MEASUREMENT OF THE MONOCHROMATIC EMISSIVITY OF COATINGS AT 100-400°C

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UDC 536.3

Results of measurement of the normal emissivities of certain coatings by a two-beam method in the 2-25 μ range are reported.

The thermal emission properties of various engineering materials are now drawing much attention [1-3]. These properties are required over a wise range of temperatures for calculation of radiative heat transfer in many types of new devices. Earlier engineering calculations were based chiefly on the hemispherical integral thermal emission characteristics, but such a crude approach to the problem can no longer satisfy modern technology. The investigation of the spectral and directional characteristics of the emission from solids over a wide temperature range has become imperative [1].

One of the most important emission characteristics of a solid is its emissivity, defined as the ratio of the heat flux emitted by the specimen at a given temperature and under particular geometric and spectral conditions to the flux emitted by a blackbody at the same temperature and under the same geometric and spectral conditions. The hemisperical integral emissivities can be measured successfully by the calorimeter method [4], while the angular spectral emissivities are measured mainly by the radiation method. There are well-developed methods for measuring these characteristics at temperatures above 400-500°C, but difficulties occur for bodies near room temperature. First, owing to the low specimen temperature the radiation flux incident on the detector is small; second, the influence of background radiation on the results of emissivity measurements must be taken into account.

We based our measurements of normal spectral emissivities at temperatures above 100°C on the UR-20 two-beam infrared spectrophotometer. This instrument has the advantage that the image of the radiation source (a globar lamp) is located at the center of the cell section. Thus the measurements could be made without changing the optical arrangement of the instrument. To do this we positioned a model of an ideal blackbody and the heated assembly with the specimen in the comparison and specimen channels, respectively, so that their radiating surfaces were exactly in the spectrophotometer globar-lamp image plane in the cell space.

Let us consider the radiant-flux balance for this geometry of the specimen and the radiation standard. The responses S_I and S_{II} of the receiver to the radiation arriving from the specimen channel and the comparison channel will be

$$S_I = [\varepsilon_\lambda(T_{sam}) e_{b\lambda}(T_{sam}) + R_{\lambda sam} e_{b\lambda}(T_b)] \cdot K, \tag{1}$$

$$S_{II} = [e_{b\lambda}(T_{i.\,b.\,b.}) D_\lambda + e_{b\lambda}(T_b)(1 - D_\lambda) + e_{b\lambda}(T_b) R_W (1 - D_\lambda)] \cdot K. \tag{2}$$

In a two-beam spectrophotometer with optical null the fluxes incident on the receiver are balanced at each instant in both channels by a photometer wedge; on the basis of this principle we can write

$$S_I = S_{II}. \tag{3}$$

Since $R_{\lambda\,sam} = 1 - \varepsilon_\lambda$ and $R_W = 0$, we have

$$\varepsilon_\lambda(T_{sam}) e_{b\lambda}(T_{sam}) + (1 - \varepsilon_\lambda) e_{b\lambda}(T_b) = e_{b\lambda}(T_{i.\,b.\,b.}) D_\lambda + e_{b\lambda}(T_b)(1 - D_\lambda), \tag{4}$$

Institute of Heat and Mass Transfer, Academy of Sciences of the BSSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 27, No. 2, pp. 203-207, August, 1974. Original article submitted November 12, 1973.

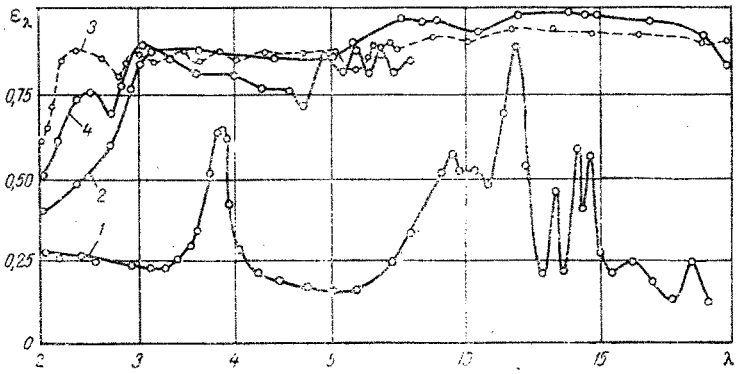

Fig. 1. Emissivity ε_λ of certain coatings as a function of wavelength λ, μm: 1) l = 0.8 mm thick layer of hardened type EKM compound, T_{sam} = 180°C; 2) compound of phenol-formaldehyde resin and 75 wt. % inorganic fillers, l = 0.8 mm, T_{sam} = 150°C; 3) type EP-255 enamel, l = 0.7 mm, T_{sam} = 150°C; 4) polished brass coated with a fused varnish layer of pentone, l = 0.015 mm, T_{sam} = 150°C.

$$\varepsilon_\lambda(T_{sam}) = D_\lambda \frac{e_{b\lambda}(T_{i.\,b.\,b}) - e_{b\lambda}(T_b)}{e_{b\lambda}(T_{sam}) - e_{b\lambda}(T_b)}. \quad (4)$$

from (1), (2), (3).

We let $T_{i.b.b.} = T_{sam}$ in the above expression, thus obtaining $\varepsilon_\lambda(T) = D\lambda$, i.e., the IR spectrophotometer describes the spectral emissivity directly. If the specimen and the black-body model differ in temperature, $T_{sam} \neq T_{i.b.b.}$, we can use (4) to compute ε_λ after measuring the three quantities $D\lambda$, T_{sam}, $T_{i.b.b.}$. Natural convection makes it difficult to stabilize the temperature of the specimen surface accurately, so we used another measurement approach by simultaneously determining $D\lambda$, T_{sam}, $T_{i.b.b.}$ at given wave-number intervals. As calculations have shown, for all practical purposes we can replace (4) by the simpler expression

$$\varepsilon_\lambda = D_\lambda \frac{e_{b\lambda}(T_{i.\,b.\,b.})}{e_{b\lambda}(T_{sam})} = D_\lambda \frac{\exp\left(\frac{c_2}{\lambda T_{sam}}\right) - 1}{\exp\left(\frac{c_2}{\lambda T_{i.\,b.\,b.}}\right) - 1}. \quad (5)$$

Thus if $T_{i.b.b.}$ = 500°K, T_{sam} = 510°K, and T_b = 300°K, for example, if follows that when λ = 4 μ the ε_λ values computed from (4) and (5) differ by about 0.001.

Our emission standard was a model of a blackbody in the form of a cylinder with a slit along the generatrix. The size of the emitting cavity (3 × 18 mm) was such that the image of it formed by the spectrophotometer optical system at the entrance slit was larger than the latter. The effective emissivity ε of such a model of an ideal blackbody, calculated in accordance with [3], was 0.99.

The test specimen was held tightly by special clamps against the face of a massive copper block which was heated by a nichrome helix. The entire specimen-assembly system was located in the cell section of the spectrometer; during the three measurements it could be moved with the aid of adjusting screws for fine positioning. The temperature of the specimen surface and the cavity of the ideal blackbody was measured by 0.1-mm thick copper-constantan thermocouples and registered by two type PP-63 potentiometers. The signal arrived at the detector with very low level, so that we had to disable the automatic slit program of the spectrophotometer (the program was matched to the spectral variation of the globar-lamp emission intensity) by disconnecting the automatic slit-width control system. This also had to be done to obtain a satisfactory signal-to-noise ratio at each wavelength. After adjusting for maximum signal of the i.b.b. model and the specimen and establishing the specified $T_{i.b.b.}$ and T_{sam}, we obtained a particular wave number in the spectrophotometer and set the minimum slit width for which an acceptable signal-to-noise ratio was still observed. This was checked by covering the ray channels for a short time; the recorder pen should return to the same place with a spread of 0.5% of the transmission. We then measured $T_{i.b.b.}$, T_{sam}, and $D\lambda$, the entire procedure being repeated when we went to a different wave

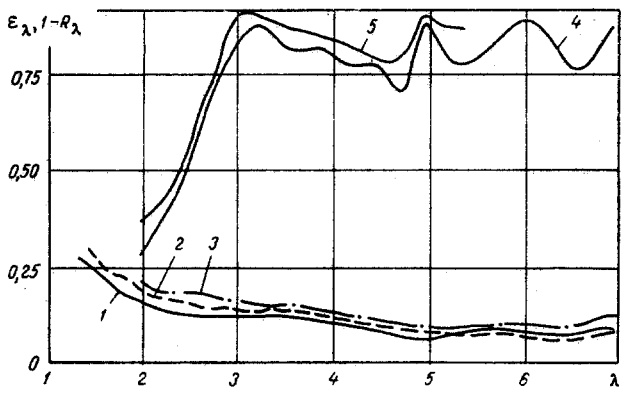

Fig. 2. Emissivity ε_λ and value of $1-R\lambda$ for materials as functions of the wavelength λ, μm.

number. Thus, measurements were made over the whole spectral region (5000-400 cm^{-1}) at points 25-50 cm^{-1} apart. This spectral interval was quite adequate for plotting the curves, since most of the materials investigated have a spectral emissivity that varies smoothly.

Figure 1 shows measurement results for the spectral normal emissivity ε_λ of certain dielectric materials, in particular coatings used in various industries. All specimens other than 4 had thicknesses corresponding to an optically infinite dense layer. This was checked by using the method described in [2, 6] to measure the hemispherical transmittance. Curve 4 gives the monochromatic emissivity of a system consisting of polished brass and a fused varnish layer of pentone since for the investigated spectral region an $l = 15\ \mu$ thick layer of varnish is semitransparent. All curves were calculated by (5) from measurements of $D\lambda$, T_{sam}, $T_{i.b.b.}$.

Figure 2 shows the results of measurements of the monochromatic emissivity for several specimens by various independent methods. Curve 2 gives the spectral emissivity $\varepsilon_\lambda = 1-R\lambda$ for a polished aluminum specimen (class 8 surface finish). The coefficient was calculated from data on spectral reflection, measured with a type IPO-12 attachment (the angle of incidence was 10°). The emissivity of the same specimen (curve 3) found by the method described above ($T_{sam} = 120°C$) is in good agreement with the $1-R\lambda$ relationship obtained by the reflection method. For comparison the ε_λ values are shown in the same figure for polished aluminum (1); the data are from [1]. As we see, all three spectral dependences lie within 2-3% of each other.

Measurements of the reflection indicatrices show that the plane-parallel layer of hardened coating 2 is nearly a Lambert surface. The directional hemispherical reflectance $R\lambda$ was measured for this specimen (Fig. 2, curve 5) by the mirror-hemisphere method [2, 6]; the spectral emissivity ε_λ (curve 4) was found by the proposed method ($T_{sam} = 120°C$). Comparing ε_λ and $1-R\lambda$ we conclude that in the investigated spectral region this specimen yields a fairly good approximation to the Kirchhoff law, i.e.,

$$\varepsilon_\lambda = 1 - R_\lambda. \tag{6}$$

One of the factors responsible for the slight discrepancies in these values is the fact that $R\lambda$ is the directional hemispherical reflectance (the reflection was measured for an angle of incidence of 18°) while ε_λ is the normal emissivity. It follows from Kirchhoff's law that ε_λ and $R\lambda$ should be determined under the same geometric conditions. This requirement is strictly valid only for rough surfaces, however. Equation (6) must be verified experimentally for a diffusing surface. For materials that scatter thermal radiation Eq. (6) may prove very useful for determination of the reflectance by measurement of the spectral emissivity. Direct measurement of $R\lambda$ for diffusing specimens in the IR region involves major experimental difficulties, as we know [7].

Thus we have described a method for measuring the normal monochromatic emissivity of engineering materials at 100-400°C that is relatively simple and quite accurate. By using a type UR-20 two-beam IR spectrophotometer in the measurement setup we can automatically prevent the results from being affected by background radiation, exclude the nonlinearity of the receiving-recording system, and provide high spectral resolving power.

NOTATION

λ	is the wavelength;
T_{sam}, $T_{i.b.b.}$, T_b	are the sample, ideal-blackbody, and background temperatures;
$\varepsilon_\lambda(T_{sam})$	is the spectral emissivity of the specimen;
$R_{\lambda\,sam}$, $R_{\lambda\,w}$	are the spectral reflectances of the specimen and the spectrometer photometric wedge;
$e_{b\lambda}(T)$	is the spectral flux density of the ideal blackbody emission;
D_λ	is the transmission coefficient of the spectrometer photometer wedge at the wavelength λ;
l	is the specimen thickness.

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