MEASUREMENT OF SPECTRAL RADIATION COEFFICIENTS OF MATERIALS BY COMPARISON WITH A BLACK BODY

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Technological developments have generated a considerable interest at the present time in studies concerning the radiation characteristics of materials [1], especially those characteristics which pertain to the thermal radiation of real objects. The availability of data on the radiation properties of materials within wide ranges of temperature and wavelength is a prerequisite not only for the solution of many engineering problems but also for the verification of theories on the relation between optical and physical properties of these materials [2].

The more stringent accuracy required of data pertaining to the radiation properties of materials, together with the variation over wide ranges of the values in the literature [3, 4] and the difficulty of determining the thermal radiation [5], has made urgent the strict selection of methods of measurement and the analysis of all factors which may in any way influence the test results. In this article we will consider some problems involved in measuring the spectral characteristics of opaque materials in the direction normal to the radiating surface by comparison with the radiation of an absolutely black body (ABB).

The basic parameter describing the radiation properties of a material is the radiation coefficient, which, according to [6], is equal to the ratio of the energy intensity of a given source to that of the ABB when both are at the same temperature. It is to be noted that no consistent terminology has yet been established in the USSR for defining the radiation properties and, therefore, the radiation coefficient is also called "blackness coefficient," "blackness index," "emissive power," or "emissivity." We will use the term "emissivity" to characterize the radiation properties of the material alone, i.e., of the material with an ideal smooth surface the radiation of which is determined by the physical properties of the material; for the radiation properties of the same material but having a rough surface (with possible traces of treatment and contamination) we will use the term "radiation coefficient," and the term "blackness index" will be used for cavities of any shape and size to define how closely their radiation approaches that of the absolutely black body.

Among many known methods of measuring the radiation properties [7-20], the most widely used is the method by which the radiation of a test specimen is compared with that of the ABB standard. All variations of this method belong to either of two types: 1) measurements with an independent black body, where the ABB standard and the specimen are separate; 2) measurements with an integral black body, where the ABB standard and the test specimen make up a single entity. The application of the first type of method is illustrated in [11], where the radiation coefficient has been determined by comparing the energy intensity of the ABB standard and that of the test specimen (tungsten ribbon) at various known temperatures. The second principle is implemented in the tube method [9], where the radiation coefficient has been determined by comparing the luminance of the test specimen surface to that of the ABB surface at the same temperature.

Sources of errors which may distort the results of measurements by comparison with a black body are:

1. imperfection of the ABB standard;

2. nonlinearity of the radiation receiver;

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3. undetermined surface condition of the test specimen;

4. inaccuracy of the temperature measurement or error in stabilizing the temperature of the specimen and of the standard;

5. effect of specimen or ABB-standard radiation scattered on the test apparatus components;

6. effect of background radiation around the specimen;

7. error in stabilizing and drift of the active wavelength in the spectrometer;

8. sensitivity limit and error in the recording system.

The weighted effect of these error sources on the results of measurements may differ depending on the type of measurements and on the temperature or wavelength range within which the measurements are made. We will evaluate the effect of the basic error sources in considering specific methods of measurement.

In measurements with an independent black body, the radiation coefficient of a specimen is defined according to the expression [11]:

$$\varepsilon(\lambda, T) = \frac{b(\lambda, T)}{b^0(\lambda, T_s)} \cdot \frac{\exp\left(\frac{C_2}{\lambda T}\right) - 1}{\exp\left(\frac{C_2}{\lambda T_s}\right) - 1}. \qquad (1)$$

When the temperature of the specimen is the same as the temperature of the ABB standard ($T_s = T$), expression (1) becomes

$$\varepsilon(\lambda, T) = \frac{b(\lambda, T)}{b^0(\lambda, T)}. \qquad (2)$$

These formulas indicate that during measurements especial importance attaches to the accurate determination of temperatures T and T_s, or their precise equalization, and the linearity of the radiation receiver ensuring a proportionality between the ratio of recorded output signals and the ratio of luminances $b(\lambda, T)/b^0(\lambda, T)$. A very high quality is attainable for the ABB standards used in these methods, since high-efficiency cavities designed by known [22-29] procedures are available. An independent black body can be used for measurements within a wide range of wavelengths, when the specimen is at a temperature at which its intrinsic radiation exceeds by far any background radiation reflected from its surface.

In the integral-black-body method, for example, in the tube method, the ABB standard and the surface of the test specimen comprise a single structure and are both at the same temperature. The radiation coefficient here is defined according to Eq. (2). The accuracy of this method has been carefully analyzed in [9] and [30]. The effect of light scattered inside the bulb containing the tube on the results of measurements has also been accounted for in [30]. According to the analysis in [31], however, the light scattered in the bulb did not affect the accuracy of the results appreciably and, therefore, the data in [9] should be considered more reliable. This has been confirmed by recent measurements using other methods [32], which yielded a close agreement with the results in [9].

Different versions of the integral-black-body method are used for measuring the radiation characteristics at both high temperatures (up to 3000°K) [33-38] and lower temperatures (up to 600°K) [39, 40]. It is evident from Eq. (2) that imperfections of the ABB standard and the nonlinearity of the radiation receiver constitute the principal sources of error in the results of measurement by the integral-black-body method. The degree of perfection of the ABB standard depends on the shape (wedge, cylinder, tube, or cone) and the geometrical proportions of the black-body-simulating cavity, on the temperature distribution at the cavity surface [41-43], on the mode of reflection at the inner walls of the cavity (diffusive reflection, mirror reflection, or oriented dispersion), and on the parameters of the optical components in the apparatus [29, 44-46]. The authors of almost all articles on radiation-coefficient measurements have, as a rule, assumed without special scrutiny that the radiation receivers were linear. While such an assumption may be valid for some types of receiver, it should be verified in the case of others. For instance, photoelectron multipliers are used widely for measurements in the ultraviolet and in the visible range of the radiation spectrum [9, 16, 19, 30, 35, 47, 48]. Although the nonlinearity of these devices is hinted at in the literature, this nonlinearity differing from model to model, it is assumed to become significant at sufficiently high anode currents only [49-52]. In our linearity tests on various types and models of photoelectron multipliers, we have established that, up to saturation, the sensitivity of these devices does not remain constant but increases as the light flux impinging on the photocathode increases. In some models, moreover, such a nonlinearity appears already at near-thermal output signals. This effect, if it was appreciable in the cited references, could have lowered the test values of the radiation coefficients and could have been a cause of discrepancies between the results obtained by different authors.

The effect of receiver (photoelectron-multiplier) nonlinearity can be eliminated by installing an auxiliary receiver (a PbS photoresistor, for example [53]) at the output of the optical system, the sensitivity spectrum of which is different from the spectrum of radiation-coefficient measurements determined by the sensitivity of the nonlinear receiver. Let the output signal of a nonlinear receiver at temperature T and wavelength λ be defined by the spectral luminance of the test specimen $b(\lambda, T)$ and the output signal N of the auxiliary receiver at a different wavelength λ' be proportional to the spectral luminance of the ABB standard cavity $b^0(\lambda', T)$. By lowering the temperature T of the specimen to T* with the aid of the nonlinear receiver, one establishes a level of spectral luminance for the black body $b^0(\lambda, T^*)$ at which the output signal of the nonlinear receiver will be equal to the signal corresponding to the spectral luminance of the specimen $b(\lambda, T)$. Regardless of the nonlinearity of the main receiver, the following equality will now be satisfied:

$$b(\lambda, T) = b^0(\lambda, T^*). \tag{3}$$

By means of the auxiliary receiver, in the meantime, signal N* proportional to the spectral luminance at the slit in the tube at temperature T*, i.e., $b^0(\lambda', T^*)$, is also measured. The spectral luminance of a specimen at wavelength λ and temperature T, within the range where Wien's law remains valid, is.

$$b(\lambda, T) = \varepsilon(\lambda, T)\frac{C_1}{\pi}\lambda^{-5}\exp\left(-\frac{C_2}{\lambda T}\right), \tag{4}$$

and the spectral luminance of the black body at the same wavelength but at temperature T* is

$$b^0(\lambda, T^*) = \frac{C_1}{\pi}\lambda^{-5}\exp\left(-\frac{C_2}{\lambda T^*}\right). \tag{5}$$

It follows from the equality of both spectral luminances that

$$\varepsilon(\lambda, T) = \exp\left[\frac{C_2}{\lambda}\left(\frac{1}{T} - \frac{1}{T^*}\right)\right]. \tag{6}$$

Equation (6) contains a difference of temperature reciprocals which is unknown. The value of this difference can be determined by measurements with the auxiliary receiver. From the ratio of spectral luminances of the black body cavity at temperatures T and T* respectively, calculated according to Wien's law, we have

$$\frac{b^0(\lambda', T^*)}{b^0(\lambda', T)} = \exp\left[\frac{C_2}{\lambda'}\left(\frac{1}{T} - \frac{1}{T^*}\right)\right]. \tag{7}$$

Rewriting expression (6) as

$$\varepsilon(\lambda, T) = \left\{\exp\left[\frac{C_2}{\lambda'}\left(\frac{1}{T} - \frac{1}{T^*}\right)\right]\right\}^{\lambda'/\lambda}, \tag{8}$$

then inserting here expression (7), and considering that the auxiliary receiver is linear, we have

$$\varepsilon(\lambda, T) = \left[\frac{b^0(\lambda', T^*)}{b^0(\lambda', T)}\right]^{\lambda'/\lambda} = \left(\frac{N^*}{N}\right)^{\lambda'/\lambda}. \tag{9}$$

Under conditions where Wien's law of radiation does not apply, (9) becomes

$$\varepsilon(\lambda, T) = \left(\frac{N^*}{N}\right)^{\lambda'/\lambda} \frac{1 - \exp\left(-\frac{C_2}{\lambda T}\right)}{\left[1 - \left(1 - \frac{N^*}{N}\right)\exp\left(\frac{C_2}{\lambda' T}\right)\right]^{\lambda'/\lambda} - \left[\left(\frac{N^*}{N}\right)\exp\left(-\frac{C_2}{\lambda' T}\right)\right]^{\lambda'/\lambda}}. \tag{10}$$

Although the additional factor here depends on temperature T, this dependence is weak. At T = 3000°K, λ = 1 μm, λ' = 2 μm, and N*/N = 0.6, for example, this factor contains an approximately ±1% error only when the temperature is imprecise within ΔT = ±180°K.

The method just described improves not only the accuracy of $\varepsilon(\lambda, T)$ measurements but also their reliability, which is achieved by obtaining values for $\varepsilon(\lambda, T)$ at several different wavelengths λ'. Another positive feature of this method is that temperature T* during the measurements does not have to be known. The principal sources of error here could be a drift in the active wavelengths λ and λ', or an imprecision in equalizing the luminances, or the imperfection of the ABB standard.

A similar method of measuring spectral radiation coefficients has been used in [40]. The absence of an auxiliary linear receiver made it necessary, however, to measure temperatures T and T* precisely (see Eq. (6)) and this presented certain difficulties. Moreover, since the measurements there were performed at moderate temperatures (550-1000°K), terms had to be added in the formula to account for background radiation, presumably equal to the radiation of the ABB standard at ambient temperature. Such a correction for background radiation is not sufficiently accurate, since it may not be uniform and it is made up of several terms. Its effect on the results is particularly significant when the radiation coefficient is measured at low temperatures, when radiation of the specimen due to reflection of background radiation is comparable to or may even exceed its intrinsic radiation.

The feasibility of eliminating noisy background radiation has been established by using two reference standards: a black one and a white one. This technique was used in [54] for measuring the total hemispherical radiation coefficient of materials. This technique may also be used for measuring the normal spectral radiation coefficient at moderate and low temperatures.

Knowing the values of $\varepsilon_b(\lambda, T)$ and $\varepsilon_w(\lambda, T)$, the output signals of a linear radiation receiver in the measuring instrument will be proportional to the spectral illuminations:

$$E_\lambda^b = E_\lambda^a + k\{\varepsilon_b(\lambda, T)\, b^0(\lambda, T) + [1-\varepsilon_b(\lambda, T)]\, b^0(\lambda, T_a)\}, \tag{11}$$

$$E_\lambda^w = E_\lambda^a + k\{\varepsilon_w(\lambda, T)\, b^0(\lambda, T) + [1-\varepsilon_w(\lambda, T)]\, b^0(\lambda, T_a)\}, \tag{12}$$

$$E_\lambda = E_\lambda^a + k\{\varepsilon(\lambda, T)\, b^0(\lambda, T) + [1-\varepsilon(\lambda, T)]\, b^0(\lambda, T_a)\}, \tag{13}$$

when the black and the white reference standards as well as the test specimen – all at the same temperature T – are found in the field of vision. The ratio of receiver signal differences due to these different illuminations will be

$$\frac{N_b - N}{N - N_w} = \frac{E_\lambda^b - E_w}{E_\lambda - E_\lambda^w}. \tag{14}$$

Inserting Eqs. (11), (12), and (13) into Eq. (14), we obtain

$$\frac{N_b - N}{N - N_w} = \frac{\varepsilon_b(\lambda, T) - \varepsilon(\lambda, T)}{\varepsilon(\lambda, T) - \varepsilon_w(\lambda, T)}, \tag{15}$$

and from this we find

$$\varepsilon(\lambda, T) = \varepsilon_b(\lambda, T)\,\frac{N - N_w}{N_b - N_w} + \varepsilon_w(\lambda, T)\,\frac{N_b - N}{N_b - N_w}. \tag{16}$$

The last expression does not explicitly include the temperature T nor the quantities which account for background radiation; this is a prerequisite for high-accuracy $\varepsilon(\lambda, T)$ measurements. The temperature must be known here only insofar as the value of the measured radiation coefficient $\varepsilon(\lambda, T)$ refers to it. As a rule, however, the value of $\varepsilon(\lambda, T)$ varies only slightly within sufficiently narrow temperature ranges and, therefore, an accurate measurement of temperature T is not mandatory in the method of two reference standards.

An essential factor contributing to the imprecision of measured radiation-coefficient values for specimens of different materials is the condition of the specimen surface, which is characterized by the presence of impurities, oxide films, or by roughness resulting from mechanical, thermal, or other treatment of the material. It is particularly important to account for the surface condition when measuring the emissivity of metals, since these data are needed for further refining the theory of the radiation of metals [2]. While the effect of roughness on the integral radiation properties of surfaces has been dealt with in several published articles [55-58], where a close agreement between theoretical and experimental data is shown, the effect of roughness on the spectral emissivity is still under study [59, 60]. There is such an effect and, as has been noted in [61], better than 2% precision in determining the normal emissivity is entirely impossible without a careful and complete evaluation of the surface condition.

NOTATION

$\varepsilon(\lambda, T)$, $\varepsilon_b(\lambda, T)$, $\varepsilon_w(\lambda, T)$ are the normal spectral radiation coefficient of the specimen, of black, and white reference standards, respectively;

λ	is the radiation wavelength;
λ'	is the radiation wavelength received by the auxiliary linear receiver;
T, T_s, T_a	are the temperatures of specimen and of the standard and the ambient temperature;
C_1, C_2	are the first and second constants in the Planck equation;
$b(\lambda, T), b^0(\lambda, T)$	are the spectral brightness of the specimen and of the absolutely black body, respectively;
N	is the output signal of the radiation receiver;
$E_\lambda, E_\lambda^b, E_\lambda^w$	are the spectral illumination of the radiation receiver when the specimen, the black, and the white reference standard, respectively, are in its field of vision;
E_λ^a	is the spectral background illumination of the radiation receiver;
k	is the proportionality factor.

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