Determining Thermal Properties of Beech and Fir Wood Samples in Longitudinal Direction *via* Modified Transient Plane Source Method

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The increasing use of wood leads to the need for a better understanding of its thermal properties with the aim of quantitatively identifying the exchange of thermal energy between wood and the surrounding solar radiation as precisely as possible. Reliable and rapid measurement of thermal conductivity is one of the most important current industrial requirements. The aim of this study is to examine the validity of using the modified transient plane source method (MTPS), which uses the principle of one-sided heating of the sample, and is defined by the ASTM D7984-21 (2021) standard, for determining the thermal conductivity of complex biocomposite composite materials such as wood. The analysis of the available literature shows a lack of data on the thermal conductivity of the type of wood originating in Croatia. In this study, the thermal conductivities of beech and fir wood samples in the longitudinal direction was determined by the MTPS method depending on the temperature and moisture content in the samples. Measurements were made on samples with a moisture content of 0%, 10%, and 20% in the temperature range from 20 to 80 °C.

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INTRODUCTION

Awareness of the benefits of green construction, wood, and wood-based materials gives preference to their use in many industrial branches. The production of wood and wood-based materials requires less energy and causes less CO_2 emissions compared to the production of some other building materials (Wang *et al.* 2014), which makes it more environmentally friendly. In addition to the construction and furniture industry, wood is increasingly being researched in the energy industry. Jiao *et al*. (2020) investigated the influence of lignocellulosic and multichannel wood microstructure on the mass transfer of ionically conductive electrolytes for charging vanadium batteries. A thorough knowledge of thermal conductivity as a quantity that describes the ability of wood to heat transfer is extremely important. An example is when determining the influence of heat dissipation on the performance of wood products (Qiu 2023). Another example is when quantitatively determining the exchanged heat between wood and the environment, *etc*. As a result, there is a need for a faster and more precise determination of their thermal conductivity (TC).

Research on TC of wood has a long history. However, despite the development of technology and experimental setup, measuring the TC of porous, biopolymer composites, such as wood, remains a challenge. The reasons for this are the anisotropic structure of wood and the influence of various factors (direction of wood fibers, moisture content, temperature, proportion of early and late wood of the measurement sample, etc.) on the measured TC of wood. Many commercial methods for determining the TC of materials are available today, which can be classified into two groups. The first group is represented by steady-state methods based on the Fourier law of heat transfer,

$$J = -\lambda \cdot \frac{d\theta}{dx} \tag{1}$$

where J is the heat flux density (W/m^2), λ is the thermal conductivity (W/mK), θ is the temperature (°C), and x is the distance (m).

These methods are often used to measure the TC of insulating materials, and are characterized by high accuracy and simple analysis of the measured data. The disadvantages of these methods are that it is primarily suitable for analyzing materials with low or average thermal conductivities at moderate temperatures, required exacting sample preparation and they are not suitable for testing samples in the liquid phase (Yesilata and Turgut 2007; Yuksel 2016). The second group is represented by dynamic methods in which TC is determined from the temperature change of the sample during its heating. Compared to steady-state methods, dynamic methods have advantages, such as shorter measurement time (which is particularly suitable when testing wood samples with a certain moisture content), the possibility of performing measurements on small samples, and the possibility of simultaneous measurement of several thermal properties. The downside of dynamic methods is lower accuracy than stationary methods and complex analysis of measured data that depends on a number of parameters (type and configuration of materials, conditions of experiment performance, *etc*.). There are several variations of dynamic methods (*e.g.*, transient line source (TLS), transient plane source (TPS), laser flash (LF), 3ω method, *etc*.), and some of them are also applied in determining the thermal conductivities of wood and wood-based materials. For example, Houngan *et al.* (2015) determined TC of two tropical wood species using dynamic TLS method. Maeda *et al.* (2021) determined TC using the dynamic (TPS) method in samples of wood species originating from China. Harada *et al.* (1998) determined the TC of various types of wood in the heating process using the laser flash method. Peron *et al.* (2020) obtained the TC of oak, fir, larch, elm, and ash using the TPS method. Some authors made their own experimental setups for measuring TC. Sonderegger *et al*. (2011) using an experimental set-up based on the TPS method determined the thermal conductivity of Norway spruce and European beech wood. In 2001, a new method of measuring TC samples called modified transient plane source (MTPS) was patented by C therm Technologies Ltd. (40 Crowther Lane – Suite 200 Fredericton, New Brunswick Canada E3C 0J1), and it has the possibility of simultaneous measurement of thermal effusivity and conductivity. Thermal effusivity (ε) is a quantity that tells about the ability of wood to exchange heat with its environment, and it is related to thermal conductivity (λ) by the following Eq. 2,

$$\varepsilon^2 = \rho \cdot c \cdot \lambda \tag{2}$$

where ε is thermal effusivity (W(s)$^{1/2}$/m^{2}K), ρ is density (kg/m^3), c is specific heat capacity (J/kgK), and λ is thermal conductivity (W/mK). The MTPS method is based on the TPS method, and the difference is in the performance of the sensor. With the MTPS method, the sensor is attached to a base that provides mechanical support, as well as electrical and thermal insulation. This modification enables one-sided measurement of the contact temperature and offers maximum flexibility in the measurement of thermal effusivity and conductivity.

Given that the measured value of thermal effusivity is affected by the roughness of the surface of measuring sample and the air flow next to the measuring surface itself (Mathis and Chandler 2004), the MTPS sensor is made with a protective ring that protects the measuring area from external air flow, while the influence of the imperfection of the measuring surface of the sample is minimized by using a contact means.

After reviewing the literature, it can be concluded that experimental research on the thermal conductivity of wood is aimed at a more precise determination of TC in three prominent directions (longitudinal, radial, and tangential), and at determining the influence of individual factors (density, moisture content (MC), temperature, *etc*.) on the measured value of TC. Sonderegger *et al.* (2011) state that the thermal conductivity of wood is the highest in the longitudinal direction, while there is no clear consensus for the radial and tangential directions. Krištak *et al.* (2019) report higher thermal conductivity values in the radial direction, while some authors (Peron *et al.* 2020) do not find significant differences in the thermal conductivities of wood in the radial and tangential directions. In the oldest found research on the influence of temperature and MC on TC of wood, Kanter (1957) determined the thermal conductivity of birch using the stationary state method and determined a linear increase in TC with increasing temperature. The linearity coefficient increased with increasing MC. In somewhat more recent research, Božikova *et al.* (2018) using the dynamic plane source (DPS) and steady state hot wire method (HW) also determined a linear increase in TC with an increase in MC in several types of wood. Through studying the influence of MC and temperature on the TC of wood, most authors report an increase in TC with an increase in MC and wood temperature.

The aim of this work is to determine whether the thermal conductivity of a complex biocomposite material such as wood can be measured using the MTPS method. The research of TC was carried out on beech and fir samples in the longitudinal direction, and the varied parameters were the temperature and MC of the samples. Measurements were made on samples with a MC of 0%, 10%, and 20% in the temperature range from 20 to 80 °C. Given that thermal effusivity is simultaneously measured with the MTPS method in addition to TC, the paper also calculated depth of heat penetration (d) and thermal resistance (R).

EXPERIMENTAL

The experimental study was conducted in two stages. In the first phase, the samples were cut and conditioned, while in the second phase, the thermal conductivity values of the samples were measured depending on the temperature and MC.

Materials

For the purposes of the experiment, samples of wood types that are often used in Croatia, beech wood (*Fagus sylvatica*) and fir wood (*Abies alba*)) were used. Samples with dimensions of (3 × 3 × 3) cm^3 (Fig. 1) were sawn from planed plank without visible defects with parallel grain distributed.

After sawing, the samples were divided into three groups. Each group contained 5 beech and 5 fir wood samples. The first group of samples was dried in a dryer to an approximately dry state (MC ≈ 0%), the second and third groups of samples were conditioned to approximately 10% and 20% MC using standard methods defined by the ASTM D4933-16 (2021). After drying and conditioning, the densities of the samples were determined (Table 1).

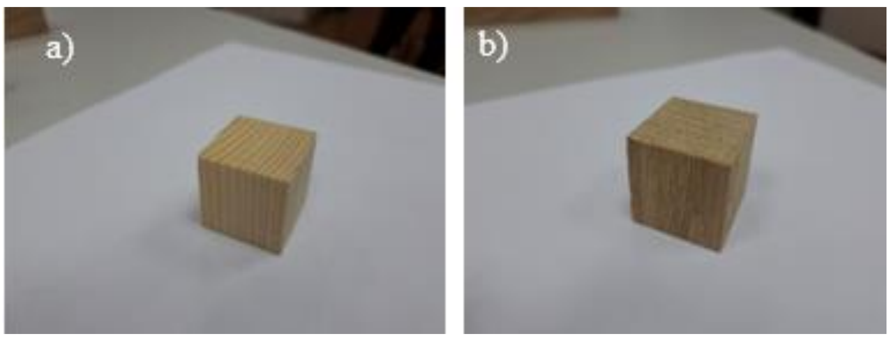

Fig. 1. Wood samples dimensions of (3 × 3 × 3) cm^3: 1a: Beech wood samples; and 1b: Fir wood samples

Table 1. Moisture Content and Density of Beech and Fir Wood Samples

Moisture Content (%)	Density of Beech Wood (kg/m^3)	Density of Fir Wood (kg/m^3)
0	570.76 ± 15.34	345.01 ± 14.22
10	627.18 ± 14.38	379.35 ± 14.53
20	684.37 ± 15.81	414.10 ± 15.07

To preserve the achieved MC of the samples, five sides of the samples were wrapped with transparent foil, and the sixth side (longitudinal direction) was coated with Wakefield type 120 Thermal Paste of known thermal conductivity (λ = 1.14 W/mK) to achieve better contact between the sample and the sensor, according to the manufacturer's recommendation (Fig. 2).

Fig. 2. Wood samples of dimensions of (3 × 3 × 3) cm^3 prepared for testing

Methods

Measurement of the thermal conductivities using the MTPS method

The experimental set-up for measuring the thermal conductivities of the samples using the MTPS method consisted of a C-THERM Trident measuring device (Fig. 3a), a one-sided interphase sensor (Fig. 3b), and computer software. The MTPS method is based on one-sided heating of the sample, while the "cold plate" is in the initial temperature of the sample, which is why it is necessary to temper the sample well before performing the measurement. The sensor has a central platinum heater in the form of a spiral with a diameter of 17 mm, which acts as a source of heat flow and a thermometer, and is protected by a ring that surrounds it. The red protective ring (Fig. 3a) is made from elastic material and is slightly thicker than the measuring sensor. In contact with the material, the protective ring protects the measuring area from external air flow. Before performing the measurement, it is necessary to carefully apply a thin layer of thermal paste to the sensor itself in order to minimize the possibility of the formation of air bubbles within the measuring area. The sensor approximates a one-dimensional heat flow into the tested sample for 1.0 s to 3 s, which is schematically shown in Fig. 4 (heat transfer through the material is much more complex than shown in Fig. 4, which is an idealized schematic representation). As a result of the heat flow, the temperature and resistance of the spiral heater increases by itself thus leading to a voltage drop.

a) b)

Fig. 3. Experimental setup for thermal effusivity and conductivity measurements: 3a: Thermal conductivity analyzer; 3b: Modified transient plane source sensor

Part of the approximated one-dimensional heat flow is taken over by the examined sample, which causes a decrease in the temperature of the sensor*, i.e.*, an increase in voltage. The voltage on the sensor is measured before and during the transient phenomenon, and the voltage data is then translated into the thermal effusivity value of the tested material, and the thermal conductivity is calculated from the slope in the voltage-time dependence diagram according to Mathis and Chandler (2004). The Trident measuring device works on the principle defined by the ASTM D7984 (2021) standard, and at the same time it measures the thermal effusivity, conductivity, and temperature of the measuring sample.

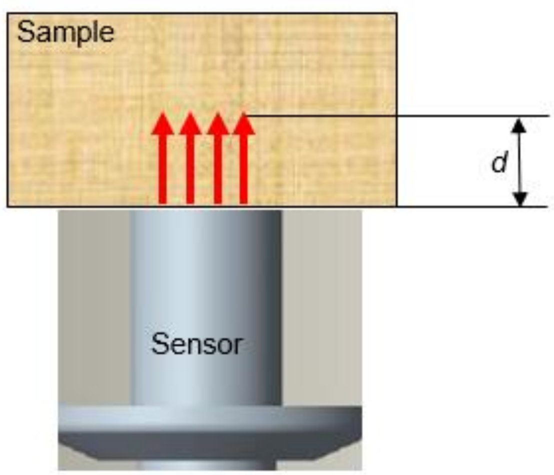

Fig. 4. Schematic representation of heat transfer from the sensor to the sample: *d* – depth of heat penetration into the sample

For the purposes of testing the temperature dependence of thermal conductivity, a Tenney Environmental thermal chamber was used. This device has the ability to cool down to -73 °C and heat up to 200 °C. The MTPS sensor is placed inside the chamber through an opening on the side (Fig. 5). The measuring sample, wrapped in foil and coated with thermal paste in the longitudinal direction, is placed on the sensor, and to achieve better contact, a 500 g weight is placed on the sample. The test was performed at four different temperatures (20, 40, 60, and 80 °C), and the samples were tempered before the measurement so that at the time of measurement the temperature of the atmosphere in the chamber was equal to the temperature of the measurement sample. The thermal chamber takes an average of 30 min to reach the set temperature of the internal atmosphere, while the sample took an average of about 1 h to reach the set temperature. The measurement lasted on average half a minute and was repeated 10 times on one sample under the same conditions.

Fig. 5. Tenney environmental thermal chamber

Using the measured values of thermal effusivity, conductivity, and the duration of the test, the depth of heat penetration into the sample was determined according to Eq. 3,

$$d = \frac{2\lambda}{\varepsilon}\sqrt{t} \tag{3}$$

where d is depth of heat penetration (m), λ is thermal conductivity (W/mK), ε is thermal effusivity ($W(s)^{1/2}/m^2K$), and t is the duration of the measurement (s). Thermal resistance was determined according to Eq. 4,

$$R = \frac{d}{\lambda} \tag{4}$$

where R is thermal resistance (m^2K/W), d is depth of thermal penetration (m), and λ is thermal conductivity (W/mK)

RESULTS

Measurements were made on three groups of samples with MC = 0%, 10%, and 20%, and in each group there were 5 samples of beech wood and 5 samples of fir wood. Thermal effusivity and conductivity measurements were repeated 10 times under the same conditions on each sample. The measurement results were recorded using the C-THERM Trident computer program and then analyzed using the SigmaPlot v. 10.0.0 program. The mean value of TC was determined, and diagrams of the dependence on temperature were made for MC = 0%, 10%, and 20%. Linear and quadratic regression curves were fitted to the measured data, and those with higher R^2 were shown. Results of the determination of thermal effusivity, depth of heat penetration into the sample, and thermal resistance are described below.

Thermal Conductivities of Beech and Fir Wood Samples at MC = 0%, 10%, and 20% in the Temperature Range from 20 to 80 °C

Figure 6 shows diagrams of the dependence of the mean value of TC of beech and fir wood samples in the longitudinal direction on temperature at 0%, 10%, and 20% MC with associated standard deviations and regression curves. The lowest mean value of TC was determined for samples with 0% MC at 20 °C; the TC of beech wood samples was found to be 0.147 W/mK and the TC of fir wood samples was 0.110 W/mK. An increase in temperature caused an increase in the mean value of TC of all measured samples of beech and fir wood samples. The smallest TC increase in the temperature interval from 20 to 80 °C was measured in the beech wood samples with 0% MC and was 0.25%/°C, while the largest TC increase measured in fir wood samples with 20% MC and was 0.8 %/°C. The highest mean value of TC was determined for samples with 20% MC at 80 °C; the TC of beech wood samples was 0.300 W/mK and TC of fir wood samples was 0.2685 W/mK. The regression curves (Eq. 5) in Fig. 6 show the linear dependence of the mean value of TC on temperature in beech and fir wood samples with 0% MC.

$$\lambda(t) = k \cdot t + l \tag{5}$$

In Eq. 5, k (W/mK^2) and l (W/mK) are the constants of the linear function. In samples with 10% and 20% MC the dependence of the mean value of TC on temperature in beech and fir wood samples is quadratic (Eq. 6), although the coefficients with the non-linear terms are extremely small.

$$\lambda(t) = a \cdot t^2 + b \cdot t + c \tag{6}$$

In Eq. 6, a (W/mK^3), b (W/mK^2), and c (W/mK) are the constants of quadratic function.

From the results of measuring the TC of samples using the MTPS method, it can be seen that in the temperature interval from 20 °C to 80 °C and 0% to 20% MC, the TC of beech wood samples was in the range of 0.147 to 0.300 W/mK, and the TC of fir wood samples was in the range of 0.110 to 0.268 W/mK. A review of the available literature found several works dealing with the research of TC of beech and fir in the longitudinal direction, and the results of these studies are shown in Table 3. At different temperatures and MC of samples, the authors published TC values of beech wood in the range from 0.134 to 0.5 W/mK, and TC fir wood in the range from 0.10 to 0.36 W/mK, which is in accordance with the data measured by the MTPS method.

Analyzing the influence of temperature on the TC of wood, according to Table 2, Flity *et al* (2023) found no significant differences in TC in the temperature range from 20 to 160 °C. However, most authors report an increase in TC with an increase in temperature. Kanter (1957) published an increase in TC by 0.2% to 0.3% with an increase in temperature by 1.0 °C, in temperature range from – 40 to 100 °C, and in the range of MC from 0 to 130%, which is in accordance with the results of measurements by the MTPS method on beech wood samples at 0% MC, while the MTPS method for the other samples gives a somewhat larger increase (the largest (0.8 %/°C) is for fir wood samples with 20% MC at 80 °C.

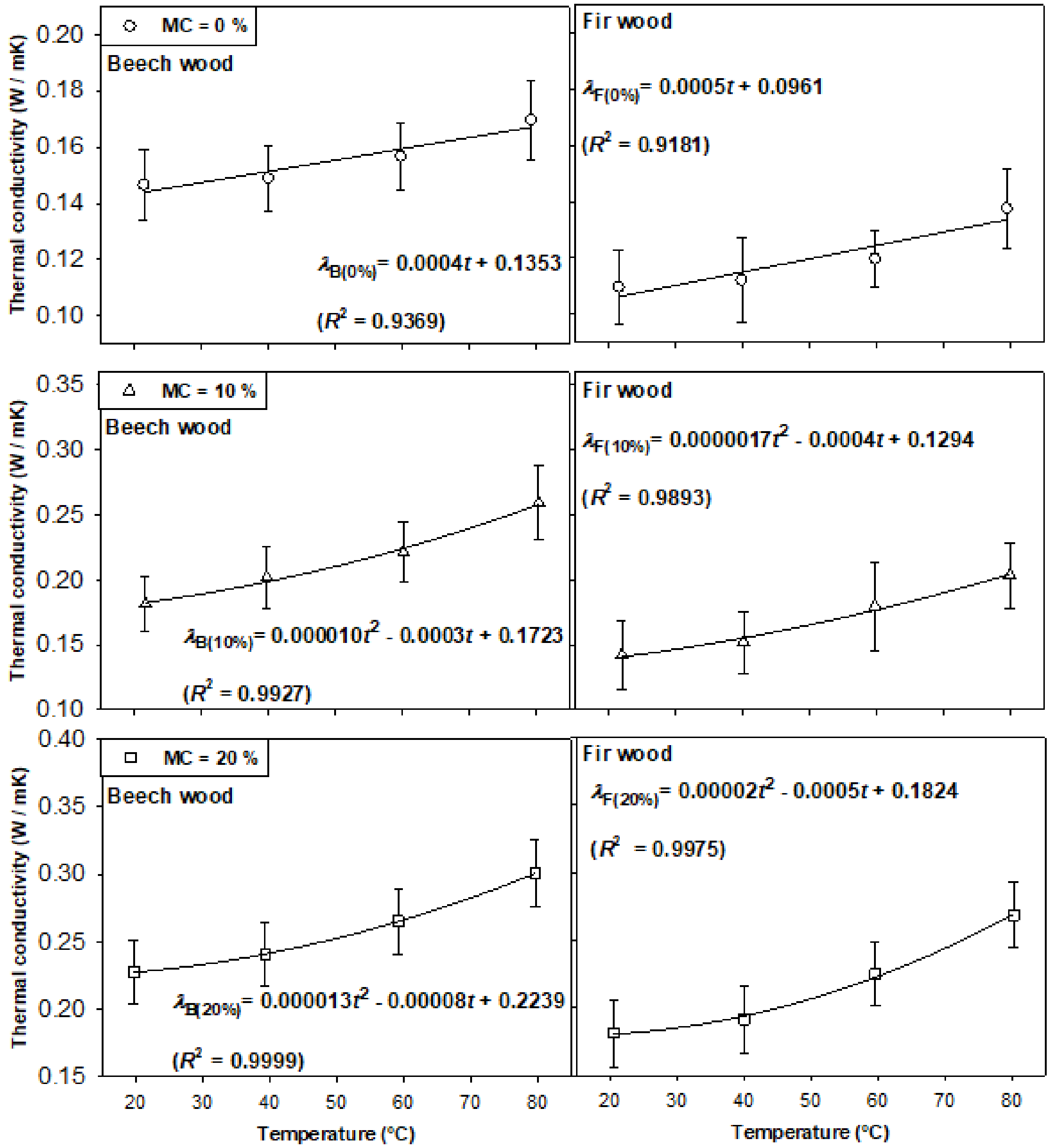

Fig. 6. Diagrams of the dependence of the mean value of thermal conductivity of beech and fir samples in the longitudinal direction on temperature with the associated standard deviations and regression curves at moisture content of 0%, 10%, and 20%

To better display the influence of MC on TC, Fig. 7 shows the dependence diagrams of the mean value of TC of beech and fir samples in the longitudinal direction on MC with the corresponding linear regression curves at t = 20, 40, 60, and 80 °C. Figure 7 shows a linear increase in the mean value of TC with an increase in MC in all measurement samples, where a higher temperature results in a greater increase in TC. The increase in TC by increasing MC from 0% to 20% at t = 20 °C in beech samples is 1.55 times and in fir samples 1.65 times, while at t = 80 °C the increase in beech samples is 1.77 times and in fir samples 1.95 times. Table 4 shows the coefficients of the linear regression curve of the shape, Eq. 7 is given as,

$$\lambda(\mathrm{MC}) = k \cdot \mathrm{MC} + l \tag{7}$$

where k (W/100 mK) and l (W/mK) are the constants of the linear function and MC is moisture content (%).

Table 2. Experimental Data of TC of Beech and Fir Wood Determined by Various Methods

	Authors	Methods	Moisture Content (%)	Temperature (°C)	Thermal Conductivity of Wood (W/mK)
Beech Wood	Flity *et al.* (2023)	PHW	2.78	20, 60, 110, and 160	0.51, 0.52, 0.51, and 0.49
	Ross (1987)	NA	0 and 12	20	0.15 and 0.18
	Sonderegger *et al.* (2011)	HP	0	10	0.257
	Hrčka and Babiak (2017)	QM	12	20	0.38
	Vay *et al*. 2015	HP	NA	20	0.428
	Kotoulek *et al.* (2019)	DPS	0, 10, 20, and 35	21.5	0.134, 0.144, 0.153, and 0.166
Fir Wood	Cavus *et al.* (2019)	THAL	12	30 - 36	0.11
	Peron *et al.* (2020)	TPS	0, 3.9, 6.9, and 10.9	20	0.150, 0.161, 0.166, and 0.174
	Ross (1987)	NA	0 and 12	20	0.10 and 0.12
	Hrčka and Babiak (2017)	QM	12	20	0.36
	Dundar *et al.* (2012)	HW	NA	20 ± 2	0.11
	Flity *et al.* (2023)	PHW	2.78	20, 60, 110, and 160	0.3, 0.3, 0.31, and 0.29

PHW - Parallel Hot Wire, HP - Hot Plate, DPS - Dynamic Plane Source, THAL - THERM 2227-2 ALHBORN TC meter, TPS - Transient Plane Source, HW – Hot Wire, and QM -Quasistationary methods

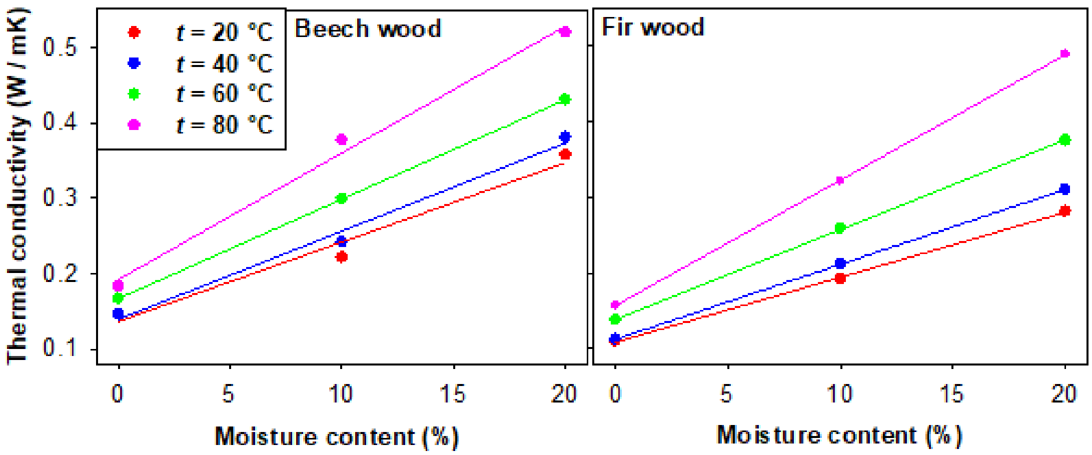

Fig. 7. Diagrams of the dependence of the mean value of thermal conductivity of beech and fir samples in the longitudinal direction on moisture content with associated regression curves at *t* = 20, 40, 60, and 80 °C

The increase in the mean value of TC is slightly higher in beech wood samples, while a higher R^2 was achieved in fir wood samples. Increasing temperature also increased the slope of the linear function against the MC axis. That is, increasing temperature increases the influence of MC on TC samples (Table 3), which is in accordance with previous research (Kanter 1957). According to research by Kotoulek *et al.* (2019) using the dynamic plane source (DPS) method the conductivity of beech wood increases linearly with the increase in MC. In the MC range from 0% to 35% TC increases 1.15, while Ross (1987) states a larger increase (1.2 times) in the smaller range of MC (0% to 12%). Yu *et al.* (2011) use the TPS method to determine the TC of several types of wood as a function of temperature and MC. An increase in temperature caused a linear growth of TC, and a higher MC causes a higher growth of TC with increasing temperature.

Table 3. Coefficients *a* (W/ K^2) and *b* (W/mK) of the Linear Regression Function of the Dependence of Thermal Conductivity on Moisture Content at Different Temperatures for Beech and Fir Wood Samples, and R^2

Temperature (°C)	Beech Wood			Fir Wood		
	k (W/mK^2)	*l* (W/mK)	R^2	*k* (W/mK^2)	*l* (W/mK)	R^2
20	0.0040	0.1447	0.9934	0.0036	0.1086	0.9967
40	0.0046	0.1512	0.9923	0.0040	0.1122	0.9999
60	0.0054	0.1600	0.9887	0.0053	0.1223	0.9932
80	0.0066	0.1743	0.9851	0.0065	0.1377	0.9999

The increase in the mean value of TC by increasing the MC of samples can be explained by a combination of two factors. First, increasing MC increases the amount of water molecules inside the wood matrix, and the TC of water molecules (λ_w) is greater than

TC of dry wood (at room temperature λ_w = 0.6 W/mK (Ramires *et al.* 1995)), and increasing MC as expected, TC of wood also increases. Second, increasing the MC also increases the space between molecules in the rigid parts of the wood, which results in greater molecular mobility and thus greater energy transfer (Gu 2001). In the case of samples with 10 and 20% MC, at 60 and 80 °C, it took 4 to 5 seconds more time to establish a stable heat flow, which enabled more time for heat dissipation, and a significant increase was visible in these samples at the specified temperatures TC by increasing MC (Fig. 7).

CONCLUSIONS

The modified transient plane source (MTPS) method is a fast and reasonably priced method of measuring thermal conductivity (TC). The aim of this study was to determine whether the MTPS method can be applied to determine the TC of wood and if there are any limitations. From this study, the following conclusions can be derived:

1. The measured TC values of beech and fir wood samples are in the same interval as the values stated in the literature, although the values in the literature vary greatly.
2. Increasing temperature and MC increased the value of TC of beech and fir wood samples in the longitudinal direction. The mentioned increase coincided with the values from the literature at 0% and 10% MC and at lower temperatures (20 and 40 °C). In samples with 20% MC and at higher temperatures, a slightly higher increase in TC was obtained with the MTPS method.
3. Study shows that the MTPS method proved to be a good method of measuring TC of beech and fir wood samples at lower temperatures and MC.

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APPENDIX

Table A1. Expressions of Regression Functions from Fig. A1

MC (%)	Thermal Effusivity of Beech Wood (W(s)$^{1/2}$/m^{2}K)	R^2	Thermal Effusivity of Fir Wood (W(s)$^{1/2}$/m^{2}K)	R^2
0	$\varepsilon_B = 0.9310t + 403.7795$	0.91	$\varepsilon_F = 1.4936t + 299.6169$	0.97
10	$\varepsilon_B = 0.0278t^2 - 0.1996t + 571.2164$	0.99	$\varepsilon_F = 0.0280t^2 - 0.2069t + 535.0043$	0.99
20	$\varepsilon_B = 0.0391t^2 - 1.1503t + 771.9980$	0.99	$\varepsilon_F = 0.0520t^2 - 1.5070t + 679.6727$	0.99
MC (%)	Depth of heat penetration of beech wood (mm)	R^2	Depth of heat penetration of fir wood (mm)	R^2
0	$d_B = 0.0095t + 4$	0.93	$d_F = 0.015t + 3.4$	0.94
10	$d_B = 0.00032t^2 - 0.0068t + 4.7$	0.99	$d_F = 0.00019t^2 - 0.0042t + 4.3$	0.99
20	$d_B = 0.00024t^2 - 0{,}00473t + 5.9$	0.99	$d_F = 0.00031t^2 - 0.00361t + 5.2$	0.99
MC (%)	Thermal resistance of beech wood (W /mK)	R^2	Thermal resistance of fir wood (W /mK)	R^2
0	$R_B = -5.7 \cdot 10^{-5}t + 0.031$	0.95	$R_F = -1 \cdot 10^{-4}t + 0.035$	0.93
10	$R_B = -4.2 \cdot 10^{-7}t^2 - 4.3 \cdot 10^{-5}t + 0.023$	0.99	$R_F = -6 \cdot 10^{-7}t^2 - 3 \cdot 10^{-5}t + 0.024$	0.99
20	$R_B = -5.5 \cdot 10^{-7}t^2 + 6.5 \cdot 10^{-6}t + 0.016$	0.99	$R_F = -7 \cdot 10^{-7}t^2 - 2 \cdot 10^{-5}t + 0.019$	0.99

ε_B is thermal effusivity of beech wood samples (W (s)$^{1/2}$ / m^{2}K), ε_F is thermal effusivity of fir wood samples (W (s)$^{1/2}$ / m^{2}K), d_B is depth of heat penetration of beech wood samples (mm), d_F is depth of heat penetration of fir wood samples (mm), R_B is thermal resistance of beech wood samples (W /mK), and R_F is thermal resistance of fir wood samples (W/mK)

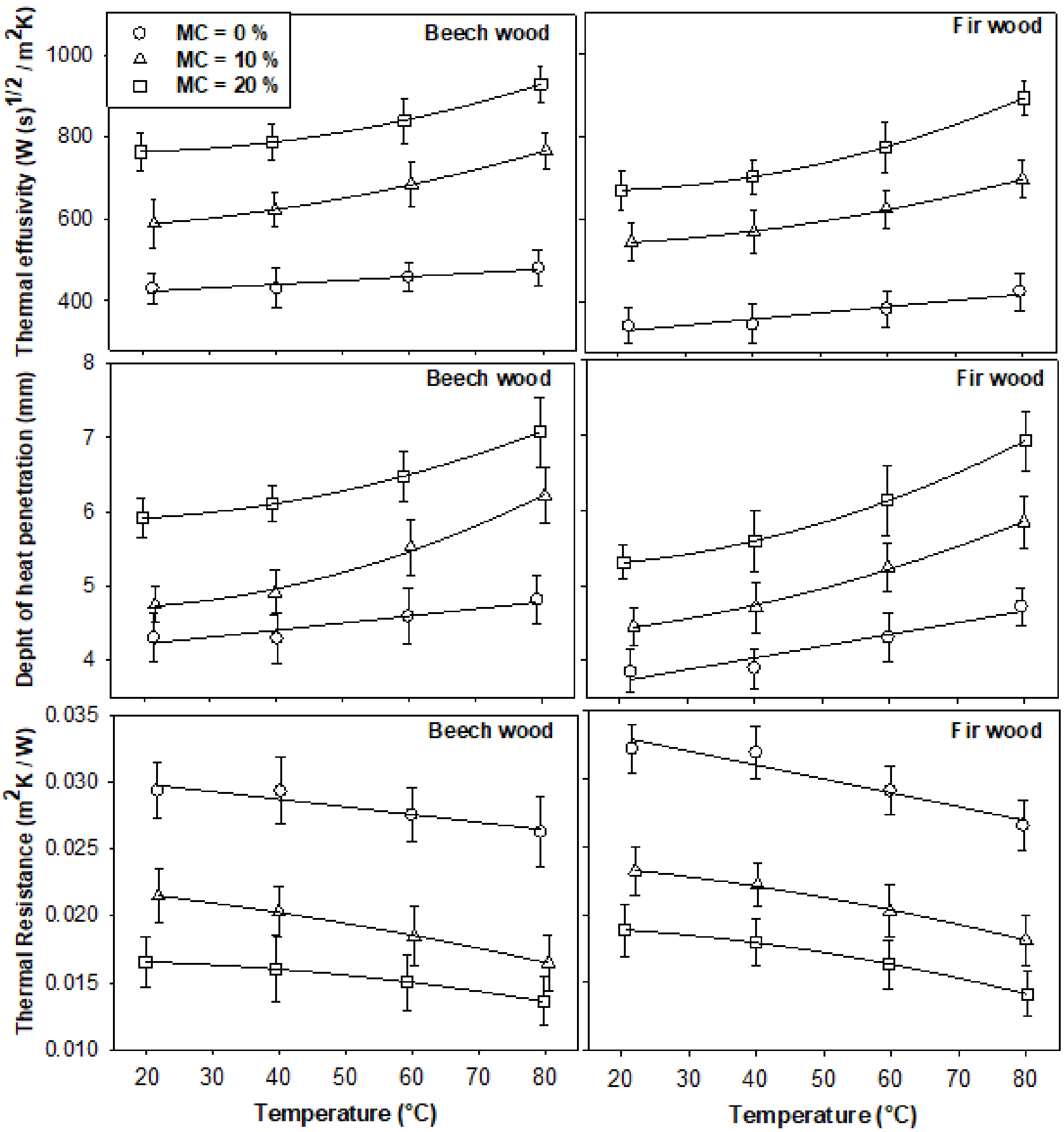

Fig. A1. Diagrams of the dependence of the mean value of thermal effusivity, depth of heat penetration an thermal resistance of beech and fir wood samples in the longitudinal direction on temperature with associated standard deviations and regression curves at moisture content of 0%, 10%, and 20%