PROCEDURE FOR DETERMINING THE OPTICAL CONSTANTS OF METALS FROM THE RESULTS OF MEASUREMENTS OF THE SELF-RADIATION OF A SAMPLE

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A procedure is described for determining the optical constants of metals in the infrared region of the spectrum.

For the solution of many applied problems such as, for example, rigorous calculations of radiative heat transfer in systems containing metal surfaces, it is necessary to know the optical constants of the metals used. However, the optical properties of engineering materials, including metals, are not adequately known [1], and only the spectral and temperature dependences of the emissivity are given in the literature [2].

Conventional methods for determining the optical constants from the parameters of a reflected light beam [3] require the fabrication of an ideally plane mirror-finish surface of the investigated sample, thereby limiting such methods for the investigation of the optical properties of engineering materials, which, as a rule, have rough surfaces. Consequently, when the temperature of the sample is sufficiently high, it is practical to resort to methods based on measurements, at several angles relative to the surface, of the ratio between the spectral luminances of self-radiation polarized parallel (p-component) and perpendicular (s-component) to the plane of emission [4,5].

It is known that the s-component of the spectral luminance of the self-emitted radiation of a metal surface decreases rapidly with increasing angle of emission and in order to impart the required sensitivity to the method it is necessary to perform measurements at large angles of emission. Consequently, the magnitude of the light fluxes corresponding to the s-component limit the measurements to the high-temperature interval and the ultraviolet and visible regions of the spectrum, where metals have a sufficiently high emissivity.

The objective of the present report is to demonstrate the possibility of using a simpler procedure for the determination of the optical constants of metals in the infrared part of the spectrum, whereby, in essence, the spectral normal emissivity $\varepsilon_{\lambda,n}$ of the investigated surface and the spectral luminances at angle θ ($L_{\lambda,\theta}$) and along the normal to that direction ($L_{\lambda,n}$) are measured.

From the expressions for the p- and s-components of the directional emissivity [6]

$$\varepsilon^{p}_{\lambda,\theta} = 4n\cos\theta/[(n\cos\theta+1)^2 + k^2\cos^2\theta], \tag{1}$$

$$\varepsilon^{s}_{\lambda,\theta} = 4n\cos\theta/[(n+\cos\theta)^2 + k^2], \tag{2}$$

which are valid for $(n^2 + k^2)^{1/2} > 3.3$ ($\hat{n} = n - ik$, where $\hat{n}$ is the complex refractive index) we obtain

$$n = \frac{1+\cos^2\theta}{4\cos\theta}\left(\frac{A_\theta - B_\theta\cos^2\theta}{\varepsilon_{\lambda,n}A_\theta B_\theta\sin^2\theta} - \frac{1}{2}\right)^{-1}, \tag{3}$$

where $A_\theta = \varepsilon^{s}_{\lambda,\theta}/\varepsilon_{\lambda,n}$; $B_\theta = \varepsilon^{p}_{\lambda\theta}/\varepsilon_{\lambda n} = 2(L_{\lambda,\theta}/L_{\lambda,n}) - A_\theta$.

It has been confirmed in an analysis of calculations carried out according to the Fresnel equations [3] for a wide range of values of $\varepsilon_{\lambda,n}$, n, and θ that the quantity A_θ can be calculated for angles $\theta > 60°$ by means of the following expression approximating those equations:

$$A_\theta = [1 + (0.444\theta - 0.259)\,\varepsilon_{\lambda,n}(1.05 + \varepsilon_{\lambda,n})]\cos\theta, \tag{4}$$

where θ is the angle reckoned from the normal to the surface, in radians.

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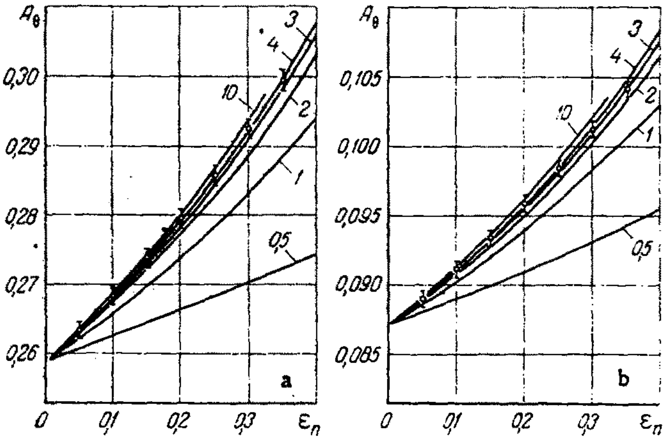

Fig. 1. Comparison of values of $A_\theta = \varepsilon^s_{\lambda,\theta}/\varepsilon_{\lambda,n}$, calculated according to Fresnel equations (solid curves) and according to (4) (dots). The vertical lines correspond to the domain of values $\Delta A_\theta/A_\theta = \pm 0.5\%$. The values of the refractive index are given alongside the curves. a) $\theta = 75°$; b) $\theta = 85°$.

TABLE 1. Values of Ratio $P = (\Delta A_\theta/A_\theta)/(\Delta\varepsilon_{\lambda,n}/\varepsilon_{\lambda,n})$

$\varepsilon_{\lambda,n}$	θ, deg		
	60	75	85
0,05	0,0117	0,0182	0,0225
0,10	0,0252	0,0388	0,0478
0,15	0,0357	0,0617	0,0755
0,20	0,0568	0,0865	0,1054

It is evident from Figs. 1a and b that the error of approximation for $\varepsilon_{\lambda,n} < 0.15$ and $n > 2$, which are typical of metals in the infrared part of the spectrum, is less than 0.5%. The relative error of A_θ due to the error of measurement of $\varepsilon_{\lambda,n}$ is estimated from the relation

$$\Delta A_\theta/A_\theta = P(\Delta\varepsilon_{\lambda,n}/\varepsilon_{\lambda,n}), \tag{5}$$

which is obtained by differentiating (4) with respect to $\varepsilon_{\lambda,n}$, where $P = (0.444\theta - 0.259)(1.05 + 2\varepsilon_{\lambda,n})\varepsilon_{\lambda,n}/[1 + (0.444\theta - 0.259)\varepsilon_{\lambda,n}(1.05 + \varepsilon_{\lambda,n})$. The values of P for various values of $\varepsilon_{\lambda,n}$ and θ are given in Table 1.

Thus, by measuring $\varepsilon_{\lambda,n}$ and $L_{\lambda,\theta}/L_{\lambda,n}$ it is possible to determine the refractive index of the metal on the basis of expressions (3) and (4).

We have used the given procedure to determine the optical constants of polycrystalline tungsten (tungsten tape) at a temperature of 170°C at a wavelength of 5 μm, which was isolated by means of a monochromator from an IKS-21 spectrometer. Errors associated with adjustment and measurement of the angle θ and the influence of the polarization properties of the monochromator were eliminated in the measurements. According to the measurement results, the value of $\varepsilon_{\lambda,n}$ was 0.040, which is 5% higher than the value obtained previously for similar samples [7]. The rms error of the results of measurement of $L_{\lambda,\theta}/L_{\lambda,n}$ was 0.5%.

The value of the absorption index k was calculated for the known values of $\varepsilon_{\lambda,n}$ and n according to the expression

$$k = [4n/\varepsilon_{\lambda,n} - (n+1)^2]^{1/2}. \tag{6}$$

To estimate the error of the values obtained in differentiation of expressions (3) and (6) with respect to the parameters A_θ, B_θ, $\varepsilon_{\lambda,n}$, and n entering into them, we have the expressions

$$\Delta n/n = C(\Delta B_\theta/B_\theta) + D(\Delta\varepsilon_{\lambda,n}/\varepsilon_{\lambda,n}), \tag{7}$$

TABLE 2. Results of Determination of Optical Constants of Tungsten (λ = 5 μm, T = 170°C, $\varepsilon_{\lambda,n}$ = 0.040).

θ, deg	$L_{\lambda,\theta}/L_{\lambda,n}$ (exp.)	A_θ	B_θ	n	k	C	D	β_θ	n^*	k^*
82	2,95	0,1415	5,758	4,19	19,79	10,12	0,88	40,696	6,24	21,65
83	3,21	0,1239	6,296	4,26	19,96	8,25	0,69	50,816	6,86	22,16
84	3,53	0,1063	6,954	4,50	20,50	6,77	0,55	65,146	6,56	21,94

in which $C = A_\theta/Q$; $D = [B_\theta \cos^2\theta(P + \varepsilon_{\lambda,n}) + \varepsilon_{\lambda,n}A_\theta]/Q$; $Q = A_\theta - (B_\theta\cos^2\theta + 0.5\varepsilon_{\lambda,n}A_\theta B_\theta \sin^2\theta)$, as well as

$$\Delta k/k = C'(\Delta n/n) - D'(\Delta\varepsilon_{\lambda,n}/\varepsilon_{\lambda,n}), \tag{8}$$

where $D' = 2(n/k)^2/n\varepsilon_{\lambda,n}$; $C' = D'[2 - \varepsilon_{\lambda,n}(n + 1)]/2$.

The results of the measurements and calculations are summarized in Table 2. The values of the coefficients in expression (8) turn out to be equal for the resulting data: $C' = 0.48$ and $D' = 0.53$. Inserting the values $\Delta\varepsilon_{\lambda,n}/\varepsilon_{\lambda,n} = 0.05$, $\Delta B_\theta/B_\theta = 0.005$, and $P = 0.017$ corresponding to our experiments into expressions (7) and (8), we obtain for $\theta = 82°$: $\Delta n/n$ = 9.5% and $\Delta k/k$ = 1.9%, and for $\theta = 84°$: $\Delta n/n$ = 6.1% and $\Delta k/k$ = 0.3%. Thus, the main source of error in the optical constants determined by the proposed procedure is the error of measurement of $L_{\lambda,\theta}/L_{\lambda,n}$ or B_θ, its contribution to the total error diminishing with increasing value of θ.

Also given in Table 2 are the values of the polarization ratio [5] $\beta_\theta = \varepsilon^p_{\lambda,\theta}/\varepsilon^s_{\lambda,\theta} = B_\theta/A_\theta$ and the optical constants calculated for three pairs of angles, 82-83°, 83-84°, and 82-84°, by the method of "intersecting circles," the analytical equations for which are given in [4]. The average values $n^*_{av} = 6.55$ and $k^*_{av} = 21.92$ exceed the average values of n and k in Table 2 by more than 50% and 9%, respectively, and the value of $\varepsilon_{\lambda,n}$, calculated with respect to n^*_{av} and k^*_{av}, the value of 0.040 by more than 20%, which is considerably higher than the error of measurement of $\varepsilon_{\lambda,n}$. It is inferred on the basis of these data that Sayapina's equations [4] provide lower accuracy in the determination of the optical constants of metals than the procedure proposed here.

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