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METHOD FOR MEASUREMENT OF RADIATION, TRANSMISSION, AND REFLECTION COEFFICIENTS OF SEMITRANSPARENT MATERIALS

G. K. Kholopov and V. I. Kopysov

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Basic principles and results of testing a technique for determining the radiation properties of materials are presented.

Solution of many problems in thermophysics and applied optics requires reliable information on the radiation properties of materials. The basic source of such information is experimental studies. In connection with this, measurement of radiation, transmission, and reflection coefficients of transparent and diffusely transmitting materials — crystals, glasses, plastics, films, tissues, grids, etc — is of special interest. Measurement of radiation coefficients of such materials involves the greatest methodological difficulties.

As a rule the known methods and apparatus for measurement of radiation coefficients of semitransparent materials at both high [1, 2] and moderate and low [3, 4] temperatures are based on comparison of the radiation from the specimen under study with that of a reference source — a black body. One of the major requirements is then the need for uniform heating (or cooling) of the specimen and equality of its temperature to that of the black body. This complicates technical realizations of the measurement apparatus and (or) leads to significant errors in measurement.

The technique to be described below realizes a new method of measuring radiation, transmission, and reflection coefficients of semitransparent materials in the infrared (IR) range of the spectrum [5], which does not require equalization of the temperatures of the specimen studied and the reference radiation source, but requires only the constancy of both those temperatures over the period of the measurement cycle.

A diagram of equipment realizing this method and explaining its basic principles is shown in Fig. 1. Two black bodies 1 and 2 are mounted by a rotation device 3 in chamber 4 with isothermal nontransparent walls. A uniform wall temperature is achieved, for example, by bathing the walls with a heat exchange agent supplied by tubes from a temperature-stabilized volume. The temperatures of the black bodies differ and are maintained stable, for

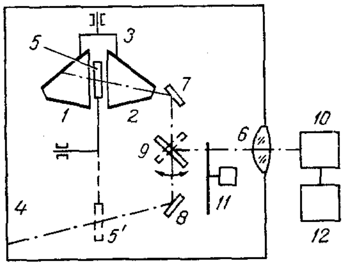

Fig. 1. Diagram of device for realization of measurement method.

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example, by individual thermostats or electric heaters. The black bodies provide hemispherical irradiation of both sides of the specimen, for which purpose they are supplied with radiating apertures opposite each other and are installed a distance apart sufficient for introduction or removal of the specimen 5 between them. Each of the black bodies has an oblique orifice on the radiating surface, required for photometry of the specimen from the side corresponding to the given black body. An optical system consisting of objective 6, two fixed mirrors 7 and 8, and a plane rotatable mirror 9, directs the radiation to be measured from the specimen, black bodies, or chamber walls onto the photodetector device (PD), for example spectral radiometer 10, which transforms the radiation received in a given spectral range into an electrical signal. Radiation modulator 11 is installed ahead of the objective 6. The values of the signals from the PD output, linearly proportional to the radiation level being measured, are measured by the meter 12.

Before commencing measurement, the working temperatures of the chamber walls 4 and black bodies 1 and 2 are established. The measurement technique then involves performing (in any sequence) the following six operations.

1) Mirror 9 is brought into the position shown by dashed lines in Fig. 1. The position of the black bodies is arbitrary, specimen 5 is removed from the PD field of view (located either between the black bodies, or in some neutral position). In this case the PD measures the energetic brightness of the chamber wall L_W.

2) From its position in paragraph 1 the specimen is introduced into the PD field of view, so that the energetic brightness of the specimen is measured against the background of the chamber wall L_{OW} (the side of the specimen seen by the PD and the opposite side are located in the radiation field of the chamber wall only).

3) Mirror 9 is brought into the position shown by the solid lines of Fig. 1. Black bodies 1 and 2 are placed in a position such that black body 2 is located between black body 1 and mirror 7. Specimen 5 is introduced into the spaces between the black bodies. The PD will now measure the energetic brightness of the specimen L_{01} corresponding to simultaneous hemispherical irradiation of the side seen by the PD by black body 2 and the opposite side by black body 1.

4) From the position of paragraph 3 specimen 5 is removed from the space between the black bodies and the brightness L_1 of black body 1 is measured.

5) Black bodies 1 and 2 are interchanged, so that black body 1 lies between black body 2 and mirror 7 and the brightness L_2 of black body 2 is measured.

6) In the configuration of paragraph 5 specimen 5 is inserted into the space between the black bodies and its energetic brightness L_{02}, corresponding to simultaneous irradiation of its visible surface by black body 1 and its opposite side by black body 2, is measured.

Assuming that in all positions corresponding to specimen brightness measurements the specimen temperature T_0 undergoes practically no change, these brightnesses can be expressed by the relationships:

$$L_{01} = \varepsilon L_0 + \tau L_1 + \rho L_2, \tag{1}$$

$$L_{02} = \varepsilon L_0 + \tau L_2 + \rho L_1, \tag{2}$$

$$L_{OW} = \varepsilon L_0 + (\tau + \rho) L_W, \tag{3}$$

where the values of the transmission and reflection coefficients replace the numerically equal values of the hemispherical brightness coefficients for transmission and reflection [6], and the quantity L_O defines the energetic brightness of the black body at the specimen temperature T_0.

Aside from Eqs. (1)-(3), in view of the law of conservation of energy and Kirchhof's law, we also have

$$\varepsilon + \rho + \tau = 1. \tag{4}$$

In system (1)-(4), aside from the brightness values recorded with the PD, there also appears the undefined value of the brightness L_O and the unknown coefficients ε, τ and ρ for which the system provides the solution:

$$\varepsilon = 1 - A, \tag{5}$$

$$\tau = (A + B)/2, \tag{6}$$

$$\rho = (A - B)/2, \tag{7}$$

$$A = \frac{L_{o1} + L_{o2} - 2L_{ow}}{L_1 + L_2 - 2L_w} \tag{8}$$

$$B = \frac{L_{o1} - L_{o2}}{L_1 - L_2}. \tag{9}$$

Given linearity and constancy of the sensitivity parameters of the photodetector (including the modulator 11 which is functionally a part of the detector) the quantities A and B can be expressed in terms of the signals at the PD output. Considering that the signal U_j produced in measurement of the j-th brightness L_j can be expressed in the form $U_j = k(L_j - L_m)$, we define the quantities L_j as $L_j = L_m + U_j/k$, and substituting their corresponding values in Eqs. (8) and (9), for L_m = const and k = const we obtain:

$$A = \frac{U_{o1} + U_{o2} - 2U_{ow}}{U_1 + U_2 - 2U_w}, \tag{8'}$$

$$B = \frac{U_{o1} - U_{o2}}{U_1 - U_2}. \tag{9'}$$

On the basis of Eqs. (3) and (4) and using the equality $(L_{ow} - L_w)/(L_1 - L_w) = (U_{ow} - U_w)/(U_1 - U_w)$ we then find the value

$$L_o = L_w + \frac{L_1 - L_w}{\varepsilon} \frac{U_{ow} - U_w}{U_1 - U_w}, \tag{10}$$

on the basis of which by using Planck's or Wien's function for the established temperature of the chamber wall and one of the black bodies the specimen temperature can be determined, to which the values of the measured coefficients should be assigned. For example, using the Wien radiation function we obtain

$$T_o = \frac{T_w}{1 - \frac{\lambda T_w}{c_2} \ln\left\{1 - \frac{U_{ow} - U_w}{\varepsilon (U_1 - U_w)}\left[1 - \exp\frac{c_2}{\lambda}\left(\frac{1}{T_w} - \frac{1}{T_1}\right)\right]\right\}}. \tag{11}$$

Thus, having summarized the essence of the method, we will note the following major advantages:

Creation of special devices insuring uniform heating (or cooling) of the specimen and maintenance of its temperature at a specified level is not required:

installation of a temperature sensor on the specimen is not required, since its temperature corresponds to that of the chamber, and can be refined using the measurement results:

measurement preparation time is reduced, since the operations of achieving and stabilizing a specified specimen temperature are eliminated.

It should be noted here that strictly speaking the specimen temperature does not remain constant as its position is changed from between the black bodies to away from them because of the different conditions of heat exchange existing between the specimen and the surrounding elements of the measurement cell. We can estimate the amount and rate of change of temperature when the specimen is inserted in the space between the black bodies. To do this we use an expression presented in [7] which gives the time dependence of temperature of a specimen subjected to drying upon radiant heating. For the method under consideration we can write this expression (with a drying layer absent and irradiation of both sides of the specimen surface by black bodies) in the form:

$$T_o - T_w = \frac{\alpha \Delta E}{a_T}\left[1 - \exp\left(-\frac{a_v a_T}{c\gamma} t\right)\right], \tag{12}$$

where ΔE is the change in mean irradiation density of both sides of the specimen by the black body relative to the level of irradiation by the chamber walls; the moment of insertion of the specimen into the space between the bodies corresponds to t = 0, and the initial specimen temperature is taken equal to that of the chamber walls.

According to the requirement $T_0 - T_W = \Delta T_0 \ll T_W$, satisfaction of which is necessary during the measurement time in order to avoid significant error, and with consideration of the fact that for planar specimens $a_V = 2/h$, Eq. (12) takes on the simpler form:

$$\Delta T_0 = \frac{2\alpha \Delta E}{c\gamma h} t, \tag{13}$$

which indicates a linear time dependence for specimen temperature at the commencement of its stay between the black bodies. On the basis of Eq. (13) we can estimate the time over which the temperature difference ΔT_0 will not exceed some allowable value. We relate the permissible ΔT_0 to the permissible relative uncertainty δ in measurement of the radiation coefficient ε. To do this we assume that the measurements of the brightnesses L_{01} and L_{02} are performed with identical superheating of the specimen by an amount ΔT_0, which corresponds to a change in the measurement of the brightness L_0 by an amount ΔL_0. In this case system (1)-(4) yields the following result:

$$\varepsilon = (1 - A) \Big/ \left(1 - \frac{2\Delta L_0}{\Delta L_1 + \Delta L_2}\right), \tag{14}$$

where $\Delta L_1 = L_1 - L_W$, $\Delta L_2 = L_2 = L_W$.

Given the condition $\Delta L_1 \ll L_W$ and $\Delta L_2 \ll L_W$ required to avoid marked superheating of the specimen, we find that according to Eq. (14) the value of the error δ in the ε measurement, using Wien's function, is practically independent of effective wavelength:

$$\delta = \frac{\varepsilon}{1 - A} - 1 \simeq \frac{2\Delta L_0}{\Delta L_1 + \Delta L_2} \simeq \frac{2\Delta T_0}{\Delta T_1 + \Delta T_2}, \tag{15}$$

where $\Delta T_1 = T_1 - T_W$ and $\Delta T_2 = T_2 - T_W$. From this condition we find the integral over the spectrum of the quantity ΔE:

$$\Delta E = 2\sigma T_W^3 (\Delta T_1 + \Delta T_2). \tag{16}$$

Solving Eq. (15) for ΔT_0 and substituting this value together with Eq. (16) in Eq. (13), we obtain an estimate of the permissible measurement time interval:

$$t = \frac{c\gamma h \delta}{8\alpha\sigma T_W^3}. \tag{17}$$

The result of Eq. (17) indicates that the permissible measurement time t depends on the physical properties of the specimen material, its thickness, the chamber temperature, and the required measurement accuracy. Somewhat unexpected is the absence of a dependence on the temperatures of the black bodies (ΔT_1 and ΔT_2). However this can be understood by considering that the higher the black body temperature, i.e., the more rapidly they heat the specimen, the higher is the temperature to which such heating is permissible, in order that the change in specimen energetic brightness not produce an increase in its contrast relative to the black bodies.

We will evaluate the permissible value of t. According to handbook data [8], at temperatures of the order of 300 K the product $c\gamma$ for both metals and for dielectric (not porous) materials always exceeds the value $1 \cdot 10^6$ $J \cdot m^{-3} \cdot K^{-1}$ (it may reach $4 \cdot 10^6$ or more). With consideration of this, taking $\alpha \lesssim 1$, we arrive at the conclusion that according to Eq. (17) the permissible measurement time comprises not less than one or several seconds for each mm of specimen thickness h and each percent of permissible measurements uncertainty δ. This confirms the relatively free applicability of the method for measurements of specimens of materials with thickness of the order of 1 mm or more. For measurements of thinner specimens (films, fine grids, foils, etc.) the method requires specialized technological realizations, insuring determination of the signals at the moment of insertion of the specimen into the place between the black bodies (for example, extrapolation to zero ($t \to 0$) of the time dependence of PD output signal (linear according to Eq. (13)). The possible technical complications of measurements on thin specimens does not hinder the practical realization of the proposed method.

The essence of the measurement method was tested with a prototype device a diagram of which is shown in Fig. 2, which has a number of simplifications compared to Fig. 1. The isothermal chamber was imitated by a closed mounting space without heating batteries or windows. Black bodies 1 and 2, constructed identically in the form of blackened surfaces with shallow triangular grooves having an aperture diameter of 400 mm, could be placed behind the

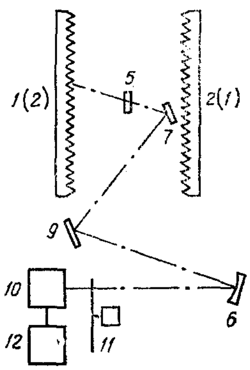

Fig. 2. Optical diagram of apparatus used for testing the measurement method. Notation as in Fig. 1.

TABLE 1. Results of Measurements for Three Variants of the Method

Signals, mV and calc. values	Variant 1		Variant 2		Variant 3	
	$T_2=30°C$				$T_2=T_W=22°C$	
	$T_1=50°C$	$T_1=90°C$	$T_1=50°C$	$T_1=90°C$	$T_1=50°C$	$T_1=90°C$
U_W	0	0	0	0	0	0
U_{01}	224	840	250	960	202	810
U_{02}	140	433	165	550	95	380
U_{OW}	0	0	26	120	0	0
U_1	546	2200	547	2210	545	2200
U_2	120	118	120	120	0	0
A	0,547	0,549	0,544	0,545	0,545	0,541
B	0,188	0,203	0,199	0,196	0,196	0,195
ε	0,453	0,451	0,456	0,455	0,455	0,459
τ	0,368	0,376	0,372	0,372	0,372	0,368
ρ	0,179	0,173	0,172	0,173	0,173	0,173
T_0, °C	22	22	26	38	22	22

specimen (up to 60 mm in size) or in front of it (behind mirror 7), or they could be moved to the side where they had no effect on specimen or chamber walls. All movements were accomplished manually. A photodetector in the form of an indium antimonide photoresistor cooled by liquid nitrogen was used. Measurements were performed with an air temperature of 22°C in the housing, temperatures of black body 1 equal to 50 and 90°C, and black body 2 temperature of 30°C. The device was calibrated beforehand, and the positions of the specimen, black bodies, and mirror 7 were determined. Provision was made for convenient installation and removal of these components from their designated locations.

Measurements were performed with modulator 11 operative in the following three variants. With black bodies and specimen removed, the signal U_W corresponding to the container walls was measured. This signal was practically always equal to the PD noise level (of the order of 2 mV) and was considered equal to zero. Then, in the first measurement variant the specimen was placed in the PD field of view and the signal U_{OW} was measured, corresponding to the energetic brightness of the specimen irradiated by only the container walls (this signal was also practically equal to zero). After this the black bodies were placed in their mountings (in Fig. 2 black body 1 is to the left of the specimen, 2 is to the right), and over a time of not more than 5 sec (usually 2-3 sec) the signal U_{O1} corresponding to the specimen brightness L_{01} was recorded, the specimen was rapidly removed, and the signal U_1 was recorded, corresponding to the brightness of blackbody 1. The black bodies were then interchanged, the singal U_2 corresponding to the brightness of black body 2 was measured, the specimen was replaced in not more than 5 sec, and the signal U_{O2} corresponding to the specimen brightness L_{O2} was recorded. In the second variant the sequence of operations was changed somewhat. First the signal U_1 was measured, after which the specimen was placed between the black bodies and maintained in that position for not less than 15 min. In this case, in contrast to the first variant, the specimen was heated somewhat, and to avoid heating of mirror 7, the latter was removed and replaced in position only when the signals were measured. The signals U_{O1}, U_{OW},

U_{O2}, and U_2 were then measured one after the other. In the third variant black body 2 was completely absent (methodologically, this corresponds to the special case of equality of the temperature and brightness of one black body to the temperature and brightness of the chamber walls, $L_2 = L_w$, $T_2 = T_w$) and the sequence of measurements coincided with the first variant, excluding measurement of the signal U_2.

As an example, Table 1 presents results of measurements performed with a frosted quartz plate 2 mm thick (matte finish not normalized). The example shows the good reproducibility of measurement results (mean values of the coefficients were $\varepsilon = 0.455$, $\tau = 0.371$ and $\rho = 0.174$ with mean square deviation from these values of not more than 0.003) and confirm the practical absence of systemic measurement errors related to indefinite specimen temperature.

The proposed method for simultaneous measurement of radiation, transmission, and reflection coefficients was tested in several variants, which confirmed its effectiveness. The question of the optimum realization of equipment for the method will require further study.

NOTATION

α, specimen integral hemispherical absorption coefficient for radiation from black bodies and chamber walls; γ, specimen material density; δ, permissible error in ε measurement; ε, measured specimen radiation coefficient; λ, effective wavelength of spectral range within photodetector sensitivity range; ρ, measured specimen reflection coefficient; $\sigma = 5.67 \cdot 10^{-8}$ $W \cdot m^{-2} \cdot K^{-4}$, Stefan—Boltzman coefficient; τ, measured specimen transmission coefficient; A, B, auxiliary quantities used in calculation of coefficients ε, τ, ρ from measurement results; a_T, net specimen heat liberation coefficient; a_V, ratio of specimen area to volume; c, specific heat of specimen material; $c_2 = 14{,}388\ \mu \cdot K$, second constant in Planck's function; E, integral irradiation of specimen surface created by black bodies and chamber walls; h, planar specimen thickness; k, photodetector conversion coefficient; L, energetic brightness; T, temperature; t, time: U, electrical signal at photodetector output. Subscripts: 1, first black body; 2, second black body; o, specimen; w, chamber wall; o1, specimen against block body 1 background; o2; specimen against black body 2 background; ow, specimen against chamber wall background (subscript j replaces one of the above); m, modulator blades.

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