Thermophysical Properties of OSB Boards *versus* Equilibrium Moisture Content

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The basic thermophysical properties of oriented strand boards were determined experimentally for use in humid conditions (OSB3) depending on the moisture content. The dependency between the thermal conductivity, thermal diffusivity, specific heat capacity, and the moisture content in the range of 0% to 10%, was examined. The non-stationary extended dynamic plane source (EDPS) experimental method was used. EDPS method was modified for anisotropic materials, *i.e.* with special considerations of heat-loss effect occurring at the edge of measuring samples, finite geometry of the sample and orthotropic thermal conductivity, for use with anisotropic materials. The validity of the experimental method was verified on polymethylmethacrylate (PMMA) samples. The error rate of measurements conducted on PMMA samples was less than 3%, and for OSB3 boards it was less than 5.5%. Based on the experimental results, regression equations of the dependency between the monitored properties and the moisture content were determined. In the case of thermal conductivity and thermal capacity, the determined dependencies showed a high correlation rate.

Keywords: Oriented strand board; Thermal conductivity; Specific heat capacity; Extended dynamic plane source method

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INTRODUCTION

Oriented strand board (OSB) is a wood-based engineering material formed by adding adhesives between layers of wood strands by compressing the layers at a specific pressure and at various temperature profiles. Such OSB has good mechanical properties, and it is therefore also widely used in many load-bearing applications in construction, especially in wooden houses. The four grades of OSB are defined in terms of their mechanical performance and relative resistance to moisture: OSB1– General purpose boards and boards for interior fitments (including furniture) for use in dry conditions; OSB2– Load-bearing boards for use in dry conditions; OSB3– Load-bearing boards for use in humid conditions; and OSB4– Heavy-duty load-bearing boards for use in humid conditions (EN 300:2006). In comparison with plywood, the price of OSB boards is lower than that of plywood and the mechanical properties are almost the same.

The thermophysical properties of wood-based materials (solid woods, wood-based composites) have been widely studied in the literature (Siau 1984; TenWolde *et al.* 1988; Akoshima and Baba 2006; Aydin *et al.* 2014; Kminiak and Gaff 2015; Gaff *et al.* 2015; Igaz *et al.* 2015, 2016; Kvietková *et al.* 2015; Ružiak *et al.* 2017). The heat transfer in wood depends on the geometry of the wood sample, as well as porosity, moisture content

(MC), and many other factors, *e.g.* wood after thermal modification (Košúth *et al.* 2012; Bekhta *et al.* 2015; Bekhta *et al.* 2016; Gaff *et al*. 2017a, 2017b). Because wood is a hygroscopic material, it mostly contains water in the form of bonded water or free water. The amount of water, which can be characterized by MC, has a profound effect on almost all properties of wood, including its thermal properties. Therefore, it is of great importance that the determined properties are given together with the actual MC (Adl-Zarrabi and Boström 2004; Fidríková *et al.* 2013a, 2013b).

Studies have focused primarily on determining the effect of the density or MC on the specific heat capacity and thermal conductivity (Eckert and Goldstein 1976). There are various models of heat conductivity and specific heat capacity in the literature, but only two standardized techniques are available for accurate thermal testing of anisotropic materials such as wood and wood composites. There are two basic measurement techniques. The first group of measurement techniques is based on steady-state techniques, which works on establishing a temperature gradient over a known thickness of a sample and monitoring the heat flow from one side to the other. These techniques are best for materials with low or average thermal conductivities at moderate temperatures (Kol 2009a,b). The second group of measurement techniques are the transient (dynamic) techniques, which measure temperature *vs.* the time response of the sample when a signal is sent to the body to create heat. These methods can be used for thermal diffusivity and thermal conductivity measurements (Yesilata and Turgut 2007). These authors focused on a simple and inexpensive thermal testing technique. The measurements were based on the analysis of transient data. Another author, Al-Ajlan (2006), used a transient plane source (TPS) technique, also called the hot disk (HD), for measuring the thermal conductivity and diffusivity of materials. Al-Ajlan discovered that the thermal conductivity increases with increasing temperature, and decreases with increasing density over the temperature and density ranges. Adl-Zarrabi and Boström (2004) investigated the thermal properties of Norway spruce, particleboard, and low-density fibreboard using the transient plane source method at different temperatures and at different MCs. Their measured values, as well as the measured effect of the temperature on the thermal properties were similar to previous studies (Adl-Zarrabi and Boström 2004). Dupleix *et al.* (2012) measured the thermal properties of green wood by the TPS technique. They tested four wood species (Douglas fir, beech, birch, and spruce), and the results were compared with literature data and with data obtained by the laser flash method. They found a linear relationship between the thermal properties and density, and between the thermal properties and MC. They also found that the TPS technique is more universal than the transient hot wire (THW) or the transient hot strip (THS) methods, where the temperature measurement is localized to the thermocouple hot junction. Comparisons with proven older techniques, such as the steady-state and laser flash method, have demonstrated similar results, establishing that the TPS technique offers new opportunities for characterizing the thermal properties of wood, especially in the green state (Dupleix *et al.* 2012; Gaff *et al*. 2016; Kvasnová *et al.* 2016; Mitterpach and Štefko 2016). Li *et al*. (2013) proposed a modified step-wise transient method with special considerations of heat-loss effect occurring at the edge of measured samples, finite geometry of the sample, and orthotropic thermal conductivity. Transient heat transfer analysis of anisotropic material was used by Zhang *et al*. (2017). These authors used the Element-Free Galerkin (EFG) method. Their model can simplify the pretreatment for anisotropic material, which make the thermal conductivity executed by orthotropic factor and off-angle. Ohmura *et al*. (2001) estimated the mean thermal conductivity of anisotropic materials. They used the method of the plane directional thermal conductivity of fibrous insulations using the cyclic heat method and the transient hot-wire method.

TenWolde *et al*. (1988) have published a complex study of solid wood and wood composites thermal properties versus density, MC, and temperature, but their publication did not involve data pertaining to OSB boards. Studies on thermal properties of OSB are scarce (especially specific heat capacity and thermal diffusivity), and comparison with other types of wood-based materials with a different construction and production technology as *e.g.* plywood, particleboard or fiberboard is not appropriate.

Authors Yapici *et al.* (2010) studied the dependence of urea formaldehyde adhesive concentration on the thermal conductivity of OSB boards. It is clear from the results that the thermal conductivity increases with the adhesive ratio, pressing time, and pressing pressure in the interval of conductivity between 0.129 $W{\cdot}m^{-1}{\cdot}K^{-1}$ and 0.170 $W{\cdot}m^{-1}{\cdot}K^{-1}$.

Thoemen *et al.* (2010) studied the dependence of thermal conductivity *versus* MC for the OSB3 board with a specific gravity of 0.562 and thickness of 18 mm. The authors found the dependence of thermal conductivity $\lambda_{10\,°C}$ *versus* MC MC (%) measured at 10 °C as shown by Eq. 1.

$$\lambda_{10\,°C} = 0.0959 + 0.00074{\cdot}MC(\%) \tag{1}$$

Many authors have also studied the dependence of thermal diffusivity *versus* MC. Most of these authors predict that the thermal diffusivity does not change significantly with the MC, and therefore the thermal diffusivity is only a function of wood material typ.

Other researchers (Rice and Redfern 2016) measured the dependence of specific heat capacity *c* in $J{\cdot}kg^{-1}{\cdot}K^{-1}$ on the MC (%). They found the dependence for specific heat capacity *c* in Eq. 2.

$$c = 1170.4 + 25.1{\cdot}\mathrm{MC} \tag{2}$$

Therefore, it is clear from previous literature that the thermophysical properties of OSB boards vary significantly with the manufacturing conditions, basic material selection (adhesive, OSB mat wood material), and many other parameters.

Kollmann and Malmquist (1956) studied the basic thermal conductivity of wood-based materials. With the help of the Kollmann model, it is possible to predict the thermal conductivity in the dry state (Kollmann and Malmquist 1956; Požgaj *et al.* 1997).

Perelygin (1965) and Kollmann and Côté (1968) studied the basic specific heat capacity in $J{\cdot}kg^{-1}{\cdot}K^{-1}$. Perelygin (1965) describes the specific heat capacity in the dry state as the function of temperature, *T* (°C) in Eq. 3,

$$c_{0\%MC} = 1571.4 + 2.93 \cdot T \tag{3}$$

Kollmann and Côté (1968) describe this dependence in Eq. 4,

$$c_{0\%MC} = 1117.2 + 5.02 \cdot T \tag{4}$$

Both studies compute the specific heat capacity dependence *versus* MC with the use of Eq. 5 (Požgaj *et al.* 1997),

$$c_{MC} = \frac{c_{0\%MC} + 0.01.MC(\%).c_{water}}{1 + 0.01.MC(\%)} \tag{5}$$

where $C_{0\%MC}$ is the specific heat capacity in the dry state ($J.kg^{-1}.K^{-1}$), MC is the moisture content in the sample (%), and c_{water} is the specific heat capacity of water, 4186 $J{\cdot}kg^{-1}{\cdot}K^{-1}$.

From Eqs. 2 through 5, it is clear that the specific heat capacity varies significantly between the authors' models.

This paper focused on the material research of basic thermophysical properties of oriented strand boards for use in humid conditions (OSB3) depending on the moisture content. The non-stationary extended dynamic plane source (EDPS) experimental method was used. This method was primary designed for synthetic polymer materials research, another goal of our research was to find out applicability of this method for wood-based materials research.

EXPERIMENTAL

Materials

The input material for creating experimental samples was the commercially available OSB3 board (Bučina DDD, Slovakia, Zvolen) with a thickness of 10 mm. The OSB board is produced as a three-layer wood composite made of oriented large-area chips. The input material for the production of OSB boards is mainly the Scots pine wood (*Pinus sylvestris*). The OSB boards are mostly used in construction for supporting and decorative elements in wooden constructions (walls, ceilings, basements), as deburring elements, or as packaging material for transport containers.

First, 100 mm × 100 mm × 10 mm experimental samples were cut from the OSB board. The sample sizes were based on the apparatus used, which is designed for researching samples of the aforementioned dimensions. The samples were not further mechanically modified. A total of 16 samples were prepared.

The experimental samples were then conditioned in an environmental chamber for 14 days (20 °C and 65%) to achieve an equilibrium MC throughout the material. The resulting average MC of the samples after individual conditioning cycles was approximately 10%, 8%, and 5%. Finally, the samples were oven-dried at 103 °C ± 2 °C until they reached a constant weight. The sample MC was determined gravimetrically using a laboratory dryer (PREMED, Warszawa, Poland) and laboratory scale (OHAUS, Greifensee, Switzerland) according to ISO 13061-1 (2014). For each MC, the bulk density values of all samples were also determined.

After each conditioning cycle and after drying, the samples were subjected to an experiment to determine the thermophysical properties - thermal conductivity (λ), thermal diffusivity (a), and specific heat capacity (c). Pairs needed for measurement on the extended dynamic plane source (EDPS) apparatus (Constantine the Philosopher University in Nitra, Nitra, Slovakia) were created from the samples. A series of five measurements was performed on each pair of samples. The resulting values of the monitored quantities were determined as the average of all measurements on the given pair of samples, and the variance and percent deviation values for the given pair were also determined. This ensured that the measurements were performed at all MCs in the range of 0% to 10%.

To validate the results obtained by the EDPS method, reference test samples made of polymethylmethacrylate (PMMA) with a thickness of 10 mm were prepared. As with the OSB boards, the sample dimensions were 100 mm × 100 mm x 10 mm. Polymethylmethacrylate has long been successfully used as a reference material for determining thermophysical properties because its properties exhibit low variance values.

For studying thermophysical properties, the authors measured the thermal conductivity and thermal diffusivity by the EDPS method at four different mean values of

MC equal to 0%, approximately 5%, 8%, and 10%. The MC in the samples was calculated by the gravimetric principle from the mass of the sample in dry state and the mass in non-dry state.

The EDPS method needs two samples from the same material for determining the thermophysical properties. Therefore, the thermophysical properties for 4 different combinations at 0% MC, 8 different sample combinations at approximately 5% and 8%, and 4 different combinations at 10% MC were measured. The samples with an average value of 10% MC were climatized at 20 °C and 65% relative humidity. All experimental measurements were performed at an ambient temperature of T_{ambient} = 21 °C ± 1 °C. All measurements were performed 5 times for each sample combination. The MC dependencies were calculated from the average values of the thermophysical properties for each sample combination and each average MC in the used sample combination. The average densities for the 0%, 5%, 8%, and 10% MC were equal to $\rho_{0\%}$ = (541.45 ± 16.52) kg·m^{-3}, $\rho_{5\%}$ = (559.77 ± 18.78) kg·m^{-3}, $\rho_{8\%}$ = (577.46 ± 17.24) kg·m^{-3}, and $\rho_{10\%}$ = (596.32 ± 17.25) kg·m^{-3}.

The average value of specific gravity calculated from all of the used samples was SG = 0.537 ± 0.015, from which the percentage error was 2.86%. Therefore, the authors assumed that the specific gravity for all samples was 0.537.

Methods

The measurements of the thermophysical properties of the samples were performed on an apparatus based on the EDPS method. This method is one of the basic transient methods listed in Table 1 (Malinarič 2004a; Božiková 2005; Božiková and Hlaváč 2014).

Table 1. Basic Transient Methods for Determining the Thermophysical Properties of Materials

Heat Generation	Heat Flow	Measured Parameters	Name of Method
Step-wise	Radial	λ	Hot wire
Pulse	1-dimensional	a, λ	Pulse transient
Step-wise	1-dimensional	a, λ	Step-wise transient
Step-wise	3-dimensional	a, λ	Hot disc
Step-wise	3-dimensional	a, λ	Gustafsson probe
Step-wise	1-dimensional	$a, \lambda > 2W.m^{-1}.K^{-1}$	DPS
Step-wise	1-dimensional	$a, \lambda < 2W.m^{-1}.K^{-1}$	EDPS

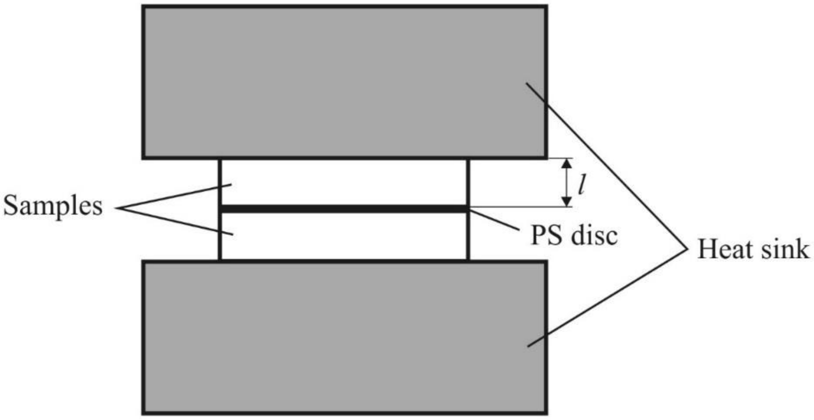

Fig. 1. Arrangement of samples and plane source (PS) disc

In the EDPS method, two samples of the measured material are positioned between two large heat sinkers (made from duralumin in this case), and the electrical resistance is measured in the place between the measured samples, as shown in Fig. 1 (Malinarič 2004b).

The measured values of electrical resistance are converted to the temperature according to the linear dependence between the temperature and electrical resistance with the temperature coefficient of the electrical resistance of the PS disc, which was equal to $4.8\cdot10^{-3}$ Ω.K^{-1} in this case.

The modified EDPS method with special considerations of heat-loss effect occurring at the edge of measuring samples, finite geometry of the sample and orthotropic thermal conductivity can be used for anisotropic materials. These variables must be considered in the theoretical temperature function in Eq. 6 (Malinarič 2004b),

$$T(t)=\frac{ql}{\lambda}\cdot\sqrt{\frac{t}{\pi.\theta}}\cdot\left(1+2\cdot\sqrt{\pi}\cdot\sum_{n=1}^{\infty}\beta^{n}\cdot ierfc\left(n\cdot\sqrt{\frac{\theta}{t}}\right)\right) \tag{6}$$

where q is the heat current density (W.m^{-2}), λ is the thermal conductivity (W.m^{-1}.K^{-1}), and the parameter β describes heat sink imperfection (-1.000 for ideal heat sink), which was calculated from known thermal properties of reference material PMMA with similar geometry (Malinarič 2004b). Ierfc is the error function integral, which was computed from a parametric fitting procedure between natural logarithm of measured temperature function and linear dependence in the shape of $\ln(T)=c_0+c_1.(t/\theta)$ with regard to anisotropic wood based samples. Sensitivity coefficients were analysed using (Malinarič, 2003, Malinarič, 2004b). Parameter θ is called the characteristic time (s), and it is bonded with thermal diffusivity a and an average thickness of used samples l with Eq. 7.

$$\theta=\frac{l^2}{a} \tag{7}$$

The values of thermal conductivity (λ) and the characteristic time (θ) are determined by the fitting procedure (Malinarič 2007; Koštial *et al.* 2010). The thermal diffusivity was then calculated from the known average thickness value of sample *A*, and the specific heat capacity was finally calculated according to the well-known formula between thermophysical properties Eq. 8,

$$\lambda=\rho\cdot a\cdot c \tag{8}$$

where ρ is the average density of used samples (kg.m^{-3}) at the known average MC (%).

Finally, the specific gravity of the material was calculated from the known density value with the MC (%) according to Eq. 9.

$$SG=\frac{\rho_{MC}}{\left(1+0.01\cdot MC(\%)\right)\cdot 1000} \tag{9}$$

RESULTS AND DISCUSSION

All measurements were performed using EDPS method with electrical parameters I = 1.0 A, U = 7.0 V during 300 seconds. With these settings, a temperature increase of about 15 °C was obtained. Ambient temperature during all measurements was 21±1 °C.

The authors will present the measured results of the thermophysical properties of OSB board samples and the results for the PMMA reference sample.

The PMMA sample was measured 10 times to obtain the measurement reproducibility. The measured values of thermal conductivity (λ), thermal diffusivity (a), and specific heat capacity (c) are listed in Table 2.

Table 2. Thermophysical Properties of the PMMA Reference Material *versus* Literature Values

Property	Experimental Values	Table Values	Percentage Error (%)
λ (W.m^{-1}.K^{-1})	0.201 ± 0.002	0.19 to 0.24	1.00
a (mm^2.s^{-1})	0.121 ± 0.003	0.109 to 0.143	2.48
c (J.kg^{-1}.K^{-1})	1452.5 ± 25.1	1460 to 1470	1.58

It is clear from Table 2 that the measured values of PMMA were in very good agreement with the table values, and that the measuring error rate for all three basic thermophysical properties did not exceed 3%.

Table 3 presents the values of thermal diffusivity *a* for OSB board samples along with the MC values. All values in Table 3 were considered for determining the effect of the MC on the thermal diffusivity.

Table 3. Values of thermal diffusivity *a* of used OSB Board Samples

MC (%)	***a* (mm^2.s^{-1})**
0.00	0.121 ± 0.003
4.86	0.124 ± 0.005
7.83	0.123 ± 0.003
10.14	0.124 ± 0.005

From Table 3 it can be seen that the thermal diffusivity *a* was not noticeably affected by the MC in the material. Therefore, based on the research results we assumed that thermal diffusivity did not noticeably change with the MC. Furthermore, data on thermal diffusivity of wood are scarce (Suleiman *et al.* 1999).

Table 4 presents the values of thermal conductivity, thermal diffusivity, and the specific heat capacity for OSB board samples, along with the MC. The values for the dry state were averaged because the MC in the dry samples was assumed 0% in all of the samples. All of the values in Table 4 were considered for determining the effect of the MC on the thermophysical properties. From Table 4 it can be seen that the measuring percentage error for all investigated samples did not exceed 5.5%. The average percentage error for the thermophysical properties did not exceed 4%, which meant excellent repeatability according to the material type. Figure 2 presents both the experimental and predicted dependence of the thermal conductivity *versus* MC, and Fig. 3 illustrates the same dependence for the specific heat capacity one.

Table 4. Values for the MC Dependence on the Thermophysical Properties of used OSB Board Samples

MC (%)	*a* (mm^2·s^{-1})	*λ* (W·m^{-1}·K^{-1})	*c* (J·kg^{-1}·K^{-1})
0.00	0.120 ± 0.002	0.083 ± 0.001	1287.6 ± 17.9
0.00	0.120 ± 0.003	0.083 ± 0.002	1326.6 ± 28.1
0.00	0.121 ± 0.004	0.086 ± 0.003	1275.8 ± 22.9
0.00	0.121 ± 0.003	0.086 ± 0.003	1282.5 ± 45.9
4.79	0.122 ± 0.004	0.096 ± 0.005	1411.9 ± 41.3
4.87	0.126 ± 0.004	0.096 ± 0.003	1405.9 ± 64.4
4.78	0.116 ± 0.005	0.095 ± 0.003	1446.3 ± 30.3
5.00	0.126 ± 0.003	0.096 ± 0.004	1435.2 ± 57.3
4.85	0.127 ± 0.002	0.101 ± 0.005	1372.9 ± 48.7
4.90	0.121 ± 0.003	0.097 ± 0.003	1376.9 ± 18.9
7.97	0.122 ± 0.002	0.111 ± 0.003	1578.1 ± 25.1
7.83	0.123 ± 0.001	0.107 ± 0.003	1561.4 ± 33.5
7.82	0.121 ± 0.002	0.111 ± 0.006	1565.6 ± 58.6
7.93	0.127 ± 0.002	0.106 ± 0.002	1523.7 ± 16.7
7.81	0.124 ± 0.005	0.110 ± 0.004	1494.4 ± 37.7
7.62	0.119 ± 0.003	0.109 ± 0.005	1536.3 ± 33.5
7.76	0.123 ± 0.004	0.111 ± 0.004	1477.7 ± 12.6
7.89	0.122 ± 0.002	0.111 ± 0.002	1578.1 ± 67.0
10.17	0.124 ± 0.003	0.117 ± 0.004	1615.8 ± 41.9
10.39	0.128 ± 0.003	0.117 ± 0.003	1594.9 ± 37.7
10.03	0.121 ± 0.004	0.118 ± 0.004	1599.1 ± 41.9
9.98	0.123 ± 0.005	0.120 ± 0.003	1603.2 ± 50.2

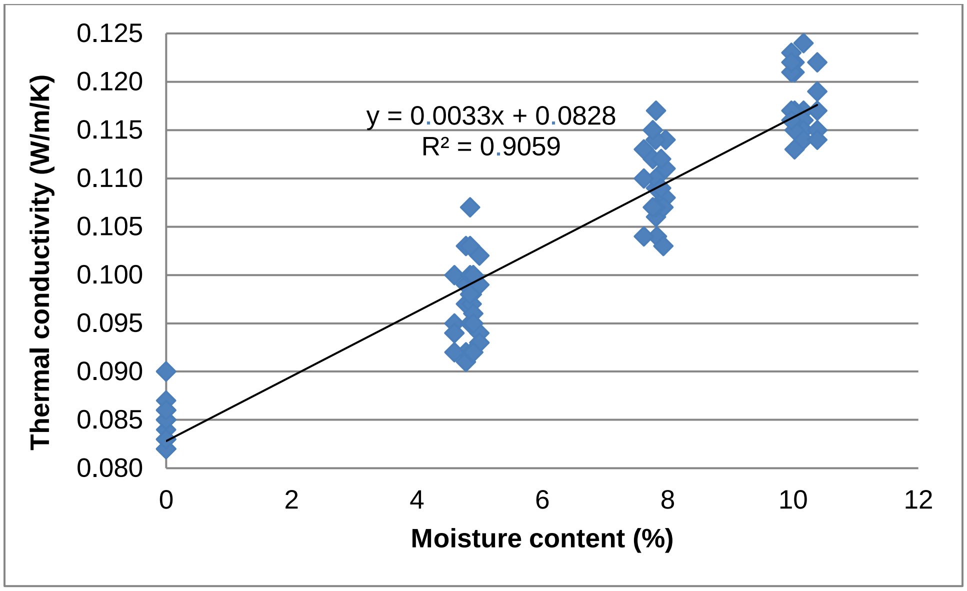

Fig. 2. Effect of the MC on thermal conductivity

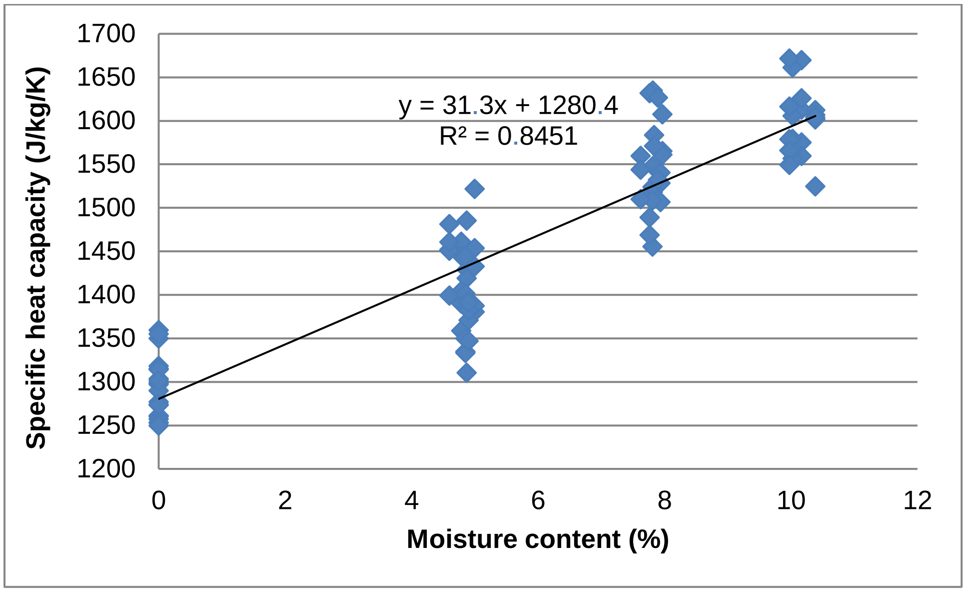

Fig. 3. Effect of the MC on the specific heat capacity

In the next part, the authors discuss the dependence of the MC on thermophysical properties. Table 5 presents the coefficient of determination (R^2), root mean square error (RMSE) for thermal conductivity, thermal diffusivity, and specific heat capacity *versus* MC.

Table 5. Statistical Parameters for the Dependence of Thermophysical Properties on the MC

	a **($mm^2.s^{-1}$)**	***λ*** **($W.m^{-1}.K^{-1}$)**	***c*** **($J.kg^{-1}.K^{-1}$)**
R^2 **(-)**	0.0724	0.9059	0.8451
RMSE	0.0004	0.0004	4.961

Tables 3 and 5 shows that the MC did not have a substantial effect on the thermal diffusivity.

From the coefficient of determination for thermal conductivity and specific heat capacity, it is clear that the effect of the MC on both thermal conductivity and specific heat capacity can be found in a linear form. The dependence of the thermal conductivity *versus* MC can be described by the formula $\lambda = 0.0828 + 0.0033$ MC. The dependence of specific heat capacity is given by the formula $c = 1280.4 + 31.3$ MC.

The measured dependence of thermal conductivity *versus* MC is different according to authors Thoemen *et al.* (2010). This difference is probably due to the different type of basic material used by the authors (Thoemen *et al.* 2010). According to the very high coefficient of correlation and very low values of RMSE and percentage error, the authors assume that the predicted dependence, as shown in Fig. 2, was correct.

The results revealed that the measured specific heat capacity corresponded with the reference values from authors Rice and Redfern (2016). The cited authors published the first study about specific heat capacity of OSB boards. Differences in the slope of specific heat capacity versus MC is approximately about 10%. Rice and Redfern predicted the specific heat capacity in the oven-dry state as equal to 1170 $J.kg^{-1}.K^{-1}$ while the present prediction is equal to 1280 $J.kg^{-1}.K^{-1}$. Differences in the oven-dry specific heat capacity can be caused by the different base of wood material.

CONCLUSIONS

The EDPS method was mainly proposed for study of thermophysical properties of low conductive polymeric materials, which mostly are not hygroscopic and have relative higher order of homogeneity. In the present work it was shown that this transient method can be successfully applied also on the wood based composite materials. For proper use of this method it is very important to perform precise analysis of heat sink imperfection and error function values with special consideration of heat-loss effect occurring at the edge of measuring samples, finite geometry of the sample, and orthotropic thermal conductivity. The percentage error for this OSB material was lower than 5.5%, which is acceptable for wood composite material.

This article presents measured data of thermal diffusivity across a range of moisture content values for the OSB boards. We find out, that the thermal diffusivity *a* was not noticeably affected by the MC in the material. Therefore, based on the research results we assumed that thermal diffusivity did not noticeably change with the MC.

Based on the measured data sets of thermal conductivity and the MC, an equation of dependence on the coefficient of thermal conductivity was determined.

For the dependency between the specific heat capacity and the MC, an equation of dependence on the coefficient of specific heat capacity was determined.

According to the low percentage error of thermal conductivity and specific heat capacity measurements these formulas can be applied for the prediction of thermal conductivity *vs.* MC and specific heat capacity *vs.* MC of OSB boards made of domestic wood processed in central Europe.

Statistical parameters R^2 and RMSE also confirmed the validity of obtained formulas for thermal conductivity and specific heat capacity *vs.* MC.

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