CHIP AND CHIPLESS WOODWORKING PROCESSES, 10(1): 255–262, 2016
Zvolen, Technical University in Zvolen, ISSN 1339-8350 (online), ISSN 2453-904X (print)

COMPUTATION OF THE 1D TEMPERATURE DISTRIBUTION IN OAK DETAILS WITH DIFFERENT LENGTHS DURING THEIR UNILATERAL CONVECTIVE HEATING BEFORE LACQUERING

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Abstract

A 1D linear mathematical model for the computation of the non-stationary temperature distribution along the thickness of subjected to unilateral convective heating of flat wood details before their lacquering has been presented.

For the computation of the temperature distribution along the details' thickness at given temperatures and velosities of the circulated hot air a software program has been prepared 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 temperature distribution along the thickness of oak details with an initial temperature of 20 ^oC, moisture content of 0.08 $kg{\cdot}kg^{-1}$, 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 heating by hot air with 100 ^oC and velocity of 5 $m{\cdot}s^{-1}$ at temperature of the surrounding air from the non-heated side 20 ^oC. The obtained results are graphically presented and analyzed.

Key words: *oak details, modelling, unilateral convective heating, temperature distribution, lacquering*

INTRODUCTION

The production of furniture details from solid wood or/and veneered boards requires their surfaces to be processed with liquid protective and decorative coatings. The flow and homogenization of liquids spread over the furniture details could be improved via preliminary heating of their surfaces.

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

Pre-heating of surfaces, subject to further lacquering, is applied with the purpose to accelerate the hardening of thin lacquer coverings with organic solvents. Upon the application of lacquer layer over the heated surface, it accelerates the evaporation of the solvents and removes the air from the wood pores (Jaić – Živanović-Trbojević 2000, Rüdiger *et al.* 1995).

Unilateral convective heating used prior to lacquering is mostly applied upon flat wooden details with thickness from 4 to 35 mm and moisture content in-between 8 – 10 %. The equipment for preliminary heating of the details are formed usually as tunnel sections

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(Figure 1), which can be part of assembly lines for protective and decorative film application (Kavalov – Angelski 2014).

In the specialized literature there is no information at all about the temperature distribution in wood details during their unilateral convective heating before lacquering. That is why each reasearch in this aria has both a scientific and a practical interest.

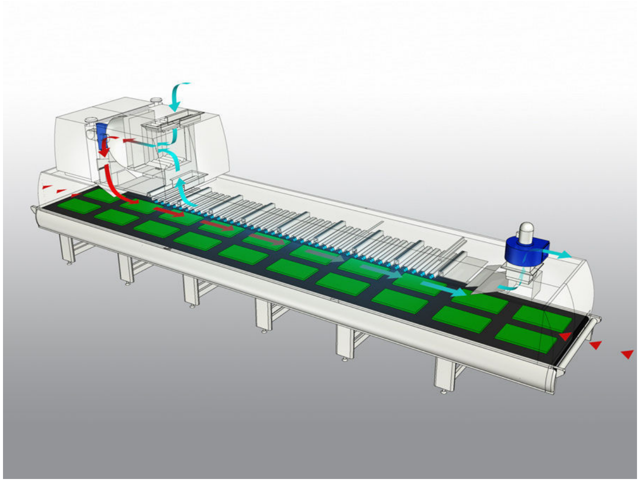

Figure 1. General view of equipment for unilateral convective heating of wood details before their subsequent lacquering

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 heating in order to improve the thermal conditions for their subsequent lacquering. Analysis of the model solutions has been provided for the case of unilateral heating of oak details with different lengths.

MECHANISM OF THE 1D HEAT DISTRIBUTION IN FLAT WOOD DETAILS DURING THEIR 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 of which lies the non-heated surface of the details (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_0 – initial temperature of the subjected to heating details, 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_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, $\mathrm{W \cdot m^{-2} \cdot K^{-1}}$;

α_nhs – convective heat transfer coefficient of the non-heated surface of the details, $\mathrm{W \cdot m^{-2} \cdot K^{-1}}$;

λ_hs – thermal conductivity of the wood on the heated details' surface, $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$;

λ_nhs – thermal conductivity of the wood on the non-heated surface, $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$;

τ – time, s.

Because of the tight contact between the details and the thin carrying rubber band on which they lie during the heating process (see Figure 1), the temperature of the non-heated surface of the details is assumed to be equal to the temperature of the band. Furthermore, the bottom surface of the rubber band, which contacts with the surrounding air, is assumed to be the bottom surface of the subjected to heating details. The thickness of the band is much less than the thickness of the details. This allows disregarding the thickness of the band, thanks to which the boundary condition of the mathematical model obtains the form given by equation (4).

It can be noted that the above mentioned simplifications of the mathematical model and its boundary condition (4) influence quite insignificantly over the accuracy of the model decisions. Practically they do not influence the calculation accuracy of the temperature change on the heated surface layer of the details. As it has been pointed out in the introduction, reaching a predetermined temperature of this surface layer of the details is of major practical interest with a view to improve the thermal conditions for the subsequent lacquering.

The calculation of the heat transfer coefficients, α_{hs} and 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 wood rectangular surfaces in atmospheric conditions of force and free convection respectively (Milchev *et al.* 1989, Telegin *et al.* 2002):

$$\alpha_{hs} = \frac{0.037\,\mathrm{Re}_{ha}^{0.8}\,\mathrm{Pr}_{ha}^{0.43}\left(\frac{\mathrm{Pr}_{ha}}{\mathrm{Pr}_{hs}}\right)^{0.25}\lambda_{ha}}{l}, \tag{5}$$

$$\alpha_{nhs} = \frac{0.65\left(\mathrm{Gr}_{nha}\,\mathrm{Pr}_{nha}\right)^{0.25}\left(\frac{\mathrm{Pr}_{nha}}{\mathrm{Pr}_{nhs}}\right)^{0.25}\lambda_{nha}}{b}, \tag{6}$$

where Re is the number of similarity of Reynolds;

Gr – number of similarity of Grashof;

Pr – number of similaritiy of Prandtl;

λ_{ha} – thermal conductivity of the air near the heated details' surface, $W \cdot m^{-1} \cdot K^{-1}$;

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

l – size of the details along the direction of the hot air circulation (i.e. length of the details), m;

b – smaller size from the two sizes of the details aired by the hot air (i.e. width of the details), m.

The indices "ha" и "hs" of the thermo-physical properties of air and of similarity numbers in equation (5) mean that those properties and numbers are calculated in relation to the temperature of **h**ot **a**ir and of **h**eated **s**urface of the blowing details, respectively.

The indices "nha" и "nhs" thermophysical properties of air and of similarity criteria in equation (6) mean that those properties and criteria are calculated in relation to the temperature of air and temperature of the surface from the non-heated side of the details, respectively.

RESULTS AND DISCUSSION

The mathematical model, which is presented in common form by the eqs. (1) ÷ (6), 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 as an example computations have been made for the determination of the 1D change of the temperature in flat oak (*Quercus petraea* Libl.) details with an initial temperature of 20 ^{o}C, moisture content of 8 %, 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 ^{o}C and velocity of 5 m·s^{-1} at temperature of the surrounding air from the non-heated details' side 20 ^{o}C.

The calculations have been done with average values of the wood temperature conductivity a = 1.9337·10^{-7} m^{2}·s^{-1} and of the wood thermal conductivity cross-sectional to the fibers of the details $\lambda = \lambda_{hs} = \lambda_{nhs}$ = 0.2738 W·m^{-1}·K^{-1} 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}, and volume shrinkage S_v = 11.9 % in the temperature range from 20 ^{o}C to 60 ^{o}C (Trebula – Klement 2002, 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 calculated values of a and λ for oak wood in the temperature range from 20 ^{o}C to 60 ^{o}C are shown in Table 1.

The calculation of the average values for a and λ has been made for the temperature range from 20 ^{o}C to 60 ^{o}C due to the fact that during the simulation experiments with the model, it has ocurred that the calculated temperature along the thickness of details changes exactly in this range (see Figures below). Despite this, a and λ depend linearly to the temperature, which allows for the solving the model to use their average values.

Table 1. Change in λ and a of an oak wood with u = 0.08 kg·kg^{-1}, depending on t

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

Figures 2, 3 and 4 present the temperature change calculated by the 1D model in 5 equidistant from one another characteristic points along the thickness of the details with thickness h = 16 mm and length l = 0.6 m, l = 1.2 m, and l = 1.8 m respectively, during their unilateral convective heating by air with t_{ha} = 100 ^{o}C and v = 5 m·s^{-1}. The coordinates of those points are shown in the legends of the figures.

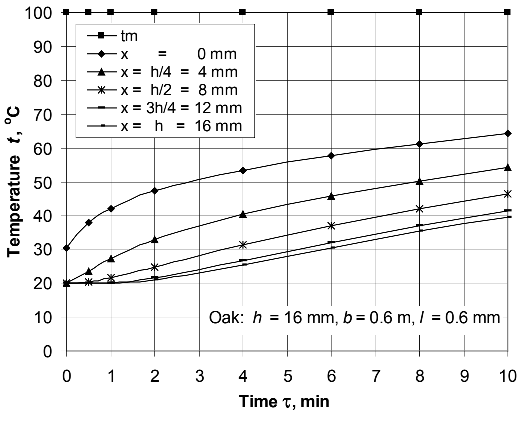

Figure 2. Change in t along the thickness of an oak detail with t_0 = 20 ^{o}C, u = 0.08 kg·kg^{-1}, and l = 0.6 m during its 10 min unilateral heating by air with $t_m = t_{ha}$ = 100 ^{o}C and v =5 m·s^{-1}

The obtained results show that through unilateral heating of details the non-stationary change of the temperature in the characteristic points of their thickness goes on according to complex curves. By increasing the heating time those curves gradually become right lines.

Upon analyzing the results, practical interest is the determination of the time, needed by the surface layers of the details with different length during their convective heating 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 details without, however, exceeding their given allowable surface temperature.

It is acknowledged the limit of $t_{hs} \leq 55$ °C to be the maximum allowable temperature of the surface of the details for the cases of subsequent application of nitrocellulose lacquer over their heated surface (Kavalov – Angelski 2014).

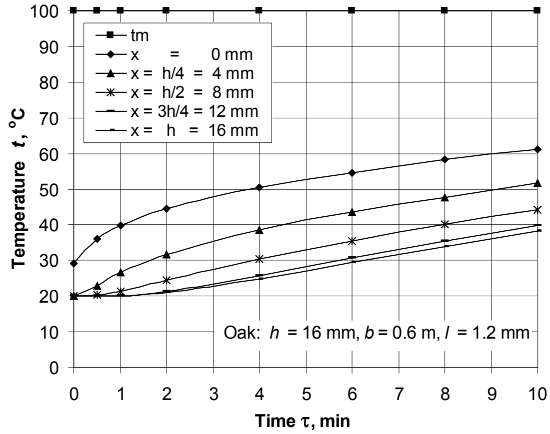

Figure 3. Change in t along the thickness of an oak detail with $t_0 = 20$ °C, $u = 0.08$ kg·kg^{-1}, and $l = 1.2$ m during its 10 min unilateral heating by air with $t_m = t_{ha} = 100$ °C and $v = 5$ m·s^{-1}

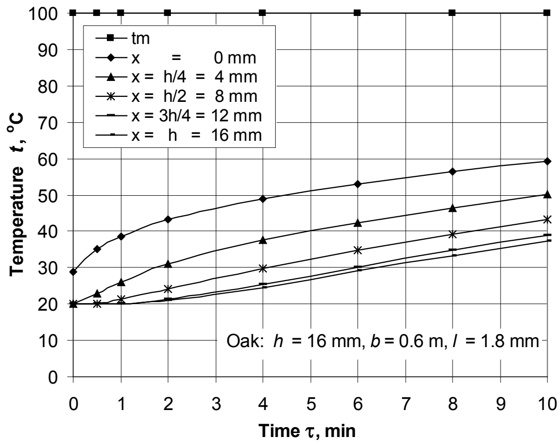

Figure 4. Change in t along the thickness of an oak detail with $t_0 = 20$ °C, $u = 0.08$ kg·kg^{-1}, and $l = 1.8$ m during its 10 min unilateral heating by air with $t_m = t_{ha} = 100$ °C and $v = 5$ m·s^{-1}

The analysis of the results shows that reaching temperatures equal to 30 °C, 35 °C and 40 °C at a point, distant 4 mm from the heated surface of the details, withint the technological constraint of $t_{hs} \leq 55$ °C, comes after duration of convective heating, as follows:

• at l = 0.6 m: respectively after 1.62 min (then t_{hs} = 45.5 °C), after 2.48 min (then t_{hs} = 49.0 °C), and after 3.92 min (then t_{hs} = 53.2 °C);

• at l = 1.2 m: respectively after 1.65 min (then t_{hs} = 43.2 °C), after 2.88 min (then t_{hs} = 47.6 °C) and after 4.55 min (then t_{hs} = 51.8 °C);

• ar l = 1.8 m: respectively after 1.78 min (then t_{hs} = 42.4 °C), after 3.13 min (then t_{hs} = 46.8 °C) and after 4.98 min (then t_{hs} = 51.1 °C).

Those results show that the increase of the length of the details causes slower change in temperature along their thickness. The reason for this fact is that by increasing l in equation (5) the heat transfer coefficient α_{hs} is decreased.

The influence of the length of the details l over the heat transfer coefficient α_{hs}, and hence over the change of the temperature along the details thickness is not significant. For example, after 2 min and 4 min of heating of the details, their surface temperature and the temperature in a point that is 4 mm distant from the surface, reach the following values:

• at l = 0.6 m: 47.2 °C and 53.4 °C on the surface and 32.9 °C and 40.3 °C at 4 mm;

• at l = 1.2 m: 44.6 °C and 50.6 °C on the surface and 31.6 °C and 38.5 °C at 4 mm;

• at l = 0.6 m: 43.2 °C and 49.0 °C on the surface and 30.9 °C and 37.5 °C at 4 mm.

It should be mentioned that the minimum required temperature, at which the details' surface layers are sufficiently heated for their subsequent lacquering, depends on their thickness, width, length, on the temperature and velosity of the circulated hot air over them, on the temperature of the surrounding air from their non-heated side, 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 wood details according to the above mentioned factors.

CONCLUSIONS

The article has presented and analyzed diagrams of 1D non-stationary distribution of the temperature along the thickness of flat wood details subject of unilateral convective heating with the purpose for improving the thermal conditions for their furhter lacquering. The diagrams are based on the results, calculated via a mathematical model, which is presented in the article as well.

With the help of the model as an example computations have been made for the determination of the 1D change of the temperature in oak details with an initial temperature of 20 °C, moisture content of 8 %, 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 $m \cdot s^{-1}$ at temperature of the surrounding air from the non-heated details' side 20 °C.

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

The model could be applied also by model-based automatic control of the process of unilateral convective heating of wood details through its introduction in the software of the programmable controllers used for such kind of process operations.

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