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COMPUTATION OF THE HEAT ENERGY AND FLUX NEEDED FOR COVERING OF THE EMISSION FROM FLAT OAK DETAILS DURING THEIR ONE SIDED HEATING BEFORE BENDING

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Abstract

A software program has been prepared in the calculation environment of Visual Fortran for solving of own 1D non-linear mathematical model of the one sided heating process of flat wood details. The model includes a mathematical description of the specific (for 1 m^2) energy consumption, q_e, and the specific heat flux, $dq_e/d\tau$, needed for covering of the emission in the surrounding environment of the subjected to one sided heating wood details aimed at their plasticizing before bending.

Using the program, computations have been carried out for the determination of the change in the energy q_e and in the flux $dq_e/d\tau$, which are consumed by flat oak details with an initial temperature of 20 °C, moisture content of 0.15 kg·kg^{-1}, and thicknesses of 12 mm, 16 mm, and 20 mm during their 30 min unilateral heating at temperatures of the heating metal body of 80 °C and of the surrounding air of 20 °C. The obtained results are graphically presented and analyzed.

Key words: *oak details, one sided heating, plasticizing, bending, heat emission, energy consumption, heat flux*

INTRODUCTION

An important component of the technologies for production of curved wood details is their plasticizing up to the stage that allows their faultless bending. The duration of the heating process and the energy consumption for one sided heating of the details aimed at their plasticizing before bending depends on many factors: wood specie, thickness and moisture content of the details, temperatures of the heating medium and of the surrounding air, desired degree of plasticizing, etc. (Chudinov 1968, Taylor 2001, Trebula and Klement 2002, Videlov 2003, Angelski 2010, Deliiski and Dzurenda 2010, Gaff and Prokein 2011).

The one sided heating of wood details is most often carried out in the specific equipment used for bending. For such heating of details with thicknesses between 10 and 25 mm, hot hydraulic presses with appropriately bent surfaces are usually used. Curved details for the back parts of chairs are produced, for example, through this method of plasticizing. These details have a relatively small thickness, a large radius *R* of the curvature and a

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relationship of $R/h = 20 \div 25$, h is the size of the cross section of the details in the direction coinciding with the plane of bending (Kavalov and Angelski 2014).

In the specialized literature information about the energy consumption needed for the one sided heating of flat wood details was given only by the authors (Deliiski et. al. 2014b, 2016). The calculation of the energy consumption in these publications was carried out using a suggested by the authors linear model for the heat distribution in subjected to one sided heating flat wood details.

The current work presents a 1D non-linear model for the calculation of the temperature distribution along the thickness of flat wood details subjected to one sided conductive heating aimed at their plasticizing in the production of curved back parts of chairs. The aim of the work is to apply the suggested by the authors earlier (Deliiski et al. 2016) numerical approach for the computation of the specific energy consumption (in kWh·m^{-2}) and the specific heat flux (in kW·m^{-2}), which are needed for covering of the heat emission from the non-heated surface of the details during their heating. In this case, the approach uses the solutions of the presented in the current work non-linear 1D model.

MECHANISM OF THE HEAT DISTRIBUTION IN FLAT WOOD DETAILS SUBJECTED TO ONE SIDED CONDUCTIVE HEATING

The mechanism of the heat distribution in wood details during their one sided conductive heating can be described by the equation of the heat conduction (Deliiski 2011, 2013, Deliiski et al. 2014a, 2014b, 2016). 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 one sided heating (i.e. along the coordinate x, which coincides with the details' thickness h_w) can be carried out with the help of the following non-linear 1D mathematical model:

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

with an initial condition

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

and following boundary conditions:

- from the side of the details' heating – at prescribed surface temperature, which is equal to the temperature of the metal heating body T_m (see Fig.1 below):

$$T_\mathrm{w}(0,\tau)=T_\mathrm{m}(\tau)\,, \quad (3)$$

- from the opposite non-heated side of the details – at convective heat exchange between the details' surface and the surrounding air environment

$$\frac{\mathrm{d}T_\mathrm{w}(X,\tau)}{\mathrm{d}x}=-\frac{\alpha_\mathrm{w}(\tau)}{\lambda_\mathrm{ws}(\tau)}\left[T_\mathrm{a}(\tau)-T_\mathrm{s}(\tau)\right]\,. \quad (4)$$

For usage of eqs. (1) and (4) it is needed to have mathematical descriptions of the wood thermal conductivity cross sectional to the fibers, λ_w, of the specific heat capacity of the non-frozen wood, c_w, and of the heat transfer coefficient between the details' surface at their non-heated side and the surrounding air, α_w. For this purpose the description of λ_w and c_w given in (Deliiski 2011, 2013) and in (Deliiski and Dzurenda 2010) can be used.

The calculation of the heat transfer coefficient α_w can be carried out with the help of the following equation, which has been suggested by Chudinov (1968) for the cases of cooling or heating of horizontally situated wood plates in atmospheric conditions of free convection:

$$\alpha_w = 3.256[T_s(\tau) - T_a(\tau)]^{0.25}. \tag{5}$$

According to eq. (3), the temperature at the details surface being in contact with the heating body (i.e. the characteristic point with *x-coordinate* = 0 mm) is equal to its temperature T_m due to the extremely high coefficient of heat transfer between the body and the wood during their very close contact.

The presenting of the mathematical model (1) ÷ (5) through its discrete analogue suitable for programming in Visual Fortran corresponds to the shown in Fig. 1 setting of the coordinate system and the positioning of the nodes in the mesh, in which the 1D distribution of the temperature along the thickness of flat wood details subjected to one sided heating is calculated.

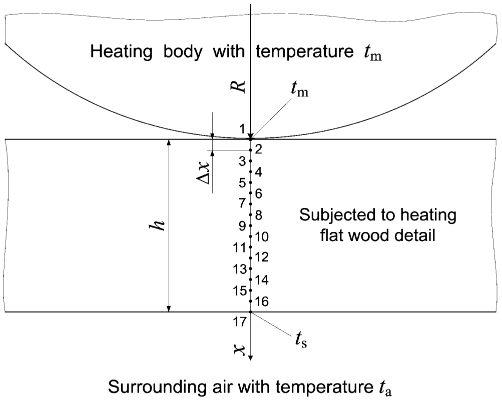

Figure 1. Positioning of the nodes of the 1D calculation mesh in a discretized detail's thickness

MODELLING OF THE SPECIFIC ENERGY CONSUMPTION AND OF THE HEAT FLUX NEEDED FOR COVERING OF THE HEAT EMISSION FROM THE NON-HEATED SIDE OF THE WOOD DETAILS

The change in the specific (for 1 m^2 of the details' surface) energy consumption q_e (in $kWh \cdot m^{-2}$), which is needed for covering of the heat emission from the non-heated side of the wood details into the surrounding air environment during the time $\Delta\tau$, can be calculated according to the following equation (Deliiski 2013):

$$\Delta Q_e = \frac{\alpha_w(\tau)\Delta\tau}{3.6 \cdot 10^6}\left[T_{ws}(\tau) - T_a(\tau)\right]. \tag{6}$$

The specific energy consumption needed for the covering of the heat emission from 1 m^2 surface of the details during their unilateral heating with duration $\tau_p = N.\ \Delta\tau$ is equal to

$$Q_e = \sum_{i=1}^{N} \Delta Q_{ei}. \tag{7}$$

The change in the heat energy Q_e during the time $\Delta\tau$, i.e. the change in the heat flux which is needed for the covering of the heat emission from the non-heated side of 1 m^2 of the subjected to unilateral heating wood details, $\frac{\mathrm{d}Q_\mathrm{e}}{\mathrm{d}\tau}$ (in kW·m^{-2}), can be calculated according to equation

$$\frac{\mathrm{d}Q_\mathrm{e}}{\mathrm{d}\tau} \approx \frac{3600\Delta Q_\mathrm{e}}{\Delta\tau} . \tag{8}$$

RESULTS AND DISCUSSION

For the numerical solution of the above presented mathematical models aimed at usage of the suggested approach for the calculation of Q_e and $\frac{\mathrm{d}Q_\mathrm{e}}{\mathrm{d}\tau}$ a software program was prepared in FORTRAN, which was input in the developed by Microsoft calculation environment of Visual Fortran Professional.

With the help of the program, as examples, computations have been made for the determination of the 1D non-stationary change of t, t_ws, Q_e, and dQ_e/dτ for non-frozen oak (*Quercus petraea* Liebl.) details with thicknesses of h = 12 mm, h = 16 mm, h = 20 mm, initial wood temperature of t_w0 = 20 °C, and wood moisture content of u = 0.15 kg·kg^{-1} during their 30 min heating at t_m = 80 °C and at t_a = 20 °C. All calculations have been carried out using the mathematical descriptions of c_w, λ_w, and ρ_w given in (Deliiski 2011, 2013) with the following values of the variables in these descriptions for oak wood: $u_\mathrm{fsp}^{293.15} = 0.29\ \mathrm{kg \cdot kg^{-1}}$, ρ_b = 670 kg·m^{-3}, and S_v = 11.9% (Videlov 2003, Deliiski and Dzurenda 2010).

The left part of Fig. 2 presents the temperatures of the heating body t_m = 80 °C, which have been entered based on the input data used for the solution of the 1D model, and also the temperature change calculated by the model in 4 equidistant from one another characteristic points along the thickness of the oak detail with thickness of h = 20 mm during its one sided heating. The coordinates of those points are shown in the legend of the figure. The right part of Fig. 2 presets t_m and the change in the temperature of the non-heated surface, t_s, (refer to Fig. 1) of the studied oak details, depending of their thickness h.

Figure 3 presents the calculated change in λ_ws and in α_w, and Figure 4 – the calculated change in Q_e and in dQ_e /dτ during the one sided heating of the oak details with studied thicknesses at t_m = 80 °C and t_a = 20 °C.

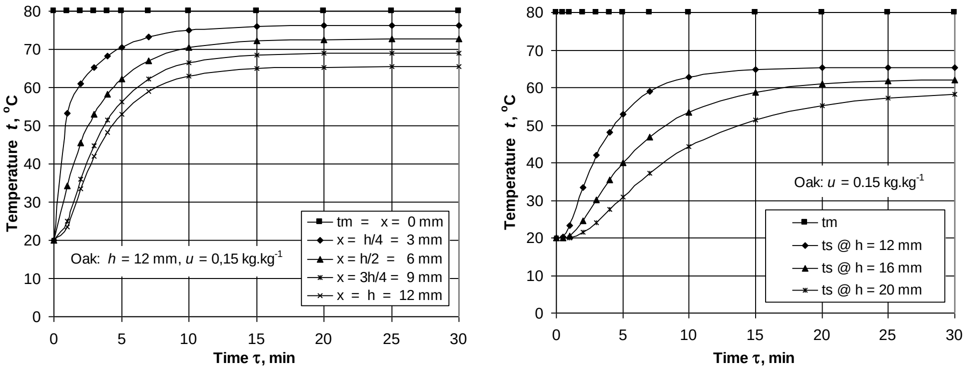

Figure 2. Change in t_w along the thickness of oak detail with h = 12 mm (left) and in t_ws = f(h) (right) during the one sided heating at t_m = 80 °C and t_a = 20 °C

The analysis of the shown on the figures results warrants the making of the following conclusions:

1. During the unilateral heating of the details the change of all studied variables takes place according to complex curves.

2. By increasing the heating time τ, the studied variables change, as follows:

• the curves of t_w gradually approach asymptotically to their biggest values, decreasingly dependent on the remoteness of the characteristic points from the heated surface of the detail;

• the curves of t_s, λ_w, α_w, and $dQ_e/d\tau$ approach asymptotically to their biggest values, decreasingly dependent on *h*;

• the specific energy consumptions Q_e increases according to non-linear dependences, which change into linear after reaching of stationary distribution of *t* along the details' thickness.

3. The values of Q_e are decreasingly dependent on *h* and the slopes of the linear sections of the dependences $Q_e = f(\tau)$ are inversely proportional to *h*.

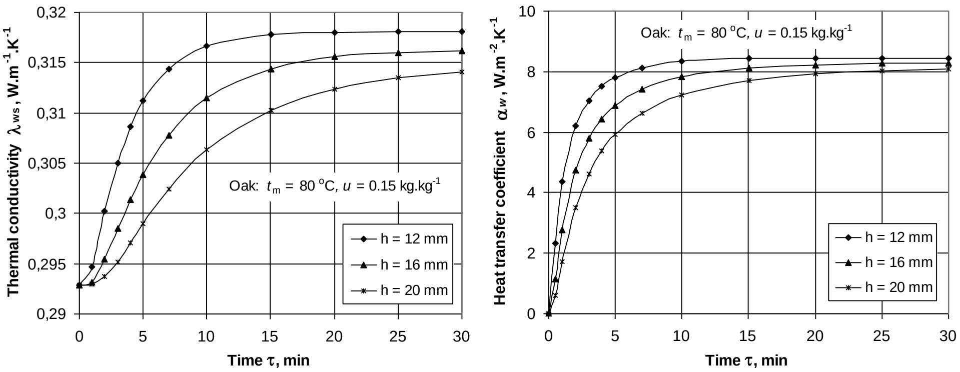

Figure 3. Change in λ_{ws} (left) and in α_w (right) of the oak details during their one sided heating at t_m = 80 °C and t_a = 20 °C, depending on *h*

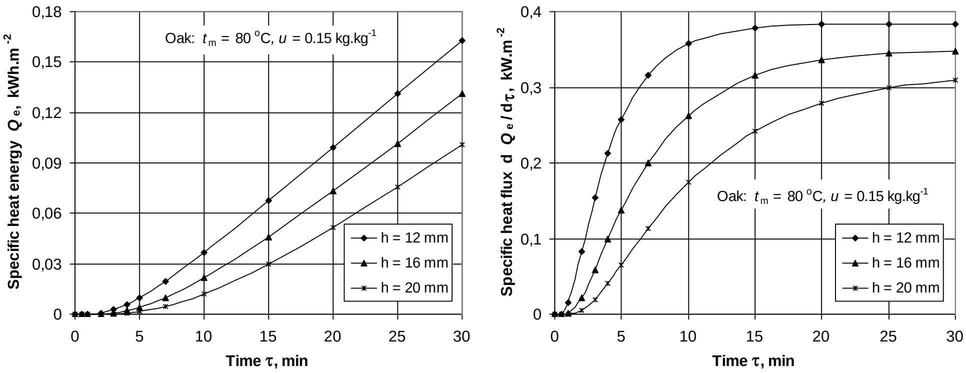

Figure 4. Change in Q_e (left) and in $dQ_e/d\tau$ (right) of the oak details during their one sided heating at t_m = 80 °C and t_a = 20 °C, depending on *h*

After 10 min and 20 min duration of the one sided heating at t_m = 80 °C of the studied oak details, the specific energy consumption Q_e reaches the following values:

- for h = 12 mm: Q_e = 0.0366 kWh·m^{-2} and Q_e = 0.0992 kWh·m^{-2} respectively;
- for h = 16 mm: Q_e = 0.0215 kWh·m^{-2} and Q_e = 0.0733 kWh·m^{-2} respectively;
- for h = 20 mm: Q_e = 0.0119 kWh·m^{-2} and Q_e = 0.0514 kWh·m^{-2} respectively.

After 10 min and 20 min duration of the one sided heating at t_m = 80 °C of the studied oak details, the specific heat flux dQ_e/dτ reaches the following values:

- for h = 12 mm: dQ_e/dτ = 0.358 kW·m^{-2} and dQ_e/dτ = 0.383 kW·m^{-2} respectively;
- for h = 16 mm: dQ_e/dτ = 0.263 kW·m^{-2} and dQ_e/dτ = 0.337 kW·m^{-2} respectively;
- for h = 20 mm: dQ_e/dτ = 0.175 kW·m^{-2} and dQ_e/dτ = 0.279 kW·m^{-2} respectively.

CONCLUSIONS

The present paper describes the suggested by the author numerical approach for the computation of the specific energy consumption, Q_e, and the specific heat flux, dQ_e/dτ, needed for covering of the emission in the surrounding environment of the subjected to one sided heating wood details aimed at their plasticizing before bending in the production of back parts of chairs. The approach is based on the integration and differentiation of the solutions of own non-linear model for the calculation of the non-stationary 1D temperature distribution along the thickness of subjected to one sided heating flat wood details.

The paper shows and analyses diagrams of a non-stationary change of Q_e and dQ_e/dτ during the one sided heating of flat oak details aimed at their plasticizing before bending for the production of back parts of chairs. All diagrams are drawn using the results calculated by the model. The change of Q_e and dQ_e/dτ for details with thicknesses of 12 mm, 16 mm and 20 mm, initial wood temperature 20 °C, and moisture content of 0.15 kg.kg^{-1} during their unilateral heating for a period of 30 min at a temperatures of the heating metal body of t_m = 80 °C and temperature of the air near the non-heated side of the details of t_a = 20 °C is calculated, visualized and analysed.

Using the scientific determined values of Q_e and dQ_e/dτ, the minimum necessary power of the heating metal body can be determined depending on the desired duration of the one sided details' heating at given values for t_m, h, and R/h.

The approach that was used for the creation of the model for computation of Q_e and dQ_e/dτ could be further applied in the development of analogous models, for example, for the calculation of the change of energy consumption and of heat flux needed for covering of the emission in the surrounding environment of flat details made of various materials.

Symbols

c = specific heat capacity (J·kg^{-1}·K^{-1})
h = thickness (m)
Q = specific energy consumption (kWh·m^{-2})
S = wood shrinkage (%)
T = temperature (°C): $t = T - 273.15$
T = temperature (K): $T = t + 273.15$
u = moisture content (kg·kg^{-1}): $u = W/100$
W = moisture content (%): $W = 100u$
x = coordinate along the thickness of the details: $0 \leq x \leq X = h$
α = heat transfer coefficient (W·m^{-2}·K^{-1})
λ = thermal conductivity (W·m^{-1}·K^{-1})

ρ = density ($kg \cdot m^{-3}$)
τ = time (s)
@ = at

Subscripts and superscripts:

a = air (for the air temperature near the non-heated side of the wood details)
avg = average (for the average mass temperature of the details at given moment of their one sided heating)
b = basic (for density, based on dry mass divided by green volume)
e = emission
fsp = fiber saturation point of the wood
m = medium (for the temperature of the heating metal body used for one sided heating)
s = surface (for the non-heated surface of the wood details)
v = volume (for the wood shrinkage)
w = wood
0 = initial (for the average mass temperature of details at the beginning of the heating)
293.15= at 293.15 K, i.e. at 20 ^{o}C (for the standard values of wood fiber saturation point)

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