Reynolds number; $\theta = T/T_e$, temperature; $f(\eta)$, Blasius function; η, self-similar variable; $h = ky$, optical depth of layer; h_0, optical thickness of layer; ω, single-scattering albedo; $h_\lambda = h_{0\lambda}(\bar{\xi}/\mathrm{Re}_L)^{1/2}\eta$, optical depth of boundary layer; $\bar{h}_{0\lambda} = k_\lambda L$, longitudinal optical thickness of layer; $\bar{B}_{0\lambda} = B_{0\lambda}/4\sigma T_e^4$; $B_{0\lambda}$, spectral intensity of ideal black body radiation; $\Phi_{*\lambda} = J_\lambda/4\sigma T_e^4$, dimensionless flux density of incident volume radiation; H, enthalpy; q, thermal flux; ρ, c_p, density and specific heat of calorimeter material; ε, integral emissivity of wall material; σ, Stefan–Boltzmann constant. Subscripts: e, parameters at external boundary of boundary layer; w, wall; λ, spectral.

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SPATIAL AND POLARIZATION CHARACTERISTICS OF RADIATION REFLECTED BY COMPOSITE MATERIALS

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In the spectral regions 0.63 and 1.15 μm, measurements are made of the degree of polarization and indicatrix of radiation reflected from the surface of composite materials before and after their heating in air by radiation from a CO_2 laser.

Increasing use is being made of composite materials in different areas of modern technology, the annual output of these materials now accounting for ~25% of production [1]. In a number of cases, lasers turn out to be the most appropriate tool for processing composites under industrial conditions. Here, one of the main parameters which characterizes the efficiency of energy expenditure in laser processing is the reflection coefficient [2, 3].

Detailed study of processes involved in the interaction of laser radiation with materials requires information not only on the reflection coefficient, but also on the polarization and spatial characteristics of the reflected radiation. This information is necessary in measuring the thermodynamic temperature by optical methods [4], in developing measurement systems to study the reflection coefficients and temperature of materials, and in calculating radiative heat transfer by high-temperature structures [5].

In the present study, at wavelengths of 0.63 and 1.15 μm, we measured the degree of polarization and indicatrix of radiation reflected from the surfaces of glass-textolite STK,

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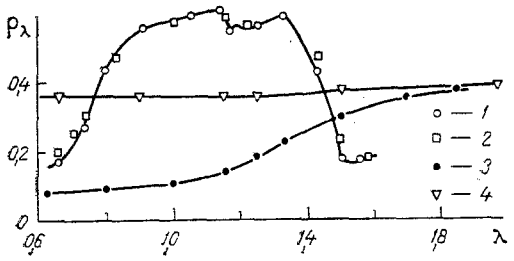

Fig. 1

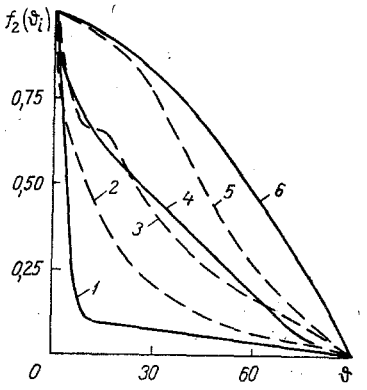

Fig. 2

Fig. 1. Spectral dependence of the reflection coefficients of glass-textolite STK before (1, 2) and after (3, 4) irradiation by a CO_2 laser in air; initial surface covered with lacquer (1), rough (2), and charred (3), with exposure of the glass-cloth layer (4). λ, μm.

Fig. 2. Indicatrices of radiation with a wavelength of 1.15 μm reflected from the initial surface (1), the rough surface (4, 6), and the charred surface (2, 3) of glass-textolite STK, as well as from the surface with a burned charred layer and exposed glass fibers (5) before (1, 4, 6) and after (2, 3, 5) irradiation in air by the CO_2 laser. ϑ, deg.

textolite PTK, and getinax. We studied specimens both with their initial surfaces and after heating in air by radiation from a CO_2 laser with a flux of 30 W/cm^2 until charring of the surface layer. In addition, the glass-textolite was irradiated so as to remove the lacquered surface layer. After the surface was heated, it was further exposed to laser radiation until the charred layer burned, exposing the glass fibers of the filler [3].

The spectral dependence of the reflection coefficients $\rho(\lambda)$ of the investigated materials in the range 0.6-2.0 μm was determined on a "Specord" spectrophotometer with an attachment for measurement of diffuse reflection. The reflection coefficients of the lacquered and rough-surfaced glass-textolites not subjected to heating by radiation from the CO_2 laser coincided in the range 0.6-1.6 μm (Fig. 1). The values of the coefficient increased from 0.15 to 0.6 in the range 0.6-1.0 μm and decreased to 0.15 on the section 1.3-1.5 μm. A similar result was obtained for the reflection coefficients of the textolite and getinax, although the values differed somewhat in absolute value. For all of the investigated materials not subjected to CO_2-laser radiation, the relations $\rho(\lambda)$ were typically nonmonotonic in the range 1.15-1.33 μm. This pattern is evidently attributable to the absorption bands of the resin binder. Heating of the components by radiation from the CO_2 laser leads to charring of the surface layer. This charring then determines the spectral dependence of the reflection coefficient of glass- and organic-fiber plastics, causing it to increase monotonically in the spectral range 0.6-1.8 μm. Subsequent burning of the charred layer of the surface of the glass-fiber plastic was accompanied by exposure of the glass cloth, which in turn led to a change in the form of the function $\rho(\lambda)$. In this case, in the wavelength range 0.6-2.0 μm, the glass-fiber plastic reflects as a graybody with a coefficient of ~0.4 (Fig. 1).

The degree of diffuseness of the reflected radiation is conveniently characterized by the equivalent solid angle [6]

$$\Omega = \Phi/I_0 = \int f(\vartheta)\, d\omega. \qquad (1)$$

In the general case, determination of this angle requires knowledge of the distribution of the reflected flow in space. However, in the case of the normal incidence of radiation on a surface not having a roughness characterized by a certain direction, the reflected flow is axially symmetric relative to the normal to the surface [7]. In this case, to determine Ω it is sufficient to measure the indicatrix of the reflected radiation in an arbitrary plane passing through the incident beam.

The degree of polarization and indicatrix were measured on a goniophotometer constructed on the basis of an IPO-12 reflectometer. The source of the polarized radiation was an He–Ne laser generating at a wavelength of 0.63 or 0.15 μm and set up so that the vector of the electric field was located in the plane of incidence. The laser radiation, modulated by a rotating disk with holes, was directed onto the test surface so as to form a spot ~3 mm in diameter. The reflected radiation passed through a slit 2 mm wide and was recorded by a photomultiplier. Located in front of the photomultiplier was an interference filter with a transmission maximum at a wavelength of 0.63 or 1.15 μm. The signal from the photomultiplier was recorded by a selective voltmeter adjusted for a modulation frequency of 600 Hz. The radiation reflected at different angles was recorded in the plane of incidence by moving the recording part of the recorder around the axis of rotation, which was located in the plane of the specimen surface at the point of incidence of the radiation.

In performing the polarization measurements, we placed a block of optical elements in the recording part ahead of the photomultiplier. The block consisted of two quartz lenses with an intervening polaroid. The first lens was located on the specimen surface at the focal length relative to the laser spot. It formed a parallel beam which passed through the polaroid and was collected by the second lens in the plane of the slit.

Whereas the solid angle of the recording system was determined by the dimensions and position of the slit and was $1.5 \cdot 10^{-4}$ sr (angular aperture ~0.25°) in the measurement of the indicatrix, in the study of polarization of the reflected radiation the solid angle depended on the diameter and focal length of the lens which formed the parallel beam passing through the polaroid. This angle was $6.1 \cdot 10^{-3}$ sr (angular aperture ~5°).

For each specimen, the distribution of reflected radiation intensity measured with normal incidence of the beam was normalized to the intensity with a recording angle $\vartheta = 0°$. The average of six such measurements was then used to construct the indicatrix. The method used to measure the indicatrix and calculate the equivalent solid angles was described in detail in [4]. The standard deviation of a single measurement of the normalized radiation intensity ranged from 0.001 to 0.07, depending on the roughness of the specimen surface and the recording angle. The relative random error of the equivalent solid angle determination depended on the form of the indicatrix and was 25 and 15%, respectively, for $\Omega = 0.1\pi$ and 1.0π and a confidence level 0.95.

With normal incidence of the beam, the design of the unit did not permit measurement of the degree of polarization of radiation reflected from the specimen at an angle of 0°. As a result, we used measurements of the degree of polarization of radiation reflected in the mirror direction with an angle of incidence of 5°. This could be done because variation of the angles of incidence within 0-10° causes only a slight change in the degree of polarization of radiation scattered in the mirror direction [8]. The degree of polarization P of the reflected radiation was determined from the ratio of the difference to the sum of the maximum I_a and minimum I_b intensities of radiation passing through the polaroid when it is rotated relative to the axis of the laser beam:

$$P = \frac{1}{\beta} \frac{I_a - I_b}{I_a + I_b}, \tag{2}$$

where β is the polarizing ability of the polaroid. In our study, we used polaroids with β = 99.99 and 99.5% for λ = 0.63 and 1.15 μm, respectively.

The error of the degree of polarization was due mainly to random errors of measurement of the extreme values of intensity. Differentiating (2) and analyzing the resulting expression, it can be shown that for $P \to 1$ and $P \to 0$ the absolute error of measurement of the degree of polarization of the reflected radiation increases from 1.0 to 4.5% with a decrease in P from 1.0 to 0.3.

Measurement of the indicatrix showed that with normal incidence of radiation reflected from the initial surface of the composites not subjected to laser heating, there is a strong mirror component (Fig. 2). Removal of the upper lacquer layer led to broadening of the indicatrix and was accompanied by an increase in the equivalent solid angle of the reflected radiation. Here, the broadening of the indicatrix may vary (lying between curves 4 and 6) up to the indicatrix corresponding to Lambert reflection. After irradiation by the laser, the indicatrices of the reflected radiation occupy an intermediate position between those of the lacquered and rough composites (between curves 2 and 3), depending on the condition of the

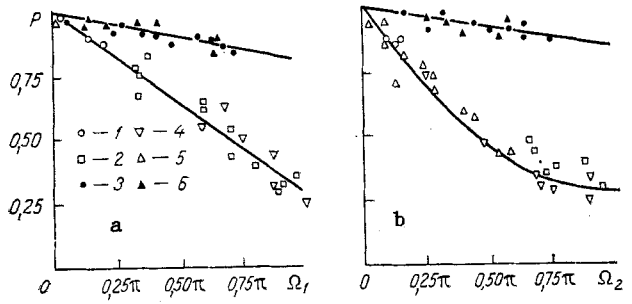

Fig. 3. Dependence of the degree of polarization on the equivalent solid angle of radiation with wavelengths of 0.63 (a) and 1.15 μm (b) reflected by glass-textolite (1, 2, 3, 4) and textolite (5, 6) with its initial (1, 5), rough (2), and charred (3, 6) surfaces. Also shown are results for glass-textolite with a burnt charred layer (4).

charred surface. Subsequent heating of the glass-fiber plastic, leading to burning of the charred layer and exposure of the glass cloth, causes additional broadening of the indicatrix (curve 5). Depending on the condition of the surface of the materials, the equivalent solid angles Ω of the reflected radiation took values from 0.009π to π.

Although the width of the indicatrix and the equivalent solid angle are spatial optical characteristics of reflected radiation, they can characterize the roughness of the surface if allowance is made for the wavelength of the radiation. The relationship between the condition of the surface and the polarization characteristics of the reflected radiation is conveniently represented in the form of the dependence of the degree of polarization on the equivalent solid angle (Fig. 3). For composites not subjected to laser heating and for glass-textolite specimens with a burned charred layer and exposed glass fibers, the polarization of the reflected radiation decreases from 1.0 to 0.3 with an increase in the solid angle from 0 to π. Here, for radiation with a wavelength of 1.15 μm (Fig. 3b), this dependence is stronger than at 0.63 μm for small values of Ω (Fig. 3a). For the charred composites, the dependence of polarization on the equivalent solid angle is negligible and is the same for $\lambda_1 = 0.63$ and $\lambda_2 = 1.15$ μm.

Such behavior of the function $P(\Omega)$, characterizing the charred and uncharred composites, can be attributed to the substantial difference in their reflection coefficients. Radiation incident on the specimens with a smaller absorption index penetrates deep into the material and is depolarized when scattered on both surface and subsurface discontinuities connected with the difference in the optical constants of the binder and filler. The nonisochromatic character of the absorption taking place causes the function $P(\Omega)$ to be dependent on the wavelength of the transmitted radiation. Measurements of the transmission of the uncharred composites with allowance for reflection allowed us to evaluate their absorption indices. These values nearly coincide for textolite and getinax and are 25-30 and 3-5 cm^{-1} for wavelengths of 0.63 and 1.15 μm, respectively. The absorption index for the glass-textolite is several times greater and takes values of 110 and 10 cm^{-1} for the same wavelengths. If we assume that the charred layer formed on the surface of composites heated in air by radiation from the CO_2 laser absorb radiation similarly to carbon–graphite materials, then according to [9] its absorption index is several times greater still in the regions 0.63 and 1.15 μm and amounts to $\sim 10^5$ cm^{-1}. We were not able to determine the absorption indices of glass-textolite with a burned charred layer because its surface consisted of a sintered mass of partly remelted glass, and we could not cut the thin specimen needed for measuring transmission from this material. However, in accordance with Fig. 3, it can be suggested that its absorption indices in the regions 0.63 and 1.15 μm are approximately 50-10 and 5-10 cm^{-1}, respectively.

To confirm the effect of the degree of absorption on the relation $P(\Omega)$, we performed measurements on materials that were opaque in the regions 0.63 and 1.15 μm (graphite, duralumin, and ultraviolet glass UFS6) and on transparent quartz specimens with surfaces ground by different grades of abrasive powder. It was found that the changes in the degree of polarization with an increase in the solid angle of the reflected radiation are the same for the opaque materials and the charred composites.

The conditions of scattering of radiation by the quartz specimens could be varied by placing white or black paper on their rear surfaces. Due to the absorption by the black paper

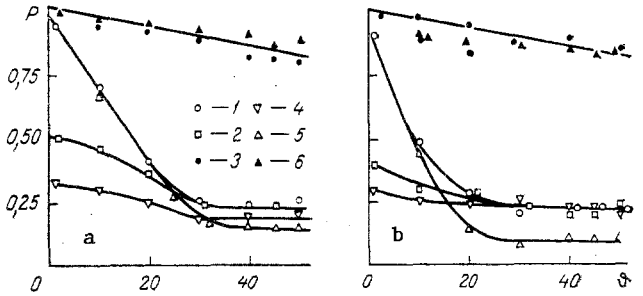

Fig. 4. Relationship between the degree of polarization and angle of recording of radiation with wavelengths of 0.63 (a) and 1.15 μm (b) scattered by glass-textolite (1, 2, 3, 4) and textolite (5, 6) in the case of normal incidence on these materials. The surfaces of the materials were lacquered (1, 5), rough (2), or charred (3, 6). Also shown is data for glass-textolite with a burnt charred layer (4).

of radiation transmitted by the quartz plate, the function $P(\Omega)$ was determined by scattering on the rough front and rear surfaces and approached the relation $P(\Omega)$ for the charred composites. When white paper was placed on the rear surface of the quartz plate, the radiation was depolarized, with scattering on the roughnesses of both the plate and the paper. In this case, the function $P(\Omega)$ approached the function $P(\Omega)$ for composites not subjected to laser heating.

The difference in the absorption indices of the composites is manifest in the dependence of the degree of polarization of the reflected radiation on the recording angle in the case of normal incidence of the beam (Fig. 4). With an increase in the recording angle, the degree of polarization of radiation reflected by the unheated composites and by the glass-textolite with a burnt charred surface decreases sharply from the initial value determined by the equivalent solid angle. It stabilizes at the level 0.1-0.3, depending on the absorption index. The greater the latter, the smaller the reduction in polarization with an increase in the recording angle and the higher its angle-independent value. An increase in the absorption index leads to a situation whereby, in the limit, the degree of polarization of radiation reflected by highly absorbent materials such as the charred composites decreases negligibly with an increase in the recording angle and is nearly the same for transmitted-radiation wavelengths of 0.63 and 1.15 μm.

Thus, for the investigated polymeric composites with an initial surface not subjected to laser heating, the reflection coefficients in the regions 0.63 and 1.15 μm are 0.15-0.2 and 0.45-0.6, respectively. The reflected radiation of both wavelengths is characterized by a degree of polarization of ~1.0 and a narrow indicatrix. When acted upon by heat, such as from the radiation of a CO_2 laser, the surface film burns without undergoing any change in reflection coefficient. However, the indicatrix broadens in this case, while the degree of polarization decreases in accordance with the increase in the equivalent solid angle. Subsequent heating of the composite results in pyrolysis in the surface layer, which leads to a reduction in the reflection coefficient to ~0.1 in the regions 0.63 and 1.15 μm. This reduction is accompanied by contraction of the indicatrix and an increase in polarization to ~0.9. The distinguishing features of the glass-fiber plastic are complete combustion of the charred surface layer and exposure of glass fibers of the filler. As a result, in the range 0.6-2.0 μm, it begins to reflect as a graybody, with a reflection coefficient increased to 0.4-0.5. Here, the indicatrices broaden at both wavelengths and approach the indicatrix of a Lambert reflector. The degree of polarization, meanwhile, again decreases and takes a value of ~0.3.

NOTATION

λ, wavelength at which measurements are made; $\rho(\lambda)$, spectral reflection coefficient; Ω, equivalent solid angle; $d\omega$, elementary solid angle; Φ, total reflected radiant flux; I_0, intensity of radiation in the direction of mirror reflection; $f(\vartheta)$, normalized indicatrix of the reflected radiation; ϑ, angle at which the degree of polarization and the intensity of the reflected radiation were measured; P, degree of polarization of the reflected radiation.

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TESTS ON A FLOW CRYOSTAT WITH SERIES COOLING

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Measurements and calculations on a flow cryostat with serial cooling have given equivalent thermal schemes that have been tested for adequacy and consequent simple working formulas.

Here we examine a cryostat in which the heat is removed from a series of units by connecting them to a common pipe by thermal bridges: copper-wire bundles. A difference from cryostatting each unit separately [1] is that the system is more compact and economical, but if the units are closely spaced, the heat transfer between them may impose constraints on the independent temperature control. One can select the bundle conductances and the points of attachment to the pipe to match the conductances for the elements, which is a complicated optimization task if one needs to minimize the coolant flow.

Sometimes, it is possible to simplify the thermal model at an early stage, e.g., by classifying the links as strong and weak [2], when simple analytic estimates are possible.

Interest attaches to the more complicated case where the system contains thermal models with lumped and distributed parameters and temperature nonlinearities, while the thermal links do not satisfy the criteria of strong or weak, so one cannot assign them to the model types described in [2]. In the first stage, a full study should be based on numerical calculations tested against measurements on a prototype and the consequent definition of ways of representing the equivalent thermal circuit. The model is thus reduced to a set of algebraic equations, which provides an analytic solution, which simplifies the early design stages.

1. In our cryostat, three units are cooled in sequence (Fig. 1a), and the conclusions can be extended to any number of units, as the formulas show.

Firstly, the working cavity is evacuated to 10^{-3} Pa, so the external heat leaks are determined only by radiative transfer and the conductances in the mounting parts, and secondly, one can restrict the temperature change in the coolant (gaseous helium) to 100-150 K with a mass flow rate of $1\text{-}5\cdot10^{-5}$ kg/sec because dimensionless criteria [3] indicate that the helium flow is laminar at these levels and the heat-transfer coefficient is only slightly dependent on temperature.

We consider only the stationary state and take the units as isothermal, while the temperature distributions in the pipe and flow are one-dimensional along the axis, and the thermal bridges have lumped parameters. The temperature of the body is taken as constant at 295 K.

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