Hindawi
Advances in Materials Science and Engineering
Volume 2019, Article ID 2303720, 9 pages
https://doi.org/10.1155/2019/2303720

Research Article

Applying the EDPS Method to the Research into Thermophysical Properties of Solid Wood of Coniferous Trees

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Received 29 December 2018; Accepted 5 March 2019; Published 3 April 2019

Academic Editor: Necmettin Maraşlı

The results of using the EDPS (extended dynamic plane source) method to determine thermophysical properties of solid wood of coniferous trees growing in Slovakia with 0% and 12% equilibrium moisture content are presented in the paper. Solid wood of two different tree species: Norway spruce (*Picea abies* L.) and Scots pine (*Pinus sylvestris* L.) was used in the research. The research was carried out independently in three anatomical planes. Coefficients of thermal conductivity, thermal diffusivity, and specific heat capacity were determined following the research. Comparing the research results to the values determined by other authors and already published models to calculate individual parameters, the fact that the data gathered using the EDPS method can be accepted in case of all studied thermophysical properties can be stated.

1. Introduction

Thermal properties of wood materials (solid wood and composite wood panels) were studied by many authors [1–4]. Thermophysical properties of wood depend on various parameters, such as geometry of the wood sample, moisture content (MC), and porosity. Wood as a hygroscopic material contains free and bound water. Almost all properties of wood, including thermal properties, are affected by the amount of water in wood (MC) [5–9].

The model of Kollmann and Malmquist from the year 1956 [10] based on the theory of thermal bridges is one of the most popular models of wood thermal conductivity [11]. This model does not take wood moisture content into consideration; i.e., it can be only applied in case of absolutely dry wood. Model created by American researchers can be considered an option to determine thermal conductivity depending on equilibrium moisture content but only in case of the direction perpendicular to the grain [12]. Assuming that the equilibrium moisture content is up to 25% and the direction is perpendicular to the grain, the mentioned model can be applied. Another data describing (mostly) the thermal conductivity obtained many years ago (e.g., [4, 13]) have been still, in many cases, applied to the heat transfer modelling despite the fact that these traditional experimental methods are not capable of dealing with dependency of the properties on temperature and moisture content (MC).

Slovakian authors were dealing with the thermal conductivity as well [14]. Their research studies were focused on the coefficient of thermal conductivity and thermal diffusivity of spruce wood under standard conditions. The method used was the quasi-dynamic method following the methods of Clark and Kingston [15] and Krischer and Esdorn [16]. The results are in compliance with those gathered in works of other authors. The authors [17, 18] investigating properties of medium-density fiberboards dealt with the quasi-dynamic method too. The research of the authors [19] was aimed at thermal conductivity and thermal diffusivity of wood. Oven-dry hardwood (birch) was analysed using the transient plane source (TPS) technique. The effect of temperature, density porosity, and anisotropy on thermal conductivity of wood was studied. The measurements were carried out in longitudinal and transverse directions. As the temperature increased from 20°C to 100°C, the thermal conductivity of each sample increased slightly in both longitudinal and transverse directions. Based on the authors, the effect of density and porosity on the thermal conductivity may relate to the presence of other scattering mechanisms such as voids and cell boundaries. It also seems that the dominant mechanism of heat transfer across the cell lumina in these types of wood is the heat conduction through the voids.

Another research was conducted by Sonderegger et al. [20]. The authors investigated thermal conductivity of three-layered solid wood panels from Norway spruce and of various wood-based materials (fiber and particle boards), which were tested with regard to temperature, moisture content, growth ring position, and variation of the central layer of three-layered solid wood panels. Thermal conductivity increases when there is an increase in temperature and moisture content. Thermal conductivity of spruce wood is 8–10% higher in the radial direction than in the tangential direction. Niemz et al. [21] measured thermal conductivity of Norway spruce and European beech in different anatomical directions. Thermal conductivity, thermal diffusivity, and heat capacity of both wood species in all principal directions (radial, tangential, and longitudinal) depending on the moisture content (MC) were determined. Thermal conductivity and thermal diffusivity depend on the anatomical direction, but heat capacity is independent of the anatomical direction. The results show that the thermal conductivity increases when the MC increases. Moreover, a dramatic increase in the tangential and smallest increase in the longitudinal direction are observed. Thermal conductivity is higher in case of beech samples than in spruce samples in all anatomical directions. Conductivity of both species is more than twice as high in the longitudinal direction as perpendicular to the grain.

Czajkowski et al. [22] developed a finite element inverse analysis procedure. When investigating wood-based panels, in-plane thermal conductivity was significantly higher in comparison to the transverse one. Therefore, anisotropy had to be taken into consideration, and the use of both in-plane and transverse thermal conductivity for modelling heat transfer was recommended. The effect of temperature on thermal conductivity was not clearly shown. The thermal conductivity values decrease when there is an increase in temperature. In some cases, the effect was not considered significant (e.g., OSB). On the contrary, the effect of temperature on the thermal conductivity of low-density fiberboard was the highest. That is why the data on thermal properties available in the literature should not be used to model the heat transfer.

Vozár et al. [23] measured thermal diffusivity of the four selected wood species. Wood samples were prepared and investigated in longitudinal and transverse (tangential and radial) directions under atmospheric pressure at the room temperature. Theory behind the step-heating method and the brief description of the experimental apparatus used was presented. The agreement between the experimental results and the theoretical curve computed using the estimated properties is shown.

Studies dealing with thermal properties of wood materials focused mostly on determining the effect of density, temperature, and MC on thermal conductivity, thermal diffusivity, and specific heat capacity [24–26]. There are many models of thermal properties in the literature, but there are only two standardized techniques for thermal investigating of wood and wood products [27]. The first technique is steady-state techniques working on establishing a temperature gradient over a known thickness of a sample and monitoring the heat flow from one side to the other. These methods are suitable for materials with low or average thermal conductivity [28, 29]. Other standardized techniques are transient dynamic techniques measuring temperature vs. the time response of the sample when a signal is sent to the body to create heat [30, 31].

When investigating the specific heat capacity of wood, especially the effect of temperature and moisture content must be taken into consideration. According to the known models, specific heat capacity of absolutely dry wood is not dependent on wood species and there is a linear correlation between heat capacity and temperature. Three basic models are used to describe specific heat capacity of absolutely dry wood. The models are as follows: Perelygin [32], Kollmann and Coté [33], and of American authors (US model) gathered by regression of experimentally observed values.

The aim of the paper is to verify whether the experimental EDPS apparatus can be applied to the research into the thermophysical properties of wood with sufficient accuracy. Solid wood of two different tree species: Norway spruce (*Picea abies* L.) and Scots pine (*Pinus sylvestris* L.), was used in the research, while basic thermophysical properties (coefficient of thermal conductivity, thermal diffusivity, and specific heat capacity) were determined in all three anatomical directions of wood with the moisture content of 0% and 12%.

2. Materials and Methods

2.1. Sample Preparation. Solid wood of two different conifers was used in the experiment. As a standard material used in Slovakia, two types of solid wood were selected: Norway spruce (*Picea abies* L.), hereafter referred to as SM, and Scots pine (*Pinus sylvestris* L.), hereafter referred to as BO. Squared timber with dimensions of 120×120 mm naturally seasoned to the moisture content of $18 \pm 2\%$ produced by cutting round wood was used as an initial material for samples. In case of samples of coniferous wood, only heartwood was used. The research was carried out in all main anatomical directions: longitudinal (L), radial (R), and tangential (T) directions.

Due to the experimental apparatus used, the material was divided into samples with dimensions of 100×100 mm and the thickness of approximately 12 mm. Direction of the grains in samples had to be the same in the whole area with the minimum differences (up to 15°). The sample set of each material with the same structural direction consists of 16 samples. Samples were air-conditioned for four weeks at the temperature of 20°C with the air humidity of 65% in order to reach the equilibrium moisture content. Measurement was carried out after air-conditioning when the average moisture content of samples was $12 \pm 1\%$. Moisture content was determined using gravimetric analysis in accordance with the standard ISO 13061-1 [34]. Laboratory dryer (PREMED, Warszawa, Poland) and laboratory scale (OHAUS, Greifensee, Switzerland) were used in the analysis. When the moisture content of samples was 0%, the samples were analysed in the drying oven at the temperature of 103 ± 2°C. The samples were weighed regularly. When the weight of the samples in two consecutive weighing remained constant, the samples were considered absolutely dry.

Measurements of the reference material were carried out in order to verify the accuracy and validity of the experimental apparatus used. Polymethyl methacrylate (PMMA) also known as acrylic or acrylic glass and by the trade names Plexiglas was used as a reference material. PMMA was selected especially due to its stability, homogeneity, as an organic material with low thermal conductivity, and poor dispersion of studied properties. This material has been used successfully as a reference material in the research into material properties of poor conductors over a long period [35].

2.2. Experimental Apparatus. The experiment was carried out using the apparatus based on the EDPS method (extended dynamic plane source). Its main role is to determine thermophysical properties of slow-conducting materials under dynamic conditions of heat transfer. The apparatus used allows researchers to determine coefficient of thermal conductivity λ and thermal diffusivity a at the same time. Moreover, samples with the thickness up to 20 mm depending on the thermal conductivity in the studied direction can be used in the experiment.

Extended dynamic plane source method (Figure 1) is one of the dynamic methods with heat gradually supplied, while one-dimensional conduction heat transfer is formed. The DPS method is modified in order to measure the properties of slow-conducting materials with the value of thermal conductivity of $\lambda \leq 2\,\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$ [36, 37]. Resistance sheet operates as a heat source and the temperature sensor (by measuring the changes in electrical resistance). Heat source is located between two samples. Temperature of the heat source can be determined as a linear correlation between electrical resistance of a material and temperature. Sample surface closely bonded with the heat source must be flat enough in order to ensure the best connection. Heat sink with the weight of approximately 4 kg is placed on the upper sample to provide better connection between samples and the heat source, to maintain stable conditions and to create the pressure between sample and the heat source. Providing quality contact between sample surface and the heat source, the temperature of the sample surface can be considered equal to the temperature of the heat source.

Due to the EDPS method used, samples used in measurements were matched. Each pair was measured three times, while the final assessment resulted from all conducted measurements. In total, 24 measurements were carried out using each sample set with an individual anatomical direction.

Nickel-based resistance sheet with dimensions of 100 mm × 100 mm was used as a heat source and temperature sensor in the experimental apparatus used in the research. Temperature coefficient of the resistance of the heat source used to measure the temperature during the experiments was $4.8 \cdot 10^{-3}\,\mathrm{K^{-1}}$. Panels of high-conducting materials are made from duralumin EN AW 6082 T6 with the thermal coefficient of $\lambda = 180\,\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$ with the dimensions of 120 mm × 120 mm × 100 mm. The surface of duralumin panels touching the laboratory power supply Matrix MPS-3003D providing accuracy and stability of output parameters in the range from 0–30 VDC and 0–3 ADC was used as a source of power to supply heat source. PC recording data in real time and the software evaluating gathered data during experiment are parts of the device.

Temperature gradient taking into consideration the experimental apparatus and experimental conditions is calculated using the following equation:

$$T(t) = \frac{ql}{\lambda} \cdot \sqrt{\frac{t}{\pi\Theta}} \left(1 + 2\sqrt{\pi} \sum_{n=1}^{\infty} \beta^n \mathrm{ierfc}\left(n\sqrt{\frac{\Theta}{t}} \right) \right), \quad (1)$$

where q is the heat flux density, λ is the thermal conductivity of a material, and Θ is the time defined using the following equation:

$$\Theta = \frac{l^2}{a}, \quad (2)$$

where l (m) is the sample thickness and a (m^2/s) is the thermal diffusivity of a material.

Parameter β defines imperfect heat transfer, and ierfc is an integral of error function. Values of thermal conductivity λ and characteristic time θ are gathered using the parametric fitting of real measured dependence of temperature on time using equation (1) [38]. Subsequently, thermal diffusivity coefficient is calculated using equation (2). Finally, correlation coefficient between theoretical curve and experimental results is determined. In case the value of the mentioned parameter is higher than 0.999, the model can be considered valid. When the volumetric weight ρ is known, specific heat capacity c is determined using the following equation:

$$c = \frac{\lambda}{a \cdot \rho}. \quad (3)$$

3. Results and Discussion

3.1. Reference Material Measurement (PMMA). PMMA samples with the dimensions of 100 × 100 × 3 mm were used as a reference material. Values of thermal conductivity, thermal diffusivity, and specific heat capacity of the samples were determined experimentally using the EDPS method. Ten measurements were carried out, while a final value was determined as the average value of all conducted measurements.

Correlation coefficient between theoretical and experimental curve of an increase in temperature in case of PMMA was higher than 0.99997. Gathered values of monitored

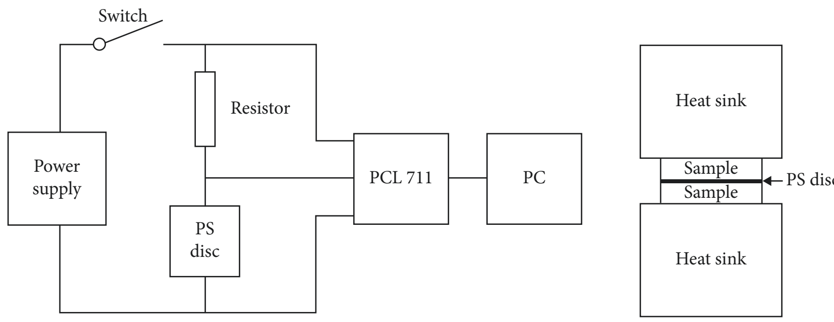

FIGURE 1: Design of experimental EDPS apparatus and setup of the experiment.

parameters are mentioned in Table 1. Table values of individual parameters are shown in Table 1 as well.

TABLE 1: Thermophysical properties of PMMA determined by the EDPS method and table values.

	EDPS	Table values
λ ($W \cdot m^{-1} \cdot K^{-1}$)	0.201 ± 0.002	0.19–0.24
a ($mm^2 \cdot s^{-1}$)	0.121 ± 0.003	0.109–0.143
c ($J \cdot kg^{-1} \cdot K^{-1}$)	$1{,}452 \pm 23$	1,460–1,470
ρ ($kg \cdot m^{-3}$)	1,195	1,150–1,190

3.2. Solid Wood Measurement. After verifying the devices used, measurements of wood samples were carried out. Three anatomical directions were measured individually. Average values of observed parameters at the moisture content of 0% determined experimentally are summarised in Table 2. Average values of studied parameters determined experimentally at the moisture content of 12% are shown in Table 3.

3.3. Effect of Density on the Thermal Conductivity of Wood. Density and moisture content are important parameters affecting thermal conductivity of wood significantly. Linear dependence of thermal conductivity on density is defined in almost all experimentally set and published models (e.g., [12, 39]). Linear dependence of thermal conductivity on moisture content of wood below the fibre saturation point is confirmed as well (e.g., [21, 27]). An increase in thermal conductivity in relation to density can be explained by an increase in portion of the wood substance [11]. Thermal conductivity of wood decreases due to low thermal conductivity of air content in cell lumens ($\lambda_{AIR} = 0.026\,W \cdot m^{-1} \cdot K^{-1}$ at 20°C). Research studies and models dealing with the issue of thermal conductivity of wood in individual anatomical directions show that thermal conductivity in the grain direction increases in relation to density faster than in direction perpendicular to the grains. Values of thermal conductivity determined following the models used were defined for real average density of samples used in the research. Density mentioned by other cited authors is the value used to determine the given value of thermal conductivity.

3.4. Thermal Conductivity. Values of thermal conductivity at the moisture content of 0% were compared to the values of the Kollmann model [39] and according to the model of American authors [12]. Following the authors of these models, thermal conductivity is determined using the other theoretical values. According to Kollmann and Malmquist, thermal conductivity is determined on the basis of thermal bridges using theoretical values of wood substance density, air conductivity, and wood substance conductivity. American authors describe dependence of thermal conductivity using so-called specific gravity defined as the ratio of wood density at the given moisture content to the water density, while they assume that the dependence of thermal conductivity on the moisture content is linear just as on specific gravity. At the same time, values of thermal conductivity and wood substance density are not taken into consideration. Constant of proportionality resulted from the regression using 1,000 measured sets of thermal conductivity of American wood species at various moisture contents with various densities. In presented research, the thermal conductivity was determined using "Slovak" wood species; therefore, the constant of proportionality can differ. Due to different approaches of authors, differences between models can be seen.

According to the model of Kollmann and Malmquist, the value of thermal conductivity of Norway spruce in the longitudinal direction at the given density when it is absolutely dry may be equal to 0.203 W/m/K. It means there is a percentage difference of 2.5% between experimental and theoretical value. In case of Scots pine, the difference is 2.8%.

According to the model of Kollmann and Malmquist, in case of samples in radial and tangential directions, theoretical values of thermal conductivity of spruce and pine wood when it is absolutely dry is $0.114\,W \cdot m^{-1} \cdot K^{-1}$ or $0.115\,W \cdot m^{-1} \cdot K^{-1}$, and it means the difference is 14.9% or 13.0%.

Theoretical values of thermal conductivity were determined also using the model of American authors valid in the direction perpendicular to the grain up to the fiber saturation point (FSP) which is at the level of 25–30%; i.e., the moisture content of measured samples is considerably lower. The value of thermal conductivity determined for Norway spruce when it is absolutely dry is $0.093\,W \cdot m^{-1} \cdot K^{-1}$, and in case of Scots pine, it is $0.094\,W \cdot m^{-1} \cdot K^{-1}$. According to the American model, percent difference between experimentally gathered values and theoretical values is, in case of Norway

Table 2: Average thermophysical properties of Norway spruce (SM) and Scots pine (BO) at the moisture content of 0% determined by the EDPS method, models, and national building standard.

	Norway spruce (SM)			Scots pine (BO)		
	L	*R*	*T*	*L*	*R*	*T*
			EDPS			
λ	0.198 ± 0.021	0.094 ± 0.006	0.100 ± 0.006	0.223 ± 0.018	0.098 ± 0.007	0.103 ± 0.007
a	0.460 ± 0.038	0.236 ± 0.029	0.256 ± 0.026	0.428 ± 0.043	0.209 ± 0.031	0.220 ± 0.019
c	1,120.4 ± 65.7	1,049.8 ± 83.2	1,025.0 ± 39.8	1,257.9 ± 92.3	1,238.3 ± 110.5	1,195.2 ± 66.6
ρ_0	385.1 ± 19.6	382.4 ± 24.0	380.8 ± 14.9	414.2 ± 18.5	383.2 ± 17.6	393.4 ± 15.8
λ	0.198 ± 0.021	0.097 ± 0.007		0.223 ± 0.018	0.100 ± 0.007	
			[39]			
λ	0.203	0.114		0.217	0.115	
			[12]			
λ	—	0.093		—	0.094	

Table 3: Average thermophysical properties of Norway spruce (SM) and Scots pine (BO) at the moisture content of 12% determined by the EDPS method, models, and national building standard.

	Norway spruce (SM)			Scots pine (BO)		
	L	*R*	*T*	*L*	*R*	*T*
			EDPS			
λ	0.268 ± 0.025	0.105 ± 0.006	0.112 ± 0.004	0.298 ± 0.012	0.131 ± 0.003	0.117 ± 0.005
a	0.415 ± 0.037	0.182 ± 0.006	0.197 ± 0.010	0.409 ± 0.014	0.200 ± 0.013	0.178 ± 0.003
c	1,510.4 ± 84.3	1,460.0 ± 49.6	1,419.7 ± 31.6	1,529.6 ± 30.2	1,529.4 ± 24.1	1,521.0 ± 41.6
ρ_{12}	428.2 ± 15.1	428.5 ± 36.6	426.7 ± 14.4	475.6 ± 6.5	451.5 ± 27.1	457.9 ± 6.9
λ	0.268 ± 0.025	0.108 ± 0.006		0.298 ± 0.012	0.126 ± 0.008	
			[11]			
λ	0.288	0.147	0.125	0.285	0.124	0.137
			[39]			
λ	0.223	0.109		0.245	0.115	
			[12]			
λ	—	0.111		—	0.117	

spruce, 4.3% and, in case of Scots pine, is 6.8%. It means the lower coefficient of variation in comparison to the EDPS apparatus is used.

Following the mentioned outcomes, the fact that all measured values of thermal conductivity when the wood is absolutely dry are in compliance with the theory of American authors as well as in compliance with the model of thermal bridges of Kollmann and Malmquist can be stated.

Coefficient of thermal conductivity in the longitudinal direction when the EDPS method is used is in compliance with experimental results for spruce wood, as mentioned by Požgaj et al. [11]. Difference is less than 7.0% in the longitudinal direction for Norway spruce; in case of Scots pine, it is even less than 4.6%. Detailed research into thermophysical properties of Norway spruce was carried out by Regináč and Babiak [14]. Thermal conductivity of spruce wood in the longitudinal direction was experimentally determined in the range from 0.229 to 0.339 $W\cdot m^{-1}\cdot K^{-1}$ ($\rho_{12} = 405$–$462\ kg\cdot m^{-3}$). Average value of thermal conductivity in the longitudinal direction resulting from our research is 0.268 $W\cdot m^{-1}\cdot K^{-1}$, and thus, it is in a given range.

Following the results [21, 40] for Norway spruce, thermal conductivity in the longitudinal direction is 0.277 $W\cdot m^{-1}\cdot K^{-1}$ ($\rho_{12} = 425\ kg\cdot m^{-3}$); it means the difference is 3.3%.

Comparing the results to the values determined using the model of Kollmann [39], the difference is 6.9% (SM) or 21.6% (BO). Later, Kollmann published another model used to determine thermal conductivity of wood [10]. Because it was created following the theory of thermal bridges, it can be used to determine the thermal conductivity only when the wood is absolutely dry.

In the radial and tangential direction, coefficient of thermal conductivity measured in the experiment is different in individual directions. In case of spruce wood (SM), the difference in the individual direction is 6.7%. In case of pine wood, the difference is 12.0%. According to Požgaj, comparing to experimental values, the largest difference of Norway spruce samples (SM) is in the radial direction (28.6%) and the smallest one is in the radial direction of Scots pine samples (5.7%). Thermal conductivity of spruce wood in the radial direction is determined by Regináč and Babiak [14] in the range from 0.133 to 0.157 $W\cdot m^{-1}\cdot K^{-1}$, and in the tangential direction, it ranged from 0.113 to 0.132 $W\cdot m^{-1}\cdot K^{-1}$ ($\rho_{12} = 405$–$462\ kg\cdot m^{-3}$). In case of the radial direction, the values resulting from our research are lower, and the difference is 21%. In case of the tangential direction, the gathered values are the lower bound. According to Niemz, thermal conductivity perpendicular to the grain equals 0.093 $W\cdot m^{-1}\cdot K^{-1}$ ($\rho_{12} = 428\ kg\cdot m^{-3}$). Therefore, the difference of results gathered using the EDPS method is 16.1%.

Following the other published model [4], thermal conductivity of spruce wood based on density of samples when they are absolutely dry with the moisture content of 12% is 0.104 W·m^{-1}·K^{-1}. In case of pine wood, thermal conductivity is 0.113 W·m^{-1}·K^{-1}. Difference of the EDPS method is 3.9% (SM) or 11.5% (BO). In this publication, thermal conductivity of spruce wood at the moisture content of 12% is in the range from 0.11 to 0.12 (ρ_{12} = 370–430 kg·m^{-3}) and for that of pine wood, it ranged from 0.11 to 0.17 (ρ_{12} = 370–620 kg·m^{-3}).

Other model to determine the dependence following the experiments was published in [41]. Density of samples used in the research was in the range from 360 to 504 kg·m^{-3}. According to the equation mentioned in this work, thermal conductivity in the direction parallel to the grain equals 0.103 W·m^{-1}·K^{-1}; thus, the difference of the EDPS method is 4.9%. Values calculated according to the model of Kollmann determining the thermal conductivity perpendicular to the grain are shown in Table 2. Comparing to the model, the difference is 0.9% (SM) or 9.6% (BO).

Difference measured when the model of American authors is used (US model) is 2.7% (SM) or 7.7% (BO). Density of samples used in the research of American authors was in the range from 360 to 504 kg·m^{-3}. This model was created following the research on 42 softwood species.

Following the comparison, the fact that the difference of results gathered using the EDPS method for the research into the solid wood is relatively small can be stated. In case of the longitudinal direction, the compliance with the values measured by Požgaj can be seen. In case of direction perpendicular to the grain, the compliance with the model of Kollmann as well as the US model is observed. In general, Figures 2 and 3 show the fact that the values calculated using theoretical models are lower than the experimentally measured values.

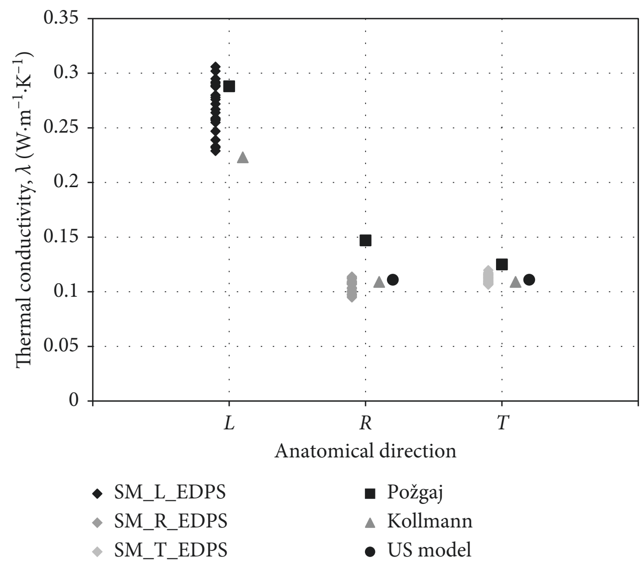

Figure 2: Thermal conductivity as a function of the anatomical direction in Norway spruce (at the moisture content of 12%).

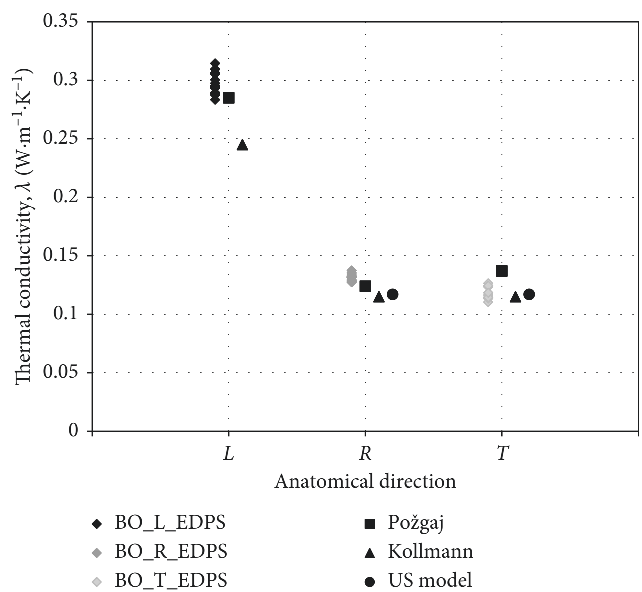

Figure 3: Thermal conductivity as a function of the anatomical direction in Scots pine (at the moisture content of 12%).

3.5. Thermal Diffusivity. Theoretical values of coefficient of thermal diffusivity in the longitudinal direction at the moisture content of 0% can be determined only using the model of Kollmann. Experimentally determined value of thermal diffusivity when Norway spruce samples are absolutely dry equals 0.437 mm^2·s^{-1}, or in case of Scots pine samples, it is 0.424 mm^2·s^{-1}. Therefore, the difference for spruce wood is 5.3%, and for pine wood, it is less than 1.0%.

Theoretical values in the direction perpendicular to the grain at the moisture content of 0% determined using the model of Kollmann equals 0.267 mm^2·s^{-1} for Norway spruce or 0.266 mm^2·s^{-1} for Scots pine. It means the difference is 7.9% for spruce wood and 19.4% for pine wood. Thermal diffusivity in the direction perpendicular to the grain determined using the calculation following the US model at the moisture content of 0% (thermal conductivity and specific heat capacity) and real sample density in cross section is, in case of both wood species, the same—0.196 mm^2·s^{-1}. Average difference is, in case of Norway spruce, approximately 25.4%, and in case of Scots pine, it equals approximately 9.6%.

Experimentally determined values of thermal diffusivity of spruce wood in the longitudinal direction at the moisture content of 12% can be compared to those published by Regináč and Babiak [14]. They determined the thermal diffusivity in the range from 0.337 to 0.495 mm^2·s^{-1}. The value resulting from our research is 0.415 mm^2·s^{-1}, and thus, it is in the mentioned range.

Values in the longitudinal direction can be compared to the values according to the model of Kollmann [39], allowing the researchers to determine thermal diffusivity and heat capacity in the longitudinal direction. Following the real values of density, the thermal diffusivity in the longitudinal direction equals 0.340 mm^2·s^{-1} (SM) or 0.336 mm^2·s^{-1} (BO). Comparing the values to those gathered using the EDPS method, the difference is 22.1% (SM) or 21.7% (BO).

Coefficient of thermal diffusivity determined using the EDPS method is in the direction perpendicular to the grain almost the same in both wood species, and the value is $0.190 \pm 0.011\,\mathrm{mm^2{\cdot}s^{-1}}$ (SM) and $0.192 \pm 0.015\,\mathrm{mm^2{\cdot}s^{-1}}$ (BO). According to Regináč and Babiak, the thermal diffusivity of spruce wood in the radial direction was determined in the range from 0.156 to $0.174\,\mathrm{mm^2{\cdot}s^{-1}}$. In the tangential direction, the thermal diffusivity ranged from 0.149 to $0.152\,\mathrm{mm^2{\cdot}s^{-1}}$. Values determined using the EDPS method in both directions are bigger. Correlation between thermal diffusivity of wood and density at the room temperature was investigated by Harada et al. [41]. When the density is $427.6\,\mathrm{kg{\cdot}m^{-3}}$ (SM), thermal diffusivity is $0.192\,\mathrm{mm^2{\cdot}s^{-1}}$, and when the density equals $454.7\,\mathrm{kg{\cdot}m^{-3}}$ (BO), thermal diffusivity is $0.190\,\mathrm{mm^2{\cdot}s^{-1}}$. The compliance with the values determined using the EDPS method can be seen.

Thermal diffusivity in the direction perpendicular to the grain determined using the calculation following the US model (thermal conductivity and heat capacity) and real density in cross section is the same—$0.172\,\mathrm{mm^2{\cdot}s^{-1}}$ for both wood species. Average difference in case of both wood species is approximately 10%. Thermal diffusivity can be determined in a similar way following the model of Kollmann. The value of thermal diffusivity calculated using the mentioned model is $0.167\,\mathrm{mm^2{\cdot}s^{-1}}$ (SM) or $0.165\,\mathrm{mm^2{\cdot}s^{-1}}$ (BO). In this case, the average difference of measured values is approximately 14.5%.

3.6. Specific Heat Capacity. Specific heat capacity at the moisture content of 0% determined using the EDPS method in individual anatomical directions is for both wood species in Tables 2 and 3. Comparison of the average specific heat capacity measured in wood and specific heat capacity calculated using the mentioned models [12, 32, 33] at the moisture content of 0% is shown in Table 4.

According to research studies, specific heat capacity of wood is a scalar quantity independent of the anatomical direction. However, experimentally set values using the EDPS methods summarised in Tables 2 and 3 show slight increase in heat capacity in the longitudinal direction in case of Norway spruce. Forasmuch as the specific heat capacity is calculated following experimentally set values of thermal conductivity, diffusivity, and density (equation (3)), the error in determining the values can be considered the reason. Diffusivity and thermal conductivity ratio must be equal in order to gather similar values of heat capacity in all directions at the same density. In case of Norway spruce in the longitudinal direction, the ratio is lower than the results calculated in higher values of specific heat capacity. The difference can be due to significant differences in the sample structure not causing the changes in density but affecting thermophysical properties (different proportions of earlywood and latewood, the size of annual rings, and reaction wood).

Following the data corresponding with the specific heat capacity at the moisture content of 0% mentioned in Table 4, the difference of the values according to Perelygin for Norway spruce and Scots pine is 34.7% or 24.2%. The difference of the values according to Kollmann for spruce wood and pine wood is 12.5% or 1.5%. The difference of the values according to the American authors for spruce wood and pine wood is 4.2% or 11.2%. Following the mentioned values of coefficient of variation, the compliance of experimentally determined values of specific heat capacity determined using the EDPS method with the theoretical values can be observed. Larger difference in case of Perelygin is due to the high value of coefficient of variation of specific heat capacity of this author in comparison to the values mentioned by Kollmann and American authors.

Table 4: Comparison of experimentally determined specific heat capacity and the specific heat capacity calculated using the models at the moisture content of 0%.

c_0 ($\mathrm{J{\cdot}kg^{-1}{\cdot}K^{-1}}$)	Norway spruce	Scots pine
EDPS	$1{,}062.3 \pm 121.2$	$1{,}232.5 \pm 95.1$
Perelygin [32]	1,626.4	
Kollmann and Côte [33]	1,214.4	
US model [12]	1,108.3	

Table 5: Comparison of experimentally determined specific heat capacity and the specific heat capacity calculated using the models at the moisture content of 0%.

c ($\mathrm{J{\cdot}kg^{-1}{\cdot}K^{-1}}$)	Norway spruce	Scots pine
EDPS	$1{,}462.5 \pm 88.4$	$1{,}520.5 \pm 35.1$
Regináč and Babiak [13]	1,830–1,960	
Perelygin [12]	1,900.6	
Kollmann and Côte [33]	1,532.8	
US model [12]	1,438.1	

Specific heat capacity at the moisture content of 12% determined using the EDPS method in individual anatomical directions is similar; and differences in individual directions are 6.0% (SM) or 0.5% (BO). Comparison of the average specific heat capacity measured in wood and specific heat capacity calculated using the mentioned models [11, 32, 33] at the moisture content of 12% is given in Table 5.

Following Table 5, the compliance of the values of specific heat capacity at the moisture content of 12% resulting from the experiment using the EDPS method with the values determined using the calculation according to the model of Kollmann and American authors can be seen. In this case, the difference is less than 4.6%. Comparing to the values determined by Regináč and Babiak, the specific heat capacity determined using the EDPS method is lower by approximately 23%. Similar difference can be observed in case of the value determined following the model of Perelygin (approx. 21.5%). The values gathered using the model of Perelygin are identical with the values determined by Regináč and Babiak.

4. Conclusions

Thermophysical properties of two types of solid wood were determined using the EDPS (extended dynamic plane source) method. The research was dealing with solid wood of Norway spruce and Scots pine, while basic thermophysical properties (coefficient of thermal conductivity, coefficient of thermal diffusivity, and specific heat capacity) were determined in all anatomical directions at the moisture content of 0% and 12%. Measurements of the reference material (PMMA) were carried out in order to verify the accuracy and validity of the experimental apparatus used. In the discussion, experimentally determined values were compared to results of other authors and the values gathered using the calculation according to available models.

Following the mentioned results, the variance of the values of individual studied parameters determined by individual authors and the results determined following mentioned models can be observed. The differences between the values given by individual authors can be due to different methodologies used to determine investigated properties, natural inhomogeneity of wood properties in individual directions, or in different parts of trunk, as well as due to a different wood density within the same tree species or the number of samples investigated by individual authors. Regarding the mentioned facts, the outcome that the EDPS method can be used to investigate thermophysical properties and results gathered using the method can be compared to the results of other authors and other experimental methods can be stated. Moreover, it can be applied to study thermophysical properties of wood and wood-based materials. This statement can be supported by the results of the research into thermophysical properties determined using the EDPS method to investigate wood-based composite materials (OSB) [27].

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was supported by Slovak Research and Development Agency under contract no. APVV-14-0506, “Lowering of formaldehyde emission from wood based panels by environmental progressive modification of polycondensation adhesives with biopolymers from leather waste, natural nanofillers, additives and activators,” and VEGA under contract no. 1/0717/19, “Assessment of environmental impacts of wood-based buildings throughout the whole life cycle.”

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