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EFFECT OF DIFFERENT MOISTURE CONTENTS ON THE THERMAL PROPERTIES OF WOOD

UTICAJ RAZLIČITOG SADRŽAJA VLAGE NA TERMALNA SVOJSTVA DRVA

Petr KOTOULEK, Monika BOŽIKOVÁ, Peter HLAVÁČ, Ana PETROVIĆ, Ján CSILLAG, Martin MALÍNEK, Matúš BILČÍK
Faculty of Engineering, 949 76 Nitra, Tr. A. Hlinku, Slovak Republic
e-mail: Monika.Bozikova@uniag.sk

ABSTRACT

Moisture content is one of the most important properties of wood. The primary purpose of this paper is to examine the dependence between thermal properties and different moisture contents of softwood, hardwood and medium hardwood samples with dimensions of 100 x 100 mm and a thickness of 10 mm (measured using the transient method). Different moisture contents of the wood samples under consideration were achieved by a gradual drying treatment in the laboratory setting. The final results obtained represent the arithmetic means computed from ten sets of measurements. The measured relationship between the thermal conductivity and the mass specific heat of the wood samples was found to indicate an increasing trend, whereas the relationship between the thermal diffusivity and the moisture content of the wood samples showed a non-linear decreasing trend. On the basis of the results obtained, it can be concluded that the thermal properties of wood are greatly affected by the type of wood and changes in the wood moisture content, which mainly depend on wood structure and water conduction in wood.
Key words: *thermal properties, moisture, softwood, hardwood, medium hardwood.*

REZIME

Sadržaj vlage je jedno od najvažnijih svojstva drveta. Primarna svrha ovog rada je da ispita zavisnost između toplotnih svojstva i različitih sadržaja vlage uzoraka mekog drveta, tvrdog drveta i srednje tvrdog drveta, dimenzija 100 x 100 mm i debljine od 10 mm (mereno primenom prelazne metode). Različiti sadržaj vlage ispitivanih uzoraka drva postignut je postupnim sušenjem u laboratoriji. Dobijeni konačni rezultati predstavljaju aritmetičke sredine izračunate iz deset setova merenja. Utvrđena je povezanost između toplotne provodljivost i specifične toplote uzoraka drveta, dok je odnos između toplotne difuzije i sadržaja vlage uzoraka drveta pokazao nelinearni trend opadanja. Na osnovu dobijenih rezultata može se zaključiti da termička svojstva drveta u velikoj meri zavise od vrste drveta i promene sadržaja vlage u drvu, koje uglavnom zavise od strukture drveta i vode u drvu.
Ključne reči: *termička svojstva, vlaga, meko drvo, tvrdo drvo, srednje tvrdo drvo.*

INTRODUCTION

Thermal properties of wood are of immense importance to fuel conversion, building construction and other types of industry *(Zi-Tao et al. 2011)*. As wood is considered a lignocellulosic material *(Avramidis and Lau 1992)*, the crystalline structure of cellulose chains in wood may be altered by temperature variations, leading to a permanent loss in the strength of wood and considerable changes in the physical behaviour of wood (namely the heat conductivity). The heat conductivity of wood depends on the following factors affecting the rate of heat flow in wood: density, moisture content, direction of heat flow, and distribution of chemical substances in wood *(Ružiak et al., 2017)*. Transient simultaneous measurements of the thermal conductivity and diffusivity of Swedish wood have been performed using the plane source technique on oven-dry hardwood – birch (*Betula*) samples by *Suleiman et al. (1999)*. The specific heat capacity of the selected types of wood was also examined relative to the temperature and moisture content (*Radmanović et al., 2014)*.

Measurements of the thermophysical properties of the wood samples analysed, i.e. the thermal conductivity, thermal diffusivity and dependence between the mass specific heat and different moisture contents, were performed in the present study.

MATERIAL AND METHOD

In this study, thermophysical property measurements were performed on three different types of wood samples: softwood – spruce (*Picea abies*), hardwood – beech (*Fagus sylvatica*) and medium hardwood – chestnut (*Aesculus hippocastanum*). The thermal conductivity of the samples was examined using the Dynamic Plane Source (DPS) method. The DPS method is based on an ideal plane sensor (PS). The PS sensor acts both as a heat source and a temperature detector. The plane source method is arranged for a one-dimensional heat flow into a finite sample. The underlying theory behind the method considers the ideal experimental conditions: ideal heater (of negligible thickness and mass), perfect thermal contact between the PS sensor and the sample, zero thermal resistance between the sample and the material surrounding the sample, and zero heat losses from the lateral surfaces of the sample *(Karawacki et al., 1992)*. If q is the total output of the power per unit area dissipated by the heater, then the temperature increase as a function of time is given by Eq. (1) *(Beck and Arnold, 2003)*,

$$\Delta T(x,t) = \frac{2\,q\,\sqrt{a\,t}}{\lambda}\; ierfc\left(\frac{x}{2\sqrt{a\,t}}\right) \tag{1}$$

where a is the thermal diffusivity of the sample, λ is the thermal conductivity of the sample, and *ierfc* is the error function. The PS sensor under consideration was placed between two identical samples with the same cross section as the sensor in the plane $x = 0$. The temperature increase in the sample as a function of time conforms to Eq. (2),

$$T(0,t) = \frac{q\,\sqrt{a}}{\lambda\,\sqrt{\pi}}\,\sqrt{t} \tag{2}$$

It corresponds to the linear heat flow into an infinite medium. The sensor is made of Ni-foil (23 μm thick) and protected from both sides by an insulating layer made of kapton (25 μm thick) at the Slovak Academy of Sciences. Several corrections have been introduced to account for the heat capacity of the wire, the thermal contact resistance between the wire and the test material, the finite dimension of the sample and the finite dimension of the wire embedded in the sample *(Wakeham et al., 1991; Liang, 1995)*.

Many physical and mechanical properties of wood depend upon the moisture content of wood. Moisture content (u) is usually expressed as a percentage and can be calculated from Eq. (3):

$$u = \frac{m_{water}}{m_{wood}} 100\% \tag{3}$$

where m_{water} is the mass of water in wood and m_{wood} is the mass of dry basis. Operationally, the moisture content of a given piece of wood can be calculated by Eq. (4):

$$u^* = \frac{m_{wet} - m_{dry}}{m_{dry}} 100\% \tag{4}$$

where m_{wet} is the mass of the specimen at a given moisture content and m_{dry} is the mass of the oven-dry specimen *(Glass and Zelinka, 2010)*.

Thermal properties of three different wood samples were examined in this study: spruce, beech and chestnut samples. All the samples examined had dimensions of 100 x 100 mm and a thickness of 10 mm. Different moisture contents of the wood samples examined were achieved by a gradual drying treatment in the laboratory settings. Moisture content measurements were performed using the moisture analyser MAC 210/WH and the gravimetric method in accordance with the EU and STN standards. The final moisture content was calculated from Eq. (4). The experimental results are summarised in Figures 1, 2 and 3, as well as in Table 1.

RESULTS AND DISCUSSION

All the wood samples examined were measured ten times at a laboratory temperature of 21.5 °C, which was stabilised 24 hours prior to the experiments. The mass specific heat, thermal conductivity and thermal diffusivity were measured in the moisture range 0 – 35 %. The reduction of wood samples moisture content was achieved by a gradual drying treatment of the wood samples under laboratory conditions. The points in Figures 1 – 3 represent the arithmetic means obtained from ten sets of measurements. All the experimentally obtained results were statistically processed. The regression analysis was performed for the identification of the regression coefficients (Table 1) and the coefficients of determination (R^2).

The relationship between the mass specific heat and the moisture content of the wood samples was determined in the first set of measurement. The highest mass specific heat value was recorded in the case of the hardwood sample (with a moisture content of 35 %), whereas the lowest mass specific heat value was obtained in the instance of the softwood sample (with a minimal moisture content of 0 %). The results obtained were in the following ranges: softwood – spruce (1.36 – 2.17) kJ·kg^{-1}·K^{-1}, hardwood – beech (1.47 – 2.46) kJ·kg^{-1}·K^{-1}, and medium hardwood – chestnut (1.40 – 2.33) kJ·kg^{-1}·K^{-1}. All the results obtained are consistent with the results of *Glass and Zelinka (2010)*. The relationship between the mass specific heat and the moisture content of the wood samples was linear in all cases. Equation 5 and the coefficients of determination shown in Table 1 were obtained using the regression analysis.

$$c = A\,u + B \text{ (kJ·kg}^{-1}\text{·K}^{-1}\text{)} \tag{5}$$

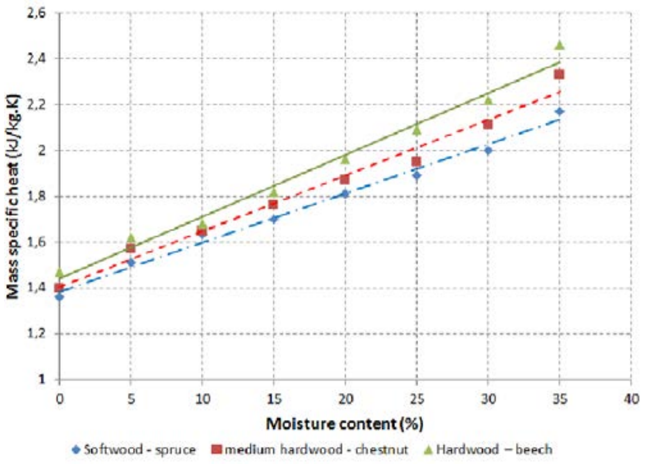

Fig. 1. Relationship between the mass specific heat and the moisture content of the wood samples

Table 1. Characteristics of Equations 5, 6 and 7

Sample				
Mass specific heat *A, B* - regression coefficients, R^2 – coefficient of determination				
Sample	*A* (kJ·kg^{-1}·K^{-1})		*B* (kJ·kg^{-1}·K^{-1})	R^2
Softwood spruce	0.0215		1.3833	0.9900
Medium hardwood chestnut	0.0243		1.4042	0.9803
Hardwood beech	0.0269		1.4441	0.9845
Thermal conductivity *C, D* - regression coefficients, R^2 – coefficient of determination				
Sample	*C* (W·m^{-1}·K^{-1})		*D* (W·m^{-1}·K^{-1})	R^2
Softwood spruce	0.0009		0.1128	0.9914
Medium hardwood chestnut	0.0009		0.1199	0.9902
Hardwood beech	0.0010		0.1330	0.9948
Thermal diffusivity *E, F, G* - regression coefficients, R^2 – coefficient of determination				
Sample	*E* ·10^{-5} (mm^2·s^{-1})	*F* (mm^2·s^{-1})	*G* (mm^2·s^{-1})	R^2
Softwood spruce	2	0.0009	0.0816	0.9936
Medium hardwood chestnut	1	0.0010	0.0598	0.9967
Hardwoodbeech	2	0.0007	0.0749	0.9971

The relationship between the thermal conductivity and the moisture content of the wood samples can be described by a linear function (Eq. 6).The following thermal conductivity values of the wood samples with different moisture contents were obtained: softwood – spruce (0.114 – 0.143 W·m^{-1}·K^{-1}), hardwood – beech (0.133 – 0.166 W·m^{-1}·K^{-1}) and medium hardwood – chestnut (0.121 – 0.152 W·m^{-1}·K^{-1}).

Upon comparing the thermal conductivity values obtained in the present study with the values reported in the literature (*Ružiak et al., 2017*), differences were found between the thermal conductivity values of hardwood and medium hardwood samples with a moisture content exceeding 20 %.

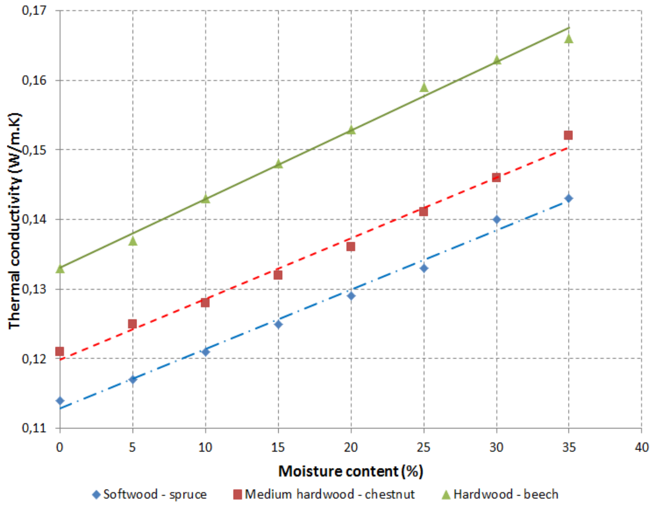

Fig. 2. Relationship between the thermal conductivity and the moisture content of the wood samples

These differences could be accounted for by the specific structure of wood fibers and their arrangement in the samples examined.

$$\lambda = C\,u + D \quad (\mathrm{W \cdot m^{-1} \cdot K^{-1}}) \tag{6}$$

Nonlinear dependencies were found to exist between the thermal diffusivity and the moisture content of the wood samples. Such nonlinear dependencies were obtained using the regression analysis and could be described by the polynomial functions of the second degree with the polynomial coefficients and the coefficients of determination shown in Table 1.

$$a = E\,u^2 + F\,u + G; \quad (\mathrm{mm^2 \cdot s^{-1}}) \tag{7}$$

Relatively high coefficients of determination (0.9936 – 0.9971) were obtained in all cases. The final relationship described by Eq. (7) is consistent with the results of *Suleiman et al. (1999), Ružiak et al. (2017).*

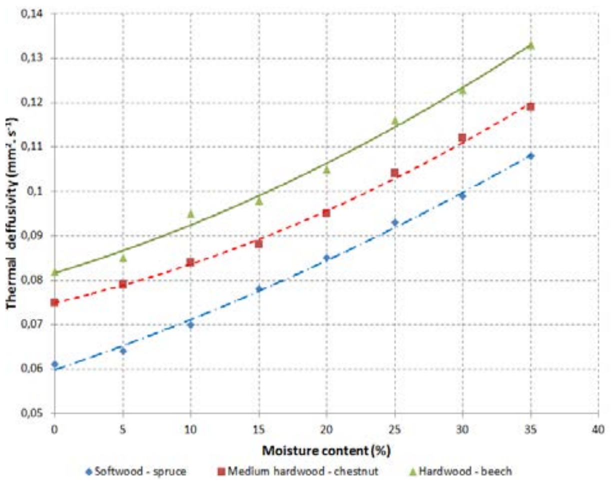

Fig. 3. Relationship between the thermal diffusivity and the moisture content of the wood samples

CONCLUSION

Heat transfer can be characterized by thermal properties such as thermal conductivity, thermal diffusivity and mass specific heat. It is influenced by many internal and external factors such as material structure, moisture content, temperature, etc. Moisture content is one of the most important properties of wood. The relationships between the mass specific heat $c = f(u)$, the thermal conductivity $\lambda = f(u)$ and the thermal diffusivity $a = f(u)$ on one hand, and the moisture contents of three different wood samples (0 – 35 %) on the other (softwood - spruce, hardwood – beech and medium hardwood - chestnut) were examined in the present study. The results obtained argue that increasing moisture contents of wood exerts a significant effect on the thermal properties of wood (for *c, λ* by the linear function and for *a* by polynomial function of the second degree). All changes in the thermal properties were dynamic, indicating the heat transfer ability of the wood samples tested, the velocity of the temperature equalization and the intensity of the temperature changes in the wood samples tested. The accurate values of these properties are of paramount importance to practical designs, as well as theoretical studies and analyses, especially in the fields of heat transfer and thermal processing.

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