INNOVATION IN WOODWORKING INDUSTRY AND ENGINEERING DESIGN, 2/2018 (14): 5–11

COMPUTATION OF THE ENERGY CONSUMPTION FOR WARMING UP OF FLAT OAK DETAILS BEFORE THEIR 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 model of the one sided heating process of flat wood details. With the help of the program, the 1D non-stationary temperature field in flat oak details with initial temperature of 20 ^{o}C, moisture content of 0.15 kg.kg^{-1}, thickness of 12 mm, 16 mm, and 20 mm during their 30 min one sided heating at temperature of 80 ^{o}C of the heating metal body has been calculated. After integration of the temperature field, the energy consumption for warming up of the details before their bending in the production of curved back parts of chairs has been calculated. The obtained results are graphically presented and analyzed.

Key words: oak details, one sided heating, bending, energy consumption.

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, Pervan 2009, 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 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 warming up of flat wood details during the one sided heating 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 details before their bending in the production of stringed music instruments.

The aim of the present work is to suggest a numerical approach for the computation of the specific energy consumption, which is needed for warming up of flat wood details during one sided heating aimed at their plasticizing in the production of curved back parts of chairs. This approach has to be based on the integration of the solutions of more complicated 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.

MECHANISM OF THE HEAT DISTRIBUTION IN 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:

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

with an initial condition

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

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):

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

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

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

For practical 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:

$$\alpha_\mathrm{w}=3.256\left[T_\mathrm{s}(\tau)-T_\mathrm{a}(\tau)\right]^{0.25}. \qquad \textbf{(5)}$$

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.

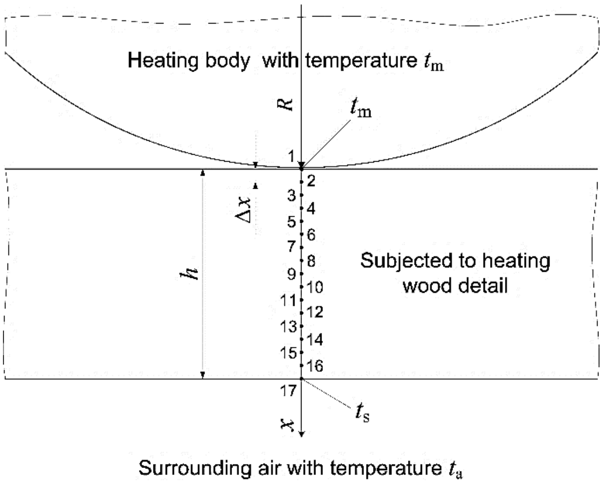

Figure 1: Positioning of the nodes of the 1D calculation mesh in a discretized detail's thickness

MODELLING OF THE SPECIFIC ENERGY CONSUMPTION FOR WARMING UP OF THE WOOD DETAILS DURING THEIR ONE SIDED HEATING

It is known that the specific energy consumption for the warming up of 1 m^3 of solid materials with an initial mass temperature T_0 to a given average mass temperature T_{avg} is determined using the equation (Deliiski 2013).

$$Q = \frac{c \cdot \rho \cdot \left(T_{\text{avg}} - T_0\right)}{3.6 \cdot 10^6}. \qquad (6)$$

After multiplying the right part of eq. (6) with the detail's thickness h the following equation for the determination of the specific mass energy consumption needed for the warming up of 1 m^2 of the subjected to unilateral heating wood details, q_{w}, is obtained:

$$Q_{\text{w}} = \frac{c_{\text{w-avg}} \cdot \rho_{\text{w}} \cdot h \cdot \left(T_{\text{w-avg}} - T_0\right)}{3.6 \cdot 10^6}, \qquad (7)$$

where according to Deliiski (2011, 2013).

$$T_{\text{w-avg}} = \frac{1}{h} \int_{(h)} T_{\text{w}}(x, \tau) \mathrm{d}h, \qquad (8)$$

$$c_{\text{w-avg}} = \frac{2097u + 826}{1+u} + \frac{9.92u + 2.55}{1+u} T_{\text{w-avg}} + \frac{0.0002}{1+u} T_{\text{w-avg}}^2 \quad @ \quad u \le u_{\text{fsp}}, \qquad (9)$$

$$\rho_{\text{w}} = \rho_{\text{b}} \frac{1+u}{1 - \frac{S_{\text{v}}}{100}\left(u_{\text{fsp}}^{293.15} - u\right)} \quad @ \; u \le u_{\text{fsp}}. \qquad (10)$$

The multiplier $3.6 \cdot 10^6$ in the denominator of eq. (7) ensures that the values of Q_{w} are obtained in kWh·m^{-2}, instead of in J·m^{-2}.

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_{w} 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 specific energy consumption, which is needed for warming up of non-frozen flat 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 one sided heating at t_{m} = 80 °C and at t_{a} = 20 °C.

Simultaneously with the solution of the 1D model, calculations of $t_{\text{w-avg}}$, $c_{\text{w-avg}}$, and of Q_{w} have been carried out, using the value of the wood density ρ_{w} = 783.6 kg.m^{-3}. This value of ρ_{w} is calculated according to eq. (10) for oak wood with u = 0.15 kg·kg^{-1},

$u_{\mathrm{fsp}}^{293.15} = 0.29\ \mathrm{kg \cdot kg^{-1}}$, ρ_b = 670 kg·m^{-3}, and volume shrinkage S_v = 11.9% (Videlov 2003, Deliiski and Dzurenda 2010). The value of $c_{\text{w-avg}}$ has been calculated according to eq. (9).

Figure 2 presents the temperature of the heating body t_m = 80 °C, which has 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 = 16 mm during its one sided heating. The coordinates of those points are shown in the legend of the figure.

Figure 3, 4, and 5 present the calculated change of $t_{\text{w-avg}}$, $c_{\text{w-avg}}$, and Q_w during the one sided heating of the oak details with studied thicknesses at t_m = 80 °C respectively.

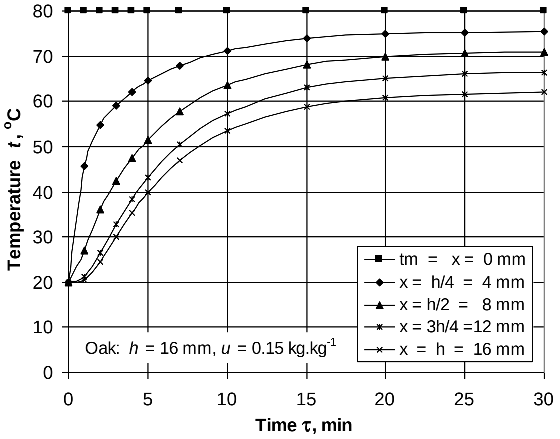

Figure 2: Change in t_w along the thickness of oak detail with h = 16 mm, t_{w0} = 20 °C, and u = 0.15 kg.kg^{-1} during its one sided heating at t_m = 80 °C and t_a = 20 °C

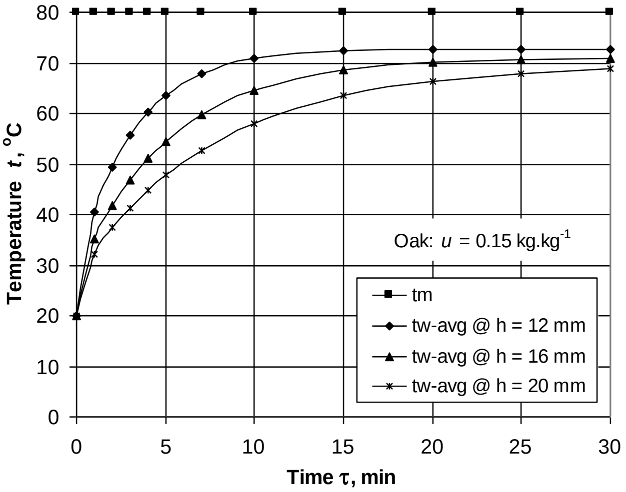

Figure 3: Change in t_m and $t_{\text{w-avg}}$ for oak details with t_{w0} = 20 °C and u = 0.15 kg.kg^{-1} during their one sided heating at t_m = 80 °C and t_a = 20 °C, depending on h

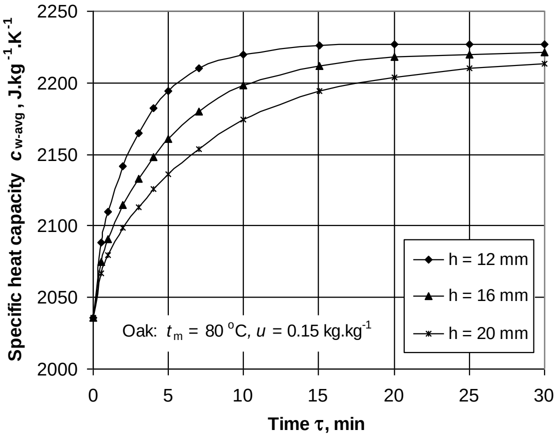

Figure 4: Change in $c_{\text{w-avg}}$ for oak details with t_{w0} = 20 °C and u = 0.15 kg.kg^{-1} during their one sided heating at t_m = 80 °C and t_a = 20 °C, depending on h

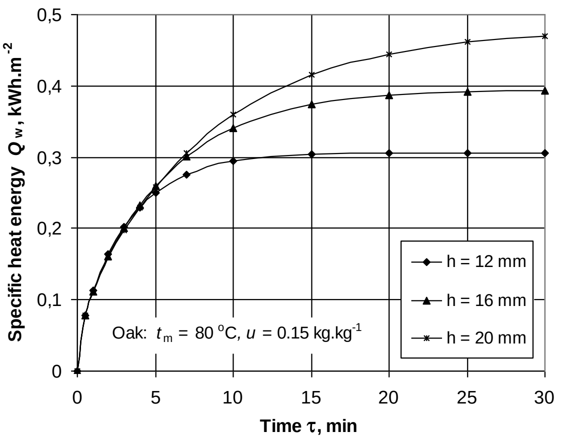

Figure 5: Change in Q_w for oak details with t_{w0} = 20 °C and u = 0.15 kg.kg^{-1} during their one sided heating at t_m = 80 °C and t_a = 20 °C, depending on h

The obtained results show that through one sided heating of details the change of all variables t_w, $t_\mathrm{w\text{-}avg}$, $c_\mathrm{w\text{-}avg}$, and Q_w go on according to complex curves. By increasing the heating time 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 (refer to Fig. 2). Analogously, the curves of the change in $t_\mathrm{w\text{-}avg}$ and $c_\mathrm{w\text{-}avg}$ approach asymptotically to their biggest values, decreasingly dependent on h. The curves of the change in Q_w approach asymptotically to their biggest values, increasingly dependent on h.

The biggest values of t_w, $t_\mathrm{w\text{-}avg}$, $c_\mathrm{w\text{-}avg}$, and Q_w are achieved when a stationary temperature distribution occurs along the details' thickness.

The specific energy consumption Q_w reaches its biggest values when at given values of h, t_m, and t_a a stationary temperature distribution along the thickness of the subjected to one sided heating wood details occurs. For example, after 10 min and 20 min duration of the one sided heating at t_m = 80 °C of the studied oak details, the energy consumption Q_w reaches the following values:

- for h = 12 mm: Q_w = 0.295 kWh·m^{-2} and Q_w = 0.306 kWh·m^{-2} respectively;
- for h = 16 mm: Q_w = 0.341 kWh·m^{-2} and Q_w = 0.387 kWh·m^{-2} respectively;
- for h = 20 mm: Q_w = 0.360 kWh·m^{-2} and Q_w = 0.445 kWh·m^{-2} respectively.

CONCLUSIONS

The present paper describes a numerical approach for the computation of the specific energy consumption (in kWh·m^{-2}), Q_w, which is needed for warming up of flat wood details during one sided heating, aimed at their plasticizing before bending in the production of back parts of chairs. The approach is based on the integration of the solutions of a non-linear mathematical model for the calculation of the non-stationary 1D temperature distribution along the thickness of subjected to one sided heating flat wood details.

For the numerical solution of the model aimed at the usage of the suggested approach a software program has been prepared, which has been input in the calculation environment of Visual Fortran Professional. As examples, computations have been carried out for the determination of the change in the specific energy, which is consumed by 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 one sided heating at temperatures of the heating metal band 80 °C and of the surrounding air 20 °C.

The obtained results show that during the one sided heating of the details the increasing in the specific energy Q_w goes on according to complex curves. The values of Q_w increasingly depend on the duration of the details' heating and on h. The results also show that by increasing the heating time the curves of Q_w gradually approach asymptotically to almost straight lines, when at given values of h, t_m, and t_a a stationary temperature distribution along the thickness of the subjected to one sided heating wood details occurs. For example, when oak details with t_0 = 20 °C and u = 0.15 kg.kg^{-1} are subjected to unilateral heating at t_m = 80 °C and t_a = 20 °C, the energy consumption Q_w reaches the following values after 10 min heating: Q_w = 0.295 kWh·m^{-2} for h = 12 mm, Q_w = 0.341 kWh·m^{-2} for h = 16 mm, and Q_w = 0.360 kWh·m^{-2} for h = 20 mm.

The obtained results can be used for a science-based determination of the total energy consumption, which is needed for one sided heating of flat wood details aimed at their plasticizing before bending in the production of curved details for different applications in the furniture and other industries. They are also of specific importance for the optimization of the technology and of the model-based automatic control (Hadjiski and Deliiski 2016) of the heating process of details before their bending.

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 (%): $W = 100 \cdot u$
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·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)
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 °C (for the standard values of the wood fiber saturation point)

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UNIVERSITY OF FORESTRY

FACULTY OF FOREST INDUSTRY

INNOVATION IN WOODWORKING INDUSTRY AND ENGINEERING DESIGN

2/2018

INNO vol. VII Sofia

ISSN 1314-6149
e-ISSN 2367-6663

Indexed with and included in CABI

INNOVATION IN WOODWORKING INDUSTRY AND ENGINEERING DESIGN

Science Journal
Vol. 07/p. 1–88
Sofia 2/2018

ISSN 1314-6149
e-ISSN 2367-6663

Edition of
FACULTY OF FOREST INDUSTRY – UNIVERSITY OF FORESTRY – SOFIA

The Scientific Journal is indexed with and included in CABI.

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