Thermal Conductivity of Graphite at High Temperatures[1]

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The new approach of definition of thermal conductivity of high-temperature materials in which basis the known stationary method of two cylinders is offered. The experiment results of thermal conductivity of isotropic graphite in density of 1700 kg/m^3 are presented. Samples represented hollow cylinders with external diameter 8 mm and the different sizes of internal diameter. Experiments carried out in an atmosphere of argon at pressure 0.1MPa. Heating carried out an electric current. The temperature was measured by optical pyrometers on length of a wave 0.65 μm. It defined in the central of an isothermal part simultaneously (two pyrometers) on external and internal surfaces of the sample. Last temperature measured through a special aperture, which simulated model of blackbody. For testing the method temperature dependence of thermal conductivity of graphite in a range 2500-3150K has been studied. Experimental statement has assumed to determine the normal spectral emissivity of a wave 0.65 μm in parallel with coefficient of thermal conductivity. In the extremely high temperatures area it is offered to enter into experiment the third cylinder and to measure the temperature dependence of coefficient of thermal conductivity. The received experimental results will well be agreed with known literature data that allows the given techniques to use up to temperature of destruction of graphite. As a whole the offered approach allows to define a complex of transfer and radiating properties in identical conditions that has basic value for graphite materials.

KEY WORDS: normal spectral emissivity; stationary method of two cylinders; temperature; thermal conductivity.

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1. INTRODUCTION

In order to specify the temperature difference in a wall the well-known method of two cylinders is applied [1, 2, 3, 4]. According to the method the two hollow cylinders, made of one material, with an identical external diameter, but with different width of a wall, are heated. In paper [1] the heating of the sample was conducted by thermal conductivity. In papers [3, 4] it is proposed to heat a sample by an electrical current (they don't realize the method in practice).

The paper presents the complex stationary method of measuring the thermal conductivity (k) and the normal spectral emissivity ε^n_λ (λ= 0.65 μm) of electrical conductive materials. The main feature of the presented method is that the measurement of heat flux density by probes (calorimetric method) is not carried out. We take the heat flux density out of the Stephan-Boltzman's law, using the known total hemispherical emissivity ε_t^h of a researched material. In the extremely high temperature area, where the ε_t^h of the material is not known, it is offered to enter into experiment the third cylinder and to measure the temperature dependence of coefficient k (method of three cylinders). The methods were tested on isotropic graphite of density 1700 kg/м^3 for area of temperatures 2600-3100K.

2. METHOD OF TWO CYLINDERS

In theory, as the equality of the heat flux density of external stream $q_{s1} = q_{s2} = q$ for two samples holds, the equality of temperatures on an external surface of both samples $T_{\rm surf1}$ = T_{surf2}=T_{surf} holds too. In this case solution of the stationary task of a thermal conductivity (k= const) in a cylindrical wall with internal sources of heating allows define the coefficient k under the following formula:

$$k = q_s (A_1 - A_2) / (T_1 - T_2), \qquad (1),$$

where $A_i = R_i\,[1 - (2\,r_i^2 \ln(R_i/r_i) / (R_i^2 - r_i^2)]/2$ (i an index of a sample), R_i – external radius, r_i- internal radius, T_1, T_2 - true values of temperature on an internal surface of samples.

The value of the heat flux density q_s is defined under the Stephan-Boltzman's law [3]:

$$q_s = \varepsilon_t^h\,\sigma\,T_{\mathrm{surf}}^4 \qquad (2),$$

where ε_t^h – total hemispherical emissivity, σ - Stephan-Boltzman's constant, T_{surf} – true value of temperature on an external surface of sample. In true value T_{surf} can be calculated [2] through the true temperatures of an internal surface T_i (method of two cylinders) under the formula:

$$T_{\mathrm{surf}} = (T_1 A_2 - T_2 A_1)/(A_1 - A_2) \qquad (3)$$

Experimental implementation of the method and processing of outcomes are the following. The measurements of T_i and T_{brigh} –the brightness temperature on an external surface of a sample are carried out. . The temperature T_i measured through a special aperture, which simulated model of blackbody. Assume that ε_t^h is known from the reference data [5] or from the independent experiment. Experimental data processing consists of constructing temperature curves $T_i = f(T_{\mathrm{brigh}})$ for two samples. Then for the fixed value of T_{brigh}, (according to which it is controlled that q_s = idem holds) T_1 and T_2 are determined, and at last sequentially T_{surf}, q_s and coefficient k are determined.

The investigation of the coefficient of k and the ε^n_λ of isotropic graphite with density 1700 kg/м^3 was conducted on plant, carefully discussed in paper [6, 7]. We made the basic sample's construction changes; the way the sample was fixed was also modified. The samples looked like slim wall long pipes of radius R=4 mm, r_1=2 mm, r_2= 2.5 mm. The length of samples constituted 70 mm, the length of isothermal area was not less than ±12 mm from the center of a pipe. The external surface of cylinders was polished before the experiments. The sample was fixed through cartridges on the extremities of copper water-cooled spring electrodes. Thus the special system of unloading from thermal deformation (conic graphite stitches - in) was used. The temperature endurance of a material took place at the temperature of 2500 K with duration more than 30 minutes before the experiments. In the Table 1 the example of the preliminary experimental data for one temperature is provided. It is important to mention here that the coefficient *k* was measured perpendicularly to the axis of the cylinder.

Table 1. Example of experimental data for definition coefficient of *k* at t_{defin}=3010 K.

T_{brigh}, K	T_1, K (R/r=4/2mm)	T_2, K (R/r=4/2.5mm)	T_{surf}, K	k, W/m K t_{defin}=3010 K
2900	3066	3037	2955.3	33.7

The experiment allows to define also the normal spectral emissivity ε^n_λ on the basis of obtained empirical data (T_{brigh}, T_{surf}, C_2=1.438 10^{-2} mK) (method of Worthing):

$$\ln\varepsilon^n_\lambda = C_2/\lambda(1/T_{surf} - 1/T_{brigh}) \qquad (4)$$

The experimental results of coefficient *k* and ε^n_λ by the method of two cylinders at known ε_t^h are given in Figure 1 and Figure 2. Figure 1 provides also the *k* values, obtained in papers [8, 9]. Figure 2 presents the recommended value ε^n_λ on a red wavelength [5] too. One can see that the order and the temperature dependence for the experimental data show a good agreement with the other papers' results. The upper temperature bound of our experimental values is limited by the upper bound of the coefficient ε_t^h [5].

The electricity characteristics I_i-current and U_i-potential-drop on specimen (all length) were additionally measured on each sample. These experimental data have allowed to evaluating temperature dependence of the electrical conductivity ρ (ρ was measured parallel to the axis of the cylinder). We have found that the investigated material has nearly constant value of ρ in a temperature range 2500-3100 K. The product $k\rho \approx$ const supports the main results provided in papers [10], where the mentioned properties of graphite samples with the same density but supplied by different producers were measured. These results in a more detailed form will be presented in the following publications.

The estimation of a systematic error provides the following results: ±10 % for k and ±5% for ε^n_λ.

3. METHOD OF TREE CYLINDERS

In the extremely high temperature area as the ε_t^h of a material can not be known, it is offered to enter into experiment the third cylinder and to define the temperature dependence of the coefficient k. The possibility of usage of the third cylinder for definition of temperature function of the coefficient k was considered in paper [1]. It was stationary task of a thermal conductivity of a multilayer wall without internal sources of heat and other boundary conditions. The given technique can be applied only for materials, which are electrical insulators. In the present work the technique is offered, in which basis the stationary task of a thermal conduction for a single-layer cylindrical wall with internal sources of heat is used, that allows study materials, which skip an electrical current.

Here we presume that all the assumptions of the method of two cylinders must be fulfilled. In our research cylinders must have the identical external diameter but different internal diameters. The usage of the third cylinder gives us a possibility to determine k for each pair of cylinders for the same value of the heat flux density and thus to eliminate q_s from a final formulas:

$k_{1-2}/k_{2-3} =[q_s (A_1-A_2)/(T_1–T_2)]/[q_s (A_2-A_3)/(T_2–T_3)]= (A_1-A_2)(T_2–T_3)/(T_1–T_2) (A_2-A_3)$ (5),

Now there is no need to measure the heat flux density or to take the reference value of ε_t^h. During the experiment two temperatures are measured for each sample: the true value on an internal surface T_i and brightness temperature on an external surface T_{brigh} in all the required range of temperatures. Then the processing of the obtained experimental data is carried out in the following way: the functional dependence $T_i = f(T_{\text{brigh}})$ is found for each sample; for three cylinders and the fixed value of brightness temperature $T_{\text{brigh},}$ = idem the values of temperature $T_{r=1}$, $T_{r=2}$, $T_{r=3}$ are calculated. The ratio of two coefficients of a thermal conduction for the appropriate values of defining temperature also characterizes relative change of coefficient k by temperature. The defining temperature for each value $k_{1-2} =k_{t1-2}$ can be found by the linear approximation, because the experiments are carried out under the condition of a small temperature difference on width of a wall: $t_{defin}=(T_{\text{surf}} +T_i)/2$. Thus from two samples is selected what has the large width of a wall [2]. The complex k_{1-2}/k_{2-3} is constructed in such a manner that the numerator responds higher values of temperature (sample with smaller internal radius), therefore it is possible to show, that the ratio of defining temperatures equals: $t_{defin1-2}/t_{defin2-3} = \frac{t_{defin2-3}+\delta}{t_{drfin2-3}} = 1+\delta$, where - δ = $t_{defin1-2}$ - $t_{defin2-3}$ is infinitesimal by the value.

The first outcomes are given in Figure 1. The temperature dependence of the coefficient k (obtained by method of two-cylinders) is close to constant in temperature range 2600-3100 K. Method of three-cylinders, the capacity for work of which was specially tested for the same temperature range, has also proved the absence of obvious temperature dependence for coefficient k. The relative value of the k coefficients in temperature range

2600-3000 K equals: $k_{tdefin=2788}/k_{tdefin=2781}$=0.998, and approximates to unity. Latest experiments were hold for cylinder diameters: 8-4mm, 8-4.5mm and 8-5mm.

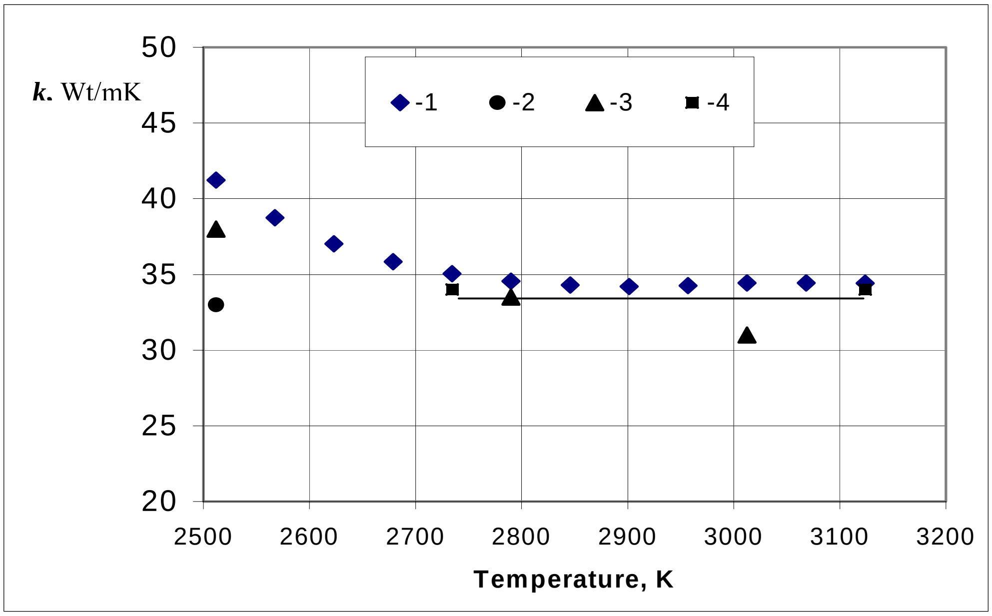

Figure 1. Thermal conductivity of graphite as a function of temperature.

1- method of two-cylinders for isotropic graphite in density of 1700 kg/m^3;

2- isotropic graphite in density of 1800 kg/m^3 [8];

3 – polycrystalline graphite in density 1660 g/m^3 [9].

4 – method of three-cylinders for isotropic graphite in density of 1700 kg/m^3.

The proposed method of measuring of the coefficient *k* permits to carry out the experiment by non-contact temperature diagnostics. This technique has two main consequences: it is possible to raise the upper temperature limit for defining the coefficient *k* and the accuracy of measurements is increased with temperature raising. The estimation of a systematic error provides the results: ±20 % for *k,* but this value can be reduced as a result of special selection of samples sizes and increase of number of data points.

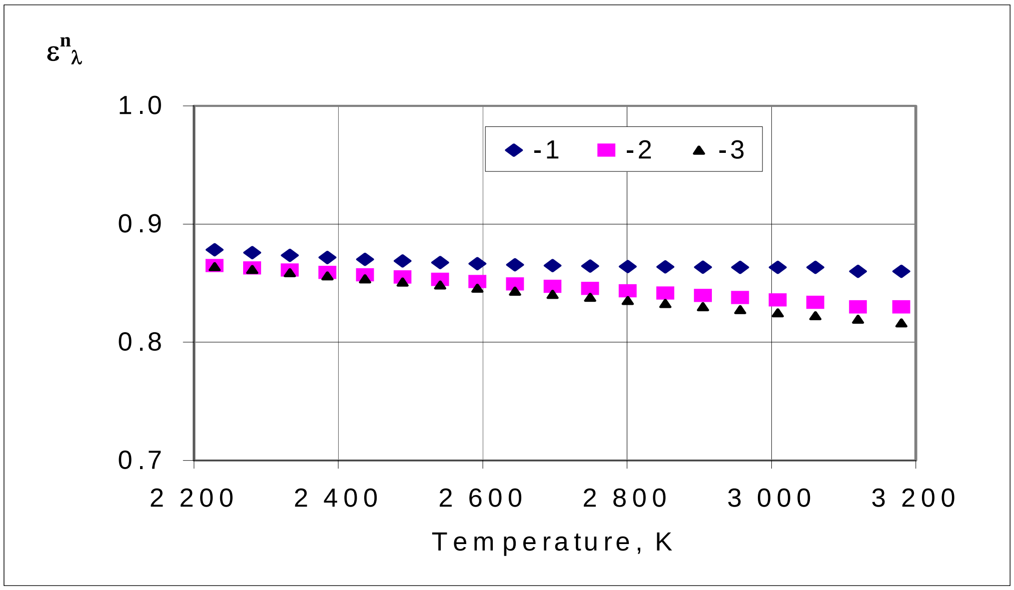

Figure 2. Normal spectral emissivity of graphite as a function of temperature.

1-two-cylinders method isotropic graphite in density of 1700 kg/m^3;

2 -[5];

3 - isotropic graphite in density of 1700 kg/m^3 [7].

CONCLUSION

The discussed above methods to measure *k* experimentally realized for the first time. The results obtained by the methods have shown good agreement with the known reference data for the isotropic graphite with density 1700 kg/m^2. The results obtained now can be characterized as more reliable to the contrary of our results [7], because properties *k* and $\varepsilon^n_{\lambda=0,65}$ were measured in the same experiment. These methods can be used for investigation of thermophysical properties of electrical conductive materials in the area of extremely high temperatures.

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