mean flow rate, m/sec; D, longitudinal diffusion coefficient, m^2/sec; τ, kinetic parameter (lag time); m_i, n_i, exponents; γ, k, Henry coefficient for isotherms f and φ, respectively.

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ENGINEERING METHOD OF DETERMINING AND DESCRIBING THE DIRECTIONAL REFLECTION CHARACTERISTICS OF OPAQUE STRUCTURAL MATERIALS

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A model for the reflective properties of opaque materials and a method for experimental determination of its parameters are proposed.

At this time, the mathematical modeling of radiant heat transfer processes of engineering systems for which it is impossible to conduct a direct experiment or is fraught with great difficulties plays an ever-increasing role. To assure the modeling, it is necessary to know not only the reflection and radiation coefficients of the materials, but also their directional characteristics which describe the spatial distribution of the reflected and intrinsic radiation. The investigations of a number of authors have shown that thermophysical computations which do not take account of the directional radiation characteristics of the structural materials can result in substantial errors [1,2].

One possible means of describing the bireflectional reflective properties of a surface, i.e., the properties characterized by two directions, illumination and observation, is the use of theoretical dependences relating the probabilistic characteristics of the reflected radiation field to the statistical characteristics of the surface roughness [3]. The optical properties of the material and the parameters adequately describing the roughness of its surface should be known. However, the use of a theoretical method is not always possible for structural materials because of the difficulties in determining their optical properties and roughness [4].

In the practice of illumination-engineering computations for materials with an isotropic surface and directionally scattered [5], or directionally diffuse nature, according to the new illumination-engineering terminology [6], of the reflection, the spatial reflection index for specific conditions of directional illumination is approximated by an ellipsoid of revolution whose major axis is oriented in the specular direction [7].

The purpose of this paper is to investigate the possibility of using the illumination-

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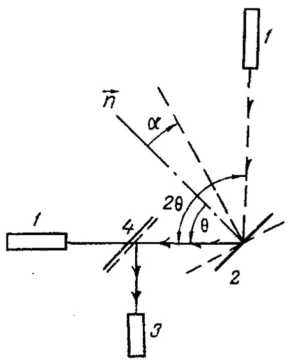

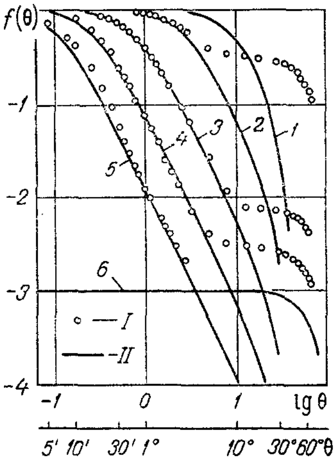

Fig. 1 Fig. 2

Fig. 1. Diagram of the measuring apparatus: 1) collimated radiation source; 2) specimen; 3) photodetector; 4) semiopaque plate.

Fig. 2. Back-reflection index [I) experiment; II) computation]: t = 2.5 (1); 10 (2); 36 (3); 100 (4); 257 (5); cos θ (6).

engineering model mentioned to describe the reflexive properties of opaque structural materials (OSM) which are opaque dielectric coverings superposed on metal substrates. Typical examples of such coatings are lacquers, tints, and enamels.

To obtain the necessary data, the dependence of the nature of OSM reflection on the angle of illumination by the collimated light beam was studied experimentally. Since known methods for the experimental investigation of OSM reflective properties [8] either cannot yield the necessary information about the directional properties of reflection because of their constraints in principle, or are characterized by great difficulties in obtaining it, a new measurement method [9] was developed which is realized by using a simple apparatus (Fig. 1).

The apparatus permitted measurement of the back-reflection index, the angular dependence of the radiation reflected in the direction opposite to the direction of the illumination, as well as the dependence of the nature of the spatial light distribution near the specular reflection direction on the angle of illumination θ. To obtain this latter dependence for each angle θ, the reflected light intensity was measured relative to its magnitude in the specular reflection direction as a function of the angle α (the angle between the normal to the specimen surface and the bisectrix of the phase angle 2θ), which could change in two mutually perpendicular planes. The dependence of the specimen brightness coefficient in the specular reflection direction on the angle of illumination was also measured.

It is known that the form of the reflection index remains practically invariant [10,11] in the 0-30° range of illumination angles. At the same time, the OSM back-reflection index for this same band of illumination angles contains almost all the information about the nature of the reflection.

A comparison between the computational and experimentally obtained back-reflection indices f(θ) is shown in Fig. 2. The computation was performed for an elliptic mode of the reflection index with different relationships between the major and minor axes of the ellipse. The results of the measurement showed that the reflection index of real OSM can be approximated by an ellipse only for certain materials with a directionally diffuse nature of the reflection. For the majority of OSM for which the combination of surface and volume light scattering mechanism is typical, the reflection index can be represented by the superposition of an ellipse and an almost cosinusoidal angular dependence (Fig. 2, curve 6).

Results of measuring the dependence of the nature of the reflection of OSM with coatings (Fig. 3a) and of a metal surface with root-mean-square roughness height σ = 0.27 μm (Fig. 3b) on the illumination angle are presented in Fig. 3. If a specular component appears for a

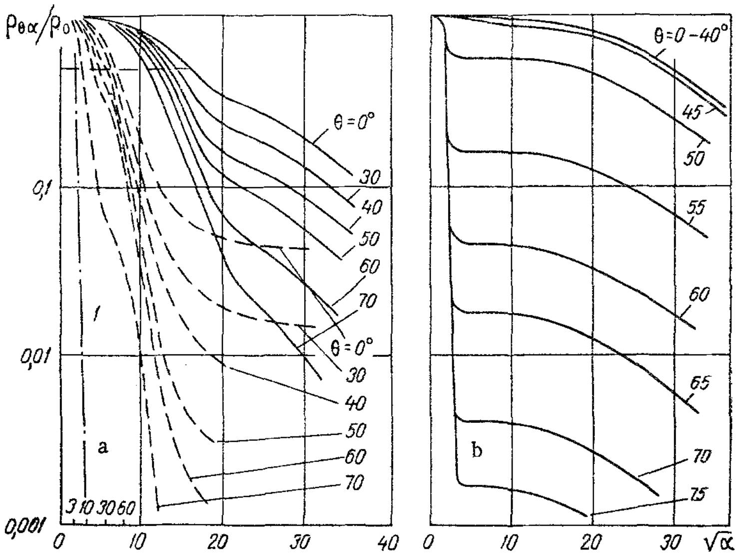

Fig. 3. Dependence of the nature of material reflection on the angle of illumination: a) OSM with different coatings; b) isotropic rough metallic surface; 1) specular; $\sqrt{\alpha}$ in min.

rough metal surface at some illumination angle (the critical angle θ_c [12]), which increases as the illumination angle grows, then for the OSM with coatings the directionally diffuse reflection component is concentrated in a smaller and smaller solid angle around the specular reflection direction as the illumination angle increases, which can be interpreted as "elongating" the ellipse corresponding to the increase in the ratio between its major and minor axes. Therefore, the difference in the nature of the reflection of the specimens examined indicates the inapplicability of the theoretical models taking account of just surface light scattering to account for the directional reflection properties of OSM with coatings.

It is known that the brightness coefficient can be represented as the product of the reflection coefficient and the corresponding value of the spatial reflection index [13]. In conformity with this, the brightness coefficient for a directionally diffuse nature of the reflection is expressed analytically thus [14]:

$$\beta(\theta,\ \gamma,\ \psi) = \frac{R_\theta (t_\theta^2 - 1)}{\ln \dfrac{t_\theta\left(\sqrt{1 + (t_\theta^2 - 1)\cos^2\theta} + t_\theta \cos\theta\right)}{1 + \cos\theta}} \cdot \frac{\cos\gamma/\cos\psi}{1 + (t_\theta^2 - 1)\sin^2\gamma}\ . \tag{1}$$

It can be assumed with adequate accuracy for practice that

$$\ln \frac{t_\theta\left(\sqrt{1 + (t_\theta^2 - 1)\cos^2\theta} + t_\theta \cos\theta\right)}{1 + \cos\theta} = \ln t_\theta^2\ . \tag{2}$$

Equality (2) is an identity for $\theta = 0$. As θ increases the error in the assumption made increases the more slowly, the greater the quantity t_θ. Since the reflection index is elongated as θ increases, i.e., the quantity t_θ increases, then (2) can be considered valid for all θ except angles directly abutting on $\theta = \pi/2$. For instance, the left side of (2) does not differ by more than 20% from its right side for $\theta \leqslant 82°$ for $t = 30$, $\theta \leqslant 85°$ for $t = 100$, $\theta \leqslant 87°$ for $t = 300$, and $\theta \leqslant 88°$ for $t = 1000$.

Taking account of (2) it follows from (1) that

$$R_\theta = \beta_\theta \cos\theta\ \frac{\ln t_\theta^2}{t_\theta^2 - 1}\ , \tag{3}$$

where β_θ is the brightness coefficient in the specular reflection direction ($\gamma = 0$, $\psi = \theta$) whose magnitude is related to the measured magnitude of the bidirectional reflection coefficient in the specular direction ρ_θ [15] by the relationship

$$\beta_\theta \cos\theta = \pi\rho_\theta/\Delta\omega. \tag{4}$$

Therefore, under the condition of conservation of the elliptical mode of the directional

TABLE 1. Parameters Characterizing the Directional Reflexive Properties of OSM Specimens ($\Delta\omega = 9.6\cdot10^{-6}$ sr, $\lambda = 0.63$ μm)

Parameter	Specimen number						
	10	2	7	5	20	16	8
β_0	0,37	7,6	47	22,6	0,93	210	1060
t_0	2,5	10	36	37	6	100	257
k	0,6	0,02	$8\cdot10^{-3}$	0,01	0,01	$3\cdot10^{-3}$	$3,4\cdot10^{-5}$
m	0,25	1	1	0,5	1	0,5	1
P	0,718	0,646	0,358	0,398	0,460	0,375	0,376
Q	1,117	1,217	1,494	1,525	1,550	1,468	1,468
p	—	—	0,773	1,28	2,19	0,983	0,996
q	10	4	—	—	—	—	—

diffuse component of the index for any illumination angle, and for a known dependence of β_θ and t_θ on θ, the magnitude of the reflection coefficient due to this component can be computed by using (3).

The magnitude of the parameter t for normal incidence was determined by analogy with the method [12] on the magnitude of the angle of illumination $\theta_{0.5}$ corresponding to the half-level of the back-reflection index of the directionally diffuse component by means of the formula

$$t_0 = (2\cos 2\theta_{0.5} - \cos^2 2\theta_{0.5})^{1/2}/\sin 2\theta_{0.5}, \quad (5)$$

which follows from the equation of the ellipse. The simple relationship

$$t_0 = 30/\theta_{0.5}, \quad (6)$$

where $\theta_{0.5}$ is expressed in degrees, can be used to replace (5) with less than 5% error.

By processing the experimental data we established that it is sufficient to measure ρ_θ at θ = 0, 70, and 80° to determine the dependence of the quantities β_θ and t_θ on the illumination angle. The values of ρ_θ obtained permit the determination of the magnitude of the parameters $P = \log\rho_{80}/\log\rho_0$ and $Q = \log\rho_{80}/\log\rho_{70}$ which are in the empirical formulas approximating the angular dependence of ρ_θ.

If $Q \geqslant 1.3$, as is characteristic for materials with a smooth (glossy) surface, the dependence of ρ_θ on θ is expressed by the formula

$$\lg\rho_\theta/\lg\rho_0 = 1 - \varphi(\theta), \quad (7)$$

but for materials with a matte (rough) surface for which $Q < 1.3$, by the formula

$$\lg\rho_\theta/\lg\rho_0 = 1 - \eta(\theta), \quad (8)$$

where

$$\varphi(\theta) = \frac{1}{2}\left[\frac{0.1\theta}{99-\theta} + (1-\cos\theta)^p\right];$$

$$p = -12\lg(1.6 - 2P); \quad (9)$$

$$\eta(\theta) = 0.1\theta/(99 - \theta + q);$$

$$q = -24\lg[(Q-1)/0.3]. \quad (10)$$

The angle θ in (9) and (10) is expressed in degrees.

Analogously, the angular dependence of the parameter t can also be approximated in conformity with the surface texture:

$$t_\theta = t_0(t_s/t_0)^{\varphi(\theta)}, \quad \text{if} \quad Q \geqslant 1.3, \quad (11)$$

and

$$t_\theta = t_0(t_s/t_0)^{\eta(\theta)}, \quad \text{if} \quad Q < 1.3, \quad (12)$$

where t_s is a parameter corresponding to the angular resolution of the measuring system. Its magnitude is determined from (3) and (4) for the case of an ideal mirror, when $\rho = R = 1$:

$$\ln t_s^2/(t_s^2 - 1) = \Delta\omega/\pi. \quad (13)$$

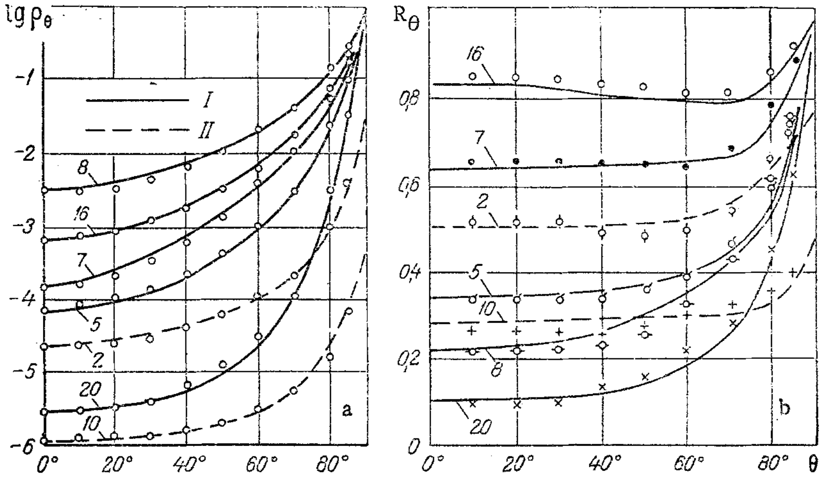

Fig. 4. Comparison of experimental and computational data: a) reflection coefficient in the specular direction ($\Delta\omega$ = 9.6·10^{-6} sr, λ = 0.63 μm; b) reflection coefficient R_θ (λ = 0.63 μm). Points are experimental values, lines are computations, numbers are the number of specimens with smooth (I) and rough (II) coating surface.

According to (13), the parameter t_s = 2230 corresponded to the quantity $\Delta\omega$ = 9.6·10^{-6} sr, whichholds in our measurements.

The contribution of the uniformly diffuse component to the magnitude of the brightness coefficient β_θ for the normal incidence case (θ = 0°) was determined by using the relationships

$$k = 2^m f(60), \quad m = 9 \lg [f(50)/f(60)], \tag{14}$$

where f(50) and f(60) are values of the back-reflection index for θ = 50 and 60°, respectively. Therefore, the magnitude of the brightness coefficient due to the directionally diffuse component equals $\beta_0(1 - k)$, and to the uniformly diffuse component is $-\beta_{ok}$, where β_{ok}, is the total brightness coefficient of the specimen.

It is known that the nature of material reflection with volume scattering is almost uniformly diffuse [16] and independent of the angle of illumination in practice, remaining isotropic even for low reflexivity of the material [17]. Consequently, a numerical equality can be assumed between the magnitudes of the reflection and brightness coefficients due to the uniformly diffuse component. For a diffuse reflector with a smooth surface, the contribution of the uniformly diffuse component to the reflection coefficient is proportional to the surface illumination, in which connection its back scattering index is a cos θ dependence. Analysis of the measurement results showed that the increase in surface roughness of volume-scattering materials changes their back-reflection index, which can be approximated by a $\cos^m \theta$ dependence, m < 1. As $\theta \to 90°$ for specimens with m ≃ 0.25 the values of the back-reflection index remain constant starting with θ = 75-80°, which can be interpreted as invariability of the effective illumination of a rough surface in this range of illumination angles.

In conformity with the above, the reflection coefficient of OSM with an isotropic surface characterized by the presence of directionally and uniformly diffuse reflection components, can be computed for any illumination angle by means of the formula

$$R_\theta = \beta_0 \left[\frac{(1-k)(\rho_\theta/\rho_0) \ln t_\theta^2}{t_\theta^2 - 1} + k \cos^m \theta \right]. \tag{15}$$

Values of the parameters used for the computations are presented in Table 1.

The results of measuring ρ_θ and the curves computed by using (7)-(10) are displayed in Fig. 4a. Comparing the computations by means of (15) with the results of measuring the angular dependence of the reflection coefficients, executed for identical illumination conditions on an integrating sphere, which assures a measurement error not exceeding 10%, is represented in Fig. 4b.

Therefore, the investigations performed showed that for opaque structural materials with an isotropic surface and an accuracy acceptable for practice, it is admissible to approximate the spatial reflection index in the form of a superposition of the uniformly diffuse component and the ellipsoid representing the directionally diffuse reflection component. An experimental method of determining the parameters of this model permits obtaining the angular dependence of the reflection coefficient without measuring the fluxes reflected in the hemisphere above the specimen, which substantially simplifies the measurement facilities.

NOTATION

θ, angle of illumination relative to the normal to the surface; γ, ψ, angles between the normal to the surface and the directions of observation and specular reflection, respectively; α, angle between the normal to the surface and the bisectrix of the phase angle 2θ; R_θ, reflection coefficient; β_θ, brightness coefficient; ρ_θ, reflection coefficient in the specular direction; $\Delta\omega$, effective value of the solid angle of the illuminator–receiver system which characterizes the angular resolution of the measuring apparatus; t_θ, a parameter equal to the ratio between the major and minor axes of the ellipse characterizing the elongation of the directionally diffuse component index; $f(\theta)$, value of the back-reflection index for the angle of illumination θ.

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