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COMPUTATION OF THE AVERAGE MASS THERMAL CONDUCTIVITY OF OAK FURNITURE ELEMENTS SUBJECTED TO CONVECTIVE HEATING BEFORE LACQUERING

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ABSTRACT

A methodology for the computation and research of the following two mutually connected problems has been suggested: 1D non-stationary temperature distribution in subjected to unilateral convective heating process of flat wooden furniture elements before lacquering and change in their average mass thermal conductivity. For the realization of the methodology, created earlier by the authors 1-dimensional nonlinear mathematical model has been solved for the transient heat conduction in the furniture elements during their unilateral convective heating. The model contains a mathematical description of the average mass thermal conductivity of the elements and their surface layer, which is intended for lacquering. For the numerical solution of the model with the aim of applying the methodology a software program has been prepared and input in the calculation environment of Visual FORTRAN Professional. Using the program, computations have been carried out for determination of the 1-dimensional non-stationary temperature distribution along the elements' thickness and of the average mass thermal conductivity for flat oak furniture elements with an initial temperature of 20 ºC, moisture content of 8 %, thickness of 16 mm, width of 0.6 m, and length of 1.2 m during their 10 min unilateral convective heating at temperature of the processing air medium of 100 ºC, which circulates above the elements with a velocity of 2 $m·s^{-1}$, 5 $m·s^{-1}$, and 8 $m·s^{-1}$ aimed at improvement of the conditions for the subsequent lacquering. During the computations a temperature of 20 ºC for the surrounding air near the non-heated surface of the carrying rubber band has been used. The change in the average mass thermal conductivity of the studied furniture oak elements and also of their heated surface layers during the heating is graphically presented and analyzed.

Because of the wide range of applications, the need for paulownia is constantly increasing.

Key words: oak furniture elements, one sided convective heating, lacquering, thermal conductivity.

INTRODUCTION

The purpose of the pre-heating of furniture details is to introduce heat in their surface layer right before the application of the liquid layer of lacquer.

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. (Jaić et al. 2000, Kavalov and Rusanov 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 goes into the atmosphere (Zhukov and Onegin 1993, Rüdiger 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 of 8 to 10 %. The equipment for preliminary heating of the details are formed usually as tunnel sections (Fig. 1), which can be part of assembly lines for protective and decorative film application (Skakić 1992, Kavalov and Angelski 2014).

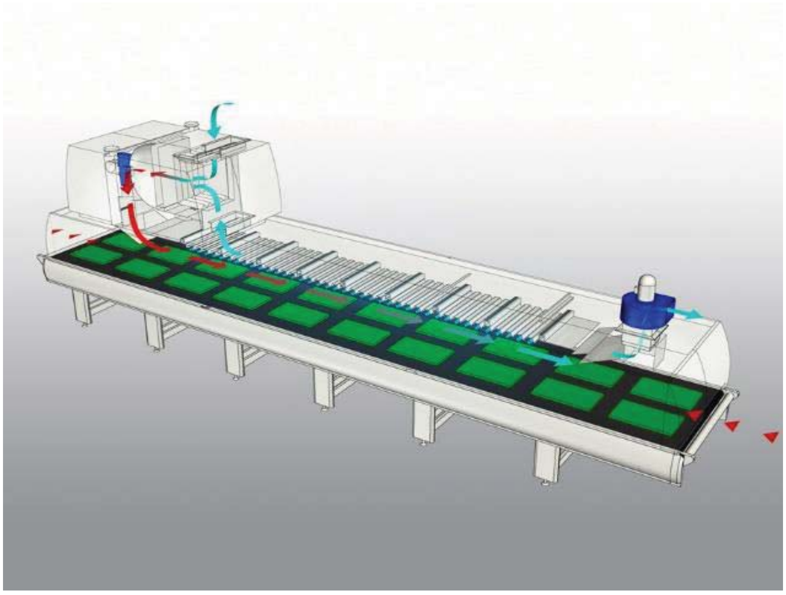

Figure 1: General view of equipment for unilateral convective heating of wood details before their subsequent lacquering

In the specialized literature there is no information about the change in the thermal conductivity of wooden furniture elements during their unilateral convective heating before lacquering. That is why each research in this aria has both a scientific and a practical interest. Information about this conductivity is needed for scientific based determination of some parameters of the considered technological process.

The aim of the current work is to suggest a methodology for the computation and research of two mutually connected problems: 1D non-stationary temperature distribution along the thickness of subjected to unilateral convective heating flat wooden furniture elements and change in the average mass thermal conductivity of the elements and of their surface layer intended for lacquering during the unilateral heating, depending on the influencing factors.

MATHEMATICAL DESCRIPTION OF Λ DURING THE CONVECTIVE HEATING OF FURNITURE ELEMENTS

A mathematical description of the thermal conductivity λ of non-frozen wood has been suggested by the first co-author earlier (Deliiski 1994, 2013) using the experimentally determined in the dissertations by Kanter (1955) and Chudinov (1966) data for its change as a function of t and u. This data for $\lambda(t,u)$ finds a wide use in both the European (Shubin 1990, Trebula and Klement 2002, Videlov 2003) and the American specialized literature (Steinhagen 1986, 1991, Khattabi and Steinhagen 1992, 1993) when calculating various processes of the wood thermal treatment. According to the suggested in (Deliiski 1994, 2013) mathematical description, the wood thermal conductivity during the convective heating of furniture elements can be calculated with the help of the following equations for $\lambda(T,u,\rho_b)$ in the hygroscopic range:

$$\lambda_w = \lambda_{w0} \cdot \left[1 + \beta(T - 273.15)\right], \quad \textbf{(1)}$$

$$\lambda_{w0} = K_{ad} \cdot \nu[0.165 + (1.39 + 3.8u) \cdot (3.3.10^{-7}\rho_b^2 + 1.015.10^{-3}\rho_b)], \quad \textbf{(2)}$$

$$\beta = (2.05 + 4u) \cdot \left(\frac{579}{\rho_b} - 0.124\right) \cdot 10^{-3}, \quad \textbf{(3)}$$

$$v = 0.15 - 0.07u. \quad \textbf{(4)}$$

In Deliiski and Dzurenda (2010) precise values of the coefficient K_{ad} in eq. (2) for different wood species have been determined. For the discussed in this paper oak wood a value K_{cr} = 1.13 for the direction cross sectional to the wood fibers has been determined.

For the thermal dimensioning of the unilateral convective heating process of furniture elements before their lacquer coating it is needed to have information about the average mass thermal conductivity of both the entire elements and of their most heated surface layer. These thermal conductivities can be determined with the help of the following equations as a function of the average mass temperatures of the elements $T_{w\text{-}avg}$ and of the considered layer $T_{wL\text{-}avg}$ after integrating of the calculated non-stationary temperature distribution along the thicknesses of the element and of the layer respectively:

$$\lambda_{w\text{-}avg} = \lambda_{w0} \cdot \left[1 + \beta(T_{w-avg} - 273.15)\right], \quad \textbf{(5)}$$

$$\lambda_{wL\text{-}avg} = \lambda_{w0} \cdot \left[1 + \beta(T_{wL-avg} - 273.15)\right], \quad \textbf{(6)}$$

where

$$T_{w\text{-}avg}(\tau) = \frac{1}{h_w} \int_{(h_w)} T_w(x,\tau)\mathrm{d}x, \quad \textbf{(7)}$$

$$T_{wL\text{-}avg}(\tau) = \frac{1}{h_{wL}} \int_{(h_{wL})} T_{wL}(x,\tau)\mathrm{d}x. \quad \textbf{(8)}$$

RESULTS AND DISCUSSION

The above presented mathematical descriptions of the thermal conductivity of non-frozen and frozen wood is introduced in the own mathematical model of the unilateral convective heating process of furniture elements before their lacquer coating, which has been suggested by the authors earlier (Deliiski et al. 2016, 2018).

For the numerical solution of our mathematical model, a software program was 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 thickness h_w = 0.016 m, length l_w = 1.2 m, initial temperature t_{w0} = 20 °C, basic density ρ_b =

670 kg·m^{-3}, and moisture content u = 0.08 kg·kg^{-1} during their 10 min unilateral convective heating by hot air with temperature t_{ha} = 100 ºC and velocity v_{ha} = 2 m·s^{-1}, v_{ha} = 5 m·s^{-1}, and v_{ha} = 8 m·s^{-1} (see Fig. 2).

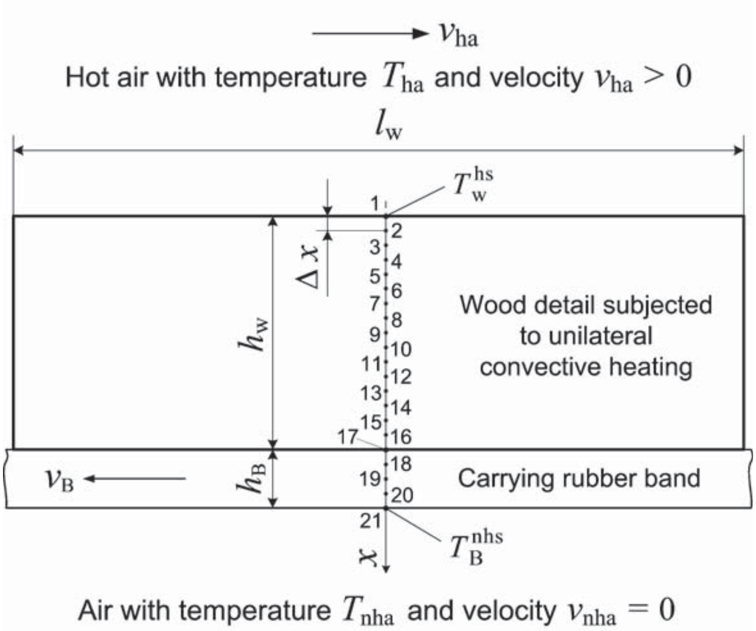

Figure 2: Positioning of the nodes of the 1D calculation mesh along the thicknesses of the flat wood detail and the wear rubber band

Simultaneously with the computation of the temperature distribution along the thickness of the furniture elements, a calculation of the change in temperatures $T_{w\text{-}avg}$, $T_{wL\text{-}avg}$ and also in the conductivities $\lambda_{w\text{-}avg}$ and $\lambda_{wL\text{-}avg}$ during the convective heating has been carried out.

Figure 3 presents the calculated 1D temperature change in 5 equidistant from one another characteristic points along the thickness of one of the studied details and its surface layer during 10 min unilateral convective heating by hot air. The coordinates of those points and also the parameters of the detail and of the hot air are shown in the legends of the figures.

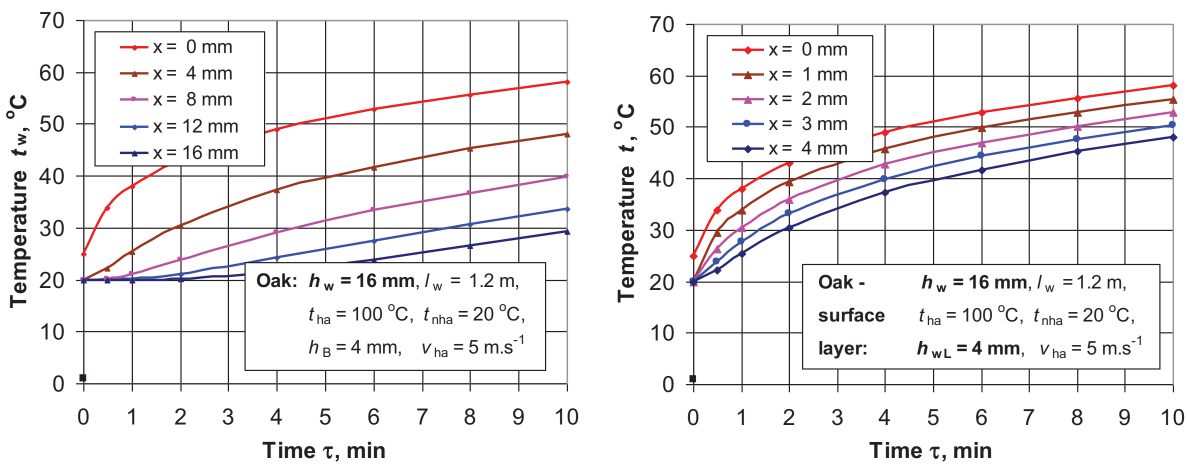

Figure 3: Change in *t* along the thicknesses of the oak detail (left) and the its surface layer (right) during the unilateral convective heating by hot air

Figure 4 presents the calculated change of $t_{w\text{-}avg}$ and $t_{wL\text{-}avg}$ of the studied details during their one sided heating, depending on the velocity of the hot air v.

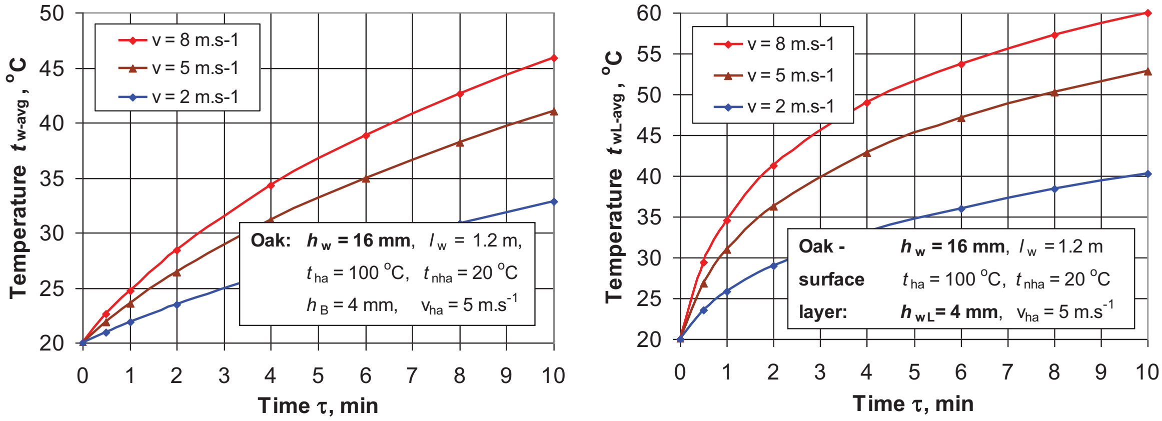

Figure 4: Change in t_{avg} of the oak detail (left) and the its surface layer (right) during the unilateral convective heating by hot air, depending on v

Figure 5 presents the calculated change of $\lambda_{w\text{-}avg}$ and $\lambda_{wL\text{-}avg}$, depending on v.
The analysis of the obtained results leads to the following statements:

1. During the unilateral convective heating of the details the change of the temperature in the points along their thickness goes on according to complex curves. By increasing the heating time those curves gradually become almost parallel to each other right lines.

2. During the 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.

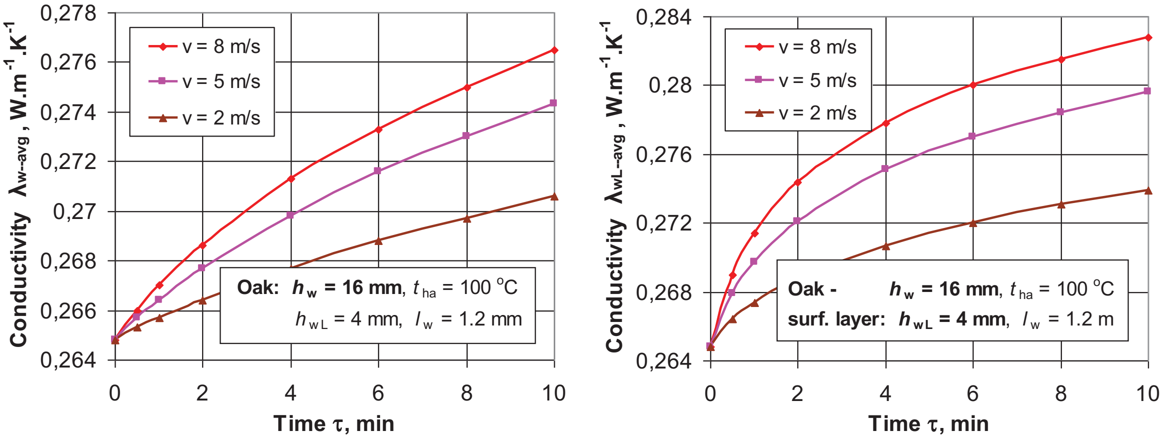

Figure 5: Change in λ_{avg} of the oak detail (left) and the its surface layer (right) during the unilateral convective heating by hot air, depending on v

3. During the heating the curves of the studied average mass temperatures and average thermal conductivities are convex outwardly and they increasingly depend on v. At the end of 10 min convective heating $\lambda_{w\text{-}avg}$ and $\lambda_{wL\text{-}avg}$, reach the following values:

• for $v = 2$ m·s^{-1}: $\lambda_{w\text{-}avg} = 0.2706$ W·m^{-2}·K^{-1} at $t_{w\text{-}avg} = 32.8$ °C and $\lambda_{wL\text{-}avg} = 0.2739$ W·m^{-2}·K^{-1} at $t_{w\text{-}avg} = 40.3$ °C;

• for $v = 5$ m·s^{-1}: $\lambda_{w\text{-}avg} = 0.2743$ W·m^{-2}·K^{-1} at $t_{w\text{-}avg} = 41.1$ °C and $\lambda_{wL\text{-}avg} = 0.2796$ W·m^{-2}·K^{-1} at $t_{w\text{-}avg} = 52.9$ °C;

• for $v = 8$ m·s^{-1}: $\lambda_{w\text{-}avg} = 0.2765$ W·m^{-2}·K^{-1} at $t_{w\text{-}avg} = 45.9$ °C and $\lambda_{wL\text{-}avg} = 0.2828$ W·m^{-2}·K^{-1} at $t_{w\text{-}avg} = 60.0$ °C.

CONCLUSIONS

In the present paper diagrams for the change of the temperature in 5 equidistant from one another points along the thickness of flat oak furniture elements and of its surface layer (intended for subsequent lacquering) during 10 min unilateral convective heating by hot air with temperature of 100 °C and velocity of circulation of 2, 5, and 8 m·s^{-1} are shown and analyzed. Diagrams for the change of the average mass temperatures $t_{w\text{-}avg}$ and $t_{wL\text{-}avg}$, and of the average mass thermal conductivities $\lambda_{w\text{-}avg}$ and $\lambda_{wL\text{-}avg}$ during the heating are also shown and analyzed. All diagrams are based on the results, which are calculated using created earlier by the authors 1D nonlinear mathematical model of the transient heat conduction in the furniture elements during their unilateral convective heating.

With the help of the model computations have been made for the determination of the 1D change of the temperature in flat oak details with thickness of 16 mm, length of 1.2 m, initial temperature of 20 °C, basic density of 670 kg·m^{-3}, and moisture content of 0.08 kg·kg^{-1} during their 10 min unilateral convective heating by hot air with temperature of 100 °C and velocity of 2 m·s^{-1}, 5 m·s^{-1}, and 8 m·s^{-1}.

The computer solutions of the model 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 moisture content, during their unilateral convective heating with different temperature and velocity of the circulated air prior to their lacquering.

The obtained results for the average mass thermal conductivities of the furniture elements, $\lambda_{w\text{-}avg}$, and of their intended for lacquering surface layer, $\lambda_{wL\text{-}avg}$, can be used for thermal dimensioning of the unilateral heating process of wooden furniture elements.

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