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THERMOPHYSICAL PROPERTIES

CALCULATION OF CHARACTERISTICS OF RETICULAR MATERIALS BASED ON A GLASSY CARBON BY ITS OPTICAL CONSTANTS DETERMINED EXPERIMENTALLY

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Results of experimental investigation of the spectrum of optical constants of a glassy carbon produced in Russia and of mathematical simulation, with them, of the spectral, kinetic, and thermophysical characteristics of composite reticular materials based on this carbon are presented. The investigations were performed with compacted samples of a composite reticular glassy carbon identical in physical properties to the glassy carbon forming the basis of highly porous cellular materials. By the hemispherical radiant reflectivity of these samples, illuminated at a right angle, the spectra of optical constants (the refractive index and the absorption coefficient) of the glassy carbon forming their basis were determined using the Kramers–Kronig relations, and a number of spectral characteristics of the composite reticular glassy carbon, related to these constants, were calculated by the simple approximate relations derived by us. The thickness of the skin layer in the samples of this composite was estimated, and some features of the interaction of the material of their fragments with an electromagnetic radiation were determined. The data on the spectral characteristics of the composite reticular glassy carbon were integrated into the statistical model developed earlier on the basis of the exact electromagnetic theory for simulating the optical properties of reticular materials having an ultrahigh porosity. This model allows one to estimate the features of the microstructure of such a material and the physical processes proceeding in it at different spatial and time scales. Results of calculations of the spectral and kinetic coefficients of the radiative transfer equation, the scattering indicatrix, the heat radiative conductivity, and the total heat conduction of the composite reticular glassy carbon are presented. The possibilities of the model proposed are demonstrated.

Keywords: *reticular glassy carbon, optical constants, experiment, spectral and kinetic coefficients, thermophysical properties, simulation.*

Introduction. Composite reticular materials based on a glassy carbon (GC) are produced by way of reticulation of a polyurethane foam (PF) that is impregnated with a binding slip and then subjected to destruction at a temperature of 1750–1850°C [1–4] in which the slip is transformed into the glassy carbon and the main part of the polyurethane foam burns out practically with no oil-carbon sludge providing the formation of inaccessible inner channels in the composite material obtained. At the final stage of formation of such a material, the surface of its reticulated skeleton is additionally packed with several layers of a low-temperature pyrocarbon (PC), which is deposited on this surface from the natural methane in a reactor at a temperature of 950–1050°C. The pyrocarbon film has a thickness of about 10 μm, which is larger than the thickness of the skin layer (fractions of a micron) of the composite material in the region of its radiation spectrum significant for the radiative heat transfer in it. For this reason, the optical properties of a composite glassy carbon may be investigated without regard for the internal closed cell rate in it.

A reticular glassy carbon (Fig. 1) is chemically inert, has a low density, a low heat conductivity, a high accessible porosity, a large specific surface inherited from the polyurethane foam of which it is made, and a solid skeleton, which allows

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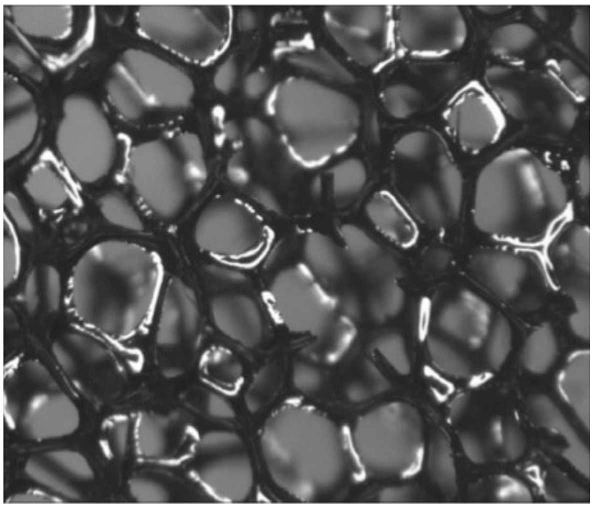


Fig. 1. Fragment of the structure of a reticular glassy carbon.

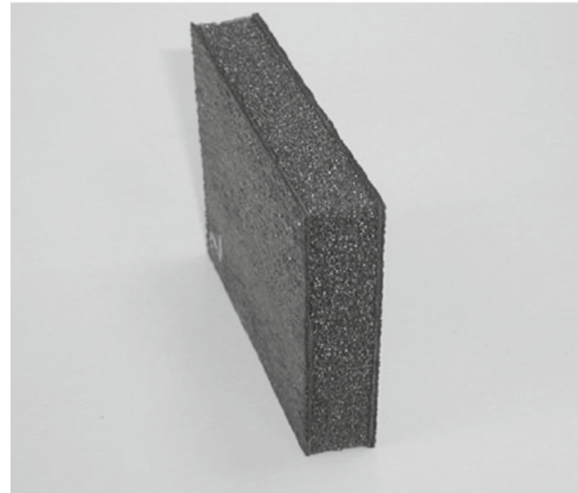


Fig. 2. Sandwich-panel made of a reticular glassy carbon.

this carbon to be used in the production of heat-resistant filters, chemical catalysts, and storage cells for medicine. A reticular glassy carbon resistant to temperatures as high as 3000 K in a vacuum and in inert and reductive media can be used as a construction medium and a heat-insulating material in the aerocosmic industry.

The characteristics of porous systems are substantially dependent on the features of their structure and the properties of the modifiers applied to them. In order for a reticular glassy carbon to be used in an oxygen-containing medium, sandwich-panels are formed of it (Fig. 2), and their reticulated skeleton is protected with special coats, e.g., of silicon carbide deposited on its surface from the gas phase [4]. A reticular glassy carbon is a brittle material. Therefore, for increasing the strength of its reticulated skeleton, nanoparticles, e.g., carbon nanotubes are added to the slip used in the production of this carbon [5]. The system of open pores in a composite reticular material can be filled with a substance capable of changing its properties, e.g., to suppress the heat conduction in the material, caused by the radiative heat transfer in it [4], which dominates in materials with an ultrahigh porosity at a high temperature [6]. In this case, of importance is the interaction of fragments of the reticular material with an electromagnetic radiation. To correctly define this interaction, it is necessary to know the values of the optical constants (the absorption coefficient and the refractive index) of the material in a fairly wide spectral range.

To investigate the above-indicated characteristics of a reticular glassy carbon, it is necessary to have its dense sample with a smooth solid surface. However, the properties of the raw material and the technology of its processing, including the regimes of thermal treatment of this material, influence the physical properties of both the subsidiary carbon materials and the composite material obtained on their basis. Because of this, there are no universal data on the properties of a reticular glassy carbon, and an experimental sample of this composite should be made of materials identical to the components of its reticulated skeleton.

The present work is devoted to solving the above-indicated problems for composite reticular materials based on a glassy carbon produced by the technology developed in Russia [1, 2, 5, 7, 8], and is a continuation of the investigations performed in [6, 7] on the development of efficient methods for determining the properties of promising high-temperature composite materials.

Experimental Samples. For investigating the spectral properties of the surface of the solid skeleton of composite reticular materials based on a glassy carbon, the technology of their production was modified so that polyurethane-foam plates impregnated with a slip are compacted prior to their thermal treatment. The existing technology of production of composite reticular glassy-carbon materials makes it possible to change the relation between the concentrations of their components depending on the purpose of these materials. The main challenge of the modified technology is the formation of a glassy carbon with the largest mass fraction in the bulk of a polyurethane-foam plate in the process of its high-temperature treatment as well as the pyrolytic densification of the plate surface for its spectral analysis [7].

Compacted plates of composition including a glassy carbon, a colloidal graphite (CG), and a pyrocarbon (Table 1) were investigated. The colloidal graphite was uniformly distributed in the glassy carbon formed in the process of carbonization of a semi-finished product of a polyurethane-foam from the binder (a liquid bakelite with a natural graphite

TABLE 1. Parameters of Composite Reticular Glassy-Carbon Plates

No.	S_{PF}, mm	H, mm	D, g/cm^3	F_{PC}	F_{CG}	F_{GC}
1	2	11	0.227	0.26	0.214	0.526
2	2	6.8	0.314	0.23	0.237	0.533
3	0.7	7.75	0.689	0.26	0.196	0.543
4	0.8	3.5	0.809	0.205	0.208	0.587
5	0.8	2.2	1.014	0.28	0.192	0.528
6	0.8	1.7	1.188	0.218	0.202	0.580

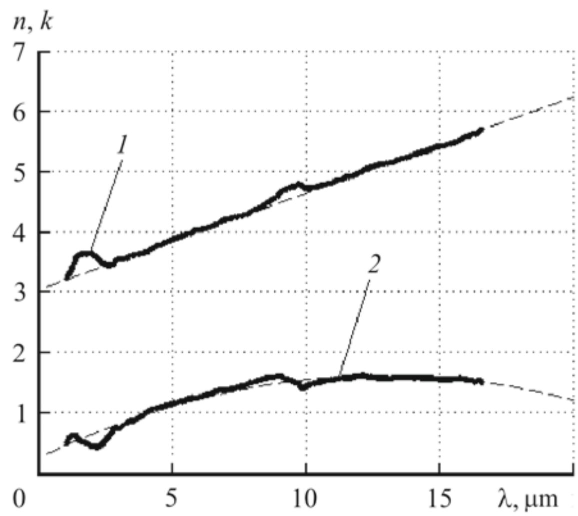
powder distributed uniformly in it) with which this product was impregnated. The pyrocarbon formed a three-layer film on the reticulated skeleton of a composite glassy-carbon material. The equivalence of the components of the initial half-finished products and the regimes of their thermal treatment provided the identity of the compacted plates of composite reticular materials in composition and structure to the highly porous composite carbon materials [1–3]. The surface of these plates was not absolutely smooth: the cells of the material on the surface of the plates, subjected to the compression in the state of semi-finished polymeric products, had the form of lentil grains. The carbonization and pyrolytic compaction of the plates practically did not change the shape of these cells and did not completely remove the irregularities on the surface of the plates. However, the linear sizes of the irregularities on the surface of such a plate were much smaller than the diameter of the light spot formed on it in the process of indirect determination of the optical constants of the glassy carbon forming its basis. Since the plates produced had no perfect flat surface, for spectral investigations we used the smoothest of them that had the densest surface and in which the mass fraction of the glassy carbon was the largest.

Spectral Properties of a Glassy Carbon. The optical constants (the refractive index and the absorption coefficient) of the glassy carbon forming the basis of a composite reticular material cannot be directly measured. These constants are determined by the hemispherical radiant reflectively of a compacted sample of such a material exposed to a plane monochromatic wave, incident on its surface at a right angle, with the use of the method, based on the Kramers–Kronig relations [9, 10], and the Fresnel formula for the complex refractive index of the material [11]. In the indicated method, the dispersion equation for the phase of the complex refractive index of a composite material is used. Therefore, the reflectance of the surface of the composite reticular glassy-carbon materials being investigated was measured in the near and intermediate infrared regions of the spectrum (0.74–20 μm) corresponding to the carrier of the Planck function at room and higher temperatures.

The measurements were performed on a Nicolet iS50 Fourier infrared spectrometer (USA) with an IntegratIR integrating sphere (PIKE). To decrease the influence of the roughness of the surface of a sample of a reticular glassy carbon on the results of measurements, it was investigated in two positions: the sample was rotated through 90^o about the axis of the light spot on its surface. The results of measurements were averaged. At first an initial dense sample with a previously cleaned surface was investigated. Then the surface of this sample was ground and cleaned and investigated once again. As a result of the grinding of the sample, pyrocarbon was removed from its surface, and this surface lost its glassy appearance and became dull and similar visually to a carbon foil. The optical coefficients of this dull surface were difficult to interpret; in particular, the values of the absorption coefficient in some spectral regions were negative. This is quite understandable if the above-indicated role of the pyrocarbon film in a composite reticular material in the process of interaction of its surface with a thermal radiation is taken into account. Because of this, we will consider only the data obtained for the initial samples of the composite reticular glassy-carbon material being investigated.

The refractive index and absorption coefficient of the glassy carbon forming the basis of the composite reticular glassy-carbon material, determined by the results of treatment of the experimental data on the hemispherical radiant reflectivity of the surface of its sample exposed to a monochromatic wave, are presented in Fig. 3. By these data, the components of the relative complex dielectric constant of the glassy carbon $\varepsilon = \varepsilon_1 + i\varepsilon_2$ are easily calculated. The dependences obtained make it possible to perform good qualitative approximation of the indicated spectral characteristics of the glassy carbon by the comparatively simple relations

$$n(\lambda) = 0.15993\lambda + 3.19453 \,, \quad k(\lambda) = -8.1354 \cdot 10^{-3}\lambda^2 + 0.19425\lambda + 4.44852 \cdot 10^{-2} \,,$$
$$\varepsilon_1(\lambda) = 3.8684 \cdot 10^{-2}\lambda^2 + 0.6698\lambda + 3.5459 \,, \quad \varepsilon_2(\lambda) = -6.1039 \cdot 10^{-2}\lambda^2 + 1.8160\lambda + 3.5459 \,, \quad (1)$$



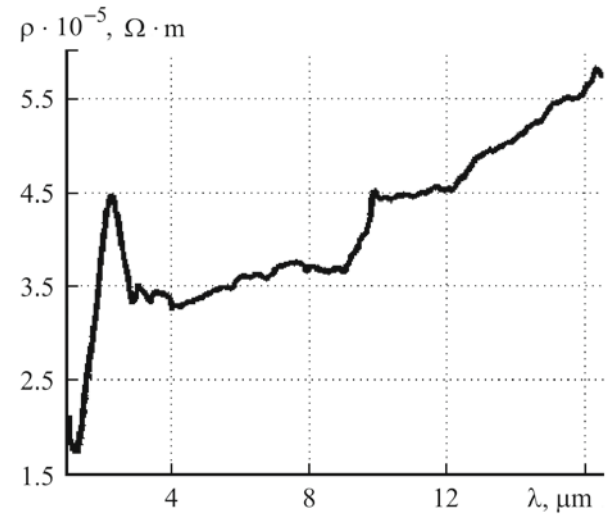


Fig. 3. Refractive index (1) and absorption coefficient (2) of the glassy carbon: dashed lines) interpolation by Eqs. (1).

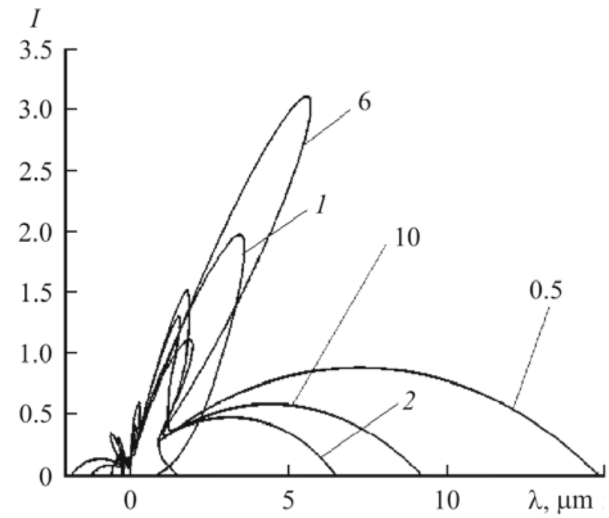
Fig. 4. Specific electrical resistance of the glassy carbon.

where λ is measured in microns. Relations (1) can be used in solving engineering problems, and they allow one to fairly exactly extrapolate the values of these characteristics beyond the limits of the spectral range used in an experiment.

For additional control of the order of the quantities obtained, the specific electrical resistances of the glassy carbon, determined as a function of the wavelength of the monochromatic radiation incident on a sample of the reticular material based on it (Fig. 4), were compared with the specific electrical resistance of the glassy carbon to a direct current at room temperature determined by the surface specific electrical resistance of this sample measured by the Van der Pauw method [12] with the use of a Shch-307ohmmeter. This resistance was $(63 \pm 8)\cdot 10^{-6}\ \Omega\cdot$m, i.e., it was approximately equal to the maximum electrical resistance of graphite [13]. It is precisely the specific electrical resistance of the surface of a reticular glassy-carbon material, determined as a function of the wavelength of the monochromatic radiation wave incident on its sample, that makes it possible to estimate the thickness of the skin layer of this material $\Delta(\lambda) = (\varepsilon_0 c \rho_e(\lambda)\lambda/\pi)^{1/2}$. It is seen from this relation that the pyrocarbon film on the surface of the reticulated skeleton of the composite plays a dominant role in the process of its interaction with a thermal radiation.

Optical Properties of Reticular Materials Based on the Glassy Carbon. In [14–16], the main elements of the mathematical model defining the local spectral characteristics of nonmetallic materials having an ultrahigh porosity are described, and a method of constructing a continuous spatial pattern of the interaction of an electromagnetic radiation with a complex (for optics) physical object consisting of orthogonal cylinders (crosspieces) and a sphere (node) is presented. This method made it possible to create an original "virtual scanner" (program instrument) for investigating the spectra of transmission, scattering, and absorption of radiation by such an object and its scattering indicatrix. The indicated method is based on the following fairly conventional suppositions [11]. On spatial scales of the order of several fractions of a micron and larger, the components of the radiation incident on a composite material and the components of the radiation scattered by its fragments are related by strict electromagnetic-theory equations or by equations of the scalar theory of diffraction. An electromagnetic wave incident on a representative element of this material is scattered by its fragments once elastically and independently in accordance with the Mie theory. In particular, the radiation scattered by one fragment of the representative element is not imposed on the radiation incident on its other fragments. The sizes of the fragments of the composite material and their compositions as well as the local properties of the radiation incident on them influence the properties of the composite. The medium in which the indicated fragments are found does not absorb electromagnetic radiation. The optical characteristics of a bulk element of the composite material associated with its representative element are determined by averaging the characteristics of the material fragments with weights proportional to their absorption and scattering cross sections.

The above-described model of spectral characteristics of a composite material was integrated into the mathematical model defining the physical properties of nonmetallic reticular materials [6, 7]. In this combined model, a reticular material is



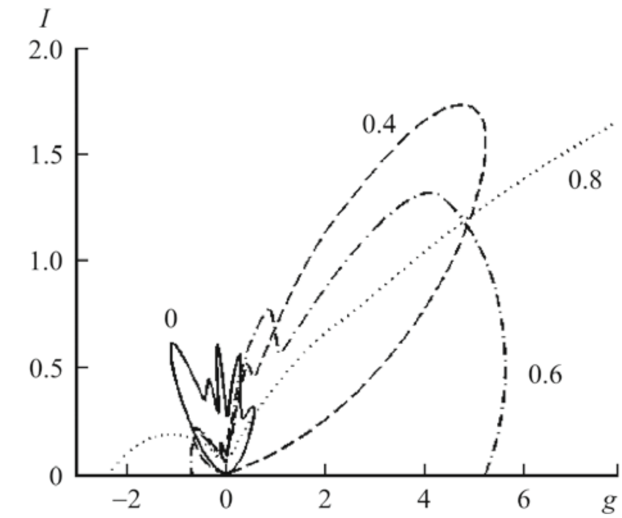


Fig. 5. Dependence of the indicatrix of scattering of radiation by a reticular glassy carbon in a vacuum on the wavelength of the radiation incident on it at $T = 1300$ K and $g = 0.4$ on the polar coordinates.

Fig. 6. Spectral pattern of scattering of radiation by a reticular glassy carbon depending on the anisotropy of the radiation incident on it at $T = 1300$ K and $\lambda = 1.83$ μm on the polar coordinates.

associated with a sequence of random orthogonal representative elements (ORE), each of which includes a node (sphere) and three to six cylindrical crosspieces different in length and diameter, oriented along the rectangular axes of the global coordinate system. The combined model is constructed in accordance with the following key rules [6]: 1) orthogonal representative elements of a composite material are generated and analyzed successively; 2) the effective density and anisotropy of the material, the statistical regularities of its structure, the presence of additional thermal and electrical resistances in the region of contact of fragments of the material with floccules in the structure of its base, and the properties of the substances forming this base are estimated; 3) the effective properties of the orthogonal representative elements are determined by the properties of the material fragments with the use of equivalent schemes of their connection, the heat conductivity of each ORE is calculated in the isothermal and adiabatic approximations, and their electrical resistance and permittivity are determined in the electrostatic approximation; 4) it is assumed that each new ORE is submerged in an effective medium, whose thermophysical properties are dependent on the properties of all the elements generated earlier; 5) the optical and radiation properties of the material are determined using the classical electromagnetic theory and quantum optics with regard for the intensity of the radiation incident on the material and its transfer; 6) the local optical characteristics of the material are determined within the framework of the modified optical mole, constructed on the basis of the above-described model of the independent interaction of individual representative elements of the material with radiation, which includes an instrument for the introduction, if need be, of cooperative corrections to the results of calculations of the scattering of radiation by individual fragments of the material [17, 18]. The model described has a set of degrees of freedom, i.e., includes unknown numerical and functional parameters that should be determined in the process of their identification by the effective optical and thermophysical characteristics of the material measured in advance. With this model, various processes and properties of reticular materials were investigated in the above-indicated works. However, in them, the optical properties of the basis of these materials, formed by a glassy carbon, cannot be taken into account in the simulation of their spectral characteristics because these properties were not known. Instead of them, the temperature dependences of the electrophysical properties of the glassy carbon, constructed on the basis of implicit data taken from the literature, were used.

Figures 5–7 show some results of simulation of the spectral and kinetic parameters of the equation for the transport of radiation in the composite reticular glassy-carbon materials being investigated in a vacuum with the use of the above-presented spectral data for their basis. The dependences obtained represent some interesting features of such composites and demonstrate the unique possibilities of the methods developed for investigating the properties of the radiation in their bulk. In the calculations we used statistical data on the properties of the glassy carbon with an effective density 59 kg/m^3 and

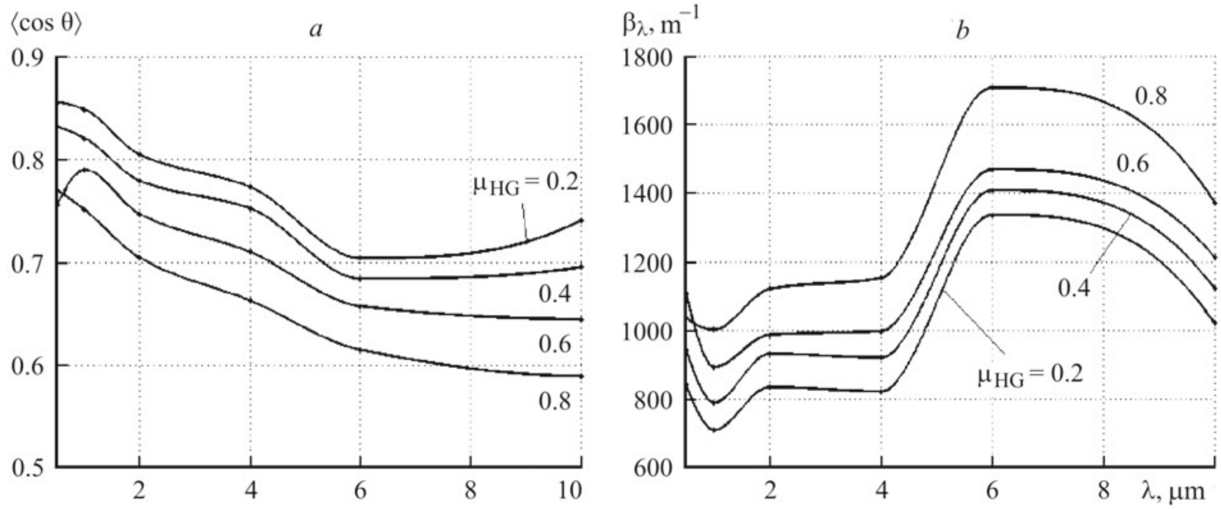
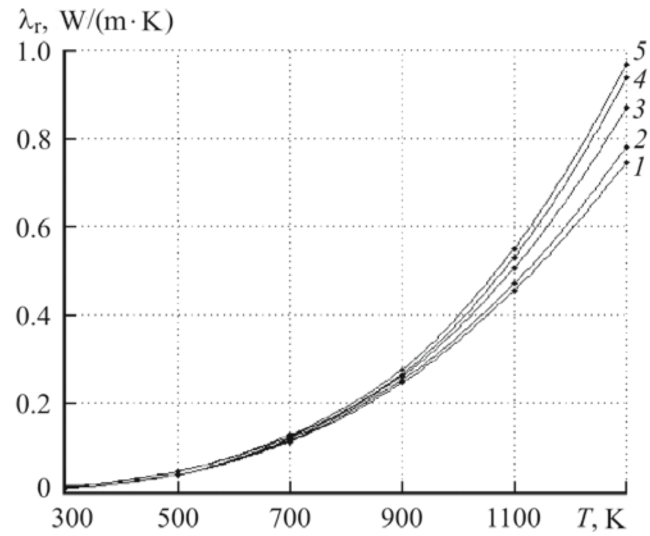


Fig. 7. Average cosine of the angle of scattering of radiation by a reticular glassy carbon (a) and its scattering coefficient (b) depending on the anisotropy of the incident radiation.

an accessible porosity of 96.1%, possessing the highest reticulation. The composite reticular materials based on this glassy carbon had nodes of effective diameter 60–200 μm and crosspieces of length 20–480 μm. The orthogonal representative elements of such a material were illuminated in the directions determined with regard for the degree of anisotropy of the incident radiation determined by the Henyey–Greenstein phase function.

In Figs. 5 and 6, variants of behavior of the indicatrix of scattering of radiation by a reticular glassy carbon depending on the wavelength of the radiation incident on it and the anisotropy of this radiation are shown. The dependences presented in these figures were constructed on the basis of the statistics for $2–3.5 \cdot 10^3$ orthogonal representative elements of the reticular glassy carbon, and the vectorial angle was measured from the inner normal in the material layer to its boundary. The time of obtaining each variant was 3–5 min. The indicatrices obtained represent functions analogous to those described in [19] and, therefore, they also can be approximated by relatively simple expressions. Figure 5 shows the dependence of the scattering indicatrix of a reticular glassy carbon on the wavelength of the radiation incident on it at $T = 1300$ K and $g = 0.4$. This value of the anisotropy parameter of the incident radiation is close to the equilibrium one obtained earlier in the simulation of the spectral properties of fibrous materials [6]. It is seen from this figure that the scattering of radiation by this carbon is selective and nonmonotone in character, which can be explained by a number of reasons. In particular, a composite reticular material with the above-indicated density and porosity can be comparatively nonuniform in electrical and physical properties. For example, in the calculations presented, the effective specific electrical resistance of the composite reticular materials along the normal to their surface changed within the range $2.1 \cdot 10^{-3}$–$6.2 \cdot 10^{-3}$ Ω·m. In Fig. 6, the influence of the anisotropy of the radiation incident on the surface of a reticular glassy carbon on the scattering of this radiation by it is demonstrated. The data presented in this figure have been obtained for the case of illumination of a layer of this carbon material by radiation with wavelength $\lambda \approx 1.83$ μm determined by the Wien law for $T = 1300$ K. It is seen that the material is practically transparent for a directional radiation, which is entirely explicable in view of its high porosity. However, as is seen from Fig. 7a, the behavior of the average cosine of the angle of single scattering of radiation in the reticular glassy carbon having an effective density of 59 kg/m^3 is fairly unusual. With increase in the anisotropy of the radiation incident on the material, this cosine decreases and not increases as might be expected. Analysis of the data presented in Fig. 7b provides explanation for this phenomenon: an increase in the directivity of the radiation can cause a substantial increase in the intensity of its scattering in the material and in the radiation-scattering coefficient. Such behaviors of the intensity of scattering of radiation by a reticular glassy carbon and of its radiation scattering coefficient are not necessary for all reticular materials, including those having an effective density of 59 kg/m^3. A certain deviation of the dependences presented in this figure from the monotone one in the case where the wavelength of the incident radiation is close to 0.5 μm is explained by the fact that the number of representative elements in the statistical method should be increased if the wavelength of this radiation λ approaches the wavelength of the near-ultraviolet radiation. In the example presented, the increase in the scattering of radiation by the composite reticular material cannot compensate the increase in the



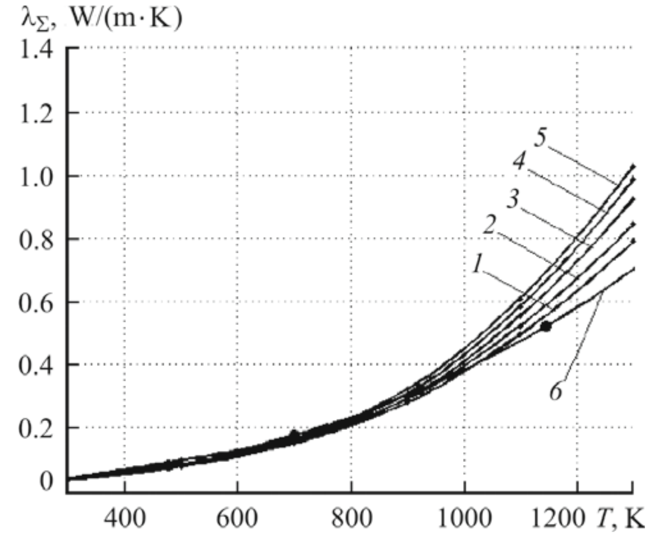


Fig. 8. Radiative heat conductivity of the reticular glassy carbon of density 59 kg/m^3 at g = 0 (1), 0.2 (2), 0.4 (3), 0.6 (4), and 0.8 (5).

Fig. 9. Total heat conduction of the reticular glassy carbon calculated by the method proposed in [7]: 1) g = 0; 2) 0.2; 3) 0.35; 4) 0.6; 5) 0.8; 6) data of [4].

penetrating power of the radiation with increase in its directivity, which is evidenced by the behavior of the heat conduction of the material that is due to the radiative heat transfer in it.

Heat Conduction of a Reticular Glassy Carbon. The heat conduction of a reticular glassy carbon that is due to the radiative heat transfer in it was calculated by the known relations [6, 7]

$$\lambda_r(T) = \frac{8\pi k_B^4 T^3}{3c^2h^3} \int_0^\infty \frac{1}{\alpha_\lambda + \beta_\lambda^*} \frac{u^4 e^{-u}}{(1 - e^{-u})^3} du = \frac{8\pi k_B^4 T^3}{3c^2h^3} \int_0^\infty \frac{1}{\alpha_\lambda + \beta_\lambda^*} \frac{\tau^{-6} e^{-1/\tau}}{(1 - e^{-1/\tau})^3} d\tau$$

$$= \frac{1.1640285 T^3 n_g^2}{10^8} \left(\int_0^1 \frac{1}{\alpha_\lambda + \beta_\lambda^*} \frac{u^4 e^{-u}}{(1 - e^{-u})^3} du + \int_0^1 \frac{1}{\alpha_\lambda + \beta_\lambda^*} \frac{\tau^{-6} e^{-1/\tau}}{(1 - e^{-1/\tau})^3} d\tau \right), \qquad (2)$$

where α_λ and β_λ are the coefficients of absorption and scattering of radiation by the composite material, $\beta_\lambda^* = \beta_\lambda (1 - \langle\cos\theta\rangle)$ is its transport scattering coefficient, and n_g is the refractive index of the medium surrounding the reticulated skeleton of the composite. The latest variant of relations (2) allows one to avoid the calculation of improper integrals in the simulation of the heat conduction of the material.

Figure 8 shows the temperature dependences of the radiative component of the heat conduction of a reticular glassy carbon in a vacuum, calculated by Eq. (2) for different values of the anisotropy parameter of the radiation incident on the composite material. Analogous dependences for the total heat conduction of this material are presented in Fig. 9. These dependences show, in particular, that the conductive heat transfer in the material is of minor importance at a high temperature. Moreover, it is seen that the total heat conduction of a highly porous material and its radiative component are not properties of such a material because the properties of this material are substantially dependent on the physical conditions in which the material is found, which is clearly demonstrated in Figs. 8 and 9. The calculation data presented in these figures have been obtained for the totally reticulated glassy carbon. The presence of residual membranes in a real reticular glassy-carbon material decreases its heat conduction that is due to the radiative heat transfer in it. Therefore, the calculation data presented can be considered as good upper estimates of this parameter of a real reticular material. For comparison, Fig. 9 presents the temperature dependence of the total heat conduction of the reticular glassy carbon produced at the ULTRAMET Company (USA) [4].

In closing we note that each calculated value of the heat conduction of the reticular glassy carbon has been obtained by averaging the results of three series of calculations in each of which about $3 \cdot 10^3$ representative elements were generated. A simulation practice shows that, in the case where the number of samples is small, the indicated organization of calculations in the method proposed in [6, 7] makes it possible to decrease the statistical error of the method determined by the characteristics of the initial elements of the sequence generated, and it is more preferable than single calculations on the basis of a comparable summary statistics ($\sim 10^4$).

Conclusions. New important data on the optical constants of the glassy carbon produced in Russia and the parameters of composite reticular materials based on this carbon, related to the indicated constants, have been obtained. These data substantially increase the reliability of the mathematical simulation of the characteristics of composite reticular materials. The thickness of the skin layer in a reticular glassy carbon was estimated, and the mechanism of interaction of its fragments with an electromagnetic radiation incident on the surface of the material was determined. It was shown that, in such a material, only the pyrocarbon layer on the surface of its reticulated skeleton interacts with the electromagnetic radiation, and the internal closed cell rate of the glassy carbon does not influence this process. The spectral and kinetic coefficients of the radiative transfer in composite reticular glassy-carbon materials and their scattering indicatrices were calculated and analyzed. Examples of calculating the total heat conduction of a reticular glassy carbon and its radiative component in a wide range of change in the parameters of this material, determined by the ambient conditions, are presented. It was shown that the kinetic parameters as well as the heat conduction of composite reticular materials based on a glassy carbon cannot be considered as their properties because these parameters are substantially dependent on the ambient conditions, e.g., on the directivity of the radiation incident on the surface of a material. Simulation and experimental investigation of the indicated parameters of such materials should be performed for conditions closest to the conditions of their use. The method proposed was realized with the use of known experimental approaches and original tools of theoretical investigation, analysis, and prediction of the properties of materials, allowing one to adequately simulate the heat exchange between a material and the environment and substantially decrease the expenses for the development of new promising materials and products of them.

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NOTATION

D and H, bulk density and thickness of a plate of a compressed composite reticular material; F_{CG}, F_{PC}, and F_{GC}, mass fractions of the colloidal graphite, pyrocarbon, and glassy carbon in a composite; g, anisotropy of the radiation incident on the surface of a composite material; I, scattering indicatrix; k, absorption coefficient; n, refractive index; q, heat flow; r, complex reflection power of the surface of a material; S_{PF}, size of a polyurethane foam cell; T, temperature; α, volume absorption coefficient; β, volume scattering coefficient; β^*, transport scattering coefficient; Θ, phase of the complex reflection power; λ, wavelength; ρ, specific electrical resistance. Subscripts: e, electrical; r, radiative.

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