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SOME NON-TRADITIONAL FACTORS INFLUENCING THERMAL PROPERTIES OF WOOD

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ABSTRACT

The present state of wood thermal properties measurement requires clear descriptions of measurement methods and dimension in flow direction regardless of standard mentioned. We used two methods for measurement of these properties on the same specimens with different thicknesses for ash wood. The methods provided different results which were compared with literature. Thickness of specimen, on assumed range, slightly influenced the thermal conductivity. The less variable property was specific heat.

KEYWORDS: Ash wood, specific heat capacity, thermal conductivity, thermal diffusivity, Isomet 104, Quasi-stationary method.

INTRODUCTION

Wood substance forms the main part of wood which can also contain water and air. We can say that wood is non-homogeneous material. Also wood is at least orthotropic material with three different eigenvectors. Basic thermal characteristics of wood as thermal conductivity, thermal diffusivity and specific heat depend or do not depend on species, anatomical direction (Požgaj et al. 1997, Niemz et al. 2010), density (Harada et al. 1998), moisture content (Hrčka 2010), temperature (Olek et al. 2003), mechanical load (Bučar and Straže 2008), etc. Specific heat as a scalar quantity is not influenced so much by species or oven dry density and we can say it is independent on it. Assumption that wood is a continuum is important to practical use of derivatives, which are used in definitions of thermal properties. In spite of this knowledge there are some non-traditional factors which influence values of wood thermal properties. The proper use of methods should give the same results, but geometry and dimensions of specimen are also important factors in deriving solutions which are part of experimental procedures.

The aim of the paper is to describe the influence of measurement method and dimensions of specimens on thermal properties of ash wood.

MATERIAL AND METHODS

Ash wood (*Fraxinus excelsior* L.) was used as experimental material. The dimensions of specimens varied significantly in thickness oriented in radial direction, so two different sets of thicknesses with average values of 4.5 mm (thin) and 10.1 mm (thick) were investigated as they influenced values of measured thermal properties. The parallelepiped was the shape of all specimens with square tangential section of average side dimension 97.5 mm. The source of 32 specimens was the outer part of 7 stems to secure the rectilinear orthogonal anisotropy as much as possible and so, all specimens contained only sapwood. Average density of thin samples was 691.2 kg.m^{-3} and of thick ones 688.2 kg.m^{-3}. The specimen surfaces were sanded on wide belt sander to be flat. Average equilibrium moisture content of all set of specimens was 8.8 %. After measurement of thermal properties for thick specimens, they were sanded to thin thickness and afterwards thermal properties measurement of thin specimens was performed. Maximum measurement time and maximum temperature increase depended on the method used but it was no more than 10 min and 10 K.

The measurement method was the second investigated factor. We employed two different methods to investigate all three simultaneously determined thermal properties. The first one utilized the commercial device Isomet 104. Such device is based on hot-wire method with flat probe touching the specimen surface. Isomet 104 is semi-automated device. The measurement can be divided into three parts. During the first part, after putting the probe on the surface of the specimen it explores and waits for the specimen's surface to reach constant temperature. During the second part, the probe provides heat and the specimen surface temperature is rising. Approximately in the middle of the measurement there is a third part beginning during which the decrease of temperature occurs because heat is not delivered by the probe any more. The advantage of Isomet 104 consists in easy operating and consequently measurements do not require special skills. The 2 cm air gap was between downside surface of specimen and upper side of laboratory table. We suppose almost zero flux of heat through the downside surface of specimen.

The second employed method was so called Quasi-stationary method named according to linear part of temperature increase in time, Fig. 1. The Quasi-stationary method was developed at Department of Wood Science at Technical University in Zvolen (Požgaj et al. 1997). The method utilized knowledge from two previous methods developed by Clark and Kingston (1950) and Krisher and Esdorn (1954). The method consists of planar heat source from NiCr thin foil (0.01 mm) to produce heat if direct current passes through it. If heat flux from foil and density of measured material are known than we are able to determine all three thermal properties simultaneously. Without information about heat flux and density we can determine only thermal diffusivity. Let us consider zero heat flux in the middle of specimen, constant heat flux, φ at the surface of specimen:

$$-\lambda \left.\frac{\partial t}{\partial x}\right|_{x=R} = \varphi \tag{1}$$

and constant initial temperature, t_0 through the specimen thickness, 2R (in radial direction). Then solution of one dimensional heat conduction equation, with constant thermal diffusivity, a, has the form (Babiak 1976):

$$t(x,\tau) - t_0 = \frac{\varphi R}{\lambda}\left(\frac{a\,\tau}{R^2} + \frac{3x^2 - R^2}{6R^2} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2} e^{-\frac{a\tau}{R^2}n^2\pi^2}\cos\left(\frac{n\,x\,\pi}{R}\right)\right) \tag{2}$$

where: x - coordinate
τ - time
t - temperature
λ - thermal conductivity.

With increasing time sum of infinite series converges to zero and a linear function between temperature increase and time holds. Adiabatic model (2), without heat losses from lateral surfaces, can be extended to three dimensions with loss of heat (3):

$$t(x,y,z,\tau)-t_0=\frac{8\varphi}{c\rho R}\sum_{r=1}^{\infty}\sum_{p=1}^{\infty}\sum_{m=1}^{\infty}\frac{(-1)^{r+1}\cos\left((2r-1)\frac{\pi}{2}\frac{z}{L}\right)}{(2r-1)\frac{\pi}{2}}\frac{(-1)^{p+1}\cos\left((2p-1)\frac{\pi}{2}\frac{y}{L}\right)}{(2p-1)\frac{\pi}{2}}\cos\left((m-1)\pi\frac{x}{R}\right)\left(\frac{1-e^{-\left(((m-1)\pi)^2\frac{a_R}{R^2}+\left((2p-1)\frac{\pi}{2}\right)^2\frac{a_T}{T^2}+\left((2r-1)\frac{\pi}{2}\right)^2\frac{a_L}{L^2}\right)\tau}}{((m-1)\pi)^2\frac{a_R}{R^2}+\left((2p-1)\frac{\pi}{2}\right)^2\frac{a_T}{T^2}+\left((2r-1)\frac{\pi}{2}\right)^2\frac{a_L}{L^2}}\right) \quad (3)$$

where: R, L, T - dimensions
a_R, a_L, a_T - thermal diffusivities in radial, longitudinal and tangential directions
c - specific heat capacity
ρ - density.

Temperature at the centre of specimen is measured with very thin thermocouple. The scheme of apparatus is depicted on Fig. 1.

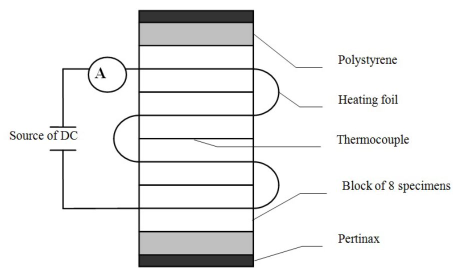

Fig. 1: Scheme of quasi-stationary apparatus.

Temperature is measured in the middle of specimen and is recorded by computer. Consequently, we search the values of thermal properties according to least square method using the macro written in Excel and a function which represents the solution was programmed in Visual Basic for Applications to simplify the computing process.

RESULTS AND DISCUSSION

As Isomet 104 is semi-automatic device, it delivered values of thermal properties almost independently on work of researcher. Typical temperature increase in time in the centre of specimen as is measured by Quasi-stationary method is contained in Fig. 2.

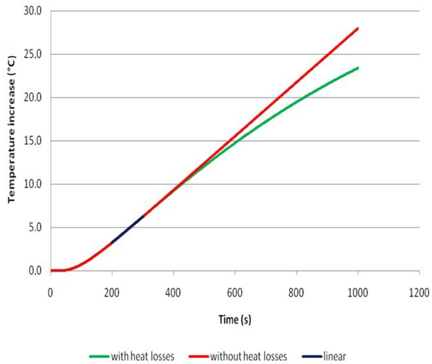

Fig. 2: Temperature increase in time in the centre of thick specimen as is measured by Quasi-stationary method.

The curve passes through three different periods. The first one in time is non-linear, and sum of infinite series influences significantly the temperature increase. Later, when we can neglect the sum, temperature increase in time is linear. After linear period, there is second non-linear one, because losses of heat through lateral surfaces are significantly present. The presence of boundary between the last two periods is influenced by thickness of specimen.

The results of thermal properties and density for ash wood in radial direction after influencing two factors, two different methods and two, in average, different thicknesses, are embedded in Tab. 1 and 2. Also there are results of significant tests of differences between means, Tabs. 1, 2, 3.

Tab. 1: Thermal conductivity, thermal diffusivity, specific heat capacity and density of thin and thick specimens of ash wood measured in radial direction with Isomet 104.

Isomet 104										
Property	**Significant test and statistics**									
	Significance	**Mean**		**Variation coefficient (%)**		**Standard deviation**		**Number of measurement**	
		thin	**thick**	**thin**	**thick**	**thin**	**thick**	**thin**	**thick**
λ $(W.m^{-1}.K^{-1})$	different	0.128	0.141	11.6	11.09	0.0149	0.0157	16	16
a $(m^2.s^{-1})$	different	$1.3.10^{-7}$	$1.8.10^{-7}$	35	6.7	$4.5.10^{-8}$	$1.2.10^{-8}$	16	16
c $(J.kg^{-1}.K^{-1})$	different	1300	1170	7.04	7.36	91.4	85.9	16	16
ρ $(kg.m^{-3})$	Equal	691.2	688.2	9.067	8.516	62.67	58.61	16	16

Alpha-level, related to critical value, was 0.05 to distinguish between equal and different.

We measured thermal properties according to different methods on the same specimens with different thicknesses. Methods yielded different results for both thicknesses with exception for thermal diffusivity in thin specimens which was caused by large variability of this property measured by Isomet, Tab. 3. Quasistationary method provided less variable values of properties in all cases. Transport coefficients were smaller or at least the same for thin specimens. It indicates easier propagation of heat and faster equilibrating of temperature for thicker specimens. The least variable property is specific heat capacity as we can expect from its dependence on factors.

Tab. 2: Thermal conductivity, thermal diffusivity, specific heat capacity and density of thin and thick specimens of ash wood measured in radial direction with Quasi-stationary method.

Quasi-stationary										
Property	**Significant test and statistics**									
	Significance	**Mean**		**Variation coefficient (%)**		**Standard deviation**		**Number of measurement**		
		thin	**thick**	**thin**	**thick**	**thin**	**thick**	**thin**	**thick**	
λ ($W.m^{-1}.K^{-1}$)	different (α=0.03)	0.16	0.17	7.7	9.3	0.012	0.016	8	8	
a ($m^2.s^{-1}$)	Equal	$1.5.10^{-7}$	$1.5.10^{-7}$	7.8	5.6	$1.1.10^{-8}$	$8.7.10^{-9}$	8	8	
c ($J.kg^{-1}.K^{-1}$)	Equal	1580	1640	6.16	2.9	97.2	47.5	8	8	
ρ ($kg.m^{-3}$)	Equal	691.2	688.2	9.067	8.516	62.67	58.61	16	16	

Tab. 3: Significance of differences as were set between means of thermal properties for thin and thick specimens measured with different methods (Isomet 104 and quasi-stationary method).

Property	thin	thick
λ ($W.m^{-1}.K^{-1}$)	different	different
a ($m^2.s^{-1}$)	equal	different
c ($kg^{-1}.K^{-1}$)	different	different

Our results can be compared with previously published, for example, Şahin (2009) published values for *Fraxinus excelsior* in radial direction at 8 % moisture content, at 20°C, from five measurements in average 0.140 $W.m^{-1}.K^{-1}$ with standard deviation 0.005 $W.m^{-1}.K^{-1}$ measured with hot-wire-method on samples 20x50x100 mm. Such values correspond almost exactly to values delivered by Isomet, as a kind of hot-wire-method, for thick specimens. The thermal conductivity values for genus *Fraxinus* are also published in Wood Handbook in chapter 3 which was written by the authors Simpson and TenWolde (1999). They published values from 0.12-0.14 $W.m^{-1}.K^{-1}$ at 0 % moisture content to 0.15-0.17 $W.m^{-1}.K^{-1}$ at 12 % moisture content.

Such values are close to values provided by Quasi-stationary method. Specific heat capacity measured with Isomet for thick values is almost on the same level as for air and this fact is not probable. The more realistic values of specific heat capacity are obtained with quasi-stationary method but these values are between values of Kanter (1957) and Kühlmann (1962).

The values are closer to Kühlmann (1962) values of specific heat capacity due to use of similar method. As the results indicate, we suggest that not only dimensions of specimens are specified but also thickness or dimension in the direction of heat flow are declared. Also at the present time, not only procedure or standard is important but also whole method with clearly stated theory is required.

CONCLUSIONS

We measured values of thermal properties for ash wood by different methods on the same specimens with different thicknesses. Isomet method provided totally different results for thin and thick specimens. On the other hand, results from Quasi-stationary method differ only slightly in thermal conductivity, which was larger for thicker specimens. The least variable property was specific heat capacity as we expected. We found different results which can be compared with literature. Finally, we suggest the specification of the specimen´s dimensions in direction of flow and clearly defining the methods of measurement regardless the standard is mentioned at the present time.

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