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A device for thermal conductivity measurement based on the method of local heat influence

***Abstract**. The requirements for the design of portable device for measuring thermal conductivity based on the method of local heat influence are theoretically formulated. The influence of the heat exchange with surrounding environment, the contact thermal resistance between the probe and the surface is discussed. Also, the influence of the size of heat influence zone on the accuracy of measurement of the thermal conductivity of materials is considered.*

***Streszczenie.** Sformułowano teoretyczne podstawy projektowe dla przenośnych urządzeń do pomiaru przewodności cieplnej materiałów metodą lokalnego wpływu ciepła. Opisano wpływ wymiany cieplnej z otoczeniem, rezystancji cieplnej kontaktu sondy z powierzchnią materiału badanego. Przeanalizowano również wpływ rozmiaru powierzchni strefy wnikania ciepła na dokładność pomiaru przewodności cieplnej materiałów. (**Teoretyczne podstawy projektowe dla przenośnych urządzeń do pomiaru przewodności cieplnej materiałów metodą lokalnego wpływu ciepła**)*

Keywords: *thermal conductivity, thermal conductivity measurements*
Słowa kluczowe: przewodność cieplna materiałów, pomiary przewodności cieplnej

Introduction

In general, it is necessary to determine the coefficient of thermal conductivity of materials not only in stationary laboratory conditions, but also in operating conditions using fast methods. For these purposes, the contact transient methods for thermal conductivity measurements which use plane or linear heating element: hot disk [1–2], hot wire [3], hot strip [4–5]; and a method of measurement of thermal conductivity based on inverse solution for one-dimensional heat conduction [6] are widely applied. All these methods have the disadvantages described in [7]. A special method for thermal conductivity measurement of low density insulating materials was proposed in [7].

The purpose of this work was to develop a new device, based on the steady state method of local heat influence, which is characterized not only by sufficiently high accuracy, wide range of measured values of coefficient of thermal conductivity, short time of sample preparation and measurement and but can measure samples of porous, low density materials.

The method of local heat influence

The method of local heat influence for determination of the coefficient of thermal conductivity is based on applying a heat flux of constant density to the material sample surface through a limited zone, the diameter of which is considerably smaller than sample size. In a steady thermal state, coefficient of thermal conductivity can be found from measurements of the heat flux density and the temperature difference between the centre of the zone and the sample surface, where the heat does not influence the temperature.

The method can be applied for the samples of different shape, in laboratory conditions as well as in industrial environment. For a given application, the influence of such factors as the convective-radiative heat exchange with the surrounding environment, the main characteristic of which is the effective coefficient of heat exchange α, should be considered. The model of heat exchange is given in Fig.1.

The method is based on the theoretical dependence between applied heat flux q and the temperature $\vartheta(r,z)$ on the surface from thermal conductivity λ [8-9].

In this case, the method can be described by differential thermal conductivity equation for steady state expressed in cylindrical system of coordinates (1):

$$\frac{\partial^2\vartheta(r,z)}{\partial z^2}+\frac{1}{r}\frac{\partial\vartheta(r,z)}{\partial r}+\frac{\partial^2\vartheta(r,z)}{\partial z^2}=0, \quad (1)$$

where $\vartheta(r,z)=T(r,z=0)-T_{amb}$ is the difference between the temperature of the surface in the zone of heat influence $T(r,z=0)$ and the ambient temperature T_{amb}.

Boundary conditions for this case are the following:

$$\frac{\partial\vartheta(r,z)}{\partial z}-\frac{\alpha}{\lambda}\cdot\vartheta(r,z)=\frac{q}{\lambda}\cdot U(r_p-r),$$

$$\vartheta(r,\infty)=0,$$

$$\vartheta(\infty,z)=0,\ \vartheta(r,0)<\infty$$

where $u(r_p-r)=\begin{Bmatrix}0, & when\ r>r_p\\ 1, & when\ r\le r_p\end{Bmatrix}$

The solution in this case is:

$$\vartheta(r,z)=-\frac{q\cdot r_p}{\lambda}\cdot I(\rho,\zeta) \quad (2)$$

where $I(\rho,\zeta)=\int_0^\infty\frac{\exp(-\zeta\cdot x)J_1(x)\cdot J_0(\rho\cdot x)}{x+Bi}dx$;

r_p is the radius of the probe influence zone; $\rho=r/r_p$ $\xi=z/r_p$ are dimensionless cylindrical coordinates; J_0 and J_1 are Bessel functions of zero and first order; $Bi=\alpha\cdot r_p/\lambda$ is Biot number, λ is the coefficient of thermal conductivity.

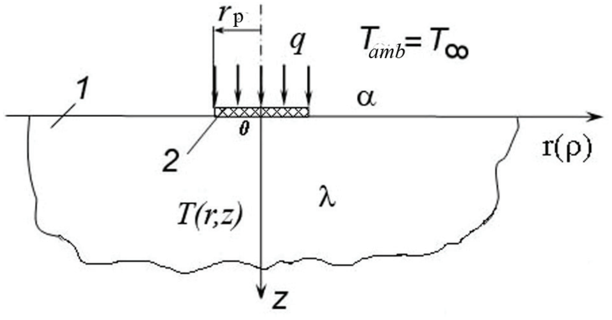


Fig.1. Model of heat exchange in the system „half-infinitive solid sample - probe": 1 - investigated object as half-infinitive solid sample; 2 – the probe for local heat influence

For the case of measuring of the mean temperature in the zone of heat influence [11], one must take into account the heat exchange and the thermal resistance R_c between the probe and the sample:

$$q/\vartheta_{mean}(0)=\left(\frac{r_p}{\lambda}\cdot I_{mean}(0)+R_c\right)^{-1}, \tag{3}$$

where $I_{mean}(\zeta)=2\int\limits_0^\infty\frac{\exp(-\zeta\cdot x)}{x+Bi}\cdot\frac{J_1^{\,2}(x)}{x}dx$, $\vartheta_{mean}(0)$ is the difference between mean temperature of the surface in the zone of heat influence $T_{mean}(z=0)$ and ambient temperature T_{amb}. It can be obtained from the relationship $\vartheta_{mean}(z=0)=T_{mean}(z=0)-T_{amb}$.

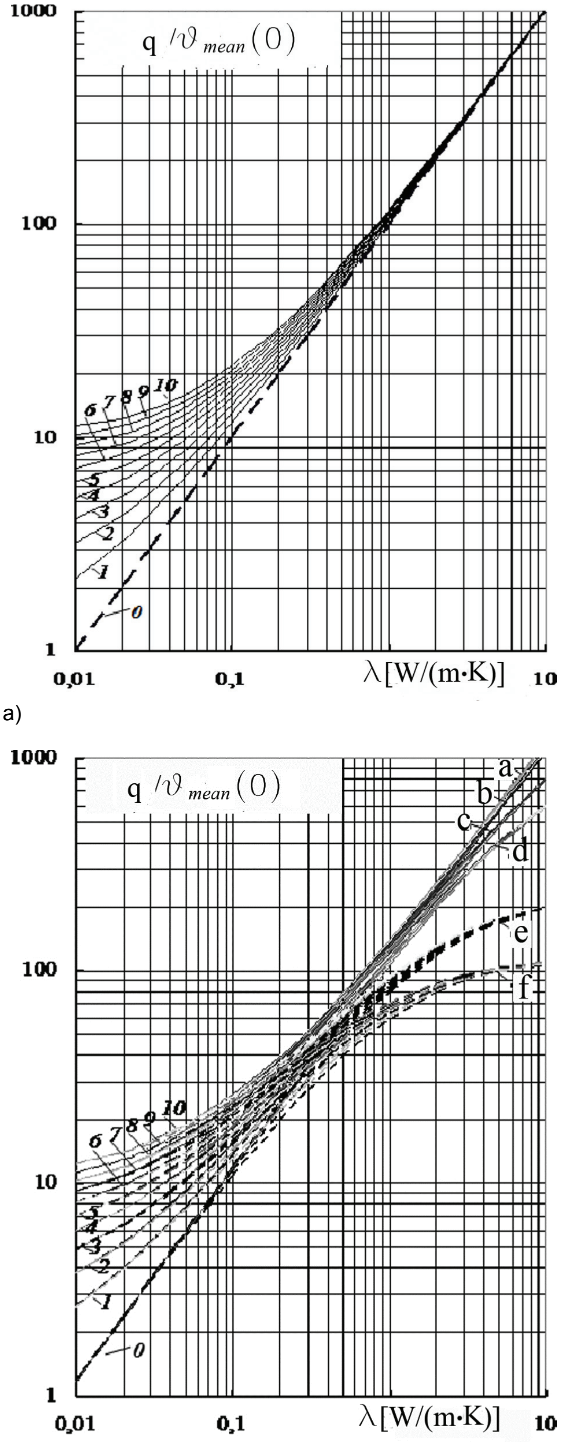
The analytical solution of (3) allows investigating the dependence of the measured values $q/\vartheta_{mean}(0)$ on the coefficient of thermal conductivity of the sample λ at the probe zone radius 10 mm at the absence of the contact thermal resistance: $R_c=0$. The calculations of the coefficient of heat exchange α in the range from 0 to 10 W/(m^2·K) with the step 1 W/(m^2·K) have been done. The results of the calculations are given in Fig. 2a. The analysis of these graphs shows that the conditions of the heat exchange of the surface of the solid sample with the surrounding environment influence the value of measured $q/\vartheta_{mean}(0)$ for low values of the coefficient of thermal conductivity $\lambda<0{,}2$ W/(m·K). Therefore, for materials having a thermal conductivity less than 0,2 W/(m·K), the steps to decrease the influence of the coefficient of heat exchange α should be done[10].

The relationships in Fig.2b show that the influence of the contact thermal resistance increases with increase of material's thermal conductivity coefficient. Thus, the steps to decrease the influence of contact thermal resistance should be done. These steps are: the grinding of the contact surface of the sample (in order to obtain given surface finish class), or applying the greases with high thermal conductivity.

Since the location of temperature T_{amb} measurement in the abovementioned model is not defined precisely, it can result in the source of systematic error in real conditions. Another source of random error is the time drift of the temperature of solid sample during the experiment.

In order to estimate the factors influence, the reference probe was applied, as shown in Fig.3.

To find out the distance l at which the zone of the reference probe is not influenced by the distortions of the local heat influence, the change in the density of the local heat flux in the direction radial to the surface of half-infinitive solid sample was calculated [10,11]. The analysis of the results shows that the reference probe should be placed at the distance of at least 5 radii of the probe influence zone, i.e. $l\geq 5r_p$ [10,11], and the material samples with known thermal conductivity used for calibration and certification of the measuring device should have the thickness least 5 times the radius of the probe.



a)

b)

Fig.2. The relationship between $q\cdot/\vartheta_{mean}(0)$ in the contact area of the radius r_p= 10 mm and the heat conductivity coefficient of material, at the change of the effective heat exchange coefficient α and contact thermal resistance R_c: a) absence of contact thermal resistance b) presence of contact thermal resistance.
0 - α =0 W/(m^2·K); 1 - α =1 W/(m^2·K); 2 - α =2 W/(m^2·K); 3 - α =3 W/(m^2·K); 4 - α =4 W/(m^2·K); 5 - α =5 W/(m^2·K); 6 - α =6 W/(m^2·K); 7 - α =7 W/(m^2·K); 8 - α =8 W/(m^2·K); 9 - α =9 W/(m^2·K); 10 – α =10 W/(m^2·K)
a - R_c=0 m^2·K/W, b - R_c=10^{-5} m^2·K/W; c - R_c=10^{-4} m^2·K/W; d - R_c=5·10^{-4} m^2·K/W; e - R_c=0,001 m^2·K/W; f - R_c=0,005 m^2·K/W; g - R_c=0,01 m^2·K/W

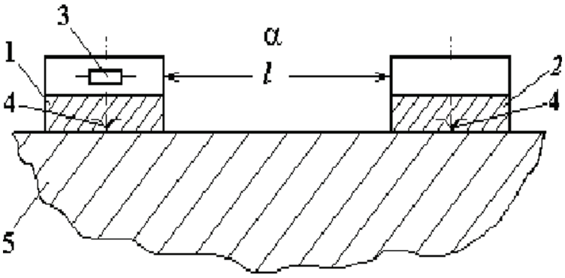


Fig.3. The differential measuring system for the method of local heat influence: 1 - main probe; 2 - reference probe; 3 - working source of heat influence; 4 - thermocouple; 5 – solid sample

The elaborated measuring device and the investigation of its dynamical characteristics

On the basis of aforementioned theoretical results, the device IT-8M was realised (Fig.4).


a)

b)

Fig.4. The outer view of the device IT-8M: a – with the sample under the device; b - with the sample on the device

The probe radius applied in the device is 10 mm; that allows measuring the porous materials with pore diameter of 3 mm, and materials with particle size up to 3 mm. The influence of contact heat resistance becomes considerable at λ >0,2 W/(m·K). Therefore, the contact greases [12] or additive temperature transducers are recommended for the investigations of solid materials. The instability of heat exchange is considerable at investigation of the samples with thermal conductivity λ <0,2 W/(m·K). In order to eliminate this instability, the special screen of low emissivity factor should be used, and the device should be placed under the sample. The influence of temperature drift can be diminished by constructing the device with two identical measuring heads, located more than 5 times the radius of the probe.

In order to determine the time required to perform valid measurements by the device, the experiments with samples of different values of thermal conductivity coefficients were performed. The results of these experiments are given in Figs.5 and 6. As it could be seen from experimental results, the process can be considered as thermally steady after 25 minutes from the beginning of the experiment.

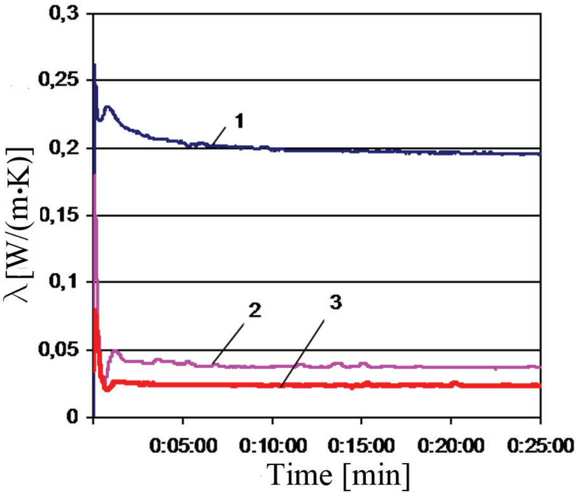


Fig.5. The experimental characteristics of reaching the onset of the steady thermal state of the device IT-8M for samples with thermal conductivity λ <0,2 W/(m·K) 1- (λ =0,196); 2- (λ =0,038); 3 (λ =0,023)

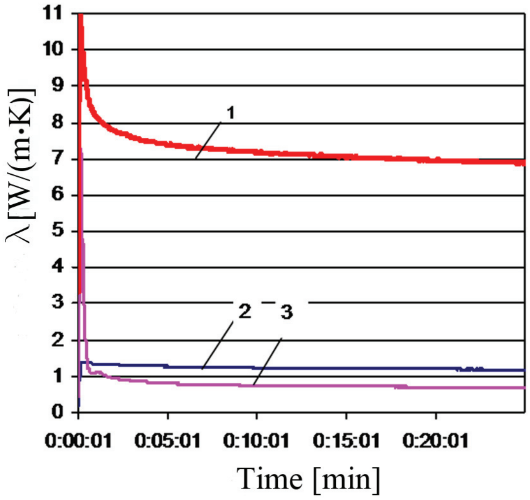


Fig.6. The experimental characteristics of reaching the onset of the steady thermal state of the device IT-8M for materials with thermal conductivity λ >0,2 W/(m·K): 1 - λ = 6,708; 2 - λ = 1,165; 3 - λ = 0,698

Conclusions

The method of local heat influence allows determining the value of thermal conductivity of materials; which are taken into account the contact thermal resistance and heat exchange with surrounding environment.

The device allows the user to measure porous materials with pore diameter of 3 mm, and materials with particle size up to 3 mm. Also, it can measure thermal conductivity of low density insulating materials.

The correction values for measurements of thermal conductivity on samples with thickness of 10 to 100 mm was calculated [11].

The measurement range of the device based on the method of local heat influence reaches from 0.023 to 7 W/(m·K) with an instrumental error no higher than 8%. The measurement time with the new device is about 25 minutes.

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