INNOVATION IN WOODWORKING INDUSTRY AND ENGINEERING DESIGN, 2/2016 (10): 49–55

COMPUTATION OF THE HEAT FLUX NEEDED FOR UNILATERAL WARMING UP OF FLAT SPRUCE DETAILS BEFORE THEIR BENDING

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ABSTRACT

An approach for the computation of the heat flux, which is needed for warming up of flat wood details during unilateral heating 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 and differentiation 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. The paper presents solutions of the model concerning the non-stationary change in the specific heat flux needed for warming up of flat spruce details with thicknesses of 6, 8 and 10 mm during their unilateral heating at temperatures of the electrically heated metal band equal to 100, 120, and 140 ºC.

Key words: unilateral heating, flat wood details, heat flux, plasticizing, bending.

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 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).

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 metal band, electrically heated up to the temperature in the range of 100 ºC ÷ 150 ºC.

In the specialized literature there are very limited reports and only by the authors of this paper about the energy consumption and temperature distribution in subjected to unilateral heating wood details (Deliiski et al. 2014a, 2014b) and there is no information at all about the heat flux needed for the heating of 1 m^2 of the subjected to such heating wood details. The knowledge of this heat flux can be used for scientifically based determination of the necessary power of the heating metal body depending on the desired duration of the unilateral details' heating at given values for the thickness of the details and for the radius of their bending.

The aim of the present work is to suggest a numerical approach for the computation of the specific heat flux, which is needed for warming up of subjected to unilateral heating flat wood details aimed at their plasticizing in the production of curved outside parts for corpuses of stringed music instruments. The approach has to be based on the integration and on the differentiation 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, which has been suggested earlier by the authors (Deliiski et al. 2014a, 2014b).

MECHANISM OF THE ONE DIMENSIONAL HEAT DISTRIBUTION IN SUBJECTED TO UNILATERAL HEATING WOOD DETAILS

The mechanism of the heat distribution in wood details during their unilateral heating can be described by the equation of the heat conduction (Deliiski 2003, 2011, 2013).

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 et al. 2014a, 2014b):

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

with an initial condition

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

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 band T_{m}:

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

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

$$\frac{\partial T(X,\tau)}{\partial x} = -\frac{\alpha(\tau)}{\lambda_{\mathrm{ws}}(\tau)}\left[T_{\mathrm{ws}}(\tau) - T_{\mathrm{a}}(\tau)\right], \qquad \textbf{(4)}$$

where

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

MODELLING OF THE SPECIFIC ENERGY CONSUMPTION AND THE SPECIFIC HEAT FLUX NEEDED FOR WARMING UP OF THE WOOD DETAILS DURING THEIR UNILATERAL HEATING

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

$$q = \frac{c_{\mathrm{w}} \rho_{\mathrm{w}} \left(T_{\mathrm{avg}} - T_0\right)}{3.6 \cdot 10^6}. \qquad \textbf{(6)}$$

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

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

where (Deliiski 2013, 2013)

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

$$c_{\mathrm{w}} = \frac{2097u + 826}{1+u} + \frac{9.92u + 2.55}{1+u}T + \frac{0.0002}{1+u}T^2 \quad @ \quad u \le u_{\mathrm{fsp}}, \tag{9}$$

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

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}.

The change in q_{w} during the time $\Delta\tau$, i.e. the heat flux needed for warming up of 1 m^2 of the subjected to unilateral heating wood details, $\mathrm{d}q_{\mathrm{w}}/\mathrm{d}\tau$ (in kW·m^{-2}), can be calculated according to equation

$$\frac{\mathrm{d}q_{\mathrm{w}}}{\mathrm{d}\tau} \approx \frac{3600\Delta q_{\mathrm{w}}}{\Delta\tau}. \tag{11}$$

TRANSFORMATION OF THE MATHEMATICAL MODEL IN SUITABLE FORM FOR PROGRAMMING

The following system of equations has been derived by passing to final increases of the derivatives in equations (1) to (5) with the usage of the same explicit form of the finite-difference method, which has been described in (Dorn and McCracken 1972, Deliiski 2003):

$$\frac{\mathrm{d}q_{\mathrm{w}}^{n+1}}{\mathrm{d}\tau} \approx \frac{3600\Delta q_{\mathrm{w}}^{n+1}}{\Delta\tau}, \tag{12}$$

where

$$\Delta q_{\mathrm{w}}^{n+1} = q_{\mathrm{w}}^{n+1} - q_{\mathrm{w}}^{n}, \tag{13}$$

$$q_{\mathrm{w}}^{n} = \frac{\rho_{\mathrm{w}} c_{\mathrm{w}} h}{3.6 \cdot 10^6}\left(T_{\mathrm{avg}}^{n} - T_0\right), \tag{14}$$

$$q_{\mathrm{w}}^{n+1} = \frac{\rho_{\mathrm{w}} c_{\mathrm{w}} h}{3.6 \cdot 10^6}\left(T_{\mathrm{avg}}^{n+1} - T_0\right), \tag{15}$$

$$T_{\mathrm{avg}}^{n} = \frac{\Delta x}{3}\left(T_1^n + 4T_2^n + 2T_3^n + 4T_4^n + 2T_5^n + 4T_6^n + 2T_7^n + 4T_8^n + T_9^n\right), \tag{16}$$

$$T_{\mathrm{avg}}^{n+1} = \frac{\Delta x}{3}\left(T_1^{n+1} + 4T_2^{n+1} + 2T_3^{n+1} + 4T_4^{n+1} + 2T_5^{n+1} + 4T_6^{n+1} + 2T_7^{n+1} + 4T_8^{n+1} + T_9^{n+1}\right). \tag{17}$$

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 the calculation environment of Visual Fortran Professional.

With the help of the program computations were made for the determination of the 1D non-stationary change of t and also of t_{avg}, q_{w}, and $\mathrm{d}q_{\mathrm{w}}/\mathrm{d}\tau$ for non-frozen spruce (*Picea Abies Karst*) details with h = 6 mm, h = 8 mm, h = 10 mm, t_0 = 20 °C, u = 0.15 kg·kg^{-1}, ρ_{b} = 380 kg·m^{-3}, and S_{v} = 11.4% during their 10 min unilateral heating at t_{m} = 100 °C and at t_{a} = 20 °C.

The computations were carried out with average values of the spruce temperature conductivity cross-sectional to the fibers, a_{w}, and of the spruce thermal conductivity cross-sectional to the fibers, $\lambda_{\mathrm{w}} = \lambda_{\mathrm{ws}}$, which have been obtained using the mathematical descriptions of a_{w} and λ_{w} depending on t, u, and

u_{fsp} of the wood species (Deliiski 2003, 2013). The calculated values of a_{w} and λ_{w} with the help of these mathematical descriptions for spruce wood with u = 0.15 kg.kg^{-1} and $u_{\text{fsp}}^{293.15} = 0.32\ \text{kg}\cdot\text{kg}^{-1}$ (Nikolov and Videlov 1987, Deliiski and Dzurenda 2010) in the temperature ranges from 20 °C to 100 °C, from 20 °C to 120 °C, and from 20 °C to 140 °C, are shown in Table 1.

Table 1: Change in a_{w}, $\lambda_{\text{w}} = \lambda_{\text{ws}}$, and c_{w} of spruce wood with u = 0.15 kg.kg^{-1}, depending on t.

Parameter of the wood	Temperature t, °C				Average arithmetic values of λ_{w}, a_{w}, and c_{w} for the temperature ranges:		
	20	60	100	140	t =20÷100 °C	t =20÷120 °C	t=20÷140 °C
$\lambda_{\text{ws}} = \lambda_{\text{w}}$, W·m^{-1}·K^{-1}	0.2341	0.2664	0.2987	0.3311	0.2664	0.2745	0.2826
$a_{\text{w}}\cdot 10^{7}$, m^{2}·s^{-1}	2.5799	2.7412	2.8818	3.0052	2.7309	2.7627	2.7926
c_{w}, J·kg^{-1}·K^{-1}	2036	2181	2326	2472	2181	2218	2254

Simultaneously with the computation of the non-stationary distribution of t along the details' thickness, calculations of t_{avg}, t_{ws}, α, q_{w}, and dq_{w}/dτ were carried out, using the value of the density ρ_{w} = 445.6 kg·m^{-3} and the given in the last row of Table 1 average arithmetic values of the specific heat capacity c_{w} in respective temperature ranges. This value of ρ_{w} was calculated according to eq. (10) for spruce wood with u = 0.15 kg·kg^{-1}, $u_{\text{fsp}}^{293.15} = 0.32\ \text{kg}\cdot\text{kg}^{-1}$, ρ_{b} = 380 kg·m^{-3}, and S_{v} = 11.4% (Nikolov and Videlov 1987).

The values of the specific heat capacity of the wood, c_{w}, given in the last row of Table 1 were calculated according to equation (9). Because of the almost linear dependence of c_{w} on t (Deliiski 2011), the average arithmetic values of c_{w} for the respective temperature ranges were used during the solution of eqs. (14) and (15).

Figures 1, 2, and 3 present the calculated change of q_{w} and dq_{w}/dτ during unilateral heating of the spruce details with studied parameters at t_{m} = 100 °C, t_{m} = 120 °C, and at t_{m} = 140 °C.

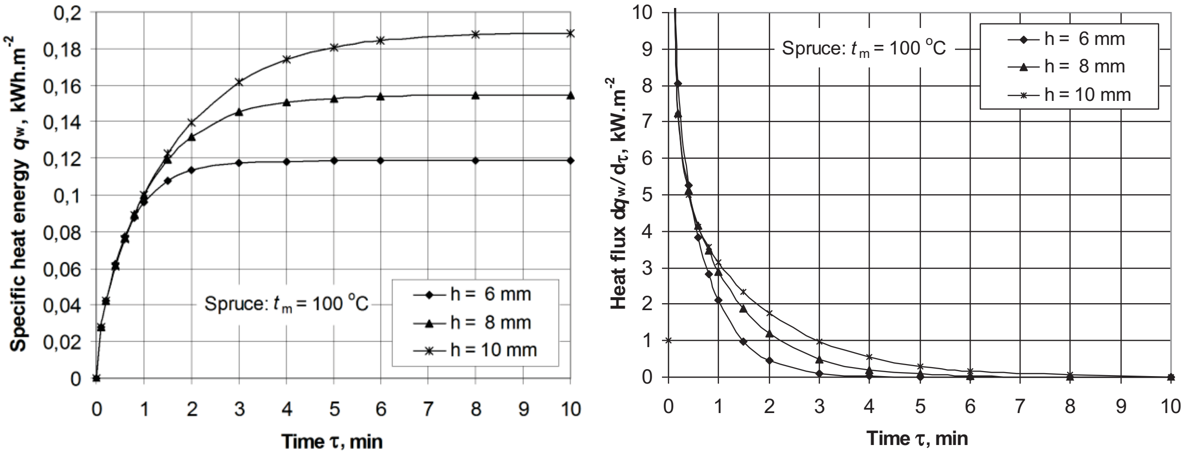

Figure 1: Change in q_{w} (left) and in dq_{w}/dτ (right) of spruce details with t_0 = 20 °C, t_{a} = 20 °C, and u = 0.15 kg·kg^{-1} during their unilateral heating at t_{m} = 100 °C, depending on h.

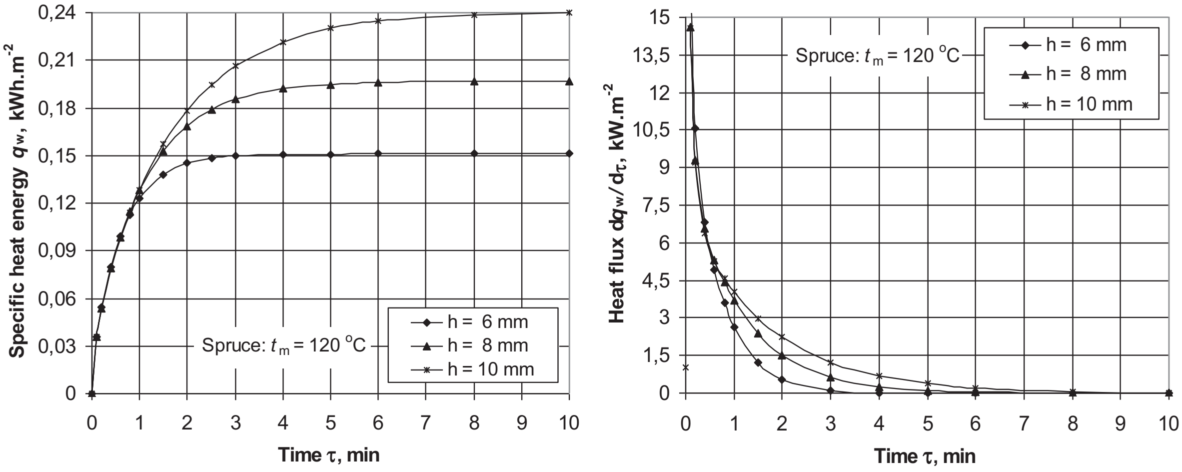

Figure 2: Change in q_w (left) and in $dq_w/d\tau$ (right) of spruce details with $t_0 = 20$ °C, $t_a = 20$ °C, and $u = 0.15$ kg·kg^{-1} during their unilateral heating at $t_m = 120$ °C, depending on h

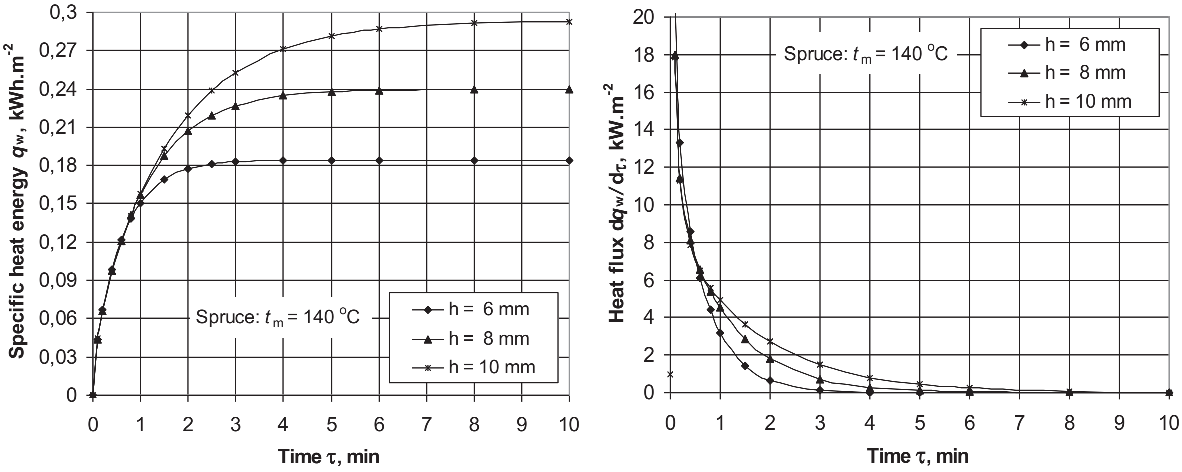

Figure 3: Change in q_w (left) and in $dq_w/d\tau$ (right) of spruce details with $t_0 = 20$ °C, $t_a = 20$ °C, and $u = 0.15$ kg·kg^{-1} during their unilateral heating at $t_m = 140$ °C, depending on h

The obtained results show that during the unilateral heating of the details the change of q_w takes place according to complex curves. The values of q_w are increasingly dependent on t_m and on h. The curves of the change in q_w approach asymptotically their largest values, increasingly dependent on t_m and decreasingly dependent on h. Our earlier study shows (Deliiski et al. 2014b) that the largest values of q_w are achieved when a stationary temperature distribution occurs along the details' thickness.

The change of $dq_w/d\tau$ during the heating time takes place also according to complex curves. The values of $dq_w/d\tau$ are also, as the values of q_w, increasingly dependent on t_m and on h.

In the beginning of the heating process $dq_w/d\tau$ increases rapidly to values, which are beyond the grading of the Y-axis on Fig. 1, Fig. 2, and Fig. 3. This rapid increase of $dq_w/d\tau$ corresponds to the very steep initial sections of the dependencies $q_w = f(\tau)$. After reaching their maximal values, the heat fluxes $dq_w/d\tau$ begin to decrease – initially very sharply and following that more smoothly. When a stationary distribution of t

along the details' thickness occurs, the heat fluxes $\mathrm{d}q_\mathrm{w}/\mathrm{d}\tau$ become equal to 0.

For example, after 1 min duration of the unilateral heating, the heat flux $\mathrm{d}q_\mathrm{w}/\mathrm{d}\tau$ reaches the following values:

- for details with h = 6 mm: $\mathrm{d}q_\mathrm{w}/\mathrm{d}\tau$ = 2.098 kW·m^{-2} at t_m = 100 °C, $\mathrm{d}q_\mathrm{w}/\mathrm{d}\tau$ = 2.633 kW· m^{-2} at t_m = 120 °C, and $\mathrm{d}q_\mathrm{w}/\mathrm{d}\tau$ = 3.198 kW·m^{-2} at t_m = 140 °C;
- for details with h = 8 mm: $\mathrm{d}q_\mathrm{w}/\mathrm{d}\tau$ = 2.905 kW·m^{-2} at t_m = 100 °C, $\mathrm{d}q_\mathrm{w}/\mathrm{d}\tau$ = 3.696 kW· m^{-2} at t_m = 120 °C, and $\mathrm{d}q_\mathrm{w}/\mathrm{d}\tau$ = 4.513 kW·m^{-2} at t_m = 140 °C;
- for details with h = 10 mm: $\mathrm{d}q_\mathrm{w}/\mathrm{d}\tau$ = 3.143 kW·m^{-2} at t_m = 100 °C, $\mathrm{d}q_\mathrm{w}/\mathrm{d}\tau$ = 4.018 kW·m^{-2} at t_m = 120 °C, and $\mathrm{d}q_\mathrm{w}/\mathrm{d}\tau$ = 4.926 kW.m^{-2} at t_m = 140 °C.

CONCLUSIONS

The article describes a numerical approach for the computation of the specific heat flux, which is needed for warming up of subjected to unilateral heating flat wood details aimed at their plasticizing before bending. The approach is based on the integration and the following differentiation 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 wood details, which has been suggested earlier by the authors.

For the applying of the suggested approach 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 specific heat flux $\mathrm{d}q_\mathrm{w}/\mathrm{d}\tau$, which is needed for warming up of flat spruce details with t_0 = 20 °C, u = 0.15 kg·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.

Using the values of $\mathrm{d}q_\mathrm{w}/\mathrm{d}\tau$, the minimum necessary power of the heating metal band can be determined depending on the desired duration of the unilateral details' heating at given values for t_m, h and R/h.

Symbols

a = temperature conductivity (m^2·s^{-1});
c = specific heat capacity (J·kg^{-1}·K^{-1});
h = thickness (m);
n = time level during the solution of the mathematical model: $n = 0, 1, 2, 3 \ldots$;
q = specific energy consumption (kWh·m^{-2});
$\mathrm{d}q/\mathrm{d}\tau$ = specific heat flux (kW·m^{-2});
R = radius of bending of the heated and plasticized wood details (m);
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·m^{-3});
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);
Δq = change of q for time equal to $\Delta\tau$ (kWh·m^{-2});
@ = at;

Subscripts and superscripts:

a = air (for the temperature of the air near to the non-heated side of the wood details);
avg = average (for the mass temperature of wood details at given moment of their unilateral 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);

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

v = volume (for the wood shrinkage);

w = wood (for energy or for heat flux needed for heating of the wood itself);

ws = wood surface (for the non-heated surface of the 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)

293.15 = at 293.15 K, i.e. at 20 °C (for the standardized value of the fiber saturation point of the wood species).

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UNIVERSITY OF FORESTRY
FACULTY OF FOREST INDUSTRY

INNOVATION IN WOODWORKING INDUSTRY AND ENGINEERING DESIGN

2/2016

INNO vol. V Sofia

ISSN 1314-6149
e-ISSN 2367-6663

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