ACTA FACULTATIS XYLOLOGIAE ZVOLEN, 61(2): 17−24, 2019
Zvolen, Technická univerzita vo Zvolene
DOI: 10.17423/afx.2019.61.2.02

THE METHOD OF WOOD EMISSIVITY MEASUREMENT

Richard Hrčka – Barbora Slováčková

ABSTRACT

The paper deals with newly proposed method of wood emissivity measurement. The emissivity is determined on the basis of Stefan-Boltzmann law and second law of thermodynamics for black body emission. The newly proposed method is inverse method based on the solution of heat conduction equation and measurement of radiated heat flux using infrared thermometer. The newly proposed method enhances the previously used method based on additional specimen of known emissivity touching the wood specimen. The method does not destruct the measured surface and does not use additional components fixed to the surface.

Key words: emissivity, thermal properties, physics of wood.

INTRODUCTION

Boundary conditions prescribe the wood surface phenomena during heat transfer and significantly affect the description of temperature field in wood. The boundary condition of the third kind is used to describe the surface heat flux on the basis of surface temperature (CARSLAW and JAEGGER 1964, LYKOV 1968). The linear function between surface temperature and surface flux was used in method of wood properties measurement as wood specimens were in contact with fluid (HRČKA 2010). Wood can be also in contact with solid. Such phenomenon is described in hot plate method (SULEIMAN et al. 1999). However, in the case of the hot plate method, the contact thermal resistance is serious problem of wood thin specimens (BUČAR and STRAŽE 2008). Therefore, thicker specimens must be used for measurement wood thermal properties, which suppose the transfer of heat through the lateral surfaces. The thermal thickness of a fuel particle may be determined from the thermal Biot number (STRÖM and THUNMAN 2013). If the Biot number is large and thermal diffusivity is small, there will be temperature gradients inside the particle as it is being heated. Woody biofuels (in the form of briquettes and chips, for example) are typically thermally thick and fall into this category (STRÖM and THUNMAN 2013). The heat transfer coefficient and Biot number are not infinity large as is describe in (BABIAK and HRČKA 2010). In general, the transfer of heat through the lateral surfaces must be involved in heat conduction equation to correctly describe the temperature field in wood specimen during wood thermal properties measurement (HRČKA and BABIAK 2017).

Boundary condition of the third kind may also be used for radiant heating or cooling (LYKOV 1968). KREMPASKÝ (1969) noted that the temperatures above 700−800°C are crucial for radiation to be dominant heat transport. KREMPASKÝ (1969) noted that the convection determines heat transport from the object if its temperature is lower than

700–800°C. The conclusions of LYKOV (1968) and KREMPASKÝ (1969) follow from their analysis of Stefan-Boltzmann law. LYKOV (1968) equaled the heat flux at the inner part of surface to the flux which is defined by Fourier law. And finally, LYKOV (1968) as well as KREMPASKÝ (1969) wrote the decomposition of Stefan-Boltzmann law to the difference of surface and surrounding temperatures. The aforementioned notes revealed the possibility to measure the wood emissivity comparing the surface flux and temperature determined from heat conduction equation at the wood surface together with data measured with infrared thermometer. The aim of the article is to describe the new method of wood emissivity measurement. The method will solve the inverse problem of wood thermal properties measurement.

THEORETICAL PART OF THE METHOD

Heat transfer coefficient h ($W\cdot m^{-2}\cdot K^{-1}$) is quantity joining the heat flux across the surface $q_{x=L}$ ($W\cdot m^{-2}$) and difference between surface temperature $T_{x=L}$ and temperature of surroundings T_0 (CARSLAW and JAEGGER 1964, LYKOV 1968):

$$q_{x=L} = h(T_{x=L} - T_0) \tag{1}$$

and according to energy-conservation law, heat quantity transferred from the body surface equals that transferred to the body surface from the inside per unit time per unit surface by heat. The radiated power P (W), as a rate of emission of electromagnetic energy, from an area S of surface (m^2) at temperature T is given by formula:

$$P = e\sigma S T^4 \tag{2}$$

where $\sigma = 5.67\cdot 10^{-8} W\cdot m^{-2}\cdot K^{-4}$ is the Stefan-Boltzmann constant. The emissivity e characterizes the emitting properties of the surface and is material property. It is dimensionless number between values 0 and 1 (KELLER et al. 1993). Emissivity value of 1 characterizes blackbody. The radiation that would be emitted by black body can be approximated as closely as desired by the radiation emerging from a small opening in a cavity and the radiated power is independent of material that forms the inside walls of the cavity (ILKOVIČ 1957, KELLER et al. 1993).

Good emitter is good absorber as can be shown using second law of thermodynamics. If closed system boundary is adiabatic wall of temperature T_0 and the system consists of object of the temperature T which is different from T_0, the nonzero net heat flux occurred between object and boundary:

$$P = e\sigma S(T^4 - T_0^4) \tag{3}$$

LYKOV (1968) equaled the heat flux (1) to the flux which is defined by Fourier law. And finally, LYKOV (1968) as well as KREMPASKÝ (1969) wrote the decomposition of right hand side of equation (3) to the difference of temperatures:

$$P = e\sigma S(T^2 + T_0^2)(T + T_0)(T - T_0) \tag{4}$$

and LYKOV (1968) summed the radiated flux and flux related to convection at the surface to surface flux linearly depending on surface temperature.

The deviation between decomposition (linear function, k, q are parameters):

$$P = kT + q = k(T_0 + \Delta T) + q \tag{5}$$

and original (forth power function, T_0 is parameter, ΔT is difference of real temperature):

$$P = T^4 - T_0^4 = (T_0 + \Delta T)^4 - T_0^4 \quad (6)$$

is determined according to method of least squares for different values of T_0 (273,15K; 293,15K; 413,15K) and is showed in fig. 1.

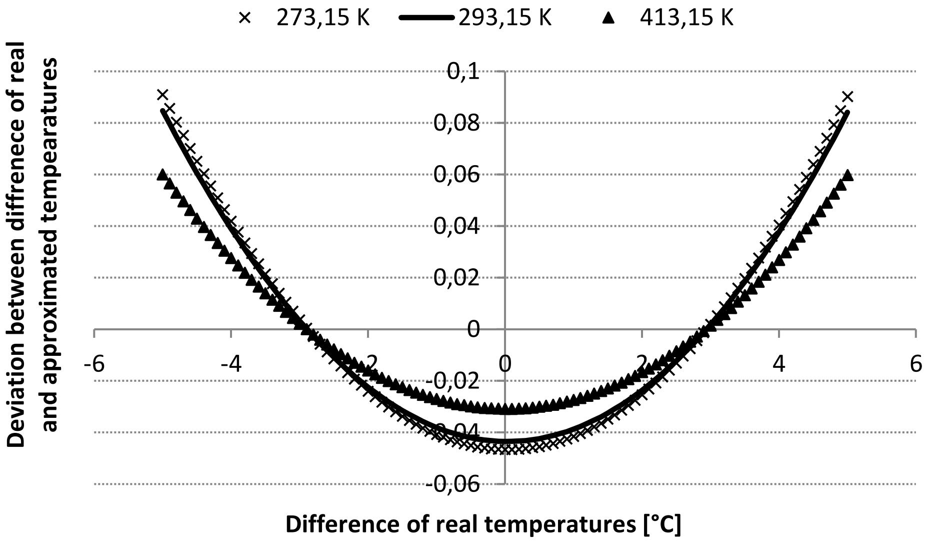

Fig. 1 The precision of linear function approximation to forth power function.

The figure 1 shows the best fit of approximation is in the range of ⟨0; 5⟩°C. So, the temperature at the rear face of the specimen must not exceed 5°C which was measured by infrared thermometer with 0.1°C resolution of readings.

The heat flux and temperature at the surface follows the determination of temperature field *T(x, y, z, t)* according to the solution of heat conduction equation:

$$\alpha_R \frac{\partial^2 T}{\partial x^2} + \alpha_T \frac{\partial^2 T}{\partial y^2} + \alpha_L \frac{\partial^2 T}{\partial z^2} = \frac{\partial T}{\partial t} \quad (7)$$

where α_L ($m^2.s^{-1}$) is thermal diffusivity in longitudinal direction, α_R in radial direction and α_T in tangential direction. The particular solution was found in the form (HRČKA and BABIAK 2017):

$$T(x,y,z,t) - T_0 = \frac{8q}{c\rho d_L} \sum_{r=1}^{\infty}\sum_{p=1}^{\infty}\sum_{m=1}^{\infty} \frac{(\sin\mu_r)(\cos\frac{\mu_r}{d_T} z)}{(\mu_r + (\sin\mu_r)(\cos\mu_r))} \frac{(\sin\mu_p)(\cos\frac{\mu_p}{d_R} y)}{(\mu_p + (\sin\mu_p)(\cos\mu_p))} \frac{\mu_m(\cos\frac{\mu_m}{d_L} x)}{(\mu_m + (\sin\mu_m)(\cos\mu_m))}$$
$$\left(\frac{1 - e^{-(\mu_m^2 \frac{\alpha_L}{d_L^2} + \mu_p^2 \frac{\alpha_R}{d_R^2} + \mu_r^2 \frac{\alpha_T}{d_T^2})t}}{\mu_m^2 \frac{\alpha_L}{d_L^2} + \mu_p^2 \frac{\alpha_R}{d_R^2} + \mu_r^2 \frac{\alpha_T}{d_T^2}} \right) \quad (8)$$

where q ($W.m^{-2}$) is the heat flux at the center of specimens, d_L, d_R, d_T are half of dimensions in longitudinal, radial and tangential directions, c ($J.kg^{-1}.K^{-1}$) is specific heat capacity and ρ ($kg.m^{-3}$) is density at given moisture content. The extension for convection at boundaries is accompanied with heat transfer coefficients *h* and Biot numbers *Bi* (-) at boundaries. Characteristic equations define the roots μ (-) (indexes m, n, p belong to the anatomical directions L, R, T):

$$\mu_m \operatorname{tg}\mu_m = \frac{h_L d_L}{\lambda_L} = Bi_L \qquad \mu_p \operatorname{tg}\mu_p = \frac{h_R d_R}{\lambda_R} = Bi_R \qquad \mu_r \operatorname{tg}\mu_r = \frac{h_T d_T}{\lambda_T} = Bi_T \tag{9}$$

with constant initial temperature through the specimen T_0. The solution (7) fulfils the following boundary conditions:

$$-\lambda_L \frac{\partial T}{\partial x}\bigg|_{x=d_L} = h_L\left(T|_{x=d_L} - T_0\right) \qquad -\lambda_R \frac{\partial T}{\partial x}\bigg|_{y=d_R} = h_R\left(T|_{y=d_R} - T_0\right) \qquad -\lambda_T \frac{\partial T}{\partial x}\bigg|_{z=d_T} = h_T\left(T|_{z=d_T} - T_0\right)$$

$$\frac{\partial T}{\partial x}\bigg|_{x=0} = -\frac{\varphi}{\lambda_L} \qquad \frac{\partial T}{\partial y}\bigg|_{y=0} = 0 \qquad \frac{\partial T}{\partial z}\bigg|_{z=0} = 0 \tag{10}$$

where λ_L ($W.m^{-1}.K^{-1}$) is thermal conductivity in longitudinal direction, λ_R in radial direction and λ_T in tangential direction, Bi_L, Bi_R, Bi_T are Biot numbers at principal anatomical sections.

STEPS OF MEASUREMENT

1. Wood thermal properties must be measured using the temperature field (equation 8, Hrčka 2010) together with measurement of the surface temperature at the rear face of the sample. The surface temperature is measured with infrared thermometer on which the emissivity is set to constant (known) value. The result of measurement is temperature field and radiated flux at the surface.
2. The temperature at the surface, computed from temperature field, is set to Stefan-Boltzmann law. The computed radiated flux is affected only by specimen emissivity.
3. The comparison of measured radiated flux (point 1) and computed radiated flux from temperature field (point 2) enables the determination of unknown emissivity using the method of least squares.

APPARATUS

The sketch of apparatus arrangement is shown on figure 2.

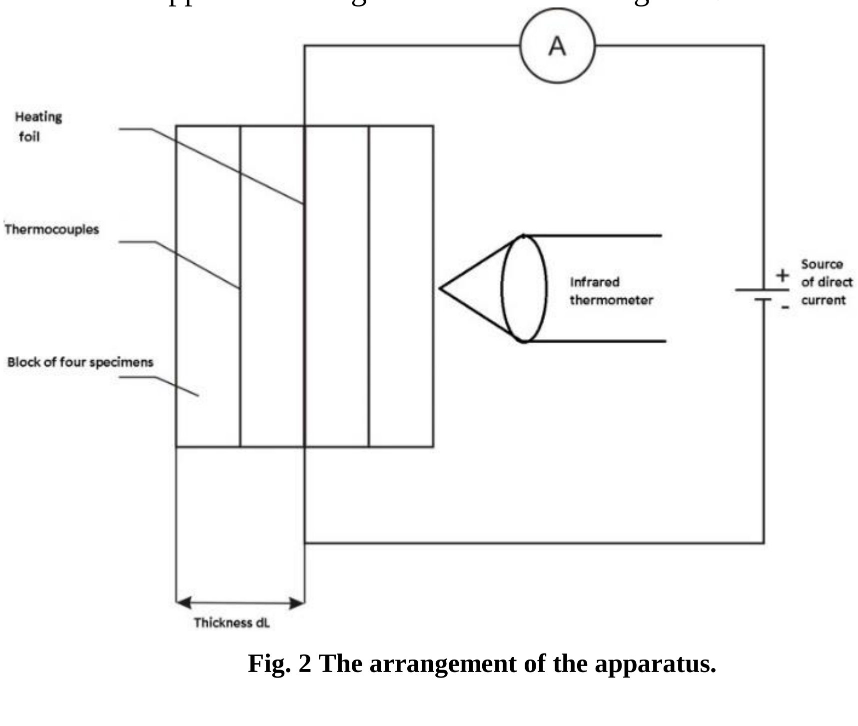

Fig. 2 The arrangement of the apparatus.

The apparatus consists of heating foil Ni-Cr (Vacronium), the laboratory source of direct current QPX 1200SP (Cambridgeshire, UK), thermocouples type K 5TC-TT-K-36-36 (Norwalk, USA), datalogger Almemo 2890-9 (Holzkirchen, Germany) and PC Toshiba (New York, USA). The direct current produces heat passing through the heating foil of known resistance to the adjacent samples. The temperatures at defined positions inside of samples are measured by thermocouples and data are recorded by datalogger at regular time intervals. Datalogger is connected to PC. The measurement is started and finished by PC. As far as temperature field is computed on the surface of the sample, the surface temperature is precisely determined. The radiant flux at the center of the largest area is measured with infrared (IR) thermometer Optris LaserSight (Berlin, Germany) parallel to the normal of the surface. Optris LaserSight infrared thermometer operates in spectral range 8-14µm with optical resolution in close focus mode: 1mm spot in 62mm distance from specimen capturing 90% of energy. Temperature resolution is 0.1°C and accuracy ±0.75°C is valid at temperature 22.0°C. The repeatability of reading is declared to value of 0.5°C. The emissivity is adjustable.

The emissivity of constant (known) value is set on the pyrometer and temperature is also recorded at regular time intervals. Distance to spot ratio (D:S ratio) is set to 62:1. The diameter of the measured area is 1mm and its position is indicated with two point laser before measurement. The specimens are located at the center of climatic chamber KBF 720 (Tuttlingen, Germany) with adjustable humidity, temperature of air and speed of fans inside it. The inside walls of chamber (dimensions of 115 × 100 × 60cm) are made of stainless steel.

SOFTWARE

The least square method implemented in nonlinear procedure Solver (MS Excel) is used to determine unknown parameters of solution (8). The adjusting of the measured radiated flux to computed radiated flux according to temperature field is again performed in procedure Solver. The value of emissivity is the final result of adjusting the measured radiated flux to computed one.

MATERIAL OF SPECIMENS

The specimens of rectangular shape of dimensions (100 × 100 × 10mm in the anatomical directions), of negligible curvature of wooden rings are used for the measurement. The surface of the specimens should be flat as much as possible; it can be prepared by sanding (P60) without visible defects. The surfaces are cleaned with compressed air before testing. It is recommended to achieve the equilibrium moisture content in the humid air with relative humidity of 65% and temperature of 20.0 °C at the beginning of experiment.

THE SOLUTION OF THE DIRECT PROBLEM

The modeling of the direct problem may be as follows:

1. The initial temperature of specimens 20.0 °C is changed due to plane heat source of 145 $W\cdot m^{-2}$ in the center of the specimens. The thickness of the specimens is 0.0232m and density at 12% moisture content is 707.4 $kg\cdot m^{-3}$ (HRČKA and BABIAK 2017).

2. The selected values of heat transport properties of wood, Biot numbers and heat transfer coefficients are shown in Table 1.

Tab. 1 Selected heat transport properties, Biot numbers and heat transfer coefficients.

a_L ($m^2 \cdot s^{-1}$)	a_R ($m^2 \cdot s^{-1}$)	a_T ($m^2 \cdot s^{-1}$)	c ($J \cdot kg^{-1} \cdot K^{-1}$)	Bi_L	Bi_R	Bi_T
$4.0 \cdot 10^{-7}$	$1.8 \cdot 10^{-7}$	$1.4 \cdot 10^{-7}$	1700	0.66	2.0	2.9

λ_L ($W \cdot m^{-1} \cdot K^{-1}$)	λ_R ($W \cdot m^{-1} \cdot K^{-1}$)	λ_T ($W \cdot m^{-1} \cdot K^{-1}$)
0.48	0.22	0.18

h_L ($W \cdot m^{-2} \cdot K^{-1}$)	h_R ($W \cdot m^{-2} . K^{-1}$)	h_T ($W \cdot m^{-2} \cdot K^{-1}$)	e_L (-)	e_R (-)	e_T (-)
14	19	23	0.80	0.96	0.98

3. Then radiated flux was computed using values of emissivity shown in Table 1.

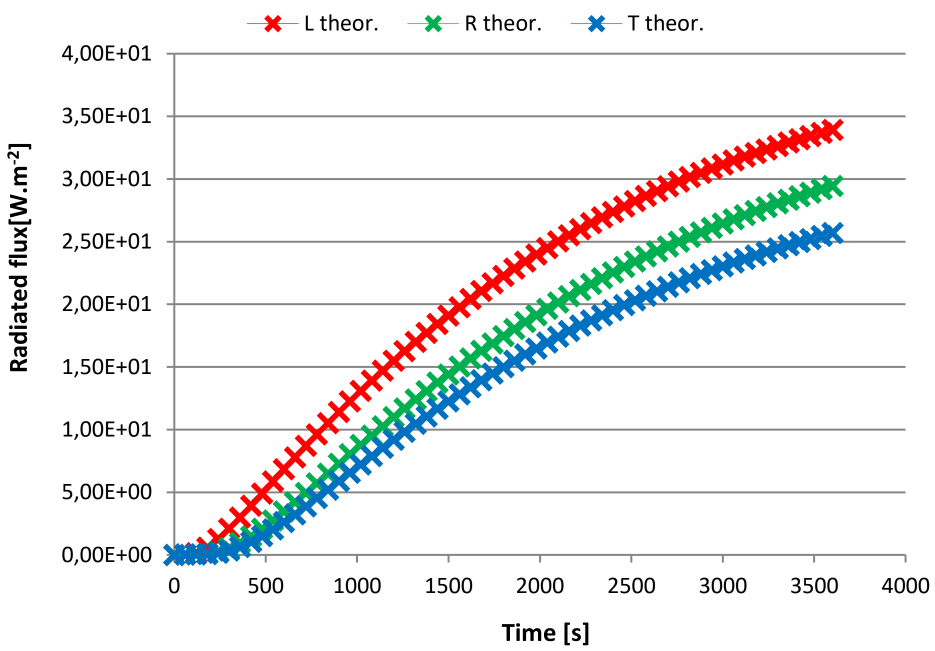

Fig. 3 Radiated flux as was modeled and computed using temperature field at specimen surface.

4. The result of direct problem is radiated flux using computed temperature from temperature field and inserted to Stefan-Boltzmann law.

COMPARISON TO ANOTHER METHODS

The theoretical part of used method of wood thermal properties measurement must describe the temperature field as precise and accurate as possible (HRČKA and BABIAK 2012).

The procedure for determining the emissivity, e, using the contact method can be described in several steps (Optris ® LaserSight):

1. Place the IR thermometer at the desired location and distance from the target to be measured.
2. Measure and compensate for the target's reflected apparent temperature.

3. Aim and focus the IR thermometer on the target and, if possible, freeze the image.
4. Use an appropriate IR thermometer measurement function (such as spot temperature, cross hairs or isotherms) to define a measurement point.
5. Use a contact thermometer to measure the temperature of the point or area just defined by the IR thermometer measurement function. Note this temperature.
6. Without moving the IR thermometer, adjust the emissivity control until the indicated temperature is the same as the contact temperature just taken. The indicated emissivity value is the emissivity of this temperature target measured with this IR thermometer.
7. For greater accuracy, repeat procedures from the 2nd to the 6th steps a minimum of three times and average the emissivity values.

The method uses the contact probe (thermocouple) at the surface producing additional error or a band or color with a known emissivity (reference emissivity material method). The newly proposed method uses the thermocouple at certain non-zero distance from specimen surface.

The third method drills hole to the body to simulate the condition of a black body with an emissivity near 1 and therefore is destructive. The newly proposed method is not destructive.

The forth method uses the recommended values of emissivity which was determined by producer and is shown inside manual table. There is necessity to measure and use the emissivity values for wood appropriately to measurement conditions.

The previous methods show easy measurement of emissivity. On the other hand, the methods bring into measurement discussed additional errors.

CONCLUSIONS

1. The new proposed method of thermal properties measurement is based on the heat conduction equation solution and measurement of radiated flux with infrared thermometer.
2. The results of the method are extended to wood emissivity values.
3. The method enhances the conventional method which is suggested for measurement of emissivity by producer of thermometer.

REFERENCES

BABIAK, M., HRČKA, R. 2010. Measurement of wood thermal properties. In 11th International IUFRO wood drying conference: Recent advances in the field of wood drying. Skelleftea: Lulea University of Technology, 50–54.

BUČAR, B., STRAŽE, A. 2008. Determination of the thermal conductivity of wood by the hot plate method: The influence of morphological properties of fir wood (*Abies alba* Mill.) to the contact thermal resistance. In Holzforschung, 62: 362–367.

CARSLAW, H. S., JAEGER, J. C. 1959. Conduction of heat in solids. Clarendon Press, Oxford.

HRČKA, R. 2010. Variation of thermal properties of beech wood in the radial direction with moisture content and density. In.: Wood structure and properties ´10. Zvolen : Arbora Publishers, 111–115.

HRČKA, R., BABIAK, M. 2012. Some non-traditional factors influencing thermal properties of wood. In Wood Research, 57(3), 367–373.

HRČKA, R., BABIAK, M. 2017. Wood thermal properties. In Wood in civil engineering. Zagreb : InTech,. dx.doi.org/10.5772/63178.

ILKOVIČ, D. 1957. Fyzika. Bratislava : SVTL.
KELLER, F.J., GETTYS, W.E., SKOVE, M.J. 1993. Physics. McGraw-Hill, 2nd Edition
KREMPASKÝ, J. 1969. Meranie termofyzikálnych veličín. Bratislava : Veda.
LYKOV, A. V. 1968. Analytical heat diffusion theory. New York and London : Academic Press.
Optris ® LaserSight, Operators manual (brochure)
STRÖM, H., THUNMAN, H. 2013. CFD simulations of biofuel bed conversion: A submodel for the drying and devolatilization of thermally thick wood particles. In Combustion and Flame, 160: 417–431. dx.doi.org/10.1016/j.combustflame.2012.10.005
SULEIMAN B. M., LARFELDT J., LECKNER B., GUSTAVSSON M. 1999. Thermal conductivity and diffusivity of wood. In Wood Science and Technology, vol. 33, no. 6, pp. 465–473, 1999.

ACKNOWLEDGMENTS

This work was funded by the following: the Scientific Grand Agency of the Ministry of Education SR and the Slovak Academy of Sciences (Grant No. 1/0822/17 "Surface modification of wood and coating materials in order to improve stability of the wood – coating material system."). This paper has been included into the project APVV-16-0177 "Progressive modifications of the wood surface, film-forming materials and their interactions at the phase interface."

ADDRESSES OF AUTHORS

Doc. Ing. Richard Hrčka, PhD.
Ing. Barbora Slováčková
Technical University in Zvolen
Faculty of Wood Sciences and Technology
Department of Wood Science
T. G. Masaryka 24
960 01 Zvolen
Slovak Republic
richard.hrcka@tuzvo.sk