INNOVATION IN WOODWORKING INDUSTRY AND ENGINEERING DESIGN, 1/2016 (9): 21–27

COMPUTATION OF THE AVERAGE WOOD TEMPERATURE AND THE RATE OF ITS CHANGE DURING UNILATERAL HEATING OF FLAT SPRUCE DETAILS BEFORE THEIR BENDING

Nencho Deliiski[1], Neno Trichkov[1], Dimitar Angelski[1], Ladislav Dzurenda[2]
[1]University of Forestry, Sofia, Bulgaria
e-mails: deliiski@netbg.com, nenotr@abv.bg, d.angelski@gmail.com
[2]Technical University in Zvolen, Slovakia,
e-mail: ladislav.dzurenda@tuzvo.sk

ABSTRACT

An approach for the computation of the average mass temperature of the wood and the rate of its change during unilateral heating of flat wood details aimed at their plasticizing in the production of curved outside parts for corpses of stringed music instruments, has been suggested. The approach is based on the numerical integration of the solutions of a linear model for the calculation of the non-stationary 1D temperature distribution along the thickness of subjected to unilateral heating flat wood details.

Key words: average mass temperature, rate of change in average temperature, spruce details, unilateral heating, plasticizing.

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 the unilateral heating of the details aimed at their plasticizing before bending depends on many factors: wood species, 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).

Unilateral heating is applied, for example, in the production of curved outside parts for the corpses of string music instruments so that they are plasticized before bending. In the practice those details are with thickness in-between 5 mm to 10 mm and about 15 % moisture content. The technology for plasticizing of such details has been using equipment with metal tube or band, electrically heated up to the temperature in the range of 100 ºC ÷ 150 ºC (Figure 1).

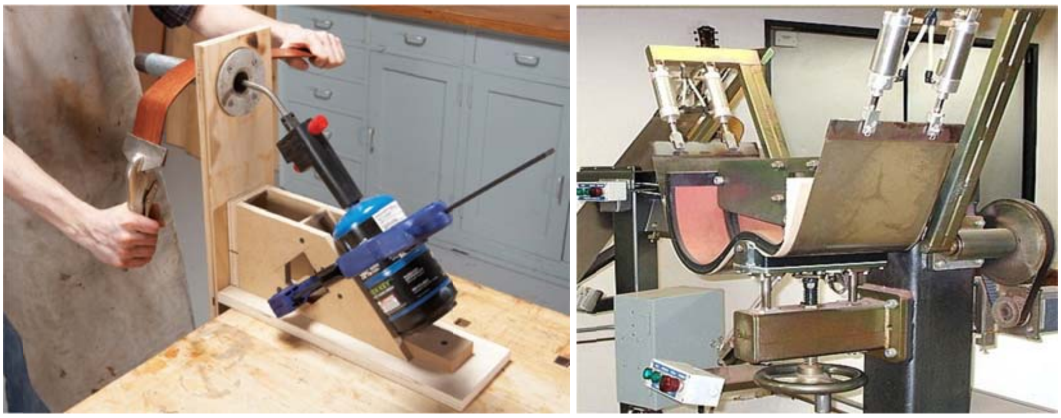


Figure 1: Equipments with electrically heated tube (left) and band (right) for unilateral heating and bending of flat wood details in the production of outside parts for corpse of stringed music instruments

In the specialized literature there is no information at all about the temperature distribution in wood details during their unilateral heating and about the energy consumption needed for realising of such heating. For precise determination of the energy, which is consumed by the wood at every moment of the details' heating it is necessary to know the current value of the average mass temperature of the wood (Deliiski, Trichkov, Angelski and Dzurenda 2014).

The aim of the present work is to suggest an approach for the computation of the average mass temperature of the wood and the rate of its change during unilateral heating of flat wood details aimed at their plasticizing before bending. The approach has to be based on the integration of the solutions of a linear model for the calculation of the non-stationary 1D temperature distribution along the thickness of subjected to unilateral heating flat details.

MODELLING OF THE PROCESS OF UNILATERAL HEATING OF FLAT WOOD DETAILS

When the width of the wood details exceeds their thickness by at least 3 ÷ 4 times, 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 h) can be carried out with the help of the following linear 1D mathematical model (Deliiski, 2003):

$$\frac{\partial T(x,\tau)}{\partial \tau} = a_{\mathrm{c}} \frac{\partial^2 T(x,\tau)}{\partial x^2} \qquad \mathbf{(1)}$$

with an initial condition

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

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}:

$$T(0,\tau) = T_{\mathrm{m}}(\tau); \qquad \mathbf{(3)}$$

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

$$\frac{\mathrm{d}T(X,\tau)}{\mathrm{d}x} = -\frac{\alpha(\tau)}{\lambda_{\mathrm{s}}(\tau)}\left[T_{\mathrm{s}}(\tau) - T_{\mathrm{a}}(\tau)\right]. \qquad \mathbf{(4)}$$

For practical usage of (1) and (4) it is needed to have mathematical descriptions of the wood temperature conductivity cross sectional to the fibers, a_{c}, of the wood thermal conductivity cross sectional to the fibers, λ_{c}, and of the heat transfer coefficient between the details' surface at their non-heated side and the surrounding air, α. For this purpose the description of a_{c} and λ_{c} given in (Deliiski 2003, 2011) can be used. The calculation of the heat transfer coefficient α can be carried out with the help of the following equation, which has been suggested by Chudinov (1968) for the cases of cooling of horizontally situated wood plates in atmospheric conditions of free convection:

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

AN APPROACH FOR THE COMPUTATION OF THE AVERAGE WOOD TEMPERATURE AND OF THE RATE OF ITS CHANGE

The average mass temperature of the wood details during their unilateral heating can be calculated after integration of the 1D non-stationary temperature distribution along the detail's thickness using the following equation (Deliiski, 2003):

$$T_{\mathrm{av}} = \frac{1}{h}\int_{(h)} T(x,\tau)\,\mathrm{d}x. \qquad \mathbf{(6)}$$

The 1D non-stationary temperature distribution along the detail's thickness for every moment of the unilateral heating,

$T(x,\tau)$, is obtained during the numerical solving of the mathematical model (1) ÷ (5). Simultaneously with the computation of the average wood temperature T_{av}, it is possible to calculate the rate of its change, $\dfrac{\mathrm{d}T_{\mathrm{av}}}{\mathrm{d}\tau}$.

TRANSFORMATION OF THE MATHEMATICAL MODEL IN SUITABLE FORM FOR PROGRAMMING

The presenting of the mathematical model (1) ÷ (5) through its discrete analogue suitable for programming corresponds to the shown setting of the coordinate system and the positioning of the nodes in the mesh shown on Fig. 2, in which the 1D distribution of the temperature along the thickness of flat wood details subjected to unilateral heating is calculated.

The system of 8 equations, which has been derived by passing to final increases in eqs. (1) ÷ (5) with the usage of the same, as well as by the described in Deliiski (2003, 2011), Deliiski and Dzurenda, 2010) explicit form of the finite-difference method, is given in (Deliiski, Trichkov, Angelski and Dzurenda, 2014). The average mass temperature of the wood details during their unilateral heating and the rate of its change can be computed using the following equations with final increases in them according to the finite-difference method:

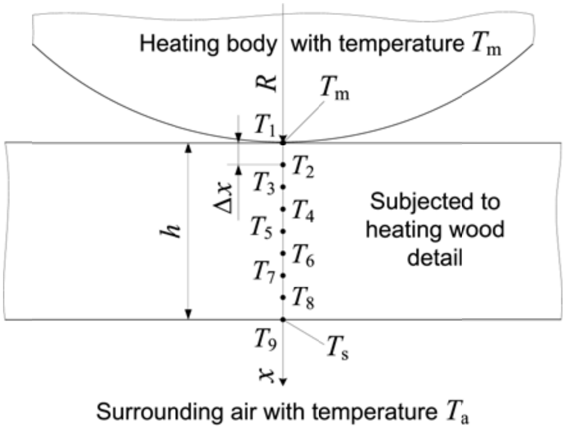


Figure 2: Positioning of the nodes of the 1D calculation mesh in a discretized detail's thickness

$$T_{\mathrm{av}}^{n} = \int_{(h)} T[x, n\Delta\tau]\mathrm{d}x, \qquad (7)$$

$$T_{\mathrm{av}}^{n+1} = \int_{(h)} T[x, (n+1)\Delta\tau]\mathrm{d}x, \qquad (8)$$

$$\frac{dT_{\mathrm{av}}^{n+1}}{d\tau} \approx \frac{\Delta T_{\mathrm{av}}^{n+1}}{\Delta\tau}, \qquad (9)$$

where

$$\Delta T_{\mathrm{av}}^{n+1} = T_{\mathrm{av}}^{n+1} - T_{\mathrm{av}}^{n}. \qquad (10)$$

Highest precision by numerical integration of eqs. (7) and (8) ensures the Simpson's method (Deliiski, 2003). According to this method and to Fig. 2, eqs. (7) and (8) obtains the following discrete analogues suitable for programming (Dorn and McCracken, 1972):

$$T_{\mathrm{av}}^{n} = \frac{\Delta x}{3}\left(T_1^n + 4T_2^n + 2T_3^n + 4T_4^n + 2T_5^n + 4T_6^n + 2T_7^n + 4T_8^n + T_9^n\right), \qquad (11)$$

$$T_{\mathrm{av}}^{n+1} = \frac{\Delta x}{3}\left(T_1^{n+1} + 4T_2^{n+1} + 2T_3^{n+1} + 4T_4^{n+1} + 2T_5^{n+1} + 4T_6^{n+1} + 2T_7^{n+1} + 4T_8^{n+1} + T_9^{n+1}\right). \qquad (12)$$

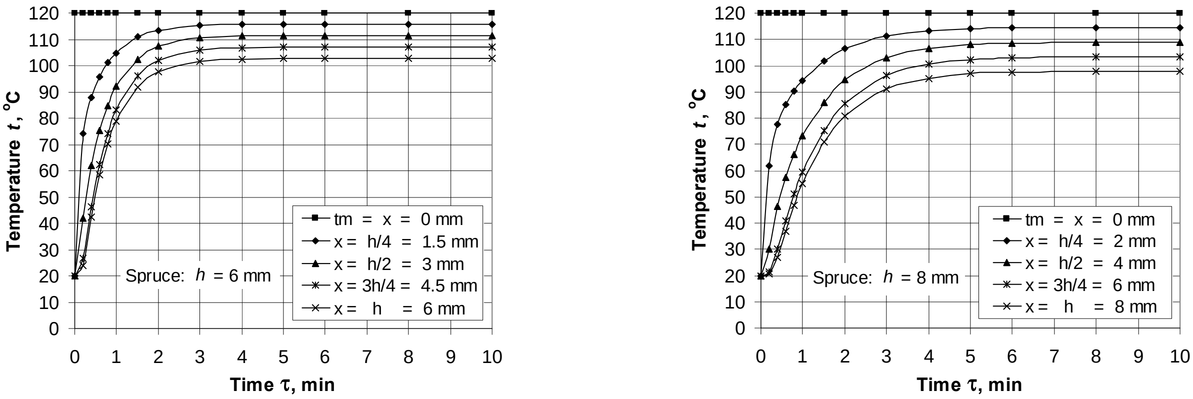
RESULTS AND DISCUSSION

For the numerical solution of the discrete analogue of the mathematical model and for the applying of the suggested approach a software program has been prepared in FORTRAN, which was input in the calculation environment of Visual Fortran Professional.

With the help of the program computations have been made for the determination of the average mass temperature and of the rate of its change for non-frozen spruce (*Picea Abies Karst*) details with thicknesses of h = 6 mm, h = 8 mm, h = 10 mm, initial wood temperature of t_0 = 20 °C, and wood moisture content of u = 0.15 kg·kg^{-1} during 10 min of their unilateral heating at t_m = 100 °C, t_m = 120 °C, t_m = 140 °C, and at t_a = 20 °C.

The computations have been done with average arithmetic values of the spruce thermal conductivity cross-sectional to the fibers, $\lambda_c = \lambda_s$ and of the spruce temperature conductivity cross-sectional to the fibres a_c, for respective ranges from 20 °C to 100 °C, from 20 °C to 120 °C, and from 20 °C to 140 °C (Deliiski, Trichkov, Angelski and Dzurenda, 2014).

Figure 3 presents the temperature change calculated by the model in 4 equidistant from one another characteristic points along the thickness of the details with thickness h = 6 mm and h = 8 mm during their unilateral heating at t_m = 120 °C. The coordinates of those points are shown in the legends of the figure.



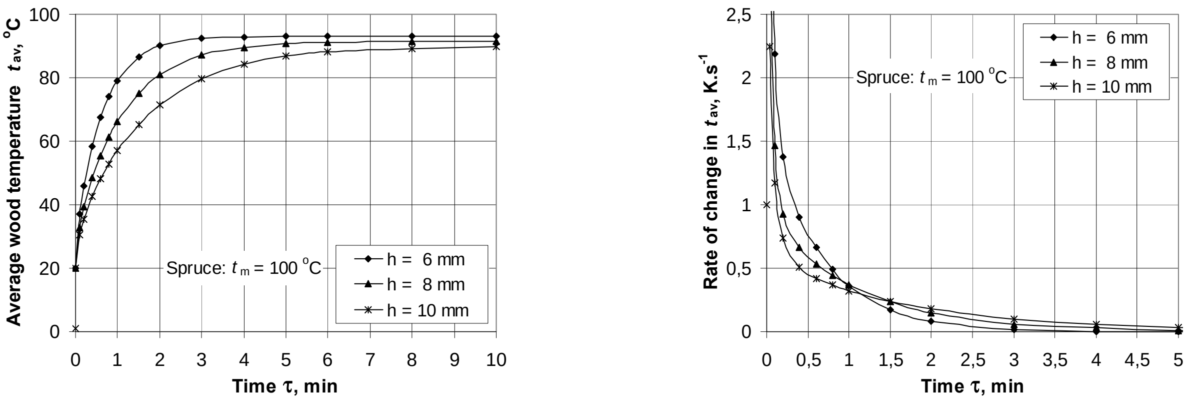
....

Figure 3: Change in t along the thickness of spruce details with t_0 = 20 °C, u = 0.15 kg·kg^{-1}, h = 6 mm (left), and h = 8 mm (right) during their unilateral heating at t_m = 120 °C and t_a = 20 °C

Simultaneously with the solution of the 1D model, calculations of t_{av} and the rate of its change have been carried out. Figures 4, 5, and 6 present the calculated change of t_{av} and its rate of change during the unilateral heating of the spruce details with studied thicknesses at t_m = 100 °C, t_m = 120 °C, and t_m = 140 °C respectively.

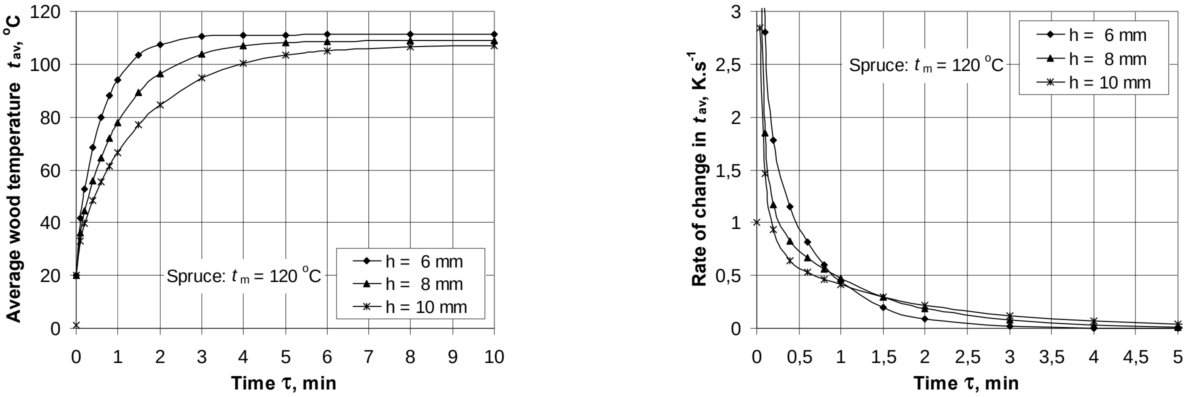
The obtained results show that through one sided heating of details the change of t, t_{av}, and the rate of change of t_{av} go on according to complex curves.

By increasing the heating time, the curves of t gradually approach asymptotically to their biggest values, decreasingly dependent on the remoteness of the characteristic points from the heated surface of the details (see Fig. 3). Analogously, the curves of change in t_{av} approach asymptotically to their biggest values, increasingly dependent on t_m and decreasingly dependent on h. The biggest values of t and t_{av} are achieved when a stationary temperature distribution occurs along the details' thickness.



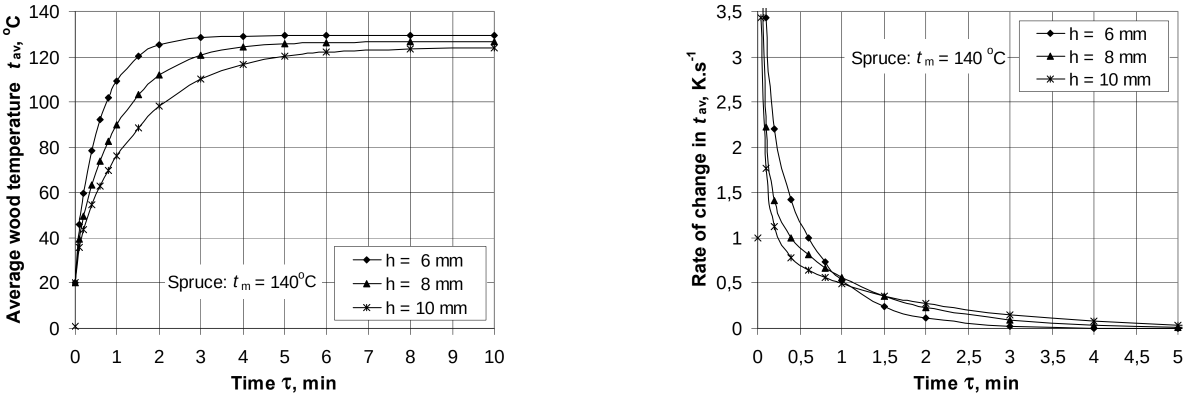
…………………

Figure 4: Change in t_{av} (left) and in the rate of its change (right) of spruce details with t_0 = 20 °C, u = 0.15 kg·kg^{-1}, during their unilateral heating at t_m = 100 °C and t_a = 20 °C, depending on h



…………………

Figure 5: Change in t_{av} (left) and in the rate of its change (right) of spruce details with t_0 = 20 °C, u = 0.15 kg·kg^{-1}, during their unilateral heating at t_m = 120 °C and t_a = 20 °C, depending on h



…………………

Figure 6: Change in t_{av} (left) and in the rate of its change (right) of spruce details with t_0 = 20 °C, u = 0.15 kg·kg^{-1}, during their unilateral heating at t_m = 140 °C and t_a = 20 °C, depending on h

The average wood temperature t_{av} 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 unilateral heating wood details occurs, as follows:

- for h = 6 mm: 92.8 °C after 3.5 min heating at t_m=100 °C, 111.0 °C after 3.8 min heating at t_m= 120 °C, and 129.1 °C after 3.9 min heating at t_m= 140 °C;
- for h = 8 mm: 91.4 °C after 6.4 min heating at t_m=100 °C, 108.8 °C after

6.7 min heating at t_m= 120 °C, and 126.5 °C after 6.8 min heating at t_m= 140 °C;

- for h = 10 mm: 89.7 °C after 9.7 min heating at t_m=100 °C, 106.9 °C after 10.2 min heating at t_m= 120 °C, and 124.2 °C after 10.4 min heating at t_m= 140 °C.

At the beginning of the heating process sharply increasing of the rate of change in t_{av} is observed and reaching of values, which go out of the graduation of the vertical coordinate axes (see the right graphs on Figs. 4, 5, and 6). This sharply increases corresponding to the initial very steep section of the dependences $t_{av} = f(\tau)$ (see the left graphs on Figs. 4, 5, and 6).

The biggest values of the rate of change in t_{av} have been reached two seconds after the beginning of the unilateral heating of the details with all studied thicknesses at all studied values of the heating temperature t_m. These biggest values increasingly dependent on t_m and decreasingly dependent on h and are equal, as follows:

- for h = 6 mm: 4.87 $K{\cdot}s^{-1}$ at t_m=100 °C, 6.16 $K{\cdot}s^{-1}$ at t_m= 120 °C, and 7.47 $K{\cdot}s^{-1}$ at t_m= 140 °C;
- for h = 8 mm: 3.08 $K{\cdot}s^{-1}$ at t_m=100 °C, 3.89 $K{\cdot}s^{-1}$ at t_m= 120 °C, and 4.71 $K{\cdot}s^{-1}$ at t_m= 140 °C;
- for h = 10 mm: 2.25 $K{\cdot}s^{-1}$ at t_m=100 °C, 2.84 $K{\cdot}s^{-1}$ at t_m=120 °C, and 3.43 $K{\cdot}s^{-1}$ at t_m=140 °C.

After reaching of its biggest values, the rate of change in t_{av} begins to decrease – at first steeply and after that lighter and lighter until reaching its zero values when a stationary temperature distribution occurs along the details' thickness.

CONCLUSIONS

The article describes a numerical approach for the computation of the wood average mass temperature and the rate of its change during unilateral heating of flat wood details aimed at their plasticizing before bending. The approach is based on the integration of the solutions of a linear mathematical model for calculation of the non-stationary 1D temperature distribution along the thickness of subjected to unilateral heating of flat wood details.

For the numerical solution of the model and for the applying of the suggested approach a software program has been prepared, which has been input in the calculation environment of Visual Fortran Professional. With the help of the program, computations have been carried out for the determination of the average wood mass temperature and of the rate of its change for spruce details with an initial temperature of 20 °C, moisture content of 0.15 $kg{\cdot}kg^{-1}$, and thicknesses of 6 mm, 8 mm, and 10 mm during their 10 min unilateral heating at temperatures of the heating body 100 °C, 120 °C, 140 °C, and of the surrounding air 20 °C.

The obtained results can be used for a scientifically based dimensioning of the heating bodies and for the determination of the energy consumption, which is needed for unilateral 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.

Symbols

a = temperature conductivity ($m^2{\cdot}s^{-1}$)
h = thickness (m)
n = time level during the solution of the mathematical model: n = 0, 1, 2, 3, …
R = radius of bending of the heated and plasticized wood details (m)
t = temperature (°C): $t = T - 273.15$
T = temperature (K): $T = t + 273.15$

u = moisture content ($kg \cdot kg^{-1}$): $u = W/100$

W = moisture content (%): $W = 100u$

x = coordinate along the thickness of the details: $0 \leq x \leq X = h$

α = heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)

λ = thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)

τ = time (s)

Δx = step on the x-coordinate, which coincides with the thickness of the detail (m)

$\Delta\tau$ = step on the τ-coordinate, i.e. interval between time levels (s)

Subscripts and superscripts:

a = air (for the temperature of the air near to the non-heated side of the wood details)

av = average (for the mass temperature of wood details at given moment of their unilateral heating)

c = cross-sectional to the fibers (for the values of the thermo physical characteristics of the wood)

m = medium (for the temperature of the heating metal body)

s = surface (for the non-heated surface of the subjected to unilateral heating wood details)

0 = initial (for the average mass temperature of the details at the beginning of the heating or for the time level at the beginning of the model's solution)

REFERENCES

1. Angelski, D., (2010). *Researches over the processes of plasticization and bending of furniture wood details*, PhD Thesis, University of Forestry, Sofia, 2010 (in Bulgarian).
2. Chudinov, B. S. (1968). *Theory of the thermal treatment of wood*, Publishing Company "Nauka", Moscow, USSR, 255 p. (in Russian).
3. Deliiski, N. (2003). *Modelling and technologies for steaming of wood materials in autoclaves*, DSc. Dissertation, University of Forestry, Sofia, 358 p. (in Bulgarian).
4. Deliiski, N. (2011). *Transient heat conduction in capillary porous bodies*, p. 149–176. In: Convection and conduction heat transfer. InTech Publishing House, Rieka, http://dx.doi.org/ 10.5772/21424.
5. Deliiski, N., Dzurenda, L. (2010). *Modelling of the thermal processes in the technologies for wood thermal treatment*, TU Zvolen, Slovakia, 224 p. (in Russian).
6. Deliiski, N., Trichkov, N., Angelski, D., Dzurenda, L. (2014). *Modelling of the energy consumption for one sided heating of wood details before their bending in the production of stringed music instruments*, Wood Design and Technology, Vol. 3, No 2, Ss. Cyril and Methodius University – Skopje (in print).
7. Dorn, W. S., McCracken, D. D. (1972). *Numerical methods with FORTRAN IV case studies*, John Willey & Sons, Inc., New York.
8. Gaff, M., Prokein, L. (2011). *The influence of selected factors on coefficient of wood bendability*, Annals of Warsaw University of Life Sciences, Forestry and Wood Technology, № 74: 78–81.
9. Taylor, Z. (2001). *Wood Bender's Handbook*, Sterling Publ. Co., Inc., New York.
10. Trebula, P., Klement. I. (2002). *Drying and hydro-thermal treatment of wood*, Technical University in Zvolen, Slovakia (in Slovak).
11. Videlov, H. (2003). *Drying and thermal treatment of wood*, Publishing House of the University of Forestry, Sofia, 335 p. (in Bulgarian)

ACKNOWLEDGEMENT

This document was supported by the grant No BG051PO001-3.3.06-0056, financed by the Human Resources Development Operational Programme (2007–2013) and co-financed jointly by the ESF of the EU and the Bulgarian Ministry of Education and Science.

UNIVERSITY OF FORESTRY
FACULTY OF FOREST INDUSTRY

INNOVATION IN WOODWORKING INDUSTRY AND ENGINEERING DESIGN

1/2016

INNO vol. V Sofia

ISSN 1314-6149
e-ISSN 2367-6663

INNOVATION IN WOODWORKING INDUSTRY AND ENGINEERING DESIGN, 2/2016 (9): 3–4

CONTENTS