values of β_{max} (ε_i) at which the energy flux becomes a maximum.

In conclusion, we note that the results of [3] are a special case of our general solution of the problem.

NOTATION

T, temperature, °K; ε, total emissivity; D, cylinder diameter; φ_{ik}, mean angular radiation coefficient (ARC); R, reflection coefficient; σ_0, Stefan–Boltzmann constant; ζ, dimensionless parameter, equal to ratio of diameters of coaxial cylinders; F, area of surface; β, ratio of total area of perforations to geometric area of cylinder; β_{max}, values of β at which the radiation energy of the surface is a maximum; β_0, values of β below which the radiation energy of the perforated cylinder is greater than, or equal to, the radiation energy of an entire cylinder; Q_r, resultant radiation flux.

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ANGULAR DEPENDENCE OF EMISSIVITY OF TUNGSTEN IN THE INFRARED REGION OF THE SPECTRUM

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UDC 536.3

A procedure is described for measuring the angular dependence of the emissivity of metals in the infrared region of the spectrum.

Investigation of the directional radiation properties of materials is of great practical and scientific importance. Experimental data on these properties permit an increase in the accuracy of calculations of radiation heat transfer [1] and are a source of information on the mechanisms of the interaction of light with the surface of a material [2]. The spectral directional radiation properties of materials are of greatest interest, but have been quite inadequately investigated experimentally [3], as shown by the almost complete lack of information on them in the latest handbook [4].

Some results of experimental studies of the angular dependence of the emissivity of metals can be found in [5], but this information is only qualitative. For a long time problems of the quantitative calculation of the spatial distribution of radiation from a heated metal surface remained only a subject of theoretical discussions [6, 7], since there were no reliable data either on the optical constants or on the angular dependence of the emissivity of metals obtained under reproducible conditions of measurement.

It is known that the optical elements of measuring equipment, particularly dispersive systems such as prisms and gratings, are sensitive to the state of polarization of the radiation, as shown by the dependence of their transmission on the polarization parameters of the radiation [8]. Thus, since the degree of polarization of monochromatic radiation from a metal surface varies over wide limits depending on the optical constants of the metal and the angle between the direction of the radiation and the normal to the emitting surface, from now on called the angle of emission, the results of measuring the angular dependence of its emissivity without taking account of the polarization properties of the measuring equipment can turn out to be incorrect.

We have attempted to obtain experimental data on the angular dependence of the emissivity of tungsten at 170°C in the 3.5-10 μm spectral range.

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The tungsten samples investigated were 20 × 180 mm^2 films 0.1-mm thick. The film surface was polished with diamond paste made with particles 5 μm in diameter and then washed successively in trichloroethylene, benzene, and alcohol. Some of the samples were annealed for 2 h in an atmosphere of pure dry hydrogen at 700°C.

A schematic diagram of the measuring equipment is shown in Fig. 1. The sample under study was mounted on a massive copper heater plate used earlier to investigate the emissivity of metals [9]. The mounting ensured good thermal contact between the sample and the copper plate and a satisfactorily uniform temperature over the surface of the sample. It was established experimentally that the mounting did not affect the measurement of the angular characteristics of the radiation. The heater was mounted on an ST-9 rotating table which was used to vary and read the angle of emission. The support of the ST-9 rotating table permitted varying the angle of emission in two planes — parallel to and perpendicular to the plane of the principal cross section (meridional plane) of the monochromator prism.

Radiation from the sample under study was focused on the entrance slit of the monochromator of an ISK-21 spectrophotometer by the system of spherical and plane mirrors. The iris diaphragm in front of mirror 3 (Fig. 1) at a distance of 1600 mm from the sample permitted a decrease in the solid angle in which the radiation was collected to a value corresponding to a plane angle of 0.0175 radians.

Cooled InSb (3-5 μm) and Ge:Hg (4-10 μm) photoresistors were used as radiation detectors. The recording apparatus was essentially the same as that used earlier [9].

The sample was carefully positioned relative to the optic axis of the system so that when the axis of rotation lay in the surface of the sample a zero value of the angle of emission corresponded to the alignment of the normal to the sample surface with the optic axis of the system. To accomplish this an NSM-9-60 miniature incandescent lamp was mounted in the entrance slit of the monochromator. The image of the filament of this lamp and the image of the slit were produced in the plane of the sample surface. The sample was considered aligned when for a zero value of the angle of emission the image of the exit slit produced by light specularly reflected from the surface of the sample coincided with the slit itself, and in a rotation of the sample the center of the image of the slit on its surface coincided with the axis of revolution, i.e., remained stationary. The photodetector was roughly in the proper position when the image of the exit slit of the monochromator fell on its sensitive area. This position was refined by displacing the photodetector with micrometer screws along three mutually perpendicular axes until the output signal was maximum.

Before the measurements were performed the uniformity of the background was confirmed by the absence of an output signal of the photodetector at the modulation frequency when the angle of emission θ was varied with the sample at room temperature. The signal appeared only at $\theta \approx 0°$ when the detector "looked" at itself in the surface of the sample. Therefore, the angular dependence of the spectral brightness of the self-radiation of the sample was measured starting from a small angle of emission ($\theta \approx 10°$) where the equality $L_{\lambda,\theta} = L_{\lambda,n}$ was sufficiently accurately satisfied. The angular dependence of the brightness was measured in air in the same way as the normal emissivity was measured in [9].

Since for a uniform background and a linear radiation detector the output signal (N) is proportional to the brightness of the surface under study (L) or the corresponding magnitude of its emissivity (ε), the identity

$$\varepsilon_{\lambda,\theta}/\varepsilon_{\lambda,n} = L_{\lambda,\theta}/L_{\lambda,n} = N_\theta/N_n, \tag{1}$$

is valid. This permits a comparison of the measured results with the calculated angular dependence of the relative emissivity known from equations in [1] to be valid for $(n^2 + k^2)^{1/2} > 3.3$.

Figure 2 shows experimental and calculated values of the angular dependence of the relative spectral brightness of tungsten samples. The values of the optical constants of tungsten in the spectral range investigated at a temperature of 170°C were obtained from their temperature dependence reported in [10].

Figure 2 shows that for a variation of the angle of emission in a plane parallel to the meridional plane of the monochromator (plane of the picture in Fig. 1) the experimental and calculated values differ at all angles of emission, reaching a maximum for values of θ corresponding to the maximum value $B_{\lambda,m}$. For a variation of the angle of emission in a plane

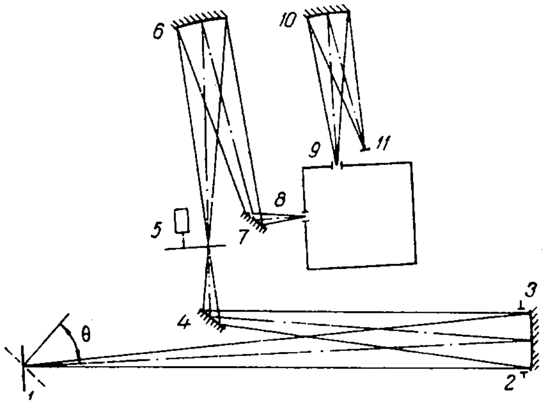

Fig. 1. Schematic diagram of equipment for measuring the angular dependence of the spectral brightness of the self-radiation of samples: 1) sample; 3) spherical mirror (d = 100 mm, f = 500 mm) with an iris diaphragm 2; 4, 7) plane mirrors; 5) modulator; 6, 10) spherical mirrors (d = 210 mm, f = 500 mm); 8, 9) entrance and exit slits of monochromator; 11) photodetector; θ, angle of emission.

perpendicular to the meridional plane of the monochromator the experimental and calculated results agree within the limits of error of the measurements over the whole range of variation except for angles corresponding to $B_{\lambda,m}$, where the difference is 3-4% for both annealed and unannealed samples.

The rms error of the experimental values of $L_{\lambda,\theta}/L_{\lambda,n}$ from the results of ten measurements for each wavelength was 0.5-1% in the $70° \leqslant \theta \leqslant 85°$ range for the corrected values of the angle of emission, and for $B_{\lambda,m}$, 1, 1.5, and 2.5% for wavelengths of 10, 5, and 3.5 μm, respectively.

Figure 3 compares the experimental and calculated values of $B_{\lambda,m}$. While the difference in these values for the second case of measurements can be accounted for by the difference between the values used for the optical constants and their actual values, due, e.g., to oxidation of the metal surface, the difference for the first case when the angle of emission varies in a plane parallel to the meridional plane of the monochromator can be accounted for only by the effect of the polarization properties of the measuring equipment.

While at θ = 0° the spectral radiation from a smooth metal surface is not polarized, as the angle of emission is increased the degree of polarization increases according to the expression

$$P_{\lambda,\theta} = \frac{(n^2 + k^2 - 1)\sin\theta}{(n^2 + k^2 + 1)(1 + \cos^2\theta) + 4n\cos\theta} . \tag{2}$$

For example, Eq. (2) shows that the radiation from tungsten at T = 170°C at an angle of 87°30' with the normal to the surface at a wavelength of 5 μm (n = 5.4, k = 22) is practically completely (99.2%) linearly polarized. Consequently, overestimated values of $L_{\lambda,\theta}/L_{\lambda,n}$ in the first case of measurements result from an increase in the transmission of the optical system of the measuring equipment with an increase in the degree of polarization of the radiation; i.e., the polarization properties of the euqipment are similar to those of a linear polarizer whose transmission is maximum for radiation polarized in a plane parallel to the meridional plane. When the angle of emission is varied in a plane perpendicular to the meridional plane of the monochromator, the transmission of the optical system of the equipment does not depend on the degree of polarization of the radiation. Consequently, the differences between the experimental values of $B_{\lambda,m}$ obtained in the first and second cases of measurements for wavelengths of 3.5, 5, and 10 μm are 6.2, 10.9, and 29.3%, respectively.

Thus, the data obtained conclusively show that the polarization properties of the meauring equipment must be taken into account in investigating the angular characteristics of radiation.

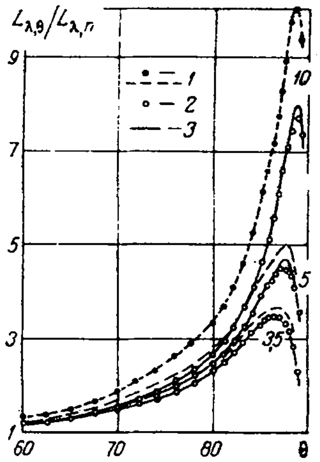

Fig. 2

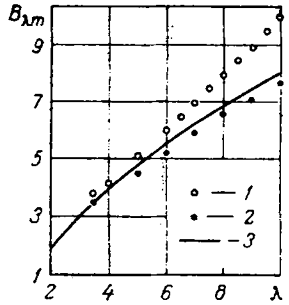

Fig. 3

Fig. 2. Angular dependence of relative spectral brightness of tungsten at T = 170°C: 1, 2) experiment (the angle of emission is varied in a plane (1) parallel to and (2) perpendicular to the meridional plane of the monochromator); 3) calculation. The numbers on the curves are wavelengths in μm•θ is in degrees.

Fig. 3. Comparison of experimental and calculated data for maximum values of the angular dependence of the relative brightness of tungsten at T = 170°C: 1, 2) experiment (the angle of emission varies in a plane (1) parallel to and (2) perpendicular to the meridional plane of the monochromator); 3) calculation. λ is in μm.

NOTATION

$L_{\lambda,n}$, $L_{\lambda,\theta}$, spectral brightness of metal surface in the direction of the normal and at an angle θ with the normal; $B_{\lambda,m} = (L_{\lambda,\theta}/L_{\lambda,n})_{max}$; $\varepsilon_{\lambda,n}$, spectral normal emissivity; $\varepsilon_{\lambda,\theta}$, spectral directional emissivity at an angle θ with the normal to the surface; n and k, real and imaginary parts of complex index of refraction $\hat{n}$ ($\hat{n} = n - ik$).

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