USE OF FUSED QUARTZ AS A REFERENCE STANDARD IN COMPARATIVE METHODS OF THERMAL CONDUCTIVITY MEASUREMENTS

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A method has been developed for taking into account radiation when the thermal flux through a quartz-standard specimen is calculated.

As is well known, a study of thermal conductivity involves numerous laborious time consuming physical experiments and, therefore, the thermophysical characteristics of many new composite materials are most often determined by relative measurements: simplification is achieved here by comparing the temperature field of the irradiated material with that of a reference specimen (standard) [1-3]. For thermal conductivities in the $\varkappa = 0.5$-10 W/m · °C range (covering most composite materials) one most often uses fused quartz, because it is very stable and suitable for the wide 100-1700°K temperature range. The thermal conductivity of this substance has been dealt with in several studies [4-6 et al.].

On account of its partial transparency to thermal radiation, however, the use of fused quartz at temperatures above 500°K becomes problematic. In view of this, it has been suggested to discontinue using fused quartz in comparative measurements [7, 8], but no other reference materials capable of replacing SiO_2 and free of radiation effects have been found yet. The use of porcelain, as suggested in [8], is hardly worth considering. According to the data in [8], the values of thermal conductivity spread from one specimen to another by as much as 8% and depend on the technology of this multicomplex material.

For this reason, it becomes worthwhile to consider how the radiative component of heat transmission can be taken into account under specific test conditions where fused quartz is used in relative measurements.

Essentially, the role of a standard specimen is to measure the thermal flux, while really the total energy flux Q through a quartz plate is to be determined. The simplest method of calculating Q from the measured effective thermal conductivity of fused quartz is not applicable here, because this thermal conductivity depends on many factors which vary from instrument to instrument (e.g., the specimen thickness, the boundary characteristics, etc.). It is necessary, therefore, to use objective characteristics of the material and to calculate Q according to the theory of compound heat transmission, where several mechanisms are assumed to operate in the medium. In the case of radiative–conductive heat transmission Q is determined according to the equation [9]:

$$Q = \varkappa \frac{\Delta T}{H} + \frac{1}{H} \int_0^H E\,[T(x)]\,dx, \tag{1}$$

and the problem reduces to determining the radiation vector E. A method has been developed in [9] by which this quantity can be calculated on the basis of the mean-spectral absorptivity. In our case such an approach will yield only a qualitative estimate of the radiation component, inasmuch as it has been shown earlier [10] that the selective absorption characteristic of fused quartz must be considered in any calculation of radiative–conductive heat transmission. One must also consider that, as has been established by

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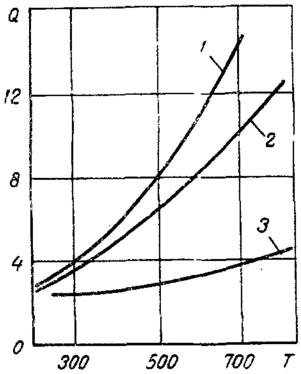

Fig. 1. Thermal flux Q (W/m^2) through a fused-quartz standard, as a function of the temperature T (°C): 1) radiation disregarded; 2) selectivity of optical properties taken into account; 3) selectivity of optical properties not taken into account.

series of calculations in [11], in thin quartz plates (H < 1 cm) the temperature field deviates very slightly from linearity.

We have then for Q:

$$Q = \varkappa \frac{\Delta T}{H} + \frac{2\pi \Delta T}{H} \int\limits_{\lambda=0}^{\infty} \left(\frac{\partial I_B}{\partial T} \right)_{T_0} n_\lambda^2 \left[\frac{F(1-R)}{k_\lambda} + \int\limits_0^H \frac{x}{H} K(x)\, dx \right] d\lambda. \qquad (2)$$

Here

$$F = \int\limits_{\varphi=0}^{\pi/2} \frac{\sin\varphi \cos\varphi}{1 - R^2 \exp\left(-\frac{2k_\lambda H}{\cos\varphi}\right)} \left(R \exp\left(-\frac{2k_\lambda H}{\cos\varphi}\right) + 1 - R \exp\left(-\frac{k_\lambda H}{\cos\varphi}\right) - \exp\left(-\frac{k_\lambda H}{\cos\varphi}\right) \right) d\varphi;$$

$$K(x) = \int\limits_{\varphi=0}^{\pi/2} \sin\varphi \cos\varphi \Bigg[\exp\left(-\frac{k_\lambda (H-x)}{\cos\varphi}\right) - \exp\left(-\frac{k_\lambda x}{\cos\varphi}\right) + \frac{R}{1 - R^2 \exp\left(-\frac{2k_\lambda H}{\cos\varphi}\right)} \Bigg(\exp\left(-\frac{k_\lambda (H+x)}{\cos\varphi}\right) + R \exp\left(-\frac{k_\lambda (3H-x)}{\cos\varphi}\right)$$
$$- \exp\left(-\frac{k_\lambda x}{\cos\varphi}\right) - R \exp\left(-\frac{k_\lambda (2H-x)}{\cos\varphi}\right) + \exp\left(-\frac{k_\lambda (H-x)}{\cos\varphi}\right) + R \exp\left(-\frac{k_\lambda (H+x)}{\cos\varphi}\right) - \exp\left(-\frac{k_\lambda (2H-x)}{\cos\varphi}\right)$$
$$- R \exp\left(-\frac{k_\lambda (2H+x)}{\cos\varphi}\right) \Bigg) \Bigg] d\varphi.$$

The integration in (2) is carried out over the entire spectrum.

The results of calculations shown in Fig. 1 pertain to thermal fluxes through a 2.4 mm thick fused-quartz plate with a platinum foil on the surface, in a test stand for comparative measurements. Both ΔT and T_0 were measured here. Curve 1 is based on the effective thermal conductivity of quartz (disregarding radiation) taken from [4].

Curve 2 is based on Eq. (2) (all calculations were made on a BÉSM-4 computer). The values of the true thermal conductivity and of k_λ were first determined at different temperature levels (k_λ within the 2.5-5.0 μ range of wavelengths was measured by Z. S. Settarova). It was assumed in the calculations that SiO_2 is almost transparent within the 0.3-2.5 μ range of wavelengths and opaque to waves longer than 5.0 μ. The relation $n = f(\lambda)$ can be approximated, with sufficient accuracy, by the linear expression $n = 1.473 - 0.021\ \lambda$. The quantity R was calculated from test values for the emissivity of the platinum foil.

Curve 3 is based on the approximate analysis by Poltz [9] without the selectivity of optical properties taken into account (the mean absorptivity of SiO_2 was taken from [12]). Quite obviously, such an approximation is too rough for the determination of Q.

We note, in conclusion, that on this test stand were also examined specimens of aluminum oxide made by the plasma-sputtering process and that the error in determining its thermal conductivity at 800° would be as high as 100-200% when radiation either was not accounted for or was accounted for incorrectly, resulting even in a much distorted $\varkappa$(T) characteristic.

NOTATION

Q is the thermal flux;
T is the temperature, °K;
$\varkappa$ is the thermal conductivity;
ΔT is the temperature drop across a layer of thickness H;
E(T) is the radiation vector, a function of the temperature and of the optical properties of the medium;
n_λ is the spectral refractive index;
k_λ is the spectral absorptivity;
T_0 is the "hot" surface temperature;
R is the reflectivity of the boundary surface;
I_P is the Planck constant.

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