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THE INFLUENCE OF SELECTED MODIFYING TEMPERATURES ON SPRUCE WOOD EMISSIVITY

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ABSTRACT

The precise and accurate result of the measurement of wood temperature using pyrometer requires the setting of the emissivity of the object. The lack of the information about wood emissivity supports the aim of this contribution. The method of the wood emissivity measurement is based on determining the surface temperature and computing the solution of heat conduction equation. The particular integral is found using the radiative boundary condition. Spruce wood is the second most abundant tree species in Slovakia with a wide use for example in constructions or pulp and paper industry. Adding heat at the modifying temperatures observed from 160°C to 220°C applying for four hours significantly influences the spruce wood thermal properties measured at standard temperature. Mass specific heat capacity and thermal conductivity in tangential direction of spruce wood showed continuous decreasing character with increasing values of the modifying temperatures. Emissivity showed more constant character. Its value significantly differs only in the case of treated wood $\varepsilon\epsilon\langle 0.74 \pm 0.09; 0.79 \pm 0.13\rangle$ compared to untreated wood $\varepsilon = 0.85 \pm 0.04$. Thermal diffusivity is the most stable property among the wood thermal properties.

Key words: spruce wood, emissivity, specific heat, thermal conductivity, thermal diffusivity

INTRODUCTION

The permeability of spruce wood is very low (POŽGAJ *et al*. 1993), especially in dry state. Therefore the dominant transport of heat through wood is conduction. Wood substance forms wood, and wood can contain water and air. Every component of wood specimen requires the definition of the domain for solution of heat conduction equation, initial and boundary conditions. Such attitude is time-consuming problem. Therefore wood is treated as continuum. Such continuum is homogeneous in its volume and may be anisotropic. In general, wood is cylindrical orthogonal anisotropic material (STEINHAGEN 1977, POŽGAJ *et al*. 1993, HRČKA and BABIAK 2016, DELISKII and TUMBARKOVA 2017). When wood is in contact with air, convection occurs on the boundary. Moreover, radiation occurs at temperatures more than absolute zero between the object and its surroundings of different temperatures. The radiation intensity is proportional to the fourth power of temperature. The Stefan-Boltzman law is linearized to match the radiative boundary condition or the boundary condition of the third kind (CARSLAW and JAEGGER 1959, LYKOV 1968). Then, solution of heat conduction equation is used to determine the transient temperature field in wood. The radiative heat intensity is measured by pyrometer and object temperature is computed with setting the value of object emissivity. The inverse problem determines the object emissivity from object surface temperature. The influencing factor is treatment temperature, which can be significant as is indicated in the publication of CZAJKOVSKI (2019). Therefore, the aim of this contribution is reporting the values of spruce wood emissivity. The computing of the surface temperature requires determining the temperature field in wood. Thermal diffusivities in principal directions along with Biot numbers are determined with solution of inversed problem. As far as, the heat intensity is known at the boundary, volume specific heat is determined, which is influenced with moisture content. The mass specific heat capacity is determined from volume specific heat and density at given moisture content. Spruce wood is the second most abundant tree species in Slovakia with wide use for example in constructions or pulp and paper industry, where spruce wood comes to contact to elevated temperatures. Thermally modified wood exhibits substantially lower moisture content, than untreated (BABIAK and NÉMETH 1998, HRČKA *et al*. 2018). And finally, question arises if is the value of spruce wood emissivity influenced with treatment temperature?

MATERIAL AND METHOD

Spruce wood (*Picea abies, Karst.*) was obtained from locality Vlčí jarok (Budča, Central Slovakia). The logs were cut into slabs of 70cm × 10cm × 2cm (L × R × T) dimensions. A final moisture content of 10% for flat sawn lumber was achieved by the kiln drying method at the Technical University in Zvolen. The five slabs were stored at the temperature of 10°C. Four of them were thermally modified at the temperatures of 160, 180, 200 and 220°C and one sample remained unmodified. The hydrothermal treatment was performed at the Arboretum of FLD (CZU in Prague) in Kostelec nad Černými lesy (Czech Republic) using heating technology in the LAC S 400/03 chamber KATRES s.r.o. (HRČKOVÁ *et al*. 2018). The slabs temperature of 60°C or lower was recorded after removal them from the chamber. Four pieces of slabs were thermally treated according to the following procedure:

the 1st period: the lumber was heated to reach target temperature.

the 2nd period: the lumber was heated at different treatment temperatures (160, 180, 200, and 220 °C) for 4 h.

the 3rd period: the lumber was cooled to an ambient temperature of 60 °C and the target moisture content was reached up to the desired value by the water spraying method.

Tab. 1 The schedule of the thermal treatment.

Temperature (°C)	1st Period (h)	2nd Period (h)	3rd Period (h)
160	10	4	3
180	12	4	4
200	14	4	5
220	16	4	6

The parts of treated spruce timbers were equilibrated with humid air in a climatic chamber Binder KBF 720 (Tuttlingen, Germany). The controlled parameters of humid air were at a relative humidity of 65% and a temperature of 20 °C for half year. The final specimens dimensions 100mm × 50mm x 8mm (L × R × T) were cut off from the slabs and radial surfaces were sanded on wide belt sander (P80). The total number of used different specimens was 100. The equilibrium was detected according to the constant mass of the moisture specimen of timber using the technical scales Kern KB 1000-2 (Balingen, Germany).

The principle of emissivity method measurement is described in the publication of HRČKA and SLOVÁČKOVÁ (2019). The difference between described method of HRČKA and

SLOVÁČKOVÁ (2019) and used method in this contribution is in the utilization of two heating foils (NiCr - Vacronium, thickeness of 0.01mm) symmetrically placed inside of four specimens block (Figure 1).

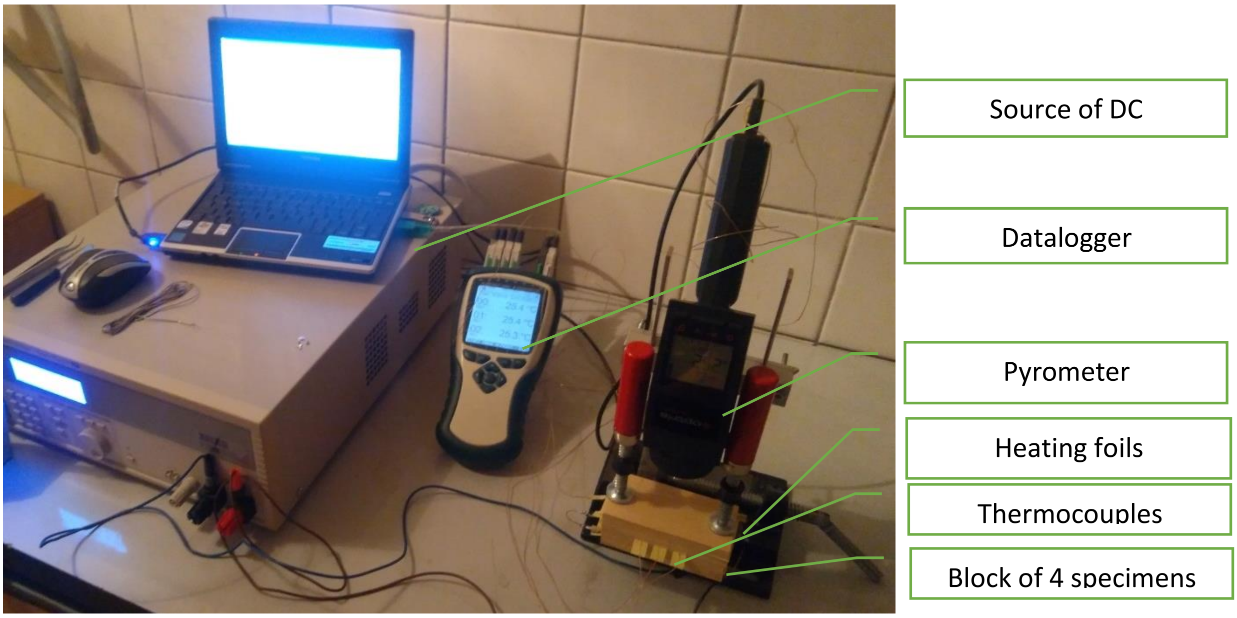

Fig. 1 Arrangement of apparatus.

Then, the position of three thermocouples of type K (Omega, USA) is shown in Figure 2.

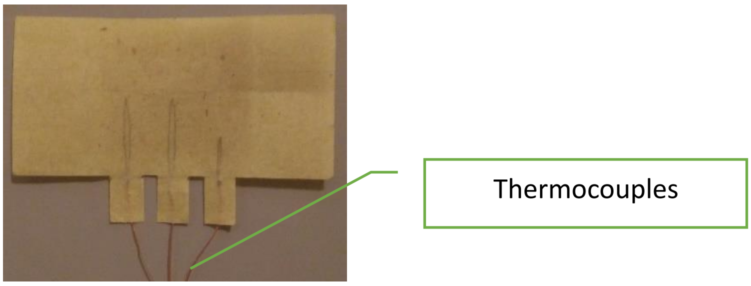

Fig. 2 Position of thermocouples.

The forth thermocouple is placed in the position of one heating foil. The form of the heating foil is structured source which consists in thin strips as is shown in Figure 3.

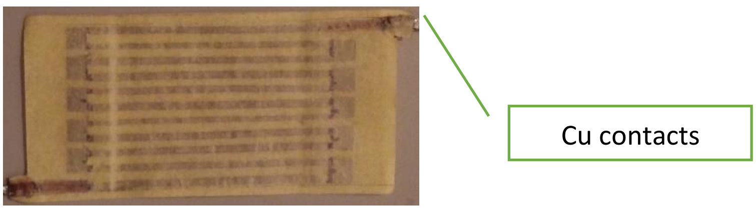

Fig. 3 Structured heating foil.

The set current was 0.12mA (QPX1200SP, TTi, UK) and expected maximum temperature rise was 20°C at the position of the heating foil. The initial condition of measurements was 20°C.

RESULTS AND DISCUSSION

Smaller amount of water inside wood influences significantly its specific heat. Also, wood substance must be modified, because reduction of equilibrium moisture content occurred. There is necessity to measure and investigate thermally modified wood thermal properties as a complex set of quantities. The results are shown in Table 2, 3 and 4.

Tab. 2 Equilibrium moisture content and average input parameters of spruce wood thermal properties measurement ($\bar{x}$ – mean, s- standard deviation; t modifying temperature; T, R, L – dimensions in principal anatomic directions; ρ – density at given moisture content w, equilibrium at relative humidity of 65% and initial temperature 20°C).

	t [°C]	T [m]	R [m]	L [m]	ρ [kg.m^{-3}]	w
$\bar{x}$	20	0.0129	0.0498	0.1010	462.7	0.120
s					29.5	0.002
$\bar{x}$	160	0.0090	0.0498	0.0950	403.5	0.096
s					25.4	0.003
$\bar{x}$	180	0.0088	0.0499	0.0952	429.5	0.079
s					16.5	0.001
$\bar{x}$	200	0.0083	0.0499	0.0954	430.0	0.074
s					8.0	0.001
$\bar{x}$	220	0.0077	0.0498	0.0957	412.0	0.060
s					14.1	0.002

Typical temperature increase inside spruce wood block of four specimens is shown in Figure 4. The curves are fitted by using the method of least squares. The four different curves provide at least 7 degree of freedom, and therefore three thermal diffusivities, three Biot numbers and one specific heat can be determine for wood as orthotropic material, when dimensions are oriented in principal anatomical directions. Then, three thermal conductivities and three transfer coefficients are computed. Moreover, if surface temperature and surface flux are recorded, then emissivity of wood is computed, Figure 5.

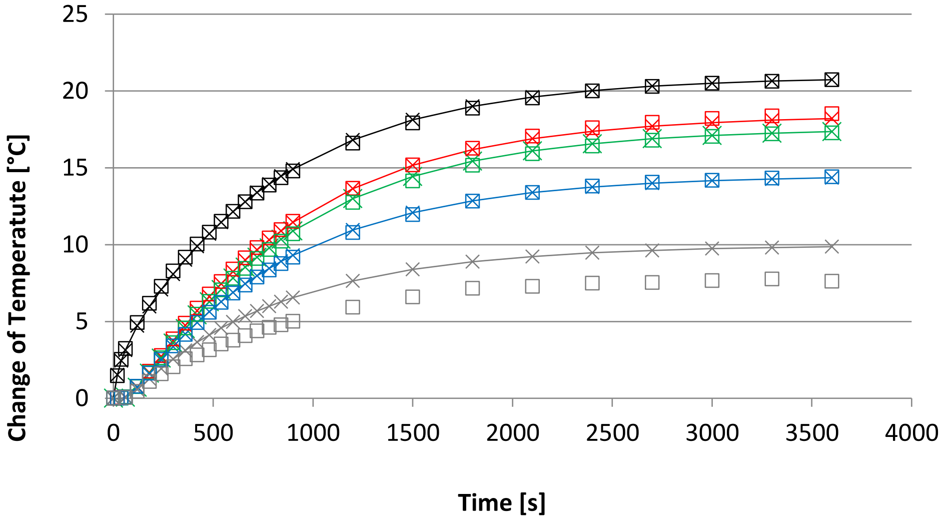

Fig. 4 Temperature increase in different thermocouples (squares) and fitted temperatures (crosses). Black curve belongs to heating foil position, red curve belongs to position of the 1st thermocouple, green one to position of the 2nd thermocouple, blue to position of the 3rd thermocouple and gray curve belongs to surface temperature which was measured by pyrometer (squares) with set emissivity to 1.000, surface temperature computed is indicated with grey crosses.

As far as, the curves do not overlap, heat flows through lateral surfaces to environment. Therefore, three dimensional inverse problems cannot be replaced by one dimensional problem.

Tab. 3 Thermal diffusivities (a), thermal conductivities (λ) in principal anatomical directions and mass specific heat capacity (c) of spruce wood and its modification form by heat at elevated temperatures (t) ($\bar{x}$ – mean, s- standard deviation).

	t [°C]	λ_R [W.(m.K)$^{-1}$]	λ_T [W.(m.K)$^{-1}$]	λ_L [W.(m.K)$^{-1}$]	c [kJ.(kg.K)$^{-1}$]	a_R [m^2.s^{-1}]	a_T [m^2.s^{-1}]	a_L [m^2.s^{-1}]
$\bar{x}$	20	0.14	0.11	0.32	1.53	$1.9\cdot10^{-7}$	$1.5\cdot10^{-7}$	$4.5\cdot10^{-7}$
s		0.02	0.01	0.02	0.01	$0.6\cdot10^{-7}$	$0.4\cdot10^{-7}$	$0.6\cdot10^{-7}$
$\bar{x}$	160	0.10	0.09	0.38	1.42	$1.8\cdot10^{-7}$	$1.5\cdot10^{-7}$	$6.7\cdot10^{-7}$
s		0.01	0.01	0.06	0.04	$0.3\cdot10^{-7}$	$0.2\cdot10^{-7}$	$1.3\cdot10^{-7}$
$\bar{x}$	180	0.11	0.09	0.34	1.40	$1.8\cdot10^{-7}$	$1.4\cdot10^{-7}$	$5.7\cdot10^{-7}$
s		0.01	$2\cdot10^{-3}$	0.03	0.03	$0.1\cdot10^{-7}$	$0.1\cdot10^{-7}$	$0.5\cdot10^{-7}$
$\bar{x}$	200	0.09	0.08	0.37	1.36	$1.5\cdot10^{-7}$	$1.5\cdot10^{-7}$	$6.4\cdot10^{-7}$
s		0.02	$4\cdot10^{-3}$	0.07	0.02	$0.3\cdot10^{-7}$	$0.1\cdot10^{-7}$	$1.3\cdot10^{-7}$
$\bar{x}$	220	0.09	0.07	0.34	1.25	$1.7\cdot10^{-7}$	$1.4\cdot10^{-7}$	$6.5\cdot10^{-7}$
s		0.01	$5\cdot10^{-3}$	0.07	0.02	$0.1\cdot10^{-7}$	$0.1\cdot10^{-7}$	$1.2\cdot10^{-7}$

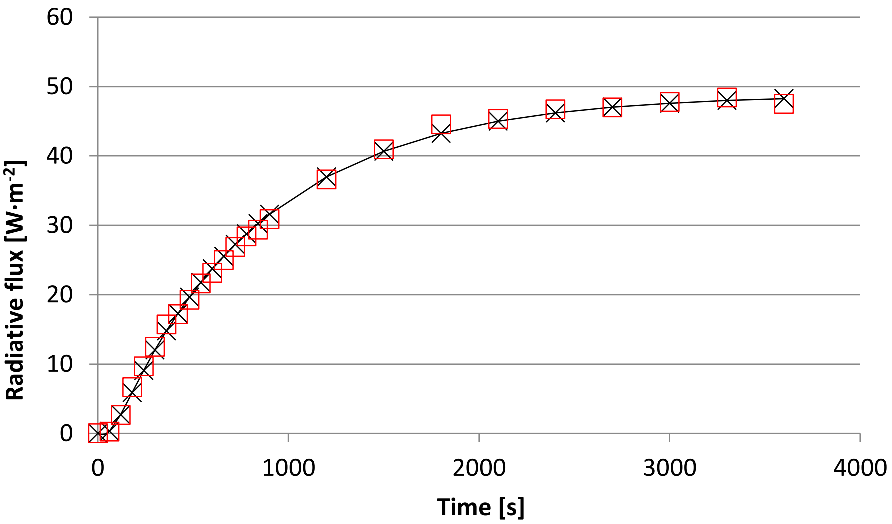

Fig. 5 Radiative flux increase in time as measured by pyrometer (red squares) and computed using adjusted emissivity (grey crosses).

Tab. 4 Emissivity (ε), Biot number and heat transfer coefficient (α_T) on radial surfaces of spruce wood ($\bar{x}$ – mean, s- standard deviation).

	t [°C]	ε	Bi_T	α_T [W.(m^2.K)$^{-1}$]
$\bar{x}$	20	0.85	0.9	7.5
s		0.04	0.2	
$\bar{x}$	160	0.77	1.8	18
s		0.07	0.6	
$\bar{x}$	180	0.74	1.7	16
s		0.04	0.3	
$\bar{x}$	200	0.79	2.2	22
s		0.13	0.8	
$\bar{x}$	220	0.74	2.3	22
s		0.09	0.5	

The transient method of measurement enables to determine specific heat capacity, eigenvalues of the wood thermal conductivity and diffusivity tensor and finally the quantities related to surface. Spruce wood emissivity differs significantly at temperature of 20°C. The emissivity average value 0.85 is in the range of wood emissivity values which were published in user manual of producer of pyrometers Optris. The emissivity coefficient of variation is always lower than Biot number coefficient of variation. The emissivity coefficient of variation is the same order as other thermal properties coefficients of variation, with exception to coefficient of variation of specific heat. This exception must be explained by performing other experiments with different wood species of substantially different oven dry densities. The values of emissivity of milled spruce wood were published by ZAŤKO *et al.* (1993). The emissivity values of spruce wood modified at 180°C and 220°C are the same after rounded to two significant digits as were measured by ZAŤKO *et al.* (1993). The difference between emissivity values at 20°C can be attributed to differences in measured wood sections. ZAŤKO *et al.* (1993) reported the emissivity values for tangential surfaces. The coefficient of variation of mass specific heat capacity for given modifying temperature is the lowest as expected (REGINÁČ and BABIAK 1977). Its value is comparable to coefficient of variation of equilibrium moisture content. The measured values continually decrease with moisture content and so does in thermally treated wood. The value at 20°C is higher than value measured by KRIŠŤÁK *et al.* (2018). KRIŠŤÁK *et al.* (2018) presented measured values of mass specific heat capacity dependence on anatomical direction. Also, treatment temperature, along with moisture content, influences the measured values of thermal conductivity. The thermal conductivity in longitudinal direction is of the same values as was measured by VAY *et al.* (2015) after rounded to two significant digits. The same is true in tangential direction values published by PASZTORY *et al.* (2017). KRIŠŤÁK *et al.* (2019), SONDEREGGER *et al.* (2011) published significantly lower values in longitudinal direction. The less variable thermal property is thermal diffusivity. Its value is the less variable with treatment temperature and density at given moisture content. The agreement of the presented values of thermal diffusivity and published values of KRIŠŤÁK *et al.* (2018) is mentionable in all anatomical directions after rounded to significant digits.

CONCLUSIONS

The presented values of spruce wood thermal properties, Biot numbers and heat transfer coefficients and their comparisons to previously published values declare the suitability of the used method to determine wood emissivity. The values of spruce wood emissivity $\varepsilon \epsilon \langle 0.74 \pm 0.09; 0.79 \pm 0.13 \rangle$ mentioned for interval of 160°C–220°C are the same rounded value to two significant digits as value published by previous researches $\varepsilon = 0.74$. The value of $\varepsilon = 0.85 \pm 0.04$ at 20°C is significantly higher than values published previously by the same researches. The method proved tensor character of thermal conductivity and diffusivity of wood from one measurement of set of four temperatures at specified position in the block of four specimens. Therefore, the method provides only one value of mass specific heat capacity, which does not depend on anatomical direction. The precise determination of surface temperature enables to determine Biot numbers, heat transfer coefficients and finally wood emissivity. The lowest variable property, due to changed treatment temperature, is thermal diffusivity. The lowest variation coefficient was determined for specific heat. As wood variability is present, every specimen has its own thermal properties.

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