THE THERMAL PROPERTIES OF SELECTED BEE PRODUCTS

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ABSTRACT

Knowledge of bee products physical properties has a decisive importance for the monitoring of their quality. The most important properties are thermophysical parameters as thermal conductivity and thermal diffusivity. The article deals with the thermophysical properties of selected bee products (honey, bee pollen and perga) which were measured by two different thermophysical measurement methods. For identification of thermal conductivity and thermal diffusivity were used transient methods - Hot Wire method and Dynamic Plane Source method. The measurements of thermal parameters were performed by the instrument Isomet 2104, which uses Hot Wire method, and Dynamic Plane Source method. The principle of measuring process is based on the analysis of time-temperature relation. In the first series of measurements were measured thermal conductivity and thermal diffusivity at constant laboratory temperature 20 °C. The second series were focused on identification of thermophysical parameters changes during temperature stabilisation in the temperature range from 5 °C to 25 °C. For samples with constant temperature were calculated basic statistical characteristics - standard deviation and probable error in %. For relations of thermal parameters to temperature were obtained graphical dependencies. Two different thermophysical methods were used for improvement of data reliability and data statistics.

Key words: thermal conductivity, thermal diffusivity, honey, bee pollen, perga

Introduction

Controlled processes in manufacturing, handling, and holding require precise knowledge of physical quantities of materials. For the quality evaluation of food materials it is important to know their physical properties particularly, mechanical and thermophysical (Božiková and Hlaváč, 2010). This article is focused on thermal properties of selected bee products (honey, bee pollen and perga). The bee products such as honey, bee pollen and perga are very special food materials which have high concentration of health-promoting substances. Some physical properties of bee products especially of honey are mentioned in literature Bhandari et al. (1999), Zaitoun et al. (2000), Chirife and Buera (1997) (Cohen – Weihs, 2010). Physicochemical characteristics of honey from different origins were described by El Sohaimy – Masry – Shehata (2015).

In this article are presented theoretical parts from thermophysics, two thermophysical measurement methods and the results of thermal conductivity and thermal diffusivity measurements for three different types of bee products.

Materials and methods

In this chapter are characterized measured bee products: honey, bee pollen and perga. Described are also transient methods of thermophysical parameters measurements.

Natural honey is one of the most widely sought products due to its unique nutritional and medicinal properties, which are attributed to the influence of the different groups of substances it contains. Codex Alimentarius Commission defined honey as the natural sweet substance produced by honey bees, *Apis mellifera*, from the nectar of plants (blossoms) or from the secretions of living parts of plants or excretions of plant sucking insects on the living parts of plants, which honey bees collect, transform by combining with specific substances of their own, deposit, dehydrate, store and leave in the honey comb to ripen and mature (CAC 2001a, CAC 2001b).

Essentially, natural honey is a sticky and viscous solution with a content of (80–85) % carbohydrate (mainly glucose and fructose), (15–17) % water, (0.1–0.4) % protein, 0.2 % ash and minor quantities of amino acids, enzymes and vitamins as well as other substances like phenolic antioxidants (James at al., 2009, White – Doner, 1980, Jeffrey – Echazarreta, 1996, Gheldof – Engeseth, 2002).

Beepollen is quite a varied plant product rich in biologically active substances. 200 substances were found in the pollen grains from different plant species. In the group of basic chemical substances, there are proteins, amino acids, carbohydrates, lipids and fatty acids, phenolic compounds, enzymes, and coenzymes as well as vitamins and bioelements (Campos et al., 2008, Campos et al., 2010).

Bee pollen is a raw material from which bees produce bee bread. They collect pollen from plant anthers, mix it with a small dose of the secretion from salivary glands or nectar, and place it in specific baskets (corbiculae) which are situated on the tibia of their hind legs. These are called pollen loads. The field bees collect and transport the bee pollen to the hive (Cuoto and Cuoto, 2006, Pereira et al., 2006).

Pollen grains, depending of the plant species, differ in shape, colour, size, and weight. The grain shapes are diverse: round, cylindrical, bell-shaped, triangular, or thorny. Their weight is equal to a dozen or several dozens of micrograms. The majority of pollens consist of single grains which are sometimes joined with two or more grains.The color of the pollen is varied ranging from bright yellow to black (Shubharani – Roopa – Sivaram, 2013).

Perga is also called fermented pollen, pergolas and bee bread. Perga is a fermented mixture of bee saliva, plant pollen, and nectar that the worker bees use as food for the larvae and for young bees to produce royal jelly. Perga increases its´ nutritional value due to the fermentation process performed by worker bees. Perga contains about 20 % proteins, (24–34) % carbohydrates and 1,5 % of lipids. Perga has a large variety of minerals and has high quantities of iron, cobalt, phosphorus, calcium. It is one of the richest natural foods containing selenium. It is also very good source of potassium and B-group vitamins. Perga is a natural nourishing supplement rich in phytohormones, flavonoids, amino acids, minerals and other active biological compounds, with bioavailability at least three times more than regular bee pollen. This complex of vital substances determines the immune stimulating nature of perga (Beepharm, 2015).

Generally, physical properties of bee products as honey, bee pollen and perga are influenced by various factors such as: the type of flowers, way of processing and most of all area of origin, etc. The research of honey and other bee products physical properties in Slovak Republic is at the beginning and particular properties are not known. Our research was oriented on measuring of selected thermophysical properties as thermal conductivity and thermal diffusivity of bee products.

Thermal conductivity and thermal diffusivity are basic thermal parameters of materials. Thermal conductivity is defined as the quantity of heat transmitted through a unit surface to a unit temperature gradient in unit time. This thermophysical parameter depends on many factors as: material's structure, pressure, temperature etc. Thermal conductivity is mathematically defined by Furrier's law (1):

$$\vec{q} = -\lambda \; grad \; T \tag{1}$$

where: q is density of thermal flow ($W \cdot m^{-2}$), λ is thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$).
Thermal diffusivity a ($m^2 \cdot s^{-1}$) characterizes the velocity of the temperature equalization in material during non-stationary processes. In numeric view it is equal to temperature change of unit volume caused by heat, which is transferred in unit time, by unit surface of coat with unit thickness, in unit temperature difference on her facing side. This thermal parameter is defined by thermal conductivity λ, specific heat c ($J \cdot kg^{-1} \cdot K^{-1}$) and density ρ by equation (2):

$$a = \frac{\lambda}{c\,\rho} \tag{2}$$

Both thermal parameters were measured by instrument Isomet 2104. It is thermal parameters analyzer which can use transient methods - hot wire and plane source method according to the used probe. In our case were measurements of thermophysical parameters realised by needle probe. This needle probe contains hot wire with heating function. The mathematical description of measurement method can be described as follows: Measuring of thermal parameters was performed by simplified transient Hot Wire (HW) technique. The simplified HW method is technique based on the measurement of the temperature rise of a linear heat source (hot wire) embedded in the tested material (Assael–Antoniadis–Wu, 2008; Parsons–Mulligan, 1978; Kadjo – Garnier – Maye – Martemianov, 2008). For an infinitely long metallic wire (length/radius ratio >>200) heated at time t > 0 with a constant heat flux per length unit q and immersed in an infinite homogeneous medium (thermal conductivity and diffusivity: λ and a with uniform initial temperature, the temperature rise $\Delta T(\tau)$ of the wire is given by equation (3) (Carslaw – Jaeger, 1959):

$$\Delta T(\tau) = \frac{q}{4\pi\lambda} \ln \frac{4F_0}{C} \tag{3}$$

with $C = e^{\gamma} = 1.781$ where γ is Euler's constant ($\gamma = 0.5772$) and F_0 is the Fourier number defined by

$$F_0 = \frac{a\,\tau}{r_0^2} \tag{4}$$

Where r_0 is the distance from the hot wire (needle probe) and τ is time. Equation (3) is the analytical solution of an ideal thermal conductive model valid for F_0 >>1 and without convective transfers (Wakeham - Nagashima, 1991; Tavman, 1996). From this ideal model and with known q values, the thermal conductivity can be calculated by equation (5).

$$\lambda = \frac{q}{4\pi} \left(\frac{dT}{d(\ln \tau)} \right)^{-1} \tag{5}$$

where $dT/d(\ln \tau)$ is a numerical constant deduced from experimental data for t values which satisfy the condition F_0 >>1. For practical applications of the HW method, wire and material sample dimensions, among other ideal model hypothesis, are finite and the deviations from the ideal model have then to be evaluated. In fact, the $e(\tau)$ answer to the wire heating $\Delta T(\tau)$ resultant of the Joule effect due to an electrical current.

For data comparison and for verifying of data reliability were used two methods of thermophysical parameters measurement. The first method was Hot wire (HW) method which was described in previous text. The second used measurement method for identification of bee products thermophysical parameters was dynamic plane source (DPS) method. DPS is one of the transient methods which are convenient for measurement of basic thermophysical parameters as thermal conductivity and thermal diffusivity (Cviklovič and Paulovič, 2014).

The DPS method is based on using an ideal plane sensor – PS. The PS sensor acts both as heat source and temperature detector. The plane source method is arranged for a one dimensional heat flow into a finite sample. The theory considers ideal experimental conditions – ideal heater (negligible thickness and mass), perfect thermal contact between PS sensor and the sample, zero thermal resistance between the sample and the material surrounding sample, zero heat losses from the lateral surfaces of the sample (Karawacki et al, 1992). If q is the total output of power per unit area dissipated by the heater, then the temperature increase as a function of time is given by (6) (Beck and Arnold, 2003).

$$\Delta T(x,t) = 2\frac{q\sqrt{at}}{\lambda} ierf\left(\frac{x}{2\sqrt{at}}\right) \tag{6}$$

Where a - is thermal diffusivity, λ - is thermal conductivity of the sample and *ierfc* is the error function (Carslaw and Jeager, 1959). We consider the PS sensor, which is placed between two identical samples having the same cross section as the sensor in the plane $x = 0$. The temperature increase in the sample as a function of time conforms (7),

$$T(0,t) = \frac{q\sqrt{a}}{\lambda\sqrt{\pi}}\sqrt{t} \tag{7}$$

which corresponds to the linear heat flow into an infinite medium. The sensor is made of a Ni-foil, 23 μm thick protected from both sides by an insulating layer made of kapton of 25 μm thick made on SAS. Several corrections have been introduced to account for the heat capacity of the wire, the thermal contact resistance between the wire and the test material, the finite dimension of the sample and the finite dimension of the wire embedded in the sample (Assael and Wakeham, 1992; Liang, 1995).

Results and discussion

In the first series of measurements were measured thermal conductivity and thermal diffusivity at constant laboratory temperature 20 °C for samples of bee products. Every thermophysical parameter was measured 50 times and results are summarised in Table 1. For each sample were obtained basic statistical characteristics: arithmetic average and relative probable error in %. From presented results is evident that thermal conductivity of honey had the highest value 0.392 W.(m.K)$^{-1}$± 0.62 %. Thermal conductivity of granular bee pollen (0.124 W.(m.K)$^{-1}$± 0.87 %.) and perga (0.146 W.(m.K)$^{-1}$± 1.21 %) had similar values because of similar composition and relative moisture content. In generally the lowest value of thermal diffusivity had sample of honey which had different structural character from granular bee pollen sample and sample of perga. The sample of bee pollen was measured in granular state, so the sample contained air gaps which have a lower thermal conductivity than the sample itself (the air has thermal conductivity 0.022 W.(m.K)$^{-1}$ at laboratory temperature 20 °C). The granules of perga were before measurement compacted to form unify structure of sample, so the air gaps were partially removed.

Table 1 Results for 1st series of bee products thermophysical parameters measurement at constant temperature 20 °C

	Coefficients	
Sample – honey		
	Arithmetic average	**Relative probable error**
Thermal conductivity	0.392 W.(m.K)$^{-1}$	± 0.62 %
Thermal diffusivity	0.094.10^{-6} m^2.s^{-1}	± 0.93 %
Sample – bee pollen		
	Arithmetic average	**Relative probable error**
Thermal conductivity	0.124 W.(m.K)$^{-1}$	± 0.87 %
Thermal diffusivity	0.148.10^{-6} m^2.s^{-1}	± 1.02 %
Sample – perga		
	Arithmetic average	**Relative probable error**
Thermal conductivity	0.146 W.(m.K)$^{-1}$	± 1.21 %
Thermal diffusivity	0.133.10^{-6} m^2.s^{-1}	± 2.02 %

In the second series of measurement were obtained relations between thermal conductivity, thermal diffusivity and temperature in the temperature range from 5 °C to 25 °C (Figures 1-6). Temperature dependencies of thermal conductivity and thermal diffusivity can be described by linear increasing functions (Eq. 8 and Eq. 9) for granular bee pollen sample and sample of perga. For honey sample was obtained linear increasing dependence described by Eq. (8) and in the case of temperature dependence of honey thermal diffusivity was identified linear decreasing function (Eq. 10) can be used:

$$\lambda = A + B\left(\frac{t}{t_0}\right) \qquad [\mathrm{W.(m.K)^{-1}}] \qquad (8)$$

$$a = C + D\left(\frac{t}{t_0}\right) \qquad [\mathrm{m^2.s^{-1}}] \qquad (9)$$

$$a = E - F\left(\frac{t}{t_0}\right) \qquad [\mathrm{m^2.s^{-1}}] \qquad (10)$$

where: t – temperature [°C], t_0 – equals to 1°C, λ – thermal conductivity [W.(m.K)$^{-1}$], a – thermal diffusivity [m^2.s^{-1}], A, B, C, D, E, F – are constants dependent on kind of material. In all cases were the coefficients of determination very high (Table 2).

Table 2 Coefficients A, B, C, D, E, F of regression Eqs 8, 9 and 10 and coefficients of determinations (R^2) for 2nd series of bee products thermophysical parameters measurement during the temperature stabilisation in temperature range (5 – 25) °C

	Coefficients		
	Sample – honey		
Thermal conductivity, W.(m.K)$^{-1}$	**A**	**B**	**R^2**
	0.339 933	0.002 516	0.993 48
Thermal diffusivity, mm^2.s^{-1}	**E**	**F**	**R^2**
	0.122 595	0.001 529	0. 988 17
	Sample – bee pollen		
Thermal conductivity, W.(m.K)$^{-1}$	**A**	**B**	**R^2**
	0.085 413	0.001 956	0.994 52
Thermal diffusivity, mm^2.s^{-1}	**C**	**D**	**R^2**
	0.078 448	0.003 541	0.986 89
	Sample – perga		
Thermal conductivity, W.(m.K)$^{-1}$	**A**	**B**	**R^2**
	0.099 675	0.002 345	0.990 95
Thermal diffusivity, mm^2.s^{-1}	**C**	**D**	**R^2**
	0.082 080	0.002 559	0.991 356

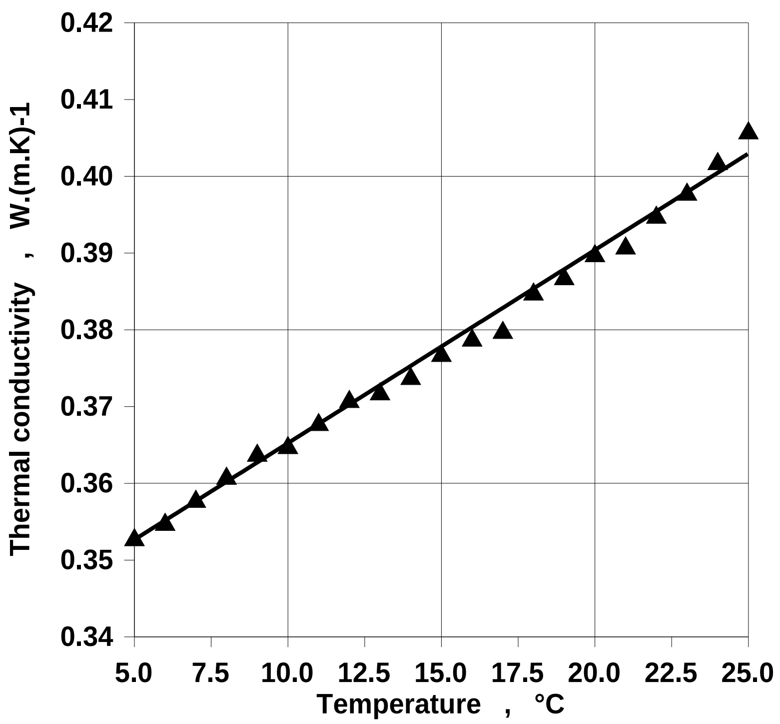

Figure 1 Relation of honey thermal conductivity to temperature during the temperature stabilisation in temperature range (5 – 25) °C

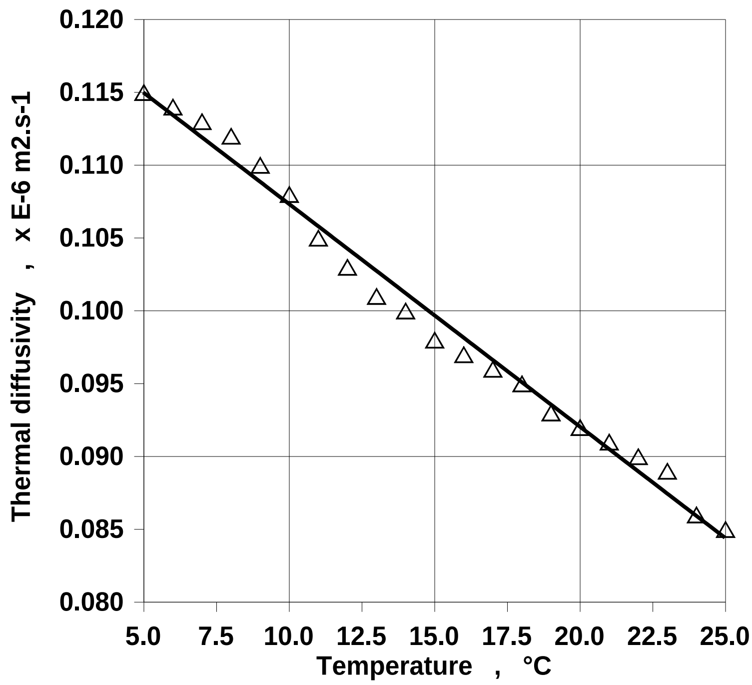

Figure 2 Relation of honey thermal diffusivity to temperature during the temperature stabilisation in temperature range (5 – 25) °C

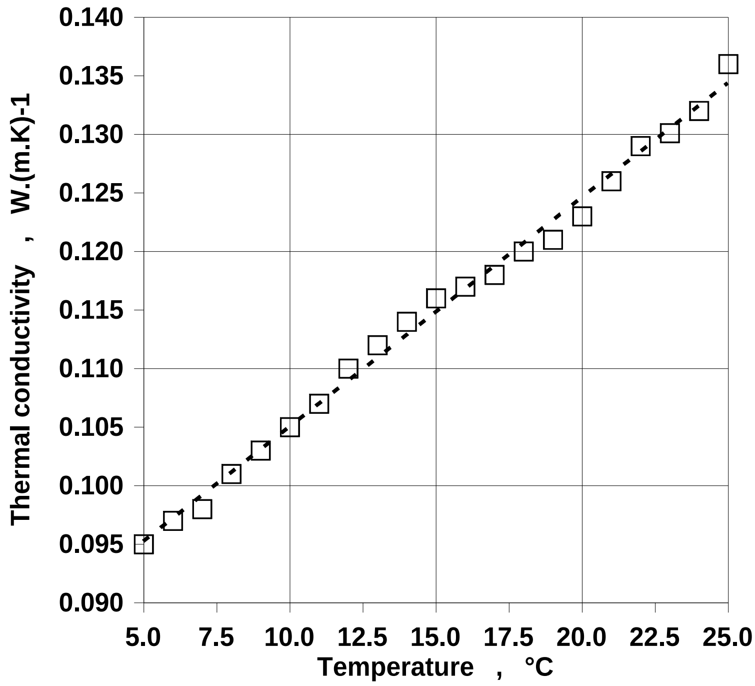

Figure 3 Relation of granular bee pollen thermal conductivity to temperature during the temperature stabilisation in temperature range (5 – 25) °C

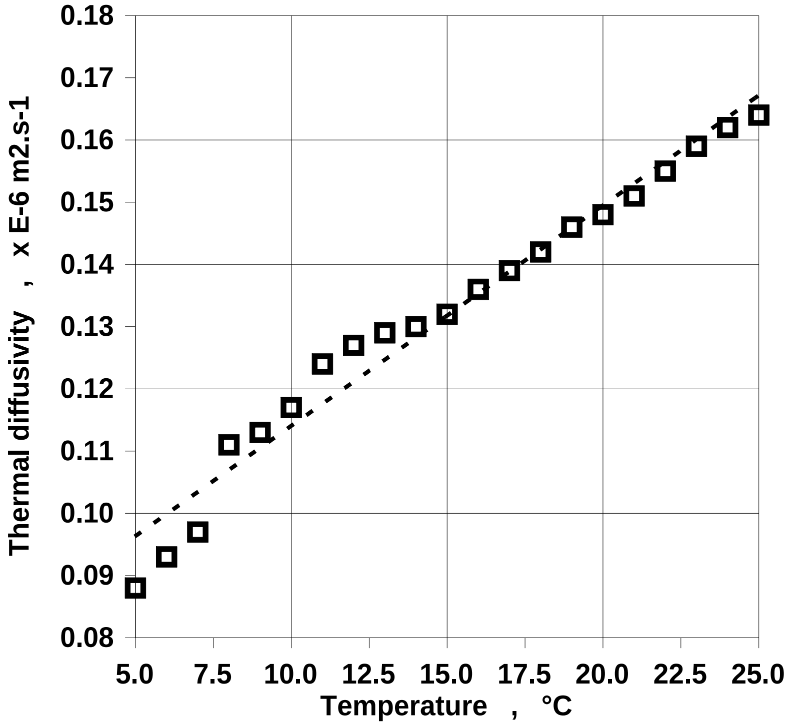

Figure 4 Relation of granular bee pollen thermal diffusivity to temperature during the temperature stabilisation in temperature range (5 – 25) °C

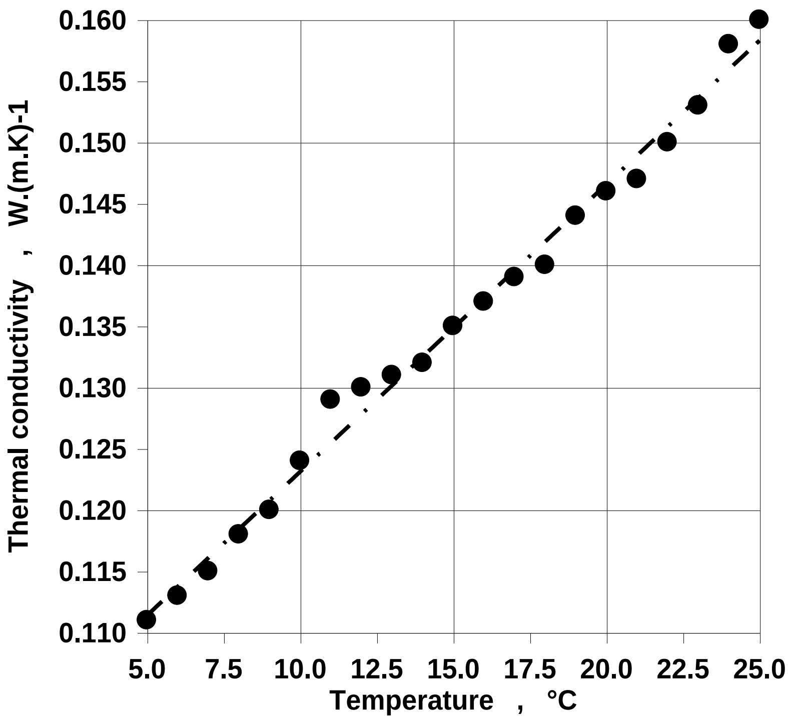

Figure 5 Relation of perga thermal conductivity to temperature during the temperature stabilisation in temperature range (5 – 25) °C

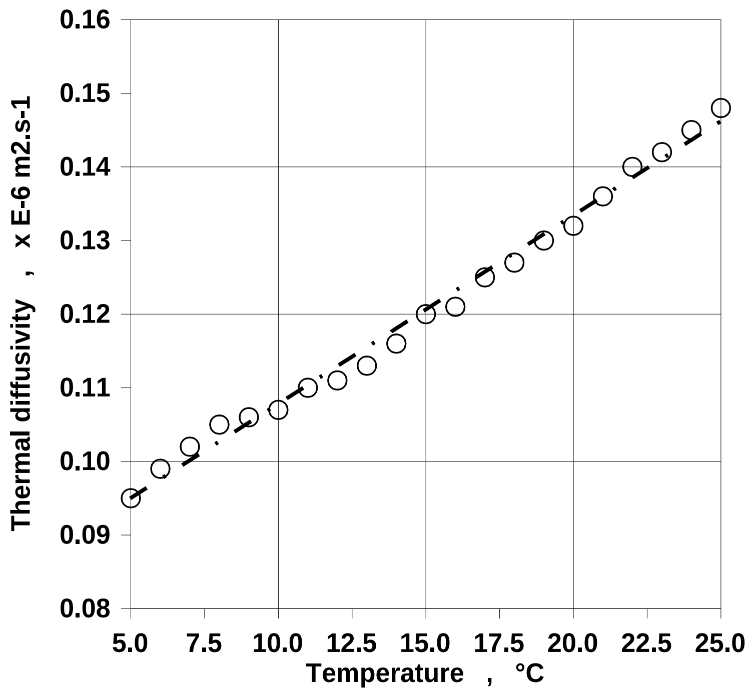

Figure 5 Relation of perga thermal diffusivity to temperature during the temperature stabilisation in temperature range (5 – 25) °C

All results obtained for thermal conductivity and thermal diffusivity of honey are in a good agreement with the literature Ginzburg (1985) and White (1975). From the presented results for thermophysical measurements it is clear that the thermal conductivity of high viscosity liquids or suspensoid materials can be measured with HW and DPS method. The thermophysical parameters as thermal conductivity and thermal diffusivity of perga and bee pollen were not presented in the literature, so presented values are new in this research field. The results of thermal parameters obtained by HW and DPS method for perga and bee pollen samples were very similar. From the practise point of view for measurement of compact samples is more appropriate DPS method and for measurement of granular samples is better HW method. For the data reliability protection, a series of fifty measurements were done for every point in the presented graphic relations (Figures 1 – 6). Each point in the graphics characteristics was obtained as the average of the measured values.

Conclusions

The thermal conductivity characterizes heat transfer ability of material and thermal diffusivity characterizes velocity of the temperature equalization and the intensity of the temperature changes in the material. Accurate values of thermal properties are critical for practical design as well as theoretical studies and analysis, especially in the fields of heat transfer and thermal processing. The knowledge of materials thermophysical properties is significant in the context of liquid, compact and granular biomaterials. Biomaterials are often thermally processed or they are exposed to natural changes of temperature conditions, so it is necessary to have knowledge about their thermal characteristics.

The results of experiments obtained by HW method and DPS method showed that both methods are suitable for identification of bee products thermal parameters. The values of thermal conductivity and thermal diffusivity obtained by the implementation of HW method and DPS method on honey, granular bee pollen and perga samples can be compared only with ranges of honey thermal parameters presented in the literature because of the bee products variety. In the literature are presented for thermal conductivity of honey values from range λ = (0.350 – 0.422) W.(m.K)$^{-1}$ and for thermal diffusivity of honey are mentioned values from range a = (0.085 – 0.120) .10^{-6} m^{2}.s^{-1}. Examined samples of honey have thermal conductivity and thermal diffusivity from these ranges. Results for samples – perga and bee pollen have not been presented in the literature yet, so they could not be compared.

Thermal properties of honey were measured by many authors. Temperature dependencies of examined bee products thermal conductivity and thermal diffusivity had linear increasing shape (Figures 1, 3, 5 and Figures 4, 6), except relation between honey thermal diffusivity and temperature, which had linear decreasing progress. It was caused by honey composition and structure. This result is in accordance with results presented in the literature. All temperature dependencies had very high coefficients of determination, which are presented in Table 2.

Presented results showed that thermophysical parameters are in significant connection with quality of bee products. The detailed knowledge about thermophysical characteristics of bee products during thermal manipulation can improve their technological processes and storage.

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