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Analytical method for determining the temperature dependence of the thermal conductivity coefficient

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The paper developed an analytical method for determining the temperature dependence of the thermal conductivity coefficient, which is based on the approximation of the temperature field obtained using an infrared thermal imaging camera by the solution of the inhomogeneous stationary equation of thermal conductivity.

From the obtained experimental dependences, it is shown that the proposed method based on the stationary heat flux can be used to determine the temperature dependence of the thermal conductivity coefficient for solids: metals, multicomponent alloys, semiconductors and dielectrics. The temperature dependences of the thermal conductivity of test samples of fluoroplastic and steel were obtained. According to these experimental results, the thermal conductivity of fluoroplastic increases, and the thermal conductivity of steel decreases with increasing temperature.

Keywords: thermal conductivity, measurement methods, temperature dependences, thermal imager, stationary equation.

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Introduction

For the experimental determination of the thermal conductivity of solids, many methods have been developed that are sensitive to the range of measured temperatures and the type of material with different thermal conductivities. Thus, one or another method may have advantages for a particular material or temperature range.

Methods for measuring thermal conductivity are divided into two groups: steady-state and non-steady-state methods. In steady-state measurement methods, the sample is subjected to a temperature profile that does not change in time; after reaching equilibrium; thermal conductivity is determined directly from the geometric dimensions and temperature gradient. In non-steady-state methods, the temperature field changes with time, analyzing the spatio-temporal temperature profile, the thermal conductivity coefficient is determined.

One of the common methods for measuring the thermal conductivity of solids is the longitudinal heat flow method. In longitudinal heat flow methods, the experimental arrangement is designed in such a way that the heat flow occurs only in the axial direction of the sample. Under steady-state conditions and in the absence of radial heat losses or heat gains, thermal conductivity is determined from the one-dimensional Fourier-Bio thermal conductivity equation [1]. Radial heat losses should be insignificant, which in practice significantly complicates the use of such methods.

In work [2], a high-precision setup was developed to determine the characteristics of thermoelectric devices in the temperature range of 350-600 K. Direct methods were chosen to measure thermal conductivity, by means of which the heat flux is directed through the thermocouple in response to the temperature gradient created between the heater and the radiator. The essence of the developed methodology is to use two identical samples located on both sides of the heating element, which are cooled by identical water radiators.

An analysis of methods for determining thermal conductivity for thin films was carried out in work [3]. The prospects for using the absolute, 3ω- and flash methods for measuring the thermal conductivity of thin films are shown. Schemes and characteristics of the methods are presented, a number of well-known theoretical and empirical formulas for calculating thermal conductivity are given.

The authors [1] conducted research related to measuring the change in thermal conductivity depending on the temperature of metals and multicomponent metal alloys. The authors modified the rod method of linear heat flow and developed a device for measuring the change in thermal conductivity with temperature. The device consisted of a hot table, a cold radiator and a sample holder. A proportional control system was implemented using a control thermocouple in a hot cascade. To obtain a linear temperature gradient in the sample, the distance between the hot and cold surfaces was 10 mm. The temperature was controlled by thermocouples.

Thermal conductivity is one of the most important parameters of heat-shielding materials. In work [4], a method for measuring the temperature dependence of thermal conductivity for thermal insulation materials is proposed. An experimental setup was built to test the efficiency of thermal insulation at large temperature differences in both stationary and transient modes, and the dependence of thermal conductivity on temperature for heat-shielding materials was obtained.

In most existing works, thermocouples or thermistors are used to measure temperature, but for measuring temperature gradients, such methods have significant drawbacks, especially for thin-film samples, since heat dissipation through thermocouple wires distorts the temperature field. For rapid measurements of temperature gradients along the surface of the sample, it is convenient to use thermal imaging methods. This is confirmed by the authors of work [5], where rapid measurements of the dependence of thermal conductivity on temperature based on thermal images were implemented. The thermal conductivity coefficient was obtained from a combined experimental and theoretical study based on the Wiedemann-Franz law. The cubic relationship between the heating time and the distance to the heat source was used to determine thermal conductivity at different temperatures.

However, the authors did not find any references to determining the temperature dependence of the thermal conductivity coefficient of a body based on heat leakage through the surface into radiation and heat transfer to the external environment.

I. Experimental methodology

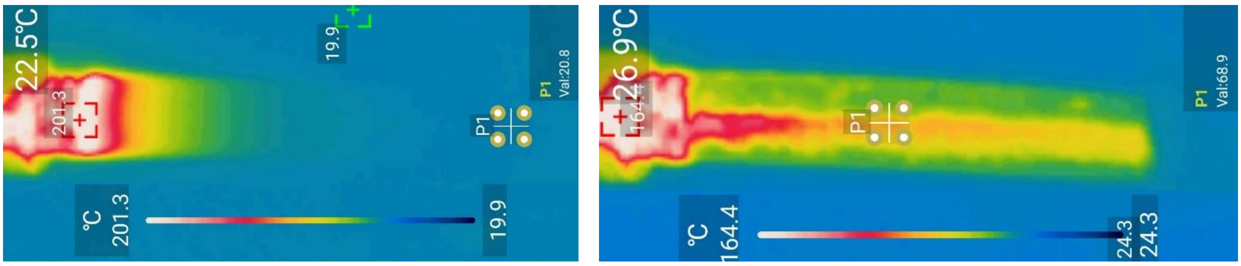
To test the method, cylindrical samples with flat parallel ends were studied. The diameters of the samples were 6 mm, and the lengths were 30 and 60 mm. Both dielectric materials with low thermal conductivity, in particular fluoroplastic, and electrically conductive materials with high thermal conductivity, in particular steel, were studied. To create a stationary temperature field, the sample was clamped between a polished copper radiator (Fig. 1, a) cooled by flowing water or a massive aluminum radiator (Fig. 1, b) and a copper heater heated by an electric spiral inside. Temperature control was carried out by chromel-aluminum thermocouples, stabilization of the heater temperature was carried out automatically according to the proportional-integral-differential (PID) algorithm. The pressing force was set using a spring. Measurements were performed in a closed volume, in air, in argon or in vacuum.

The temperature field along the sample was obtained from images from the Unit-T 120 thermal imager. The distance to the temperature markers was determined using a screen caliper.

Fig. 2 shows a thermal image for a material with low thermal conductivity (fluoroplastic) (Fig. 2, a), and a material with high thermal conductivity (stainless steel) (Fig. 2, b).

a) b)

Fig. 1. General view of the measuring cell and configuration of samples for measurement.



a) b)

Fig. 2. Thermal images of the temperature gradient for a material with low thermal conductivity.

II. Theoretical model and solution options

The steady-state inhomogeneous heat conduction equation describes the temperature distribution in a body when the temperature does not change with time. We use this equation to find the temperature dependence of the thermal conductivity coefficient.

Consider the steady-state equation for the temperature field along a thin rod of diameter d:

$$\frac{d}{dx}\left(\lambda(T)\frac{d}{dx}T(x)\right) = \frac{4}{d}\left\{\sigma(T(x)^4 - T_\infty^4) + \alpha(T(x) - T_\infty)\right\}, \quad (1)$$

where the Stefan-Boltzmann constant $\sigma = 5.67\times10{-}8$ W/m²·K⁴, T_∞ is the ambient temperature, the heat transfer coefficient α for natural convection in air varies within 3 – 10 W/m²·K.

If the temperature field is well approximated by the dependence

$$T(x) = T_\infty + T_1 \exp(-x/L), \quad (2)$$

then after substituting $t = T/T_\infty$ i $\xi = x/L$ we obtain the equation

$$\frac{d}{d\xi}\left(\lambda^*(t)\frac{d}{d\xi}t(\xi)\right) = t^4 - 1 + \alpha^*(t - 1), \quad (3)$$

where $\lambda^* = \lambda d/4L^2\sigma T_\infty^3$, and $\alpha^* = \alpha/\sigma T_\infty^3$.

The solution to equation (3) is

$$\lambda^*(t) = (25 + 12\alpha^* + 13t + 7t^2 + 3t^3)/12. \quad (4)$$

If the temperature field is poorly approximated by dependence (2), then equation (1) is solved numerically, and the boundary condition t(0) and t`(0) for equation (3) and the coefficients $\lambda^*(t_0)$ and $\lambda^{*\prime}(t_0)$ of the expansion $\lambda^*(t) = \lambda^*(t_0) + \lambda^{*\prime}(t_0)(t - t_0)$ are obtained from the approximation of the experimental t(ξ) by the theoretical one.

III. Measurement and approximation results

Fig. 3 shows the dependence of the temperature of the fluoroplastic rod on the coordinate along the axis, as well as the temperature dependence of the thermal conductivity coefficient.

The dependence of the temperature of the steel rod on the coordinate along the axis, as well as the dependence of the thermal conductivity coefficient on temperature, is given in Fig. 4.

IV. Discussion of the results obtained

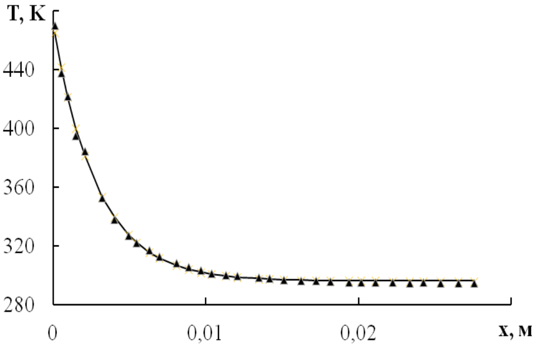
Fluoroplastic is a typical heat insulator, the temperature dependences of the thermal conductivity coefficient for some grades are given in [6, 7]. In [7] it is shown that porous fluoroplastic has a thermal conductivity coefficient 3.5–4 times lower than compact fluoroplastic-4. The degrees of blackness ε for pure fluoroplastic are 0.9–0.95, for fluoroplastic with impurities or a rough surface 0.8–0.9. The selected heat transfer coefficient α also significantly affects the processing results. Thus, the reproduction of the temperature dependence of λ and its value with an accuracy of 6% for a typical heat insulator is considered satisfactory.

The thermal conductivity λ of steel depends on its composition; with increasing temperature, the thermal conductivity of steel usually decreases:

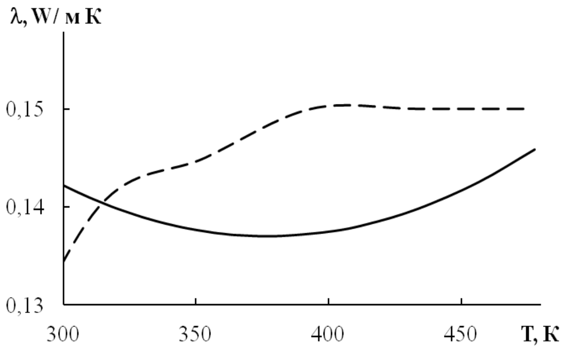
$$\lambda(T)=\lambda_0\cdot(1 - \beta\cdot(T - T_0)),$$

where: λ_0 — thermal conductivity at 20 °C, β – temperature coefficient ≈ 0.0005 − 0.002 K⁻¹, λ_0 ≈ 45−50 W/m·K (carbon steel type St3, 10, 20), λ_0 ≈ 14 − 16 W/m·K (stainless steel type 304, 316).

The degree of blackness of the steel ε depends on the surface treatment, for polished steel ≈ 0.1 – 0.3, for oxidized 0.7–0.9. Thus, the radiation flux strongly depends on the degree of blackness of the surface: oxidized or painted surfaces emit 3–4 times more energy than polished ones.

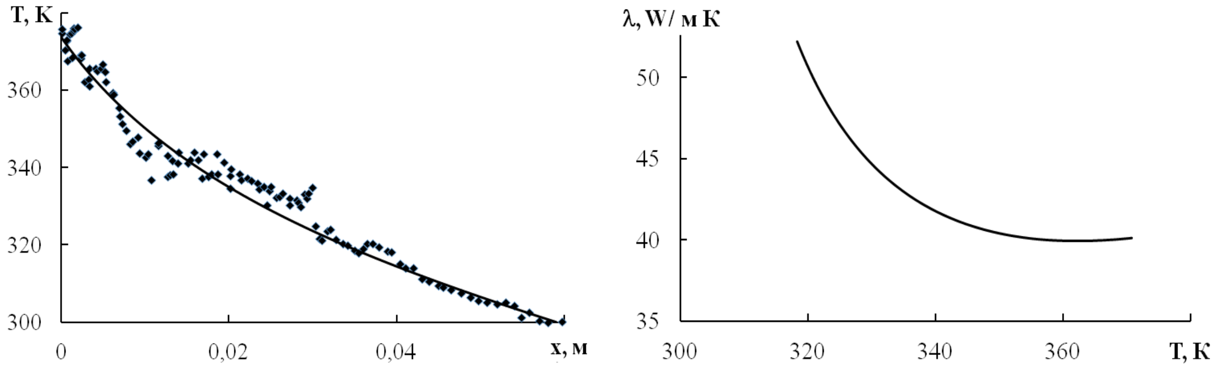


a)



b)

Fig. 3. a) Temperature field along a 6 mm diameter and 3 cm long fluoroplastic rod obtained using an infrared thermal imaging camera. The smooth line is curve (2).
b) The temperature dependence (solid line) of the thermal conductivity coefficient was calculated, the heat transfer coefficient α = 12 W/m²·K was used, the degree of blackness ε = 1; and for comparison, the thermal conductivity of fluoroplastic F-4NA [6] is given (dashed line).



a) b)

Fig. 4. a) Temperature field along a rod with a diameter of 6 mm and a length of 6 cm made of steel, obtained using an infrared camera. The smooth line is the result of numerical integration of equation (3). b) The temperature dependence of the thermal conductivity coefficient was calculated, the heat transfer coefficient α = 10 W/m²·K was used, the degree of blackness ε = 1.

Therefore, we consider the reproduction of the temperature dependence decay λ and its magnitude with an error of 12% for a typical heat conductor to be also satisfactory.

Conclusions

A method for measuring the temperature dependence of the thermal conductivity coefficient has been developed, which is based on the analysis of the temperature field obtained from an infrared thermal imaging camera and the solution of the stationary inhomogeneous thermal conductivity equation.

It is shown that the developed method can be used to measure the temperature dependence of the thermal conductivity coefficient for solid materials, in particular metals, multicomponent alloys, semiconductors and dielectrics.

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Аналітичний метод визначення температурної залежності коефіцієнта теплопровідності

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В роботі розроблено аналітичний метод визначення температурної залежності коефіцієнта теплопровідності, який ґрунтується на апроксимації температурного поля, отриманого за допомогою інфрачервоної тепловізійної камери, розв’язком неоднорідного стаціонарного рівняння теплопровідності.

З отриманих експериментальних залежностей показано, що запропонований метод на основі стаціонарного теплового потоку можна використовувати для визначення температурної залежності коефіцієнта теплопровідності для твердих тіл: металів, багатокомпонентних сплавів, напівпровідників та діелектриків. Отримано температурні залежності теплопровідності тестових зразків фторопласту та сталі. Згідно з даними експериментальними результатами, теплопровідність фторопласту зростає, а теплопровідність сталі зменшуються зі збільшенням температури.

Ключові слова: теплопровідність, методи вимірювання, температурні залежності, тепловізор, неоднорідне стаціонарне рівняння.