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COMPUTATION OF THE HEAT TRANSFER COEFFICIENTS DURING UNILATERAL CONVECTIVE HEATING OF FLATS OAK DETAILS WITH DIFFERENT LENGTHS BEFORE LACQUERING

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Abstract

Based on the differential equation of the thermo-conductivity, a 1D linear mathematical model of the unilateral convective heating process by air of flat furniture details before their lacquering has been presented. A software program has been prepared for the numerical solution of the model with the help of an explicit scheme of the finite difference method, which has been input in the calculation environment of Visual Fortran Professional.

Using the program, computations have been carried out for the determination of the change in the temperatures and the convective heat transfer coefficients of both surfaces of flat oak details with an initial temperature of 20 ^{o}*C, moisture content of 0.08 kg·kg*$^{-1}$*, 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 unilateral heating by hot air with temperature of 100* ^{o}*C and velocity of 5 m·s*$^{-1}$*.*

Key words: *oak details, unilateral convective heating, heat transfer coefficient, lacquering*

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 – Živanović-Trbojević 2000, Rüdiger *et al.* 1995).

Flat wood details with a thickness from 4 to 35 mm and moisture content of approximately 8 ÷ 10% are subjected to one sided convective heating before their lacquering. The equipment for the pre-heating of the details is usually shaped as tunnel sections, adapted for the turning into assembly lines for the formation of protective-decorative coatings (Kavalov – Angelski 2014).

In the specialized literature there is no information about the temperature distribution in wood details during their unilateral convective heating and also about the change of the heat transfer coefficients of the details' surfaces during such heating. That is why each study in this aria is has both a scientific and a practical interest.

The current work presents a 1D linear model for the calculation of the temperature distribution along the thickness of flat wood details subjected to unilateral convective

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heating in order to improve the thermal conditions for their subsequent lacquering. The aim of the work is to suggest an approach for the computation by the help of the model of the convective heat transfer coefficients of the heated and of the non-heated surfaces of the details during their unilateral heating.

MECHANISM OF THE 1D HEAT DISTRIBUTION IN FLAT WOOD DETAILS DURING THEIR UNILATERAL CONVECIVE HEATING

During the heating of wood details along with the purely thermal processes, a moisture-exchange occurs between the processing medium and the details. The values of the moisture diffusion in the details are usually hundreds of times smaller than the values of their temperature conductivity (Chudinov 1966). These facts determine a not so big change in diffusing moisture in the details, which lags significantly from the distribution of heat in them during the heating.

This allows disregarding the exchange of moisture between the details 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 wood details can be described by the equation of heat conductivity.

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 during their unilateral heating (i.e. along the coordinate x, which coincides with the thickness) can be carried out with the help of the following 1D mathematical model (Deliiski 2003):

$$\frac{\partial T(x,\tau)}{\partial \tau} = a(T,u,\rho_{\mathrm{b}})\frac{\partial^2 T(x,\tau)}{\partial x^2} \tag{1}$$

with an initial condition

$$T(x,0) = T_0 \tag{2}$$

and following boundary conditions:

• from the side of the heating – at conditions of forced convective heat exchange between the upper surface of the details and the circulated hot air with temperature T_{ha}:

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

• from the opposite side – at conditions of free convective heat exchange between the thin wear rubber band, where the non-heated surface of the details lies (see Fig. 1), and the surrounding air environment with temperature T_{nha}:

$$\frac{\mathrm{d}T(X,\tau)}{\mathrm{d}x} = -\frac{\alpha_{\mathrm{nhs}}(\tau)}{\lambda_{\mathrm{nhs}}(X,\tau)}\left[T(X,\tau) - T_{\mathrm{nha}}(\tau)\right], \tag{4}$$

where x is the coordinate along the thickness of the details: $0 \le x \le X = h$, m; h – thickness of the details, m; a – temperature conductivity of the details' wood, $\mathrm{m^2 \cdot s^{-1}}$; u – moisture content of the details' wood, $\mathrm{kg \cdot kg^{-1}}$; ρ_{b} – basic density of the details' wood specie, equal to the dry mass divided to green volume, $\mathrm{kg \cdot m^{-3}}$; T – temperature, K; $T(x,0)$ – temperature of all points along the detail's thickness at the beginning (i.e. at $\tau = 0$) of the heating process, K; $T(0,\tau)$ – temperature of subjected to heating upper surface of the details, K; $T(X,\tau)$ – temperature of the non-heated bottom surface of the details, K; T_0 – initial temperature of the subjected to heating details, K; T_{ha} – temperature of the hot air near the heated surface during the heating, K; T_{nha} – temperature of the air near the non-heated surface during the heating, K; α_{hs} – convective heat transfer coefficient of the heated details' surface, $W \cdot m^{-2} \cdot K^{-1}$; α_{nhs} – convective heat transfer coefficient of the non-heated surface of the details, $W \cdot m^{-2} \cdot K^{-1}$; λ_{hs} – thermal conductivity of the wood on the heated details' surface, $W \cdot m^{-1} \cdot K^{-1}$; λ_{nhs} – thermal conductivity of the wood on the non-heated surface, $W \cdot m^{-1} \cdot K^{-1}$; τ – time, s.

DETERMINATION OF THE HEAT TRANSFER COEFFICIENT α_{hs}

The calculation of the heat transfer coefficient α_{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 (Telegin *et al.* 2002):

$$\alpha_{hs} = \frac{Nu_{ha} \lambda_{ha}}{l}, \tag{5}$$

where l is the linear size of the details along the direction of the hot air circulation (i.e. length of the details), 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 with 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 $Re_{ha} \le 4 \cdot 10^4$):

$$Nu_{ha} = 0.66 \, Re_{ha}^{0.5} \, Pr_{ha}^{0.43} \left(\frac{Pr_{ha}}{Pr_{hs}} \right)^{0.25} \tag{6}$$

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

$$Nu_{ha} = 0.037 \, Re_{ha}^{0.8} \, Pr_{ha}^{0.43} \left(\frac{Pr_{ha}}{Pr_{hs}} \right)^{0.25}, \tag{7}$$

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

$$Pr_{ha} = \frac{w_{ha}}{a_{ha}}, \tag{8}$$

$$Pr_{hs} = \frac{w_{hs}}{a_{hs}}, \tag{9}$$

$$Re_{ha} = \frac{\rho_{ha} v_{ha} l}{\mu_{ha}} = \frac{\rho_{ha} v_{ha} l}{\rho_{ha} w_{ha}} = \frac{v_{ha} l}{w_{ha}}. \tag{10}$$

In equations (5) – (10) the following thermo-physical characteristics of the air participate: λ – thermal conductivity, $\mathrm{W}\cdot\mathrm{m}^{-1}\cdot\mathrm{K}^{-1}$; $a=\dfrac{\lambda}{c\cdot\rho}$ – temperature conductivity, $\mathrm{m}^2\cdot\mathrm{s}^{-1}$; c – specific heat capacity, $\mathrm{J}\cdot\mathrm{kg}^{-1}\cdot\mathrm{K}^{-1}$; $w=\dfrac{\mu}{\rho}$ – cinematic viscosity coefficient, $\mathrm{m}^2\cdot\mathrm{s}^{-1}$; ρ – density, $\mathrm{kg}\cdot\mathrm{m}^{-3}$; μ – dynamic viscosity coefficient, Pa·s; v – velocity, $\mathrm{m}\cdot\mathrm{s}^{-1}$; α – convective heat transfer coefficient of the subjected to heating surface of the details, $\mathrm{W}\cdot\mathrm{m}^{-2}\cdot\mathrm{K}^{-1}$.

The indexes “ha” and “hs” of the thermo-physical characteristics of the air and of the numbers of the similarity in equations (5) – (10) mean that these characteristics and criterions must be calculated depending on the temperature of the **h**ot **a**ir and of the **h**eated **s**urface of the aired details.

DETERMINATION OF THE HEAT TRANSFER COEFFICIENT α_{nhs}

The calculation of the heat transfer coefficient α_{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 (Telegin *et al.* 2002, Milchev *et al.* 1989, Rohsenow – Hartnett 1973):

$$\alpha_{\mathrm{nhs}}=\frac{1.3\cdot \mathrm{Nu}_{\mathrm{nha}}\lambda_{\mathrm{nha}}}{b}, \tag{11}$$

where b – smaller size from the two sizes of the details aired by the hot air (i.e. width of the details), m; λ_{nha} – thermal conductivity of the air from the non-heated surface of the details, $\mathrm{W}\cdot\mathrm{m}^{-1}\cdot\mathrm{K}^{-1}$; $\mathrm{Nu}_{\mathrm{nha}}$ – 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 details according to following equations:

$$\mathrm{Nu}_{\mathrm{nha}}=0.5\left(\mathrm{Gr}_{\mathrm{nha}}\cdot \mathrm{Pr}_{\mathrm{nha}}\right)^{0.25}\left(\frac{\mathrm{Pr}_{\mathrm{nha}}}{\mathrm{Pr}_{\mathrm{nhs}}}\right)^{0.25} \quad @ \quad 10^3<\mathrm{Gr}_{\mathrm{nha}}\cdot \mathrm{Pr}_{\mathrm{nha}}<10^9, \tag{12}$$

where the Grashoff’s number of similarity $\mathrm{Gr}_{\mathrm{nha}}$ and the Prandtl’s numbers of similarity $\mathrm{Pr}_{\mathrm{nha}}$ and $\mathrm{Pr}_{\mathrm{nhs}}$ are calculated according to the equations

$$\mathrm{Gr}_{\mathrm{nha}}=\frac{g\cdot\beta_{\mathrm{nha}}b^3}{w_{\mathrm{nha}}^2}\left(T_{\mathrm{nhs}}-T_{\mathrm{nha}}\right), \tag{13}$$

$$\mathrm{Pr}_{\mathrm{nha}}=\frac{w_{\mathrm{nha}}}{a_{\mathrm{nha}}}, \tag{14}$$

$$\mathrm{Pr}_{\mathrm{nhs}}=\frac{w_{\mathrm{nhs}}}{a_{\mathrm{nhs}}}. \tag{15}$$

In equations (11) – (15) the following, not yet explained above, variables take part: $g=9.81\mathrm{m}\cdot\mathrm{s}^{-2}$ – 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 (11) – (15) mean that these variables and criterions must be calculated depending on the temperature of the **n**ot **h**eating **a**ir and of the **n**ot **h**eated **s**urface of the details.

It can be noted that a mathematical description of the thermo-physical characteristics of the air λ, β, *w*, and *a*, which participates in eqs. (6) – (15), depending on the temperature *T*, could be found in (Deliiski 2003, Deliiski – Dzurenda 2010).

RESULTS AND DISCUSSION

The mathematical model, which is presented by the eqs. (1) – (15), has 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) for the solution of a model of the heating process of prismatic wood materials. For the solution of the model, 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 in the wood temperature and also in the heat transfer coefficients of both surfaces of flat oak (*Quercus petraea* Libl.) details with an initial temperature of 20 °C, moisture content of 0.08 $\text{kg}\cdot\text{kg}^{-1}$, thickness of 16 mm, width of 0.6 m, lengths of 0.6 m, 1.2 m, and 1.8 mm during their 10 min unilateral convective heating by hot air with 100 °C and velocity of 5 $\text{m}\cdot\text{s}^{-1}$ at a temperature of 20 °C of the surrounding air from the non-heated details' side.

The calculations have been made with average values of the wood temperature conductivity $a = 1.9337\cdot10^{-7}\ \text{m}^2\cdot\text{s}^{-1}$ and of the wood thermal conductivity cross-sectional to the fibers of the details $\lambda = \lambda_{\text{hs}} = \lambda_{\text{nhs}} = 0.2738\ \text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ (Deliiski *et al.* 2016) for oak wood with basic density $\rho_{\text{b}} = 670\ \text{kg}\cdot\text{m}^{-3}$, moisture content $u = 0.08\ \text{kg}\cdot\text{kg}^{-1}$, fiber saturation point $u_{\text{fsp}} = 0.29\ \text{kg}\cdot\text{kg}^{-1}$, and volume shrinkage $S_{\text{v}} = 11.9$ % in the temperature range from 20 °C to 60 °C (Videlov 2003). These average values if *a* and λ have been obtained using the mathematical description of *a* and λ depending on *t*, *u*, and u_{fsp} of the wood species (Deliiski 2003, 2013, Deliiski – Dzurenda 2010).

The thermo-physical characteristics of the air *a*, λ, β, and *w*, which participate in the numbers of similarity above, have been calculated according to the equations given in (Deliiski – Dzurenda 2010).

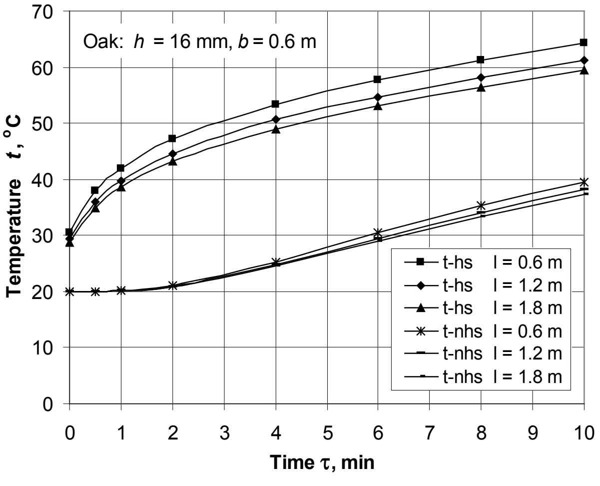

Figure 1. Change in *t* on both surfaces of an oak detail with t_0= 20 °C, $u = 0.08\ \text{kg}\cdot\text{kg}^{-1}$, and $l = 0.6$ m during its 10 min unilateral heating by air with $t_{\text{ha}} = 100$ °C and $v = 5\ \text{m}\cdot\text{s}^{-1}$

Figure 1 presents the calculated temperature change on both surfaces of the details depending on *l*.

Figures 2 and Figure 3 show the calculated change in the convective heat transfer coefficients of the heated and non-heated surfaces of the details, respectively, depending on the length *l*.

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

1. During the unilateral convective heating of the details the change of the temperature in their surfaces goes on according to complex curves. 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 (Figure 1).

After 10 min convective heating of the details the temperature on their surfaces obtains the following values:

- at $l = 0.6$ m: $t_{hs} = 64.3$ °C and $t_{nhs} = 39.6$ °C;
- at $l = 1.2$ m: $t_{hs} = 61.2$ °C and $t_{nhs} = 38.1$ °C;
- at $l = 1.8$ m: $t_{hs} = 59.4$ °C and $t_{nhs} = 37.2$ °C.

2. The change of the convective heat transfer coefficient of the heated details' surface, α_{hs}, is insignificant during the heating process (Figure 2). This coefficient decreases when the aired length of the details, *l,* increases. The influence of *l* on decreasing of α_{hs} is partly compensated by the increasing of the numbers of similarity Re_{ha} and Nu_{ha} when *l* increases (see equations (10), (6), (7), and (5)). Because of these reasons the influence of *l* on α_{hs} is non-linear.

At the beginning of the heating process and after 10 min of convective heating of the details by hot air with $t_{ha} = 100$ °C and $v = 5\ \mathrm{m\cdot s^{-1}}$ the coefficient α_{hs} obtains the following values, respectively:

- at $l = 0.6$ m: 20.77 $\mathrm{W\cdot m^{-2}\cdot K^{-1}}$ and 20.84 $\mathrm{W\cdot m^{-2}\cdot K^{-1}}$;
- at $l = 1.2$ m: 18.08 $\mathrm{W\cdot m^{-2}\cdot K^{-1}}$ and 18.14 $\mathrm{W\cdot m^{-2}\cdot K^{-1}}$;
- at $l = 1.8$ m: 16.67 $\mathrm{W\cdot m^{-2}\cdot K^{-1}}$ and 16.72 $\mathrm{W\cdot m^{-2}\cdot K^{-1}}$.

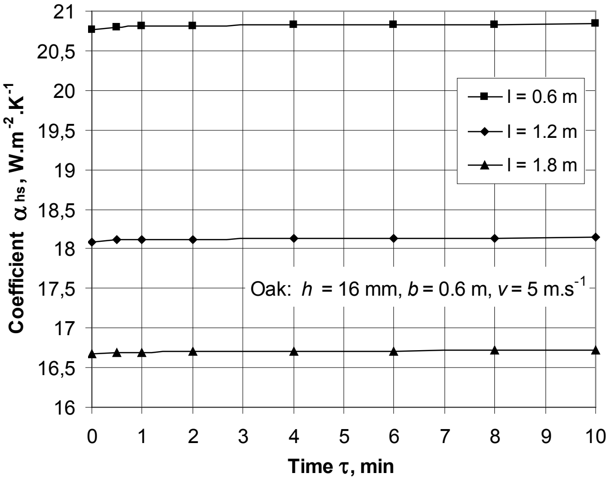

Figure 2. Change in α_{hs} of oak details with $t_0 = 20$ °C and $u = 0.08\ \mathrm{kg\cdot kg^{-1}}$ during their 10 min unilateral heating by air with $t_{ha} = 100$ °C and $v = 5\ \mathrm{m\cdot s^{-1}}$, depending on *l*

3. The convective heat transfer coefficient of the non-heated surface of the details, α_{nhs}, increases curvilinear depending on the heating time and decreases non-linearly

depending on *l* (Figure 3). This coefficient depends on the temperature difference $T_{nhs} - T_{nha}$ according to eqs. (13), (12), and (11). At the beginning of the heating process there is no difference between T_{nhs} and T_{nha}. That is why then the coefficient α_{nhs} is equal to null. After 10 min of convective heating of the details this coefficient reaches the following values:

- at *l* = 0.6 m: 4.06 W·m^{-2}·K^{-1};
- at *l* = 1.2 m: 3.98 W·m^{-2}·K^{-1};
- at *l* = 1.8 m: 3.93 W·m^{-2}·K^{-1}.

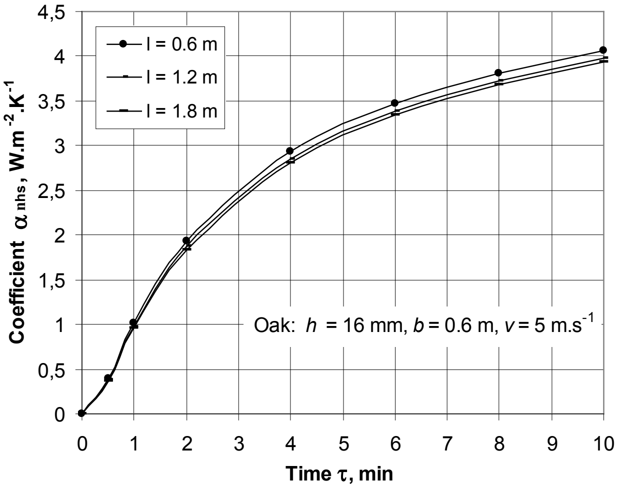

Figure 3. Change in α_{nhs} of oak details with t_0= 20 °C and *u* = 0.08 kg·kg^{-1} during their 10 min unilateral heating by air with t_{ha} = 100 °C and *v* = 5 m·s^{-1}, depending on *l*

CONCLUSIONS

An approach for the calculation of the heat transfer coefficients of the heated and non-heated surfaces of flat wood details during their unilateral convective heating by circulated hot air has been suggested. The approach is based on the usage of the numbers of similarity of Nusselt, Reynolds and Prandtl for the determination of the heat transfer coefficient of the details' heated surface at forced air convection, α_{hs}, and also of the numbers of Nusselt, Grashoff, and Prandtl for the determination of the heat transfer coefficient of the details' non-heated surface at free air convection, α_{nhs}.

The obtained equation for the determination of α_{hs} and α_{nhs} has been implemented into a 1D linear model for the computation of the temperature distribution along the thickness of subjected to unilateral convective heating flat wood details. A software program has been prepared for the numerical solution of the model 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 made for the determination of the 1D change in the wood temperature and also in the heat transfer coefficients of the both surfaces of oak details with an initial temperature of 20°C, moisture content of 0.08 kg·kg^{-1}, thickness of 16 mm, width of 0.6 m, and lengths of 0.6 m, 1.2 m, and 1.8 mm during their

10 min unilateral convective heating by hot air with 100 °C and velocity of 5 m·s^{-1} at a temperature of 20 °C of the surrounding air from the non-heated details' side.

The suggested approach in this work could be used for the determination of heat transfer coefficients of the surfaces of different materials subjected to convective heating.

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