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# TRANSFORMATION OF TWO MUTUALLY CONNECTED MODELS FOR CONVECTIVE HEATING OF WOOD DETAILS BEFORE THEIR LACQUERING IN A FORM, SUITABLE FOR PROGRAMMING

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## ABSTRACT

Using the explicit form of the finite-difference method, two suggested by the authors mutually connected mathematical models have been transformed in a form, suitable for programming. For the numerical solution of the transformed models, a software program has been prepared in the calculation environment of Visual Fortran Professional. With the help of the program, the 1D distribution of the temperature along the thicknesses of flat oak details and of their carrying transport rubber band with $h_{\mathrm{w}}$ = 16 mm, $l_{\mathrm{w}}$ = 0.6 m, $u$ = 0.08 kg.kg$^{-1}$, $h_{\mathrm{B}}$ = 4 mm, $b_{\mathrm{B}}$ = 0.8 m, and $t_0$ = 20 ºC, during unilateral convective heating for a period of 10 min at $t_{\mathrm{ha}}$ = 100 ºC, $v_{\mathrm{ha}}$ = 2 m·s$^{-1}$, 5 m·s$^{-1}$, 8 m·s$^{-1}$, and $t_{\mathrm{nha}}$ = 20 ºC in order to ensure suitable thermal conditions for the subsequent details' lacquering has been calculated, visualized and analyzed.

**Key words:** oak details, unilateral convective heating, lacquering, carrying rubber band.

## INTRODUCTION

The pre-heating of subjected to lacquering furniture elements and details 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 surface of the wood, the evaporation of the solvents is speeded up and the air is removed from the pores of the wood (Jaić and Živanović-Trbojević 2000, Rüdiger et al. 1995, Zhukov and Onegin 1993, Kavalov and Angelski 2014). Flat wood details with a thickness from 4 to 35 mm and moisture content of approximately 8 ÷ 10% are subjected to unilateral convective heating before their subsequent lacquering.

In the specialized literature there is very limited information about the temperature distribution in wood details during their unilateral convective heating (Deliiski et al. 2016a, 2016b). That is why each research in this aria has both a scientific and a practical interest.

The current work presents the transformation of two suggested by the authors mutually connected mathematical models of the unilateral convective heating process of wood details before their lacquering in a form, suitable for programming. The transformation of the models has been carried out with the help of an explicit form of the finite-difference method.

## MECHANISM OF THE HEAT DISTRIBUTION IN SUBJECTED TO UNILATERAL CONVECTIVE HEATING WOOD DETAILS

The mechanism of the heat distribution in wood details during their unilateral convective heating can be described by the equation of the heat conduction (Deliiski 2003, 2011, 2013). When the width and length of the wood details 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 details in the center of their flat side during the unilateral heating (i.e. along the coordinate $x$, which coincides with the details' thickness $h_{\mathrm{w}}$) can be carried out with the help of the following non-linear 1D mathematical model (Deliiski, 2003, 2011, Deliiski et al., 2016b):

$$c_{\mathrm{w}}(T,u)\rho_{\mathrm{w}}(\rho_{\mathrm{b}},u,u_{\mathrm{fsp}},S_{\mathrm{v}})\frac{\partial T_{\mathrm{w}}(x,\tau)}{\partial\tau}=\lambda_{\mathrm{w}}(T,u,\rho_{\mathrm{b}})\frac{\partial^2 T_{\mathrm{w}}(x,\tau)}{\partial x^2}+\frac{\partial\lambda_{\mathrm{w}}(T,u,\rho_{\mathrm{b}})}{\partial T}\left(\frac{\partial T_{\mathrm{w}}}{\partial x}\right)^2 \quad \textbf{(1)}$$

with an initial condition

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

and following boundary conditions:

- from the side of the details' heating – at conditions of forced convective heat exchange between the upper surface of the details and the circulated hot air with temperature $T_{\mathrm{ha}}$ and velocity $v_{\mathrm{ha}}$ (see Fig.1 below):

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

- from the opposite non-heated side of the details – at temperature, which is equal to the temperature $T_{\mathrm{B\text{-}hs}}$ of the upper (heated) side of the carrying rubber band, on which the non-heated surface of the details lies (see Fig. 1):

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

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

**MECHANISM OF THE HEAT DISTRIBUTION IN THE CARYING RUBBER BAND DURING THE UNILATERAL CONVECTIVE HEATING OF THE WOOD DETAILS**

The change in the temperature along the thickness of the carrying rubber band, on which the non-heated surface of the details lies during the details' heating (i.e. along the coordinate $x$, which coincides with the thicknesses of the details and of the band – see Fig. 1), can be computed using the following 1D mathematical model (Deliiski et al. 2016a, 2016b):

$$\frac{\partial T_{\mathrm{B}}(x,\tau)}{\partial\tau}=a_{\mathrm{B}}(T)\frac{\partial^2 T_{\mathrm{B}}(x,\tau)}{\partial x^2}\,. \quad \textbf{(5)}$$

with an initial condition

$$T_{\mathrm{B}}(x,0)=T_{\mathrm{B0}} \quad \textbf{(6)}$$

and following boundary conditions:

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

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

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

$$\frac{\mathrm{d}T_{\mathrm{B-nhs}}(\tau)}{\mathrm{d}x}=-\frac{\alpha_{\mathrm{B\text{-}nhs}}(\tau)}{\lambda_{\mathrm{B\text{-}nhs}}}\left[T_{\mathrm{B\text{-}nhs}}(\tau)-T_{\mathrm{nha}}(\tau)\right]. \quad \textbf{(8)}$$

## MATHEMATICAL DESCRIPTION OF THE CONVECTIVE HEAT TRANSFER COEFFICIENTS $\alpha_{W\text{-}HS}$ AND $\alpha_{B\text{-}NHS}$

The calculation of the heat transfer coefficient $\alpha_{w\text{-}ha}$ in eq. (3) 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 (Milchev et al. 1989, Telegin et al. 2002, Deliiski et al. 2016b):

$$\alpha_{\text{w-hs}} = \frac{\text{Nu}_{\text{ha}}\lambda_{\text{ha}}}{l_{\text{w}}}, \quad \textbf{(9)}$$

where at laminar regime of the forced convection of the air (i.e. at $\text{Re}_{\text{ha}} \le 4\cdot10^4$):

$$\text{Nu}_{\text{ha}} = 0.66\,\text{Re}_{\text{ha}}^{0.5}\,\text{Pr}_{\text{ha}}^{0.43}\left(\frac{\text{Pr}_{\text{ha}}}{\text{Pr}_{\text{hs}}}\right)^{0.25} \quad \textbf{(10)}$$

and at turbulent regime of the forced convection (i.e. at $\text{Re}_{\text{ha}} > 4\cdot10^4$):

$$\text{Nu}_{\text{ha}} = 0.037\,\text{Re}_{\text{ha}}^{0.8}\,\text{Pr}_{\text{ha}}^{0.43}\left(\frac{\text{Pr}_{\text{ha}}}{\text{Pr}_{\text{hs}}}\right)^{0.25}. \quad \textbf{(11)}$$

The calculation of the heat transfer coefficient $\alpha_{\text{B-nhs}}$ in eq. (8) 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 (Telegin et al. 2002):

$$\alpha_{\text{B-nhs}} = \frac{1.3\,\text{Nu}_{\text{nha}}\lambda_{\text{nha}}}{b_{\text{B}}}, \quad \textbf{(12)}$$

where

$$\text{Nu}_{\text{nha}} = 0.5\left(\text{Gr}_{\text{nha}}\cdot\text{Pr}_{\text{nha}}\right)^{0.25}\left(\frac{\text{Pr}_{\text{nha}}}{\text{Pr}_{\text{nhs}}}\right)^{0.25} \quad @ \quad 10^3 < \text{Gr}_{\text{nha}}\cdot\text{Pr}_{\text{nha}} < 10^9. \quad \textbf{(13)}$$

## TRANSFORMATION OF THE MATHEMATICAL MODELS IN SUITABLE FORM FOR PROGRAMMING

The following system of equations has been derived after the transformation of equations (1) to (12) according to Figure 1 with the usage of the same explicit form of the finite-difference method, which has been described in (Dorn and McCracken 1972, Deliiski 2011, 2013):

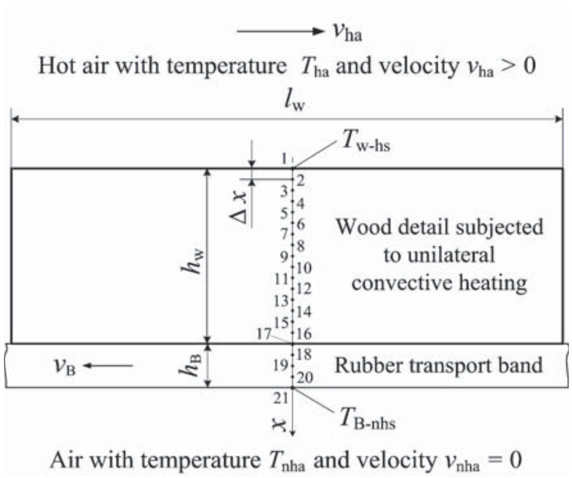


**Figure 1: Positioning of the nodes of the 1D calculation mesh along the thicknesses**

- For the computation of the temperature field along the thickness of the wood details:

$$T_i^0 = T_{\text{w0}} \quad @ \quad 1 \le i \le 17, \quad \textbf{(14)}$$

$$T_i^{n+1} = T_i^n + \frac{\lambda_{\mathrm{w0c}}\Delta\tau}{c_{i\text{-w}}^n \rho_{\mathrm{w}} \Delta x^2}\left\{\left[1+\beta\left(T_i^n - 273.15\right)\right]\left(T_{i+1}^n + T_{i-1}^n - 2T_i^n\right) + \beta\left(T_i^n - T_{i-1}^n\right)^2\right\} \quad @ \quad 2 \le i \le 17, \tag{15}$$

$$T_1^{n+1} = \frac{T_2^n + \alpha_{\mathrm{w-hs}}^n T_{\mathrm{ha}}^n \Delta x}{1 + \dfrac{\alpha_{\mathrm{w-hs}}^n \Delta x}{\lambda_{\mathrm{w0}}(1+\beta T_1^n)}}, \tag{16}$$

$$\alpha_{\mathrm{w-hs}}^n = \frac{\mathrm{Nu}_{\mathrm{ha}}^n \lambda_{\mathrm{ha}}^n}{l_{\mathrm{w}}}, \tag{17}$$

where

$$c_{i\text{-w}}^n = \frac{2097u + 826}{1+u} + \frac{9.92u + 2.55}{1+u}T_i^n + \frac{0.0002}{1+u}(T_i^n)^2 \quad @ \quad 1 \le i \le 17 \quad \& \quad u \le u_{\mathrm{fsp}}, \tag{18}$$

$$\lambda_{\mathrm{w0}} = K_{\mathrm{wa}}(0.15 - 0.07u)\cdot[0.165 + (1.39 + 3.8u)\cdot(3.3\cdot 10^{-7}\rho_{\mathrm{b}}^2 + 1.015\cdot 10^{-3}\rho_{\mathrm{b}})], \tag{19}$$

$$\gamma = (2.05 + 4.0u)\left(\frac{579}{\rho_{\mathrm{b}}} - 0.124\right)\cdot 10^{-3} \quad @ \quad u \le u_{\mathrm{fsp}}, \tag{20}$$

$$\rho_{\mathrm{w}} = \rho_{\mathrm{b}}\frac{1+u}{1 - \dfrac{S_{\mathrm{v}}}{100}\left(u_{\mathrm{fsp}} - u\right)} \quad @ \quad u \le u_{\mathrm{fsp}}, \tag{21}$$

$$\lambda_{\mathrm{ha}}^n = 0.0036 + 7.8\cdot 10^{-5} T_{\mathrm{ha}}^n; \tag{22}$$

- For the computation of the temperature field along the thickness of the rubber band:

$$T_i^0 = T_{\mathrm{B0}} \quad @ \quad 18 \le i \le 21, \tag{23}$$

$$T_i^{n+1} = T_i^n + \frac{a_{\mathrm{B}}^n \Delta\tau}{\Delta x^2}\left(T_{i-1}^n + T_{i+1}^n - 2T_i^n\right) \quad @ \quad 18 \le i \le 21, \tag{24}$$

$$T_{21}^{n+1} = \frac{T_{20}^n + \alpha_{\mathrm{B-nhs}}^n T_{\mathrm{nha}}^n \Delta x}{1 + \dfrac{\alpha_{\mathrm{B-nhs}}^n \Delta x}{\lambda_{\mathrm{B\text{-}nhs}}}}, \tag{25}$$

$$\alpha_{\mathrm{B-nhs}}^n = \frac{1.3\mathrm{Nu}_{\mathrm{nha}}^n \lambda_{\mathrm{nha}}^n}{b_{\mathrm{B}}}, \tag{26}$$

$$\lambda_{\mathrm{nha}}^n = 0.0036 + 7.8\cdot 10^{-5} T_{\mathrm{nha}}^n, \tag{27}$$

where according to Juma et al. (2001)

$$\begin{gathered} a_{i\text{-B}}^n = 1.4409\cdot 10^{-7} - 4.14765\cdot 10^{-10} T_i^n + 1.0791\cdot 10^{-12}(T_i^n)^2 \\ @ \quad 18 \le i \le 21 \quad \& \quad 293.15 \text{ K} \le T \le 440.15 \text{ K} \end{gathered}. \tag{28}$$

The value of the step $\Delta\tau$ in eqs. (15) and (24) is determined by the condition for stability of the solution of these equations with the help of explicit form of the finite-difference method. It must not exceed the smaller of the two values obtained from the equations (Deliiski 2011)

$$\Delta\tau = \frac{c_{\mathrm{w}}\left(T_{\min},u\right)\rho_{\mathrm{w}}\left(\rho_{\mathrm{b}},u,u_{\mathrm{fsp}},S_{\mathrm{v}}\right)\Delta x^2}{2\lambda_{\mathrm{w}}\left(T_{\min},u,\rho_{\mathrm{b}}\right)} \text{ and } \Delta\tau = \frac{c_{\mathrm{w}}\left(T_{\max},u\right)\rho_{\mathrm{w}}\left(\rho_{\mathrm{b}},u,u_{\mathrm{fsp}},S_{\mathrm{v}}\right)\Delta x^2}{2\lambda_{\mathrm{w}}\left(T_{\max},u,\rho_{\mathrm{b}}\right)}, \quad (29)$$

in which $T_{\min}$ and $T_{\max}$ are correspondingly the smallest and biggest of all values of the temperatures, encountered in the initial and boundary conditions of the heat transfer when solving the mathematical models.

## RESULTS AND DISCUSSION

For the numerical solution of the discrete analogues of the mathematical models a software program has been prepared 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 the temperature in flat oak details with thickness $h_{\mathrm{w}} = 0.016$ m, lengths $l_{\mathrm{w}} = 0.6$ m, initial temperature $t_{\mathrm{w0}} = 20$ ºC, basic density $\rho_{\mathrm{b}} = 670$ kg·m$^{-3}$, volume shrinkage $S_{\mathrm{v}} = 11.9\%$, moisture contents $u = 0.08$ kg·kg$^{-1}$ and fiber saturation point $u_{\mathrm{fsp}} = 0.29$ kg·kg$^{-1}$ (Nikolov and Videlov 1987) during their 10 min unilateral convective heating by hot air with temperature $t_{\mathrm{ha}} = 100$ ºC and velocity $v_{\mathrm{ha}} = 2$ m·s$^{-1}$, $v_{\mathrm{ha}} = 5$ m·s$^{-1}$, and $v_{\mathrm{ha}} = 8$ m·s$^{-1}$.

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 fibres, on which the non-heated surfaces of the subjected to unilateral heating wood details lie (see Fig. 1). The band was accepted to be with thickness $h_{\mathrm{B}} = 0.004$ m, width $b_{\mathrm{B}} = 0.8$ m, and initial temperature $t_{\mathrm{B0}} = 20$ ºC. The temperature of the surrounding air from the non-heated surface of the band during the details' heating was accepted to be equal to $t_{\mathrm{nha}} = 20$ ºC. The computations have been carried out with an average value of the band's thermal conductivity perpendicular to the textile fibres $\lambda_{\mathrm{B\text{-}nhs}} = 0.281$ W m$^{-1}$·K$^{-1}$ (http://www. axelproducts.com).

All computations have been carried out with 21 nodes of the calculation mesh, i.e. with a step along the thicknesses of the details and of the band $\Delta x = 1.0$ mm. With the numbers 1 to 17 and 17 to 21 on Fig. 1 is marked the following number of the nodes of the 1D calculation mesh along the thickness of the wood detail and along the thickness of the rubber band, respectively.

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

The right parts of the Figures 2, 3, and 4 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 during 10 min its heating simultaneously with the unilateral convective heating of the oak details by air with $v_{\mathrm{ha}} = 2$ m·s$^{-1}$, $v_{\mathrm{ha}} = 5$ m·s$^{-1}$, and $v_{\mathrm{ha}} = 8$ m·s$^{-1}$, respectively. The coordinates of those points are also shown in the legends of the figures.

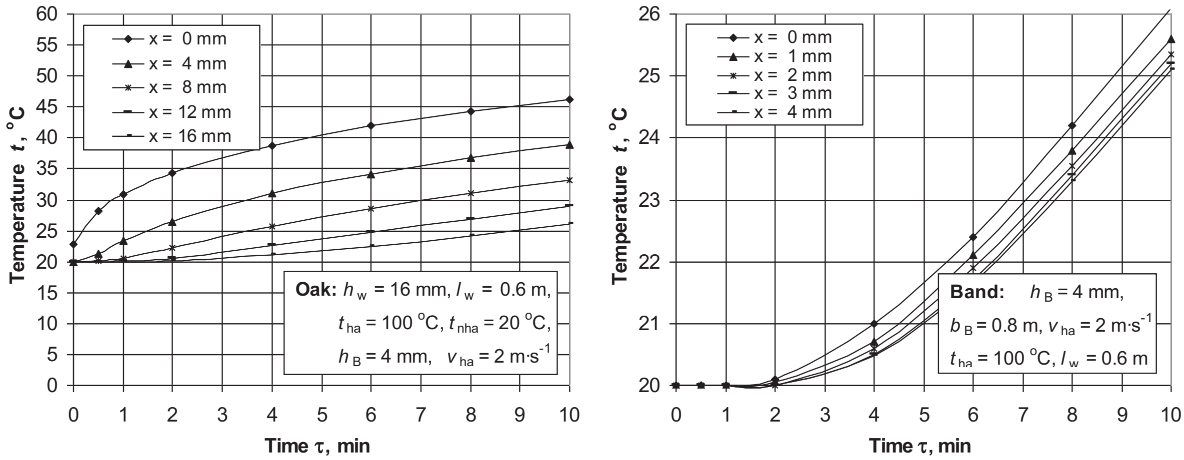


**Figure 2: Change in $t$ along the thicknesses of the oak detail (left) and of the carrying rubber band (right) during the unilateral convective heating by hot air with $t_{ha}$ = 100 ºC and $v_{ha}$ = 2 m·s$^{-1}$**

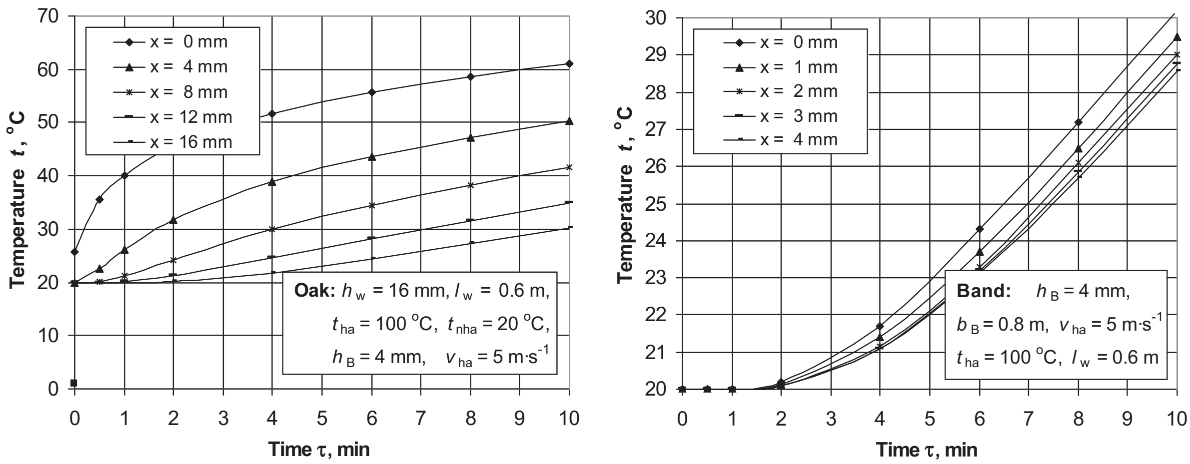


**Figure 3: Change in $t$ along the thicknesses of the oak detail (left) and of the carrying rubber band (right) during the unilateral convective heating by hot air with $t_{ha}$ = 100 ºC and $v_{ha}$ = 5 m·s$^{-1}$**

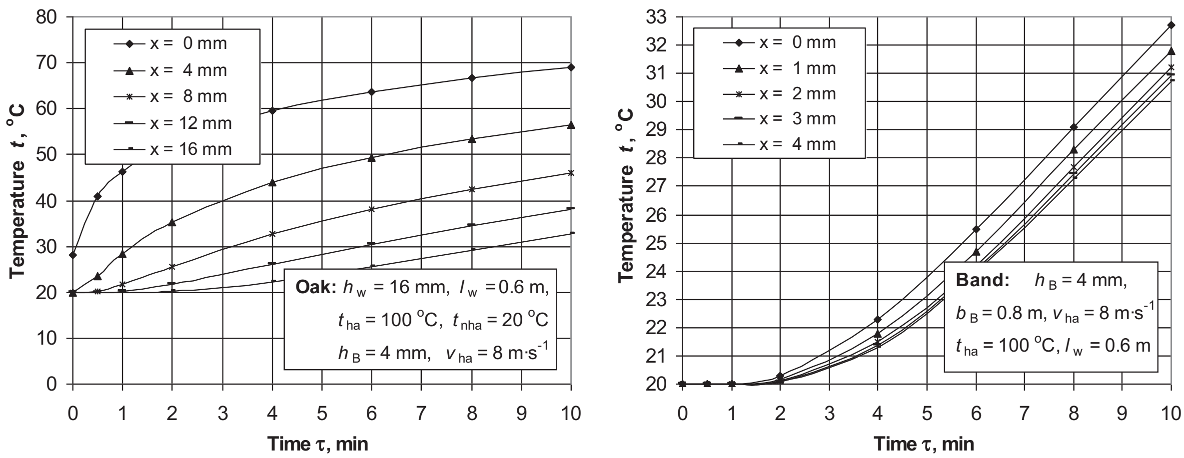


**Figure 4: Change in $t$ along the thicknesses of the oak detail (left) and of the carrying rubber band (right) during the unilateral convective heating by hot air with $t_{ha}$ = 100 ºC and $v_{ha}$ = 8 m·s$^{-1}$**

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

1. During the unilateral heating of the details, the change of the tempera-

ture in all 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 velocity of the hot air.

2. During the details' heating, the curve of the temperature on the heated details' 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 details the temperature on their surfaces and on the surfaces of the carrying band obtains the following values:

- at $v_{ha} = 2$ m·s$^{-1}$: $t_{w\text{-}hs} = 46.2$ °C, $t_{w\text{-}nhs} = t_{B\text{-}hs} = 26.1$ °C , and $t_{B\text{-}nhs} = 25.1$ °C;
- at $v_{ha} = 5$ m·s$^{-1}$: $t_{w\text{-}hs} = 61.0$ °C, $t_{w\text{-}nhs} = t_{B\text{-}hs} = 30.2$ °C , and $t_{B\text{-}nhs} = 28.6$ °C;
- at $v_{ha} = 8$ m·s$^{-1}$: $t_{w\text{-}hs} = 68.9$ °C, $t_{w\text{-}nhs} = t_{B\text{-}hs} = 32.7$ °C , and $t_{B\text{-}nhs} = 30.7$ °C.

## CONCLUSIONS

This paper shows and analyzes diagrams of 1D non-stationary change in the temperature along the thickness of flat oak details subjected to unilateral convective heating in order to ensure better thermal conditions for their subsequent lacquering. It presents also diagrams of 1D non-stationary change in the temperature along the thickness of the carrying rubber band, on which the non-heated surface of the details lies during their heating. The diagrams are built according to the results calculated with the help of the non-linear mathematical models, which have been presented in the paper. Using the explicit form of the finite-difference method, the both models have been transformed in a form, suitable for programming. For the numerical solution of the transformed models, a software program has been prepared in the calculation environment of Visual Fortran Professional. With the help of the program, the 1D distribution of the temperature along the thicknesses of flat oak details and of their carrying rubber band with $h_w = 16$ mm, $l_w = 0.6$ m, $u = 0.08$ kg.kg$^{-1}$, $h_B = 4$ mm, $b_B = 0.8$ m, and $t_0 = 20$ °C, during unilateral convective heating for a period of 10 min at $t_{ha} = 100$ °C, $v_{ha} = 2$ m·s$^{-1}$, $v_{ha} =5$ m·s$^{-1}$, $v_{ha} = 8$ m·s$^{-1}$, and $t_{nha} = 20$ °C in order to ensure suitable thermal conditions for the subsequent details' lacquered has been calculated, visualized and analyzed.

The solutions of both mathematical models could be used for visualization and technological analysis of the temperature change along the thickness of details made of different wood species, different thickness, length and water content, during their unilateral convective heating with different temperature and velocity of the circulated air prior to their lacquering.

### Symbols

*a* = temperature conductivity (m$^2$·s$^{-1}$)
*b* = width (m)
*c* = specific heat capacity (J·kg-1·K-1)
Gr = number of similarity of Grashof
*i* = following number of the nodes in 1D calculation mesh: i = 1, 2, …, 21
*h* = thickness (m)
*l* = length (m)
*M* = number of the steps on the x-coordinate using which the model was solved
*n* = time level during the solution of the mathematical model: n = 0, 1, 2, 3, …..
Nu = number of similarity of Nusselt
Pr = number of similarity of Prtandtl
Re = number of similarity of Reynolds
*S* = wood shrinkage (%)

*t* = temperature (oC): t = T – 273.15
*T* = temperature (K): T = t + 273.15
*u* = moisture content (kg·kg-1): u = W/100
*W* = moisture content (%): W = 100u
*v* = velocity (m·s-1)
*x* = coordinate along the thicknesses of the detail and of the carrying rubber band
α = heat transfer coefficient (W·m-2·K-1)
λ = thermal conductivity (W·m-1·K-1)
ρ = density (kg·m-3)
τ = time (s)
Δx = step on the x-coordinate, which coincides with the thicknesses of the detail and of the band (m)
Δτ = step on the τ-coordinate, i.e. interval between time levels (s)
@ = at

**Subscripts and superscripts:**

a = air (for the temperature of the air near to the non-heated side of the wood details)
b = basic (for density, based on dry mass divided by green volume)
B = band
B-hs = band's heated surface
B-nhs = band's not heated surface
B0 = initial (for the mass temperature of the rubber band at the beginning of the heating
fsp = fiber saturation point of the wood
ha = heating air
hs = heated surface
nha = not heating air
nhs = not heated surface
v = volume (for the wood shrinkage)
w = wood
w-hs = wood's heated surface
w-nhs = wood's not heated surface
w0 = initial (for the mass temperature of the details at the beginning of the heating
0 = initial (for the time level at the beginning of the models' solution)

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