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

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ABSTRACT

Two mutually connected 1D mathematical models have been created and solved. The first of them allows the computation of the non-stationary temperature distribution along the thickness of subjected to unilateral convective heating furniture elements before their subsequent lacquer coating. The second one allows the computation of the non-stationary distribution of temperature, *t*, along the thickness of the carrying rubber band, on which the non-heated surface of the furniture elements lies. A software program has been prepared for the simultaneous numerical solution of both models with the help of an explicit scheme of the finite difference method, which has been input in the calculation environment of Visual Fortran Professional. With the help of the program, computations have been made for the determination of the 1D change of *t* in flat oak elements and in the rubber band, on which the non-heated surfaces of the elements lie. In the simulation experiments the oak elements were with thickness of 16 mm, length of 1.2 m, initial temperature of 20 ºC, and moisture content of 8 %. The duration of the elements' unilateral convective heating by air with temperature of 100 ºC and speed of 2 $m\cdot s^{-1}$, 5 $m\cdot s^{-1}$, and 8 $m\cdot s^{-1}$ was equal to 10 min. The rubber band was with thickness of 4 mm, width of 0.8 m, initial temperature of 20 ºC, and the temperature of the surrounding air was 20 ºC. The computer solutions of both mathematical models could be used for visualization and technological analysis of the 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 speed of the circulated air prior to their lacquering.

Key words: furniture elements, carrying rubber band, 1D modelling, unilateral convective heating, temperature distribution, surface finishing.

INTRODUCTION

The production of furniture elements from solid wood and/or veneered boards requires their surfaces to be processed with liquid protective and decorative coatings. The flow and homogenization of liquids spread over the furniture elements could be improved via preliminary heating of their surfaces (ZHUKOV – ONEGIN 1993, KAVALOV – ANGELSKI 2014).

The purpose of the pre-heating of furniture elements is to introduce heat in their surface layer right before the application of the liquid layer of lacquer. In this way, during the film-forming process heat from the wood surface layer is carried to the lacquer covering.

Pre-heating of surfaces, subject to further lacquering, is applied with the purpose to accelerate the hardening of the thin lacquer coverings with organic solvents. Upon the application of a lacquer layer over the heated surface, it accelerates the evaporation of the solvents and removes the air from the wood pores (JAIĆ – ŽIVANOVIĆ 2000). When the surface of the wood is heated, after the applying the lacquer a heating of its bottom layer and an intensive evaporation of the solvent from this layer occurs. Because of this, the hardening of the lacquer starts from its bottom layer and the solvent vapour leaves unimpeded the lacquer and evaporates into the atmosphere (ZHUKOV – ONEGIN 1993, RÜDIGER 1995).

Unilateral convective heating used prior to lacquering is mostly applied on flat wooden details with thickness from 4 to 35 mm and moisture content of 8–10 %. The equipment for preliminary heating of the details 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).

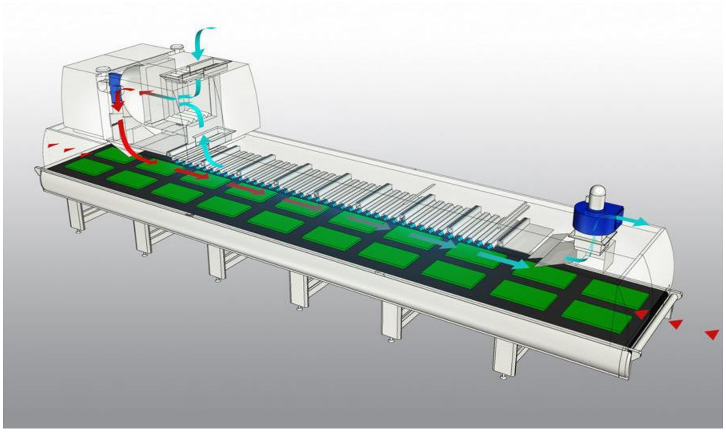

Fig. 1 General view of equipment for unilateral convective heating of furniture elements before their subsequent lacquering.

In the accessible specialized literature there is no information at all about the temperature distribution in furniture elements during their unilateral convective heating before lacquer coating. That is why each reasearch in this area has both a scientific and a practical interest.

The aim of the current work is to create and solve two mutually connected 1D mathematical models. The first of them must allow the computation of the non-stationary temperature distribution along the thickness of subjected to unilateral convective heating flat furniture elements immediately before their subsequent lacquering. The second one should make it possible to compute the non-stationary distribution of the temperature along the thickness of the carrying transport rubber band on which the non-heated surface of the details lies. A part of the aim is to show an application of the created models for the computations of the mentioned temperature distributions for the case of unilateral convective heating of flat oak elements by hot air with different speeds in order to improve the thermal conditions for their subsequent lacquering.

MATERIAL AND METHODS

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

During the heating of wood furniture elements along with the purely thermal processes, a moisture-exchange occurs between the processing medium and the elements. The values of the moisture diffusion in the elements are usually hundreds of times smaller than the values of their temperature conductivity (CHUDINOV 1968, NIKOLOV – VIDELOV 1987, SHUBIN 1990, POŽGAJ *et al*. 1997, VIDELOV 2003, DELIISKI 2003, 2013A, 2013B, DELIISKI *et al*. 2015, 2016B, RADMANOVIC *et al*. 2014). These facts determine a not so big change in diffusing moisture in the elements, which lags significantly from the distribution of heat in them during the heating. This allows disregarding the exchange of moisture between the elements and the heating medium and the change in temperature in them to be viewed as a result of a pure thermo-exchange process, where the heat in them is distributed only through thermo-conductivity. Because of this the mechanism of heat distribution in the furniture elements can be described by the equation of heat conductivity.

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 during their unilateral heating (i.e. along the coordinate *x*, which coincides with the elements' thickness) can be carried out with the help of the following 1D mathematical model (DELIISKI 2003, 2011, 2013c):

$$\frac{\partial T_{\mathrm{w}}(x,\tau)}{\partial \tau} = a_{\mathrm{w}}(T,u,u_{\mathrm{fsp}},\rho_{\mathrm{b}})\frac{\partial^2 T_{\mathrm{w}}(x,\tau)}{\partial x^2} \tag{1}$$

with an initial condition

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

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 speed v_{ha} (see Fig. 1):

$$\frac{\mathrm{d}T_{\mathrm{w}}^{\mathrm{hs}}(\tau)}{\mathrm{d}x} = -\frac{\alpha_{\mathrm{w}}^{\mathrm{hs}}(\tau)}{\lambda_{\mathrm{w}}^{\mathrm{hs}}(0,\tau)}\left[T_{\mathrm{w}}^{\mathrm{hs}}(\tau) - T_{\mathrm{ha}}(\tau)\right], \tag{3}$$

• from the opposite non-heated side of the furniture elements – at temperature, which is equal to the temperature of the upper (heated) side of the carrying rubber band, on which the non-heated surface of the elements lies:

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

where x is the coordinate along the thickness of the elements and the carrying rubber band: $0 \le x \le X = h_{\mathrm{w}} + h_{\mathrm{B}}$, m;

h_{w} – thickness of the elements, m;

h_{w} – thickness of the rubber band, m;

a_{w} – temperature conductivity of the elements' wood, $\mathrm{m^2 \cdot s^{-1}}$;

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

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

ρ_{b} – basic density of the elements' wood specie, equal to the dry mass divided to green volume, $\mathrm{kg \cdot m^{-3}}$;

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's thickness at the beginning (i.e. at $\tau = 0$) of the heating process, K;

T_w^{hs} – temperature of subjected to heating upper surface of the elements, K;

T_B^{hs} – temperature of the upper (heated) surface of the rubber band, K;

T_{ha} – temperature of the hot air near the heated surface during the heating, K;

α_w^{hs} – convective heat transfer coefficient of the heated elements' surface, $W \cdot m^{-2} \cdot K^{-1}$;

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

τ – time, s.

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

Mechanism of the 1D heat distribution in the carrying rubber band during heating

Analogously to the model presented above, the calculation of the change in the temperature along the thickness of the carrying rubber band during elements' unilateral heating (i.e. along the coordinate x, which coincides with the thicknesses of the elements and of the band – see Fig. 2 below) can be carried out with the help of 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) surface 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:

$$\frac{dT_B^{nhs}(\tau)}{dx} = -\frac{\alpha_B^{nhs}(\tau)}{\lambda_B^{nhs}(0,\tau)}\left[T_B^{nhs}(\tau) - T_{nha}(\tau)\right], \tag{8}$$

where a_B is the temperature conductivity of the rubber band perpendicular to the textile fibres by which it is reinforced, $m^2 \cdot s^{-1}$;

T_B – temperature of the rubber band, K;

$T_B(x,0)$ – temperature of all points along the bands's thickness at the beginning of the details' heating process, K;

T_{B0} – initial temperature of the rubber band, K;

T_B^{hs} – temperature of the upper (heated) surface of the rubber band, K;

T_w^{nhs} – temperature of the bottom (non-heated) surface of the furniture elements, K;

T_B^{nhs} – temperature of bottom (non-heated) surface of the band, K;

T_{nha} – temperature of the air near the bottom surface of the band during the heating, K;

α_B^{nhs} – convective heat transfer coefficient of the non-heated band's surface, $W \cdot m^{-2} \cdot K^{-1}$;

λ_B^{nhs} – thermal conductivity of the rubber on the non-heated band's surface, $W \cdot m^{-1} \cdot K^{-1}$.

Mathematical description of the heat transfer coefficient α_w^{hs}

The calculation of the heat transfer coefficient α_w^{hs} can be carried out with the help of the following equations, which are valid for the cases of heating of horizontally situated rectangular surfaces in conditions of force air convection (BAR-COHEN – ROHSENOW 1984, TELEGIN *et al*. 2002, BUCHLIN 2002, CERNECKY *et al*. 2015, DELIISKI *et al*. 2016a):

$$\alpha_w^{hs} = \frac{Nu_{ha} \lambda_{ha}}{l_w}, \tag{9}$$

where l_w is the linear size of the furniture elements along the direction of the hot air circulation (i.e. length of the elements), m;

λ_{ha} – thermal conductivity of the hot air at its technological temperature, $W \cdot m^{-1} \cdot K^{-1}$;

Nu_{ha} – number of similarity of Nusselt, which is calculated using the thermo-physical characteristics of the hot air according to following equations:

• at laminar regime of the forced convection of the hot air (i.e. at $Re_{ha} \le 4 \cdot 10^4$):

$$Nu_{ha} = 0.66\, Re_{ha}^{0.5}\, Pr_{ha}^{0.43} \left(\frac{Pr_{ha}}{Pr_{hs}} \right)^{0.25} \tag{10}$$

• at turbulent regime of the forced convection of the hot air (i.e. at $Re_{ha} > 4 \cdot 10^4$):

$$Nu_{ha} = 0.037\, Re_{ha}^{0.8}\, Pr_{ha}^{0.43} \left(\frac{Pr_{ha}}{Pr_{hs}} \right)^{0.25}, \tag{11}$$

where the Prandtl' numbers of similarity Pr_{ha} and Pr_{hs}, and also the Reynolds' number of similarity Re_{ha} are calculated according to the equations

$$Pr_{ha} = \frac{w_{ha}}{a_{ha}}, \tag{12}$$

$$Pr_{hs} = \frac{w_{hs}}{a_{hs}}, \tag{13}$$

$$Re_{ha} = \frac{\rho_{ha} v_{ha} l_w}{\mu_{ha}} = \frac{\rho_{ha} v_{ha} l_w}{\rho_{ha} w_{ha}} = \frac{v_{ha} l_w}{w_{ha}}. \tag{14}$$

In equations (9) ÷ (14) the following thermo-physical characteristics of the air participate:

λ – thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$;

$a = \frac{\lambda}{c \cdot \rho}$ – temperature conductivity, $m^2 \cdot s^{-1}$;

c – specific heat capacity, $J \cdot kg^{-1} \cdot K^{-1}$;

$w = \frac{\mu}{\rho}$ – kinematic viscosity coefficient, $m^2 \cdot s^{-1}$;

ρ – density, $kg \cdot m^{-3}$;

μ – dynamic viscosity coefficient, $Pa \cdot s$;

v – speed, $m \cdot s^{-1}$;

α_w – convective heat transfer coefficient of the subjected to heating surface of the furniture elements, $W \cdot m^{-2} \cdot K^{-1}$.

The indexes "ha" and "hs" of the thermo-physical characteristics of the air and of the numbers of the similarity in equations (9)–(14) mean that these characteristics and numbers must be calculated depending on the temperature of the hot air and of the heated surface of the aired furniture elements, respectively.

Mathematical description of the heat transfer coefficient α_{B}^{nhs}

The calculation of the heat transfer coefficient α_{B}^{nhs} can be carried out with the help of the following equations, which are valid for the cases of heating or cooling of horizontally situated rectangular surfaces in conditions of free air convection (ROHSENOW – HARTNETT 1973, MILCHEV *et al*. 1989, TELEGIN *et al*. 2002, DELIISKI *et al*. 2016a):

$$\alpha_{B}^{nhs} = \frac{1.3 Nu_{nha} \lambda_{nha}}{b_{B}}, \tag{15}$$

where b_B is the width of the carrying transport rubber band on which the furniture elements lie (see Fig. 1), m;

λ_{nha} – thermal conductivity of the air from the non-heated surface of the band, $W \cdot m^{-1} \cdot K^{-1}$;

Nu_{nha} – Nusselt's number of similarity, which is calculated with the help of the thermo-physical characteristics of the air from the non-heated side of the band according to following equations:

$$Nu_{nha} = 0.5 \left(Gr_{nha} \cdot Pr_{nha} \right)^{0.25} \left(\frac{Pr_{nha}}{Pr_{nhs}} \right)^{0.25} \quad @ \quad 10^{3} < Gr_{nha} \cdot Pr_{nha} < 10^{9}, \tag{16}$$

where the Grashoff's number of similarity Gr_{nha} and the Prandtl's numbers of similarity Pr_{nha} and Pr_{nhs} are calculated according to the equations

$$Gr_{nha} = \frac{g \cdot \beta_{nha} b_{B}^{3}}{w_{nha}^{2}} \left(T_{B}^{nhs} - T_{nha} \right), \tag{17}$$

$$Pr_{nha} = \frac{w_{nha}}{a_{nha}}, \tag{18}$$

$$Pr_{nhs} = \frac{w_{nhs}}{a_{nhs}}. \tag{19}$$

In equations (15)–(19) the following, not yet explained above, variables take part: g = 9.81 $m \cdot s^{-2}$ – acceleration of gravity; β – coefficient of the volume expansion of the air, K^{-1}.

The indexes "nha" and "nhs" of the variables and of the numbers of the similarity in equations (15)–(19) mean that these variables and numbers must be calculated depending on the temperature of the not heating air and of the not heated surface of the details, respectively.

It must be noted that a mathematical description of the thermo-physical characteristics of the air λ, β, w, and a, which participates in eqs. (9)–(19), depending on the temperature T, could be found in DELIISKI *et al*. (2016a).

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 2003, 2011) for the solution of a model of the heating process of prismatic wood materials. 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 nodes 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 (DORN – MCCRACKEN 1972) the calculation environment of Visual Fortran Professional.

With the help of the program as an example computations have been made for the determination of the 1D change of the temperature in flat oak (*Quercus petraea* Libl.) elements with thickness h_w = 16 mm, length l_w = 1.2 m, initial temperature t_{w0} = 20 °C, moisture content u = 0.08 kg·kg^{-1} (i.e. 8 %) during their 10 min unilateral convective heating by hot air with temperature t_{ha} = 100 ºC and speed v_{ha} = 2 m·s^{-1}, v_{ha} = 5 m·s^{-1}, and v_{ha} = 8 m·s^{-1}.

The calculations of the temperature distribution along the elements' thickness have been done with average values of the wood temperature conductivity a_w= 1.9337·10^{-7}m^2·s^{-1} and of the wood thermal conductivity cross-sectional to the fibers of the details $\lambda_w = \lambda_w^{hs}$ = 0.2738 W·m^{-1}·K^{-1} in the temperature range from 20 °C to 60 °C for oak wood with basic density ρ_b = 670 kg·m^{-3}, moisture content u = 0.08 kg·kg^{-1}, fiber saturation point u_{fsp} = 0.29 kg·kg^{-1} (i.e. 29 %), and volume shrinkage S_v = 11.9 % (NIKOLOV – VIDELOV 1987). These average values if a_w and λ_w have been obtained using the mathematical description of a_w and λ_w depending on t, u, u_{fsp}, and ρ_b of the wood species (DELIISKI 2003, 2013a, 2013c, DELIISKI *et al*. 2015). The calculated values of a_w and λ_w for oak wood in the temperature range from 20 °C to 60 °C are shown in Table 1.

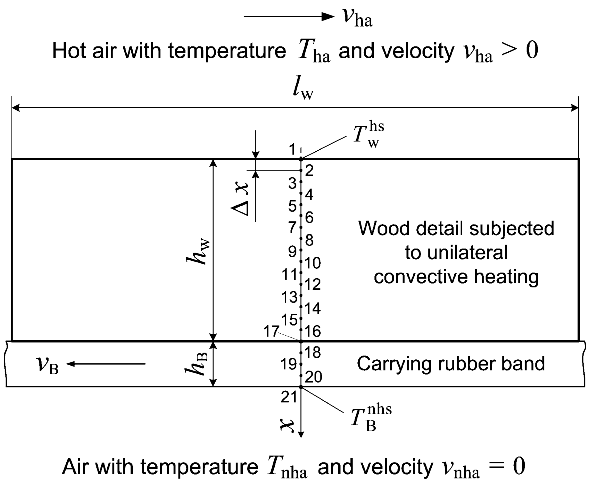

Fig. 2 Positioning of the nodes of the 1D calculation mesh along the thicknesses of the furniture elements and the carrying rubber band.

Tab. 1 Change in λ_w and a_w of an oak wood with u = 0.08 kg·kg^{-1}, depending on t.

Parameter of the wood	Temperature t, ºC					Average value for t = 20÷60 ºC
	20	30	40	50	60	
λ_w, W·m^{-1}·K^{-1}	0.2648	0.2693	0.2738	0.2783	0.2828	0.2738
a_w·10^7, m^2·s^{-1}	1.9351	1.9344	1.9337	1.9331	1.9325	1.9337

The calculation of the average values for a_w and λ_w has been made for the temperature range from 20 ºC to 60 ºC due to the fact that during the simulation experiments with the models, it has ocurred that the calculated temperature along the thickness of the furniture elements changes exactly in this range (see the left parts of Figures 3, 4, and 5 below). Despite this, a_w and λ_w depend linearly to the temperature, which allows for the solving the model to use their average values.

With the help of the program 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 fibers, on which the non-heated surfaces of the subjected to unilateral heating furniture elements lie (see Fig. 1).The band was accepted to be with thickness h_B = 4 mm, width b_B = 0.8 m, and initial temperature t_{B0} = 20 °C. The temperature of the surrounding air from the non-heated surface of the band during the elements' heating was accepted to be equal to t_{nha} = 20 °C (see Fig. 2). The computations have been done with average values of the band's temperature conductivity perpendicular to the textile fibers $a_B = 1.1655 \cdot 10^{-7}$ m$^2 \cdot$s^{-1} and of the thermal conductivity of the band $\lambda_B = \lambda_B^{nhs} = 0.281$ W·m^{-1}·K^{-1} (www.axelproducts.com). The average value for a_B has been obtained using the following equation (JUMA *et al*. 2000):

$$a_B = 1.4409 \cdot 10^{-7} - 4.14765 \cdot 10^{-10} T + 1.0791 \cdot 10^{-12} T^2 \quad @ \quad 293.15 \text{ K} \le T \le 440.15 \text{ K}. \qquad (20)$$

The calculation of the average values for $a_B = 1.1655 \cdot 10^{-7}$ m$^2 \cdot$s^{-1} has been made for the temperature range from 293.15 K to 303.15 K (i.e. from 20 °C to 30 °C) due to the fact that during the simulation experiments with the models, it has become evident that the calculated temperature along the thickness of the band changes exactly in this range.

All computations have been carried out with 21 nodes of the calculation mesh, i.e. with a step along the thicknesses of the furniture elements and the band, equal to 1.0 mm (see Fig. 2).

The left parts of Figures 3, 4 and 5 present the 1D temperature change calculated by the model (1)÷(4) in 5 equidistant from one another characteristic points along the thickness of the elements with h_w = 0.016 m, l_w = 1.2 m, and t_{w0} = 20 ºC, during their 10 min unilateral convective heating by air with t_{ha} = 100 ºC, v_{ha} = 2 m·s^{-1}, v_{ha} = 5 m·s^{-1}, and v_{ha} = 8 m·s^{-1}, respectively when t_{nha} = 20 °C. The coordinates of those points are shown in the legends of the figures.

The right parts of the Figures 3, 4 and 5 present the 1D temperature change calculated by the model (5)÷(8) in 5 equidistant from one another characteristic points along the thickness of the carrying rubber band with h_B = 4 mm, b_B = 0.8 m, and t_{B0} = 20 °C during 10 min its heating simultaneously with the unilateral convective heating of the furniture elements by air with t_{ha} = 100 °C, v_{ha} = 2 m·s^{-1}, v_{ha} = 5 m·s^{-1}, and v_{ha} = 8 m·s^{-1}, respectively when t_{nha} = 20 °C. The coordinates of those points are also shown in the legends of the figures.

The left and the right parts of Figure 6 show the calculated change in the convective heat transfer coefficients of the heated elements' surface and of the non-heated surface of the carrying rubber band, respectively, depending on the hot air speed v_{ha}.

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 in the points along their thickness and also in the points along the carrying band's thickness goes on according to complex curves. By increasing the heating time, those curves gradually become almost straight lines, whose slope increases with the increasing of the hot air's speed.

2. During the elements' heating, the curve of the temperature on the heated elements' surface is convex outwardly, but the curve of the temperature on the non-heated surface is concave inwardly. All curves of the temperature along the band's thickness are concave inwardly. After 10 min convective heating of the elements the temperature on their surfaces and on the surfaces of the carrying band obtains the following values:

- at v_{ha} = 2 m·s^{-1}: t_w^{hs} = 43.9 °C, $t_w^{nhs} = t_B^{hs}$ = 25.5 °C , and t_B^{nhs} = 24.6 °C;
- at v_{ha} = 5 m·s^{-1}: t_w^{hs} = 58.7 °C, $t_w^{nhs} = t_B^{hs}$ = 29.5 °C , and t_B^{nhs} = 28.0 °C;
- at v_{ha} = 8 m·s^{-1}: t_w^{hs} = 67.0 °C, $t_w^{nhs} = t_B^{hs}$ = 32.1 °C , and t_B^{nhs} = 30.1 °C.

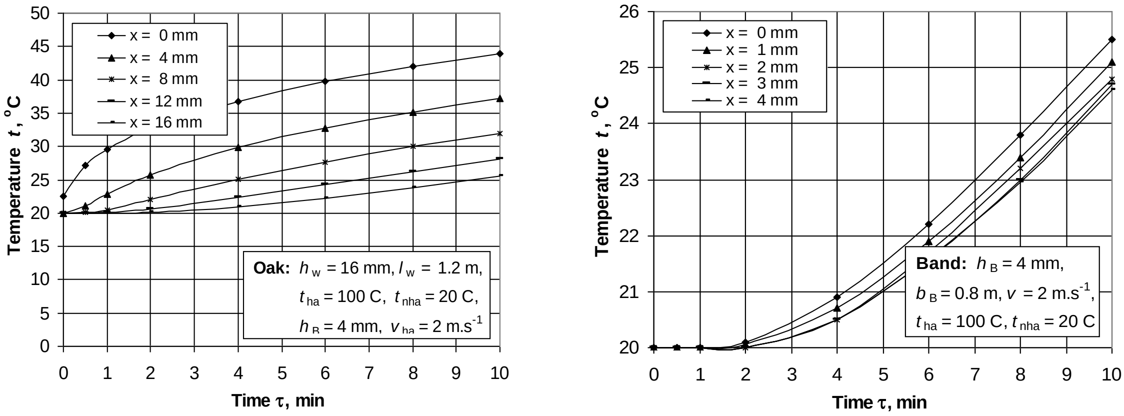

Fig. 3 Change in *t* along the thicknesses of the oak element (left) and the carrying rubber band (right) during the unilateral heating by hot air with t_{ha} = 100 °C and v_{ha} = 2 m·s^{-1}.

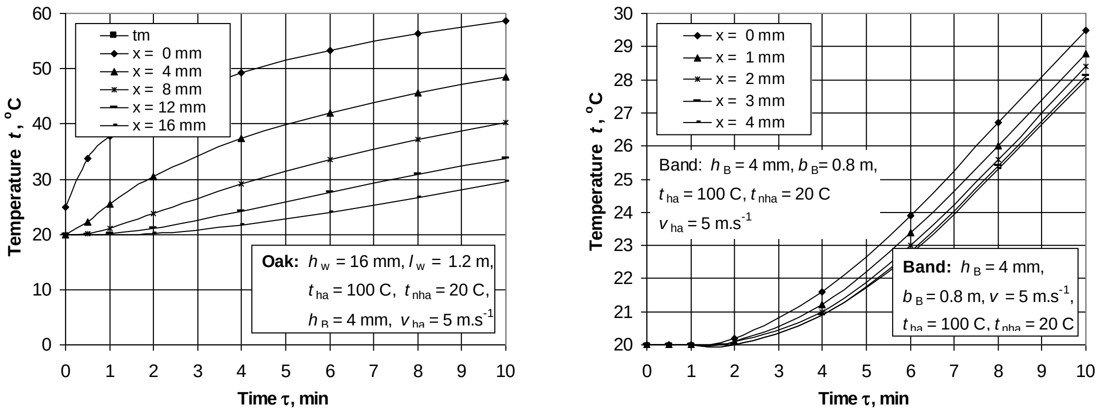

Fig. 4 Change in *t* along the thicknesses of the oak element (left) and the carrying rubber band (right) during the unilateral heating by hot air with t_{ha} = 100 °C and v_{ha} = 5 m·s^{-1}.

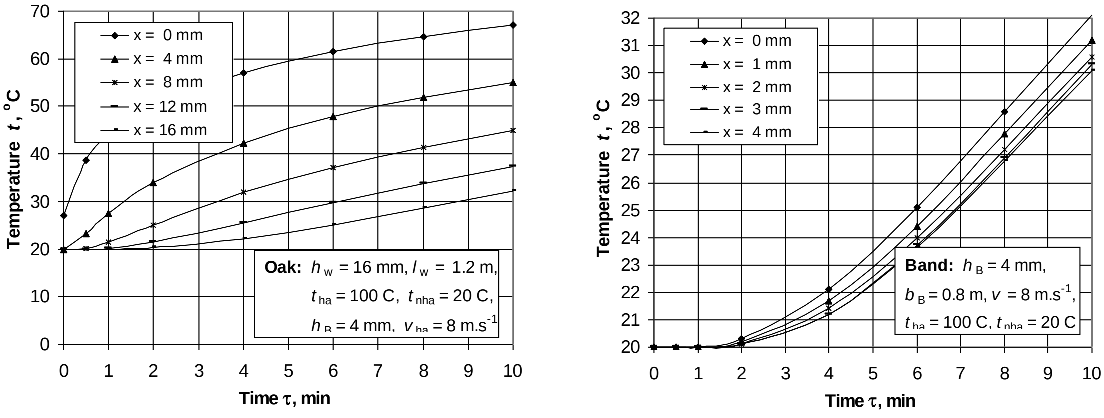

Fig. 5 Change in *t* along the thicknesses of the oak element (left) and the carrying rubber band (right) during the unilateral heating by hot air with t_{ha} = 100 °C and v_{ha} = 8 m·s^{-1}.

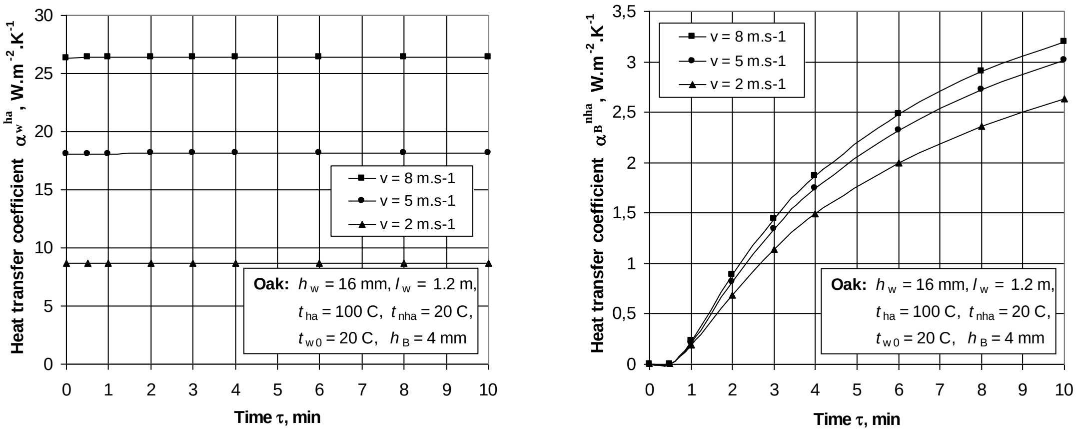

Fig. 6 Change in α_{hs} of flat oak elements with h_w = 16 mm, l_w = 1.2 m, u = 0.08 kg·kg^{-1}, and t_{w0}= 20 °C (left) and in α_{nhs} of the carrying rubber band with h_B = 4 mm (right) during their 10 min unilateral heating by air with t_{ha} = 100 °C at t_{nha} = 20 °C, depending on v_{ha}.

3. The change of the convective heat transfer coefficient of the heated elements' surface, α_w^{hs}, is insignificant during the heating time (see Fig. 6 – left). This coefficient increases almost linearly when the speed of the hot air, v_{ha}, increases. At the beginning of the heating process and after 10 min of the convective heating of the details by hot air with t_{ha} = 100 °C and l_w = 1.2 m the coefficient α_w^{hs} obtains the following values, respectively:

- at v_{ha} = 2 m·s^{-1}: 8.69 W·m^{-2}·K^{-1} and 8.70 W·m^{-2}·K^{-1};
- at v_{ha} = 5 m·s^{-1}: 18.08 W·m^{-2}·K^{-1} and 18.13 W·m^{-2}·K^{-1};
- at v_{ha} = 8 m·s^{-1}: 26.34 W·m^{-2}·K^{-1} and 26.42 W·m^{-2}·K^{-1}.

4. The convective heat transfer coefficient of the non-heated surface of the carrying rubber band, α_B^{nhs}, increses curvilinearly depending on the heating time and increases non-linearly depending on v_{ha}. This coefficient according to eq. (17) depends on the temperature difference $T_B^{nhs} - T_{nha}$. At the beginning of the heating process there is no difference between T_B^{nhs} and T_{nha}. That is why then the coefficient α_B^{nhs} is equal to null. After 10 min of convective heating of the details this coefficient reaches the following values:

- at at v_{ha} = 2 m·s^{-1}: 2.63 W·m^{-2}·K^{-1};
- at at v_{ha} = 5 m·s^{-1}: 3.02 W·m^{-2}·K^{-1};
- at at v_{ha} = 8 m·s^{-1}: 3.20 W·m^{-2}·K^{-1}.

Upon analyzing the obtained results, it is of practical interest the determination of the time, needed by the surface layers of the furniture elements during their convective heating by air with different speed to reach specific temperature, which is necessary for improving the thermal conditions for further lacquering. In this case, at that stage of the problem solving, it is acceptable to use the time for reaching a predetermined temperature at a point that is 4 mm distant from the heated surface of the elements without, however, exceeding their given allowable surface temperature.

It is acknowledged that the limit of $t_w^{hs} \leq 55$ °C is to be the maximum allowable temperature of the heated surface of the furniture elements for the cases of subsequent application of nitrocellulose lacquer over this surface (KAVALOV – ANGELSKI 2014).

The analysis of the results shows that reaching temperatures equal to 25 °C, 30 °C and 35 °C at a point, distant 4 mm from the heated surface of the elements, within the technological constraint of $t_{\mathrm{w}}^{\mathrm{hs}} \le 55\ ^{\mathrm{o}}\mathrm{C}$, comes after duration of convective heating, as follows:

- at v_{ha} = 2 m·s^{-1}: respectively after 1.73 min (then $t_{\mathrm{w}}^{\mathrm{hs}} = 32.0\ ^{\mathrm{o}}\mathrm{C}$), after 4.13 min (then $t_{\mathrm{w}}^{\mathrm{hs}} = 37.0\ ^{\mathrm{o}}\mathrm{C}$), and after 7.82 min (then $t_{\mathrm{w}}^{\mathrm{hs}} = 41.8\ ^{\mathrm{o}}\mathrm{C}$);
- at v_{ha} = 5 m·s^{-1}: respectively after 0.93 min (then $t_{\mathrm{w}}^{\mathrm{hs}} = 37.4\ ^{\mathrm{o}}\mathrm{C}$), after 1.88 min (then $t_{\mathrm{w}}^{\mathrm{hs}} = 42.5\ ^{\mathrm{o}}\mathrm{C}$) and after 3.22 min (then $t_{\mathrm{w}}^{\mathrm{hs}} = 47.2\ ^{\mathrm{o}}\mathrm{C}$);
- ar v_{ha} = 8 m·s^{-1}: respectively after 0.71 min (then $t_{\mathrm{w}}^{\mathrm{hs}} = 41.2\ ^{\mathrm{o}}\mathrm{C}$), after 1.35 min (then $t_{\mathrm{w}}^{\mathrm{hs}} = 46.5\ ^{\mathrm{o}}\mathrm{C}$) and after 2.18 min (then $t_{\mathrm{w}}^{\mathrm{hs}} = 51.0\ ^{\mathrm{o}}\mathrm{C}$).

Those results show that the increase of v_{ha} causes more intensive change in temperature along the elements' thickness. The reason for this fact is that by increasing v_{ha} the heat transfer coefficient $\alpha_{\mathrm{w}}^{\mathrm{hs}}$ is also increased (see Fig. 6 – left).

The influence of v_{ha} on the heat transfer coefficient $\alpha_{\mathrm{w}}^{\mathrm{hs}}$, and hence on the change of the temperature along the furniture elements' thickness is very significant. For example, after 2 min and 4 min of heating of the elements, their surface temperature and the temperature in a point that is 4 mm distant from the surface, reach the following values:

- at v_{ha} = 2 m·s^{-1}: 32.7 °C and 36.8 °C on the surface and 25.7 °C and 29.8 °C at 4 mm;
- at v_{ha} = 5 m·s^{-1}: 43.0 °C and 49.3 °C on the surface and 30.5 °C and 37.4 °C at 4 mm;
- at v_{ha} = 8 m·s^{-1}: 50.1 °C and 57.1 °C on the surface and 34.9 °C and 42.3 °C at 4 mm.

The time needed for reaching of the minimum required temperature, at which the elements' surface layers are sufficiently heated for their intensified subsequent lacquering, depends on their thickness, length, on the temperature and speed of the circulated hot air over them, on the temperature of the surrounding air from the non-heated side of the carrying rubbar band, as well as on the wood specie and the moisture content of the wood. The presented and solved mathematical model allows us to calculate the necessary duration of the unilateral convective heating of furniture elements according to the above mentioned factors.

CONCLUSIONS

This paper presents two mutually connected 1D mathematical models. The first of them provides the computation of the non-stationary temperature distribution along the thickness of subjected to unilateral convective heating flat furniture elements before their subsequent lacquering. The second one allows the computation of the non-stationary distribution of the temperature along the thickness of the carrying rubber band on which lies the non-heated surface of the elements.

The both models are based on the equation of the thermo-conductivity. The convective boundary condition of the first model is calculated using the numbers of similarity of Nusselt, Reynolds and Prandtl for the determination of the heat transfer coefficient of the elements' heated surface at forced air convection. The convective boundary condition of the second model is calculated with the help of the numbers of similarity of Nusselt, Grashoff, and Prandtl for the determination of the heat transfer coefficient of the band's non-heated surface at free air convection. Because of the tight contact between the furniture elements and the carrying rubber band on which they lie during the heating process, the temperature of the non-heated surface of the elements is assumed to be equal to the temperature of the band's upper surface.

A software program has been prepared for the numerical solution simultaneously of the both models with the help of explicit scheme of the finite difference method, which has been input in the calculation environment of Visual Fortran Professional. With the help of the program, computations have been carried out for the determination of the 1D change of the temperature in flat oak elements with thickness of 16 mm, length of 1.2 m, initial temperature of 20 °C, and moisture content of 0.08 $kg \cdot kg^{-1}$ during their 10 min unilateral heating by hot air with temperature of 100 °C and speed of 2 $m \cdot s^{-1}$, 5 $m \cdot s^{-1}$, and 8 $m \cdot s^{-1}$. Simultaneously with these, computations have been carried out for the determination of the 1D change in the temperature along the thickness of the rubber band reinforced by textile fibers, on which the non-heated surface of the elements lies. In the simulation experiments the band was with thickness of 4 mm, width of 0.8 m, initial temperature of 20 °C, and the temperature of the surrounding air from its non-heated surface was equal to 20 °C. The obtained results show that during the unilateral convective heating of the furniture elements, the change of the temperature in the points along their thickness and also in the points along the carrying rubber band's thickness goes on according to complex curves.

The computer solutions of both mathematical models could be used for visualization and technological analysis of the 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 speed of the circulated air prior to their lacquering.

The approach used in this work could be applied for mathematical modelling of the temperature distribution in two or more layer's structures from different materials subjected to convective or/and conducting heating.

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