mathematical models (1) ÷ (4) and (5) ÷ (8) are synchronously solving, s;

n – current number of the steps $\Delta\tau$: n = 1, 2, 3, ….., N.

RESULTS AND DISCUSSION

The mathematical models, which are presented in common form by the eqs. (1) ÷ (8), have been solved with the help of explicit schemes of the finite difference method. This has been done in a way, analogous to the one used and described in (DELIISKI 2011, 2013b, DELIISKI – DZURENDA 2010, DELIISKI *et al.* 2016b) for the solution of a model of the heating process of prismatic wood materials. This schemes allows during the computations to determine the temperatute at each knot of the calculation mesh using the current values of the thermo-physical characteristics of the furniture elements and of the rubber band depending on the momentous value of the temperature in separate knots.

The presenting of the eqs. (1) and (5) from the mathematical models through their discrete analogues corresponds to the shown in Fig. 2 setting of the coordinate system and the positioning of the knots in the mesh, in which the 1D non-stationary distribution of the temperature along the thicknesses of the furniture elements and the carrying rubber band during the unilateral convective heating of the elements is calculated.

For the solution of the models a software program has been prepared in FORTRAN in the calculation environment of Visual Fortran Professional, which is a part of the office-package of Windows. In this program the mathematical descriptions of the thermo-physical characteristics of the wood in the hygroscopic range were used, which have been presented in (DELIISKI 2011, 2013a, 2013b, 2013c, DELIISKI *et al.* 2010, 2015).

With the help of the program, computations for the determination of the 1D change of the temperature in flat oak (*Quercus petraea* Libl.) furniture elements with thickness h_w = 0.016 m, lengths l_w = 0.6 m, l_w = 1.2 m, l_w = 1.8 m, initial temperature t_{w0} = 20 °C, basic density ρ_b = 670 kg·m^{-3}, volume shrinkage S_v = 11.9 %, moisture contents u = 0.08 kg·kg^{-1} (i.e. of 8%) and u_{fsp} = 0.29 kg·kg^{-1} (DELIISKI – DZURENDA 2010) during their 10 min unilateral convective heating by hot air with temperature t_{ha} = 100 °C and velocity v_{ha} = 5 m·s^{-1} have been carried out.

Simultaneously with the above described 1D calculations, computations have been carried out for the determination of the 1D change in the temperature along the thickness of the carrying rubber band reinforced by textile fibres, on which the non-heated surface of the subjected to unilateral heating wooden furniture elements lies (see Fig. 2). The band was accepted to be with thickness h_B = 0.004 m, width b_B = 0.8 m, and initial temperature t_{B0} = 20 °C. The temperature of the surrounding air near the non-heated surface of the band during the elements' heating was accepted to be equal to t_{nha} = 20 °C. The computations have been carried out with an average values of the thermal conductivity perpendicular to the textile fibers $\lambda_{B\text{-}nhs} = 0.281\ W{\cdot}m^{-1}{\cdot}K^{-1}$, specific heat capacity $c_B = 1580\ J{\cdot}kg{\cdot}K^{-1}$ and density of the rubber band $\rho_B = 1520\ kg{\cdot}m^{-3}$ (http://www. axelproducts.com).

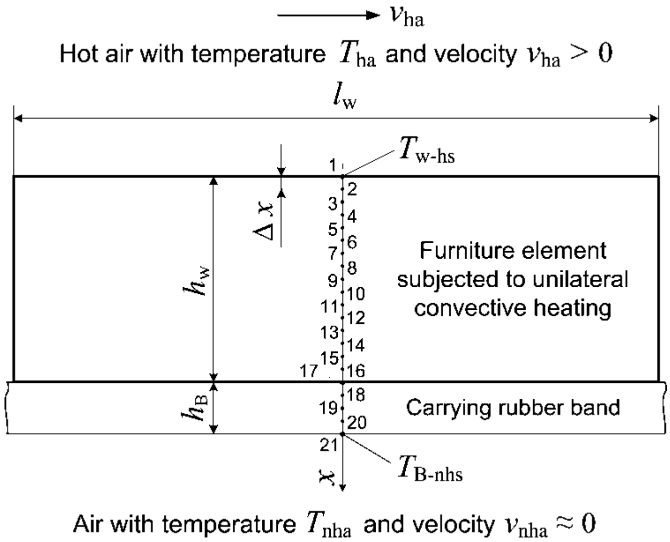

Fig. 2 Positioning of the knots of the 1D calculation mesh along the thicknesses of the wooden furniture element and the carrying rubber band.

With the help of the software program, computations have been carried out also for the determination of the change in the specific energies q_w, q_B, q_e, and q_{total}.

For achieving the highest precision of the energy computations the Simpson's method (DORN – MCCRACKEN 1972) instead of trapezoidal or of Gregory's ones is used for the integration of the temperature fields along the element's and band's thicknesses according to eqs. (13) and (17) respectively.

All computations have been carried out with 21 knots of the calculation mesh, i.e. with a step along the thicknesses of the furniture elements and the band Δx = 1.0 mm (Fig. 2). With the numbers 1 to 17 and 17 to 21 is marked the following number of the knots of the calculation mesh along the thickness of the wooden furniture element and along the thickness of the rubber band, respectively.

Fig. 3 presents the calculated change in t_w on both surfaces and in the center, $t_{w\text{-}c}$, of the studied furniture elements, depending on the elements' length l_w.

Fig. 4 presents the calculated change in t_B on both surfaces of the rubber band during unilateral heating process, depending on the elements' length l_w.

Fig. 5 shows the calculated change in the convective heat transfer coefficients of the heated elements' surface, $\alpha_{w\text{-}hs}$, and of the non-heated surface of the rubber band, $\alpha_{B\text{-}nhs}$, depending on l_w.

On Fig. 6 the calculated change in $t_{w\text{-}avg}$ and in q_w of the studied oak elements during their 10 min unilateral convective heating, depending on l_w is presented.

On Fig. 7 the calculated change in $t_{B\text{-}avg}$ and in q_B of the carrying rubber band during 10 min of the unilateral convective heating, depending on l_w is presented.

On Fig. 8 (left) the calculated change in q_e of the carrying rubber band during 10 min of the unilateral convective heating, depending on l_w is presented. On Fig. 8 (right) the calculated change in q_{total} during 10 min of the elements' unilateral convective heating, depending on l_w is presented.

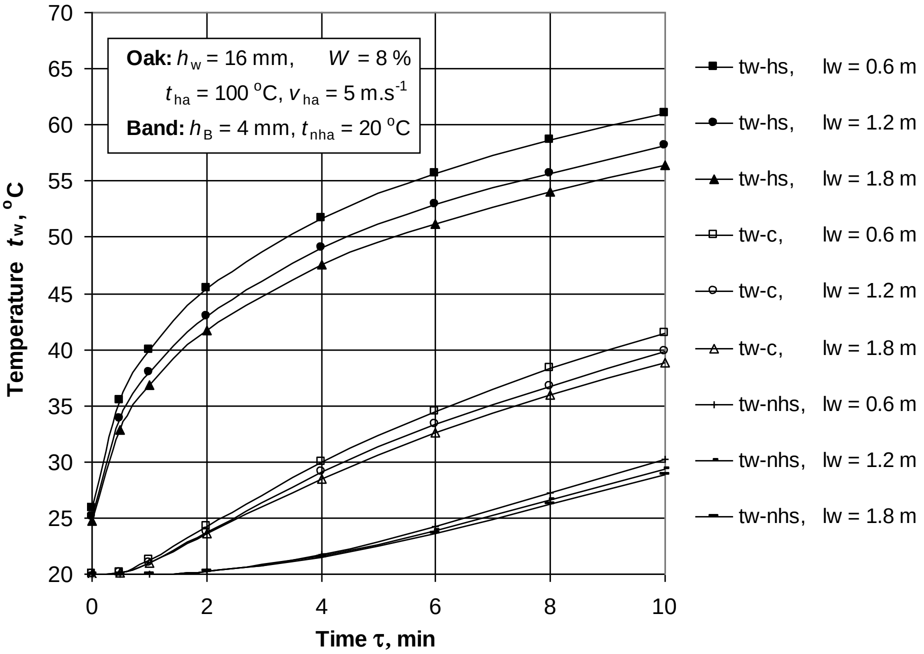

Fig. 3 Change of t_w on the surfaces and in the center of the oak furniture elements, depending on l_w.

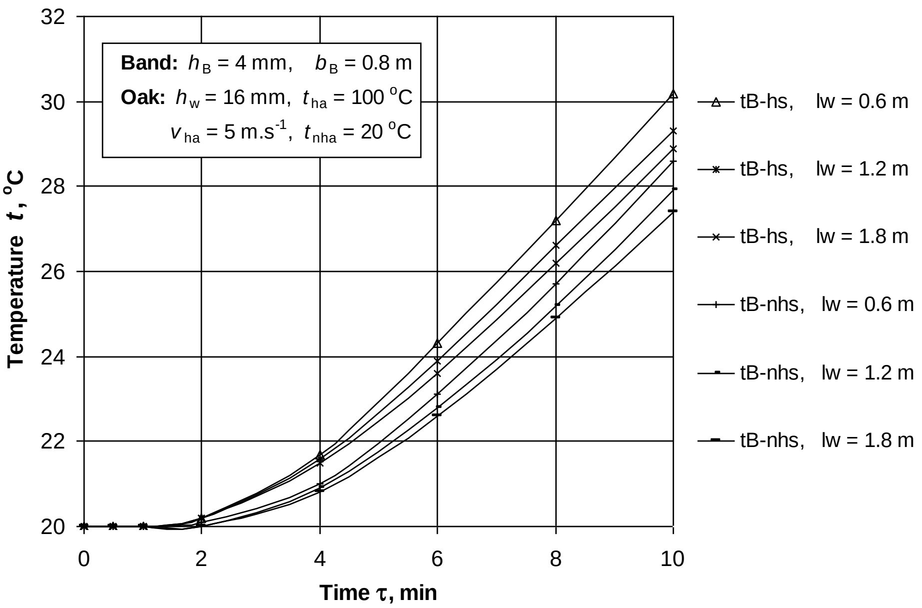

Fig. 4 Change in t_B on the band's surfaces during the unilateral convective heating, depending on l_w.

The analysis of the obtained results leads to the following conclusions:

1. During the unilateral convective heating of the furniture elements the change of the temperature on their surfaces and also in their center goes on according to complex curves. The curve of the t_w on the heated elements' surface is convex outwardly, but the curve of the temperature on the non-heated surface is concave inwardly (Fig. 3). The curves of $t_{w\text{-}c}$ have both convex and concave sections.

2. The change of the convective heat transfer coefficient of the heated elements' surface, $\alpha_{w\text{-}hs}$, is insignificant during the heating time (Fig. 5-left). This coefficient decreases when the aired length of the furniture elements, l_w, increases. The decreasing of $\alpha_{w\text{-}hs}$ with an increase of l_w causes a decrease of the intensity of the elements' heating process when l_w increases.

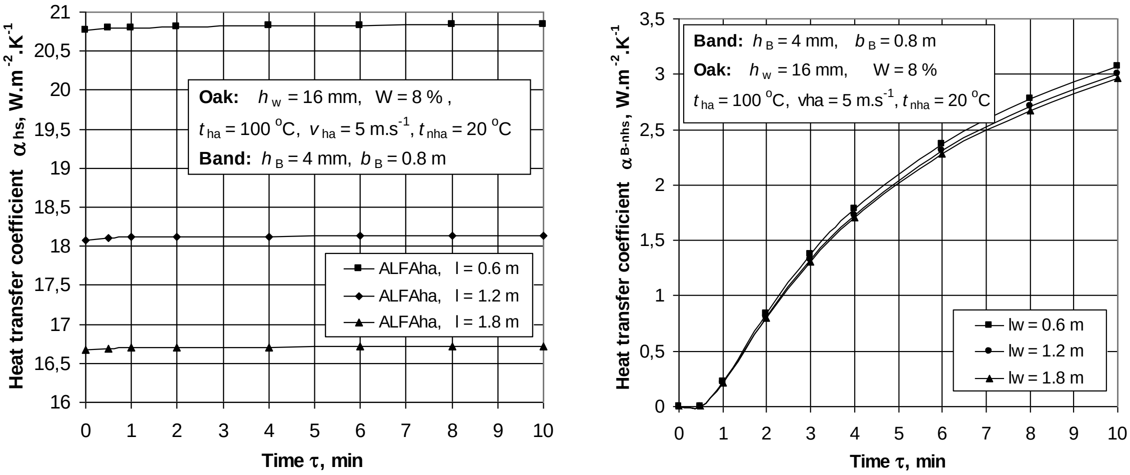

Fig. 5 Change of $\alpha_{w\text{-}hs}$ (left) and $\alpha_{B\text{-}nhs}$ (right) of the oak furniture elements during the unilateral convective heating, depending on l_w.

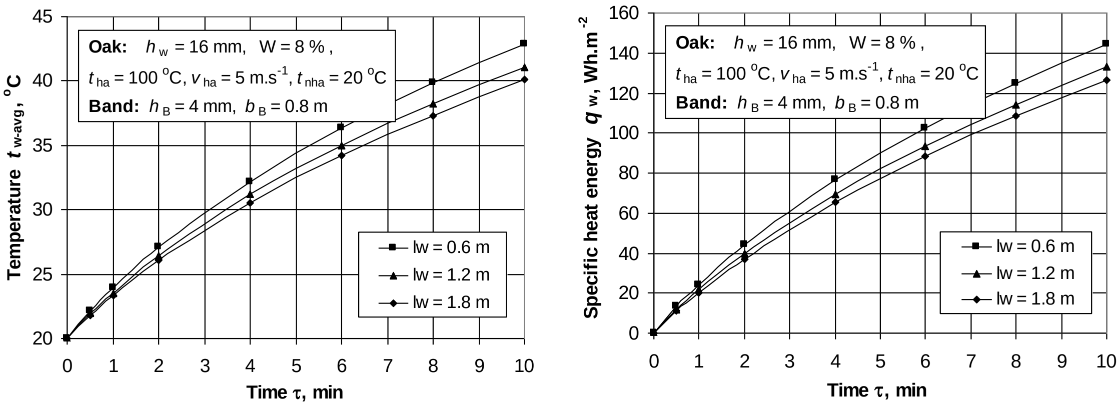

Fig. 6 Change in $t_{w\text{-}avg}$ (left) and q_w (right) during 10 min heating of the elements, depending on l_w.

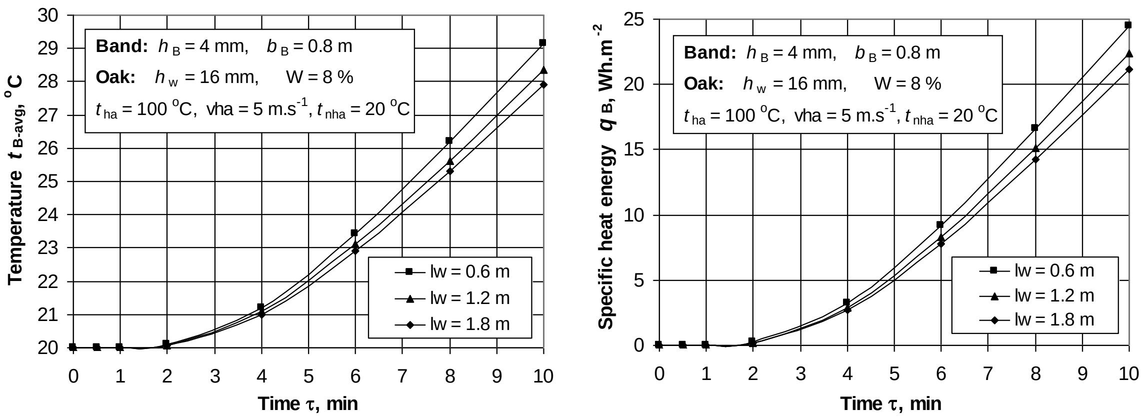

Fig. 7 Change in $t_{B\text{-}avg}$ (left) and q_B (right) during 10 min heating of the elements, depending on l_w.

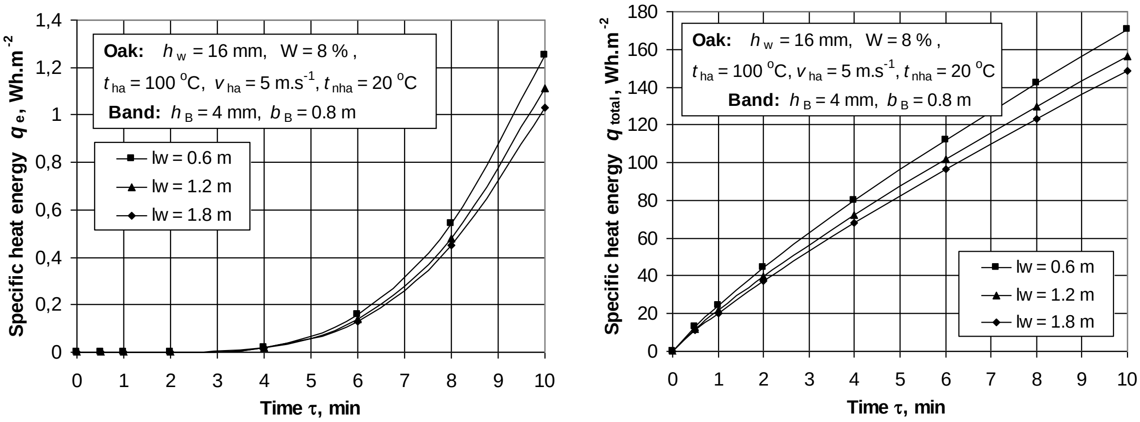

Fig. 8 Change in q_e (left) and q_{total} (right) during 10 min heating of the elements, depending on l_w.

3. The convective heat transfer coefficient of the non-heated surface of the carrying rubber band, $\alpha_{B\text{-}nhs}$, increases curvilinearly depending on the heating time and decreases non-linearly depending on l_w (Fig. 5-right).

4. The increasing of the average mass temperature $t_{w\text{–}avg}$ and also of the specific energy consumption q_w during the unilateral heating of the furniture elements goes on according to curvilinear dependences, which are convex outwardly. The slope of the dependences $t_{w\text{-}avg} = f(\tau)$ and $q_w = f(\tau)$ slightly decreases with an increase of l_w. After 10 min heating of the oak furniture elements with studied parameters, the energy consumption q_w reaches the following values:

- q_w = 144.54 Wh·m^{-2} at l_w = 0.6 m;
- q_w = 133.01 Wh·m^{-2} at l_w = 1.2 m;
- q_w = 126.42 Wh·m^{-2} at l_w = 1.8 m.

5. The increase of the average mass temperature $t_{B\text{–}avg}$ and also of the specific energy consumption q_B during the unilateral heating of the furniture elements goes on according to curvilinear dependences, which are concave inwardly. The slope of the dependences $t_{B\text{-}avg} = f(\tau)$ and $q_B = f(\tau)$ slightly decreases with an increase of l_w. After 10 min heating of the elements q_B reaches the following values:

- q_B = 24.46 Wh·m^{-2} at l_w = 0.6 m;
- q_B = 22.35 Wh·m^{-2} at l_w = 1.2 m;
- q_B = 21.17 Wh·m^{-2} at l_w = 1.8 m.

6. The increase of the specific energy consumption q_e during the unilateral heating of the furniture elements goes on according to curvilinear dependences, which are also concave inwardly. The slope of the dependences $q_e = f(\tau)$ slightly decreases with an increase of l_w. After 10 min heating of the elements q_e reaches the following values:

- q_e = 1.25 Wh·m^{-2} at l_w = 0.6 m;
- q_e = 1.11 Wh·m^{-2} at l_w = 1.2 m;
- q_e = 1.03 Wh·m^{-2} at l_w = 1.8 m.

7. The increase of the total specific energy consumption, q_{total}, during the unilateral heating of the furniture elements goes on according to curvilinear dependences, which are convex very slightly outwardly. The slope of the dependences $q_{total} = f(\tau)$ slightly decreases with an increase of l_w. After 10 min heating of the elements, the energy consumption q_{total} reaches the following values:

- q_{total} = 170.25 Wh·m^{-2} at l_w = 0.6 m;
- q_{total} = 156.47 Wh·m^{-2} at l_w = 1.2 m;
- q_{total} = 148.62 Wh·m^{-2} at l_w = 1.8 m.

CONCLUSIONS

This paper presents two mutually connected 1D non-linear mathematical models and based on the integration of their solutions a numerical approach for the computation of the specific (for 1 m^2) energy consumption for unilateral heating process of flat wooden furniture elements before their subsequent lacquering.

The first model provides the computation of the non-stationary temperature distribution along the thickness of the furniture elements and of the non-stationary change in the specific energy needed for warming up of the elements.

The second model allows for the computation of the non-stationary distribution of the temperature along the thickness of the carrying rubber band on which the non-heated surface of the elements lies, and also of the non-stationary change in the specific energy needed for warming up of this band and in the specific energy needed for covering of the heat emission from the non-heated side of the band in the surrounding air.

For the first time suggested numerical approach provides the calculation of the specific energy consumption of the studied process integrating the computed temperature fields along the elements' and band's thicknesses. For the solution of the mathematical models, a software program was prepared in FORTRAN in the calculation environment of Visual Fortran Professional developed by Microsoft.

As examples for the use of the models and the suggested approach, computations have been carried out for the determination of the change in the specific energy, which is consumed by oak furniture elements with an initial temperature of 20 ^{o}C, moisture content of 8 %, thickness of 16 mm, length of 0.6 m, 1.2 m and 1.8 m during their 10 min unilateral convective heating by hot air with temperature of 100 ^{o}C and velocity of 5 $m \cdot s^{-1}$.

The obtained results show that the total specific energy consumption at the end of 10 min unilateral convective heating process of the studied oak furniture elements decreases from 170.25 $Wh \cdot m^{-2}$ to 148.62 $Wh \cdot m^{-2}$ (i.e. by about 15%) when the elements' length increases from 0.6 m to 1.8 m. The warming up of the elements and of the rubber band consumes then about 85% and 14% respectively from the total energy, and the covering of the heat emission of the band consumes only about 1%.

The computer solutions of the mathematical models could be used for visualization and technological analysis of the non-stationary temperature change along the thickness of furniture elements made of different wood species, different thickness, length and moisture content, during their unilateral convective heating with different temperature and velocity of the circulated air prior to their lacquering. They could be also used for computation of the specific energy consumption of the convective heating process of furniture elements at all these boundary conditions.

The solutions of the models allow determining the duration of the elements' heating, which is necessary for achieving the most suitable thermal conditions for the subsequent lacquer coating at concrete characteristics of the lacquer, depending on the elements' and hot air's parameters. The models could be applied also for optimal model-based automatic control (HADJISKI 2003, HADJISKI – DELIISKI 2015, 2016, HADJISKI *et al.* 2018) of the process of unilateral convective heating of furniture elements through their input in the software of the programmable controllers used for such kind of process operations.

The methodology and the approach suggesteed and used in this work could be applied for mutualy connected mathematical modeling of the heat distribution and specific energy consumption in two or more layer's structures from different materials subjected to convective or/and conducting heating.

REFERENCES

CHUDINOV B. S. 1968. Theory of the Thermal Treatment of Wood. Moscow : Nauka, 255 pp.

DELIISKI N. 2011. Transient Heat Conduction in Capillary Porous Bodies. In Ahsan A (ed) Convection and conduction heat transfer. Rieka : InTech Publishing House, 149–176.

DELIISKI N. 2013a. Computation of the Wood Thermal Conductivity during Defrosting of the Wood. In Wood research, 58(4): 637–650.

DELIISKI N. 2013b. 3D Modeling and Visualization of Non-stationary Temperature Distribution during Heating of Frozen Wood. In Drvna Industrija, 64(4): 293–303.

DELIISKI N. 2013c. Modelling of the Energy Needed for Heating of Capillary Porous Bodies in Frozen and Non-frozen States. Saarbrücken : Lambert Academic Publishing, Scholars' Press, Germany, 116 pp., ISBN 978-3-639-70036-7, http://www.scholars-press.com//system/covergenerator/build/1060.

DELIISKI N., DZURENDA L. 2010. Modelling of the Thermal Processes in the Technologies for Wood Thermal Treatment. Zvolen : TU vo Zvolene, Slovakia, 224 pp.

DELIISKI N., DZURENDA L., MILTCHEV R. 2010. Computation and 3D Visualization of the Transient Temperature Distribution in Logs during Steaming. In Acta Facultatis Xylologiae Zvolen, 52(2): 23–31.

DELIISKI N., DZURENDA L., TUMBARKOVA N., ANGELSKI D. 2015. Computation of the Temperature Conductivity of Frozen Wood during its Defrosting. In Drvna Industrija, 66(2): 87–96.

DELIISKI N., DZURENDA L., TRICHKOV N., GOCHEV Z., ANGELSKI D. 2016a. Modelling of the Unilateral Convective Heating Process of Furniture Elements before their Lacquer Coating. In Acta Facultatis Xilologiae Zvolen, 58(2): 51–64.

DELIISKI N., STANEV R., ANGELSKI D., TRICHKOV N., GOCHEV Z. 2016b. Heat Transfer Coefficients during Unilateral Convective Heating of Wood Details before their Lacquering. Engineering sciences, Bulgarian Academy of Sciences, 53 (3): 26-42.

DELIISKI N., TUMBARKOVA N., DZURENDA L., BREZIN V. 2016c. Numerical Approach for Computation of the Heat and Heat Flux for Covering of the Emission in the Surrounding Air of Subjected to Unilateral Heating Flat Wood Details before their Bending. Key Engineering Materials. 688: 153–159.

DORN W. S., MCCRACKEN D. D. 1972. Numerical Methods with FORTRAN IV: Case Studies. New York : John Willej & Sons, Inc., 451 pp.

HADJISKI M. 2003. Mathematical Models in Advanced Technological Control Systems. Automatic & Informatics 37(3): 7–12.

HADJISKI M., DELIISKI N. 2015. Cost Oriented Suboptimal Control of the Thermal Treatment of Wood Materials. IFAC-PapersOnLine 48–24 (2015): 54–59, www.sciencedirect.com.

HADJISKI M., DELIISKI N. 2016. Advanced Control of the Wood Thermal Treatment Processing. Cybernetics and Information Technologies, Bulgarian Academy of Sciences, 16 (2): 179–197.

HADJISKI, M. – DELIISKI, N. – GRANCHAROVA A. 2018. Spatiotemporal Parameter Estimation of Thermal Treatment Process via Initial Condition Reconstruction Using Neural Networks, 51-80. In: Intuitionistic Fuzziness and Other Intelligent Theories and Their Applications. Springer International Publishing, 193 pp., ISBN 978-3-319-78930-9.

JAIĆ M., ŽIVANOVIĆ R. 2000. Surface Processing of Wood – Theoretical Base and Technological Processes. Beograd.

JUMA M., BAFRNEC M., BREZANI J. 2001. Thermal Diffusivity of Thick Fibre-elastomer Composites. http://www.tpl.ukf.sk/engl_vers/thermophys/proceedings/juma.pdf: 95–101.

KAVALOV A., ANGELSKI D. 2014. Technology of Furniture. Sofia : University of Forestry, 390 pp.

RÜDIGER A. 1995. Grundlagen des Möbel- und Innenausbaus, DRW-Verlag, 306 pp.

SHUBIN G. S. 1990. Drying and Thermal Treatment of Wood. Moscow : Lesnaya promyshlennost, 337 pp.

SKAKIĆ D. 1992. Final Processing of Wood. Beograd.

VIDELOV H. 2003. Drying and Thermal Treatment of Wood. Sofia : University of Forestry, 335 pp.

ZHUKOV E. V., ONEGIN V. I. 1993. Technology of Protective and Decorative Coatings of Wood and Wood Materials. Moscow : Ecologia, 304 pp.

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