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INFLUENCE OF TRANSPARENCE OF HEAT-RESISTANT COATINGS ON THE THERMAL REGIME OF CONSTRUCTIONS

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We present a computational-experimental method and the results of investigating the influence of transparence to solar radiation of the heat-resistant coating on the thermal regime of the space-vehicle construction in orbital flight.

Keywords: *radiating capacity, absorptivity, reflectivity, transmission capacity, solar radiation, semitransparent materials, vehicles in orbital flight.*

Introduction. Many heat-resistant materials and their thermoregulating coatings used on space vehicles are semitransparent in the spectral ranges characteristic of external radiant fluxes, in particular, from the sun, plasma, etc. [1–5]. This can strongly influence the temperature regime of the space vehicle in outer space (in orbital flight). In the literature, e.g., in [4, 5], methods for calculating the radiant heat transfer in semitransparent media are widely presented. However, because of the complex structure of modern, porous, heat-insulating materials and lack of data on their local spatial and spectral optical characteristics, the application of the above computing methods in solving practical problems involves considerable difficulties. In this connection, in the literature there is practically no information on the influence of transparence of heat-insulating materials on the thermal regimes of space-vehicle constructions.

In this paper, we present a computational-experimental method and the results of investigating the influence of transparence to solar radiation of the heat-resistant fibrous material based on silicon oxide (SiO_2) and the thermoregulating coating from the same material on the thermal regimes of space vehicles in flight.

The experimental part contains three test series. In the first series, measurements were made and dependences of the transmission capacity, reflectivity, and absorptivity with respect to solar radiation on the thickness of samples of the above material without a coating and with a coating were obtained. In the second and third series, we tested samples imitating a fragment of a heat shield consisting of a layer of the above material of various thicknesses with a substrate — a metal plate pasted to its underside. In the second test series, the samples were irradiated with an imitated solar flux of density 1400 W/m^2. In the third series, the same samples were irradiated with an infrared radiant flux at the same density. In the process of tests, the substrate temperature was measured. As a result of comparing the temperatures of the metal substrates of samples in the second and third series, it has been established that the effect of transparence of the heat-resistant material leads to an increase in the substrate temperatures by about 25%.

The computational part includes the interpolation of the experimental dependence (obtained in the first test series) of the transmission capacity on the layer thickness of the investigated material and numerical calculations of the heat-conduction equations for the aforesaid model of the fragment of the heat shield with and without account for the transparence of the heat-resistant material. Temperature calculations were made for three circumterrestrial orbits and two layer thicknesses of the heat-resistant material. The results obtained have shown that the transparence to solar radiation of the investigated material has a strong effect on the thermal regime of the heat shield and, consequently, of the construction of the space vehicle in outer space. The results of calculating the temperatures of the model of the heat-shield fragment irradiated by a solar flux of constant density are in good agreement with the results of the second test series.

Method for Determining the Transmission Capacity, Reflectivity, and Absorptivity of Materials Semitransparent to Solar Radiation. The method is based on the irradiation of a flat semitransparent sample with an imitated solar flux and measurements of the solar radiation reflected from the sample and transmitted through the sample.

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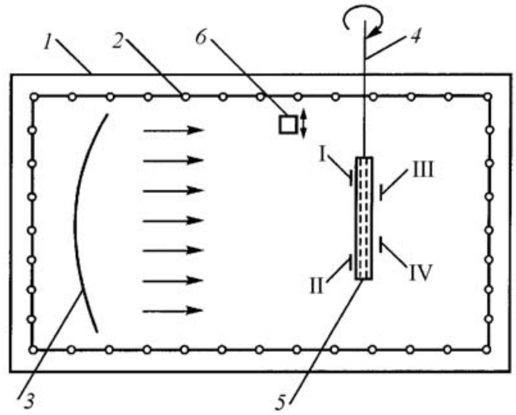

Fig. 1. Scheme of the experimental facility for determining the transmission capacity, reflectivity, and absorptivity of semitransparent materials and coatings.

Figure 1 shows the scheme of the experimental facility on which the thermal conditions of outer space are imitated. The facility consists of a vacuum chamber 1, an internal black shield 2 cooled down to cryogenic temperatures, a solar imitator 3, a holder 4 with a control mechanism for setting the investigated sample 5 at a given angle with the solar radiation, and a radiation detector 6 for measuring and controlling the solar-radiation intensity. In the imitator, the energy, spectral, and geometric parameters of the solar radiation in circumterrestrial space are reproduced. The investigated sample is a square plate with a side of 0.15 m and thickness δ. In front of the sample and behind it, with respect to the solar radiation, in each plane parallel to the sample, two temperature sensors were set. In each pair of sensors, the surface of one of them had a white coating with a low value of α_s/ε, and the surface of the second sensor had a black coating with a high value of α_s/ε. The geometric parameters of the sensors and their position relative to the sample were chosen to be optimal, which permitted minimizing the shading of the sample with respect to the radiation from the solar imitator, as well as the radiative heat exchange between the sample and the sensor. On the sensors, thermocouples were set.

The above radiative characteristics of the sample are determined as follows. The chamber is evacuated (the residual pressure of the gaseous medium in the chamber $P \leq 0.01$ Pa), the black shield is cooled by liquid nitrogen to a temperature $T = 77$ K, the solar imitator is activated, and the given solar radiant power is set. In the testing process, the sample and the sensors are heated by the solar radiation. When the thermal regime of the sample reaches the steady state, the sensor temperatures and the solar radiant power are recorded. In these tests, the radiant flux from the cooled black shield can be neglected. Then the energy-balance relations between the sensors and the radiant fluxes for the investigated sample can be written as follows:

$$\alpha_{s1}(E_s + E_{s.r}) + \alpha_{i1}E_{i.f} = 2\varepsilon_1\sigma T_{I}^{4},$$

$$\alpha_{s2}(E_s + E_{s.r}) + \alpha_{i2}E_{i.f} = 2\varepsilon_2\sigma T_{II}^{4},$$

$$\alpha_{s1}E_{s.t} + \alpha_{i1}E_{i.b} = 2\varepsilon_1\sigma T_{III}^{4}, \tag{1}$$

$$\alpha_{s2}E_{s.t} + \alpha_{i2}E_{i.b} = 2\varepsilon_2\sigma T_{IV}^{4},$$

$$E_{s.r} + E_{s.t} + E_{s.a} = E_s .$$

Taking into account the low values of the temperatures and the closeness of the infrared radiation spectra of the temperature sensors and the samples, on the basis of the Kirchhoff law we can assume that $\alpha_i = \varepsilon$. Then from the solution of Eq. (1) we obtain

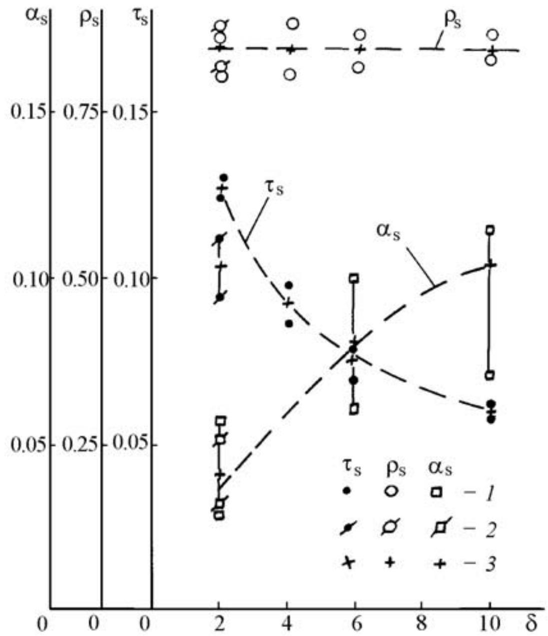

Fig. 2. Measurement data on the transmission capacity, reflectivity, and absorptivity of samples of the fibrous, silicon-oxide-based, heat-insulating material with respect to the solar radiation: 1) uncoated samples; 2) coated samples; 3) mean values of the quantities for uncoated samples. δ, mm.

$$E_{s.r} = \frac{2\sigma\,(T_{\mathrm{I}}^4 - T_{\mathrm{II}}^4)}{\dfrac{\alpha_{s1}}{\varepsilon_1} - \dfrac{\alpha_{s2}}{\varepsilon_2}} - E_s\,,$$

$$E_{s.t} = \frac{2\sigma\,(T_{\mathrm{III}}^4 - T_{\mathrm{IV}}^4)}{\dfrac{\alpha_{s1}}{\varepsilon_1} - \dfrac{\alpha_{s2}}{\varepsilon_2}}\,, \tag{2}$$

$$E_{s.a} = E_s - E_{s.r} - E_{s.t}\,.$$

The transmission capacity, reflectivity, and absorptivity of the investigated sample are determined from the relations

$$\tau_s = \frac{E_{s.t}}{E_s}\,, \quad \rho_s = \frac{E_{s.r}}{E_s}\,, \quad \alpha_s = \frac{E_{s.a}}{E_s}\,. \tag{3}$$

Before the tests, we calibrated α_s/ε to check the ratio of each temperature sensor (on the same equipment without a sample). The ratios α_s/ε were determined from the thermal-balance relation for each temperature sensor irradiated with a controlled solar flux in the thermal equilibrium state:

$$\frac{\alpha_s}{\varepsilon} = \frac{2\sigma T^4}{E_s}\,.$$

The accuracy of determining the values of τ_s, ρ_s, and α_s of the sample depends on the errors in measuring the solar radiant power (δE_s), the sensor temperatures (δT), and the ratio [$\delta\alpha_s/\varepsilon$)] for the temperature sensors. Analysis of the measurement accuracy has shown that in the tests carried out the above relative errors were equal to (δE_s) $\leq$ 2%,

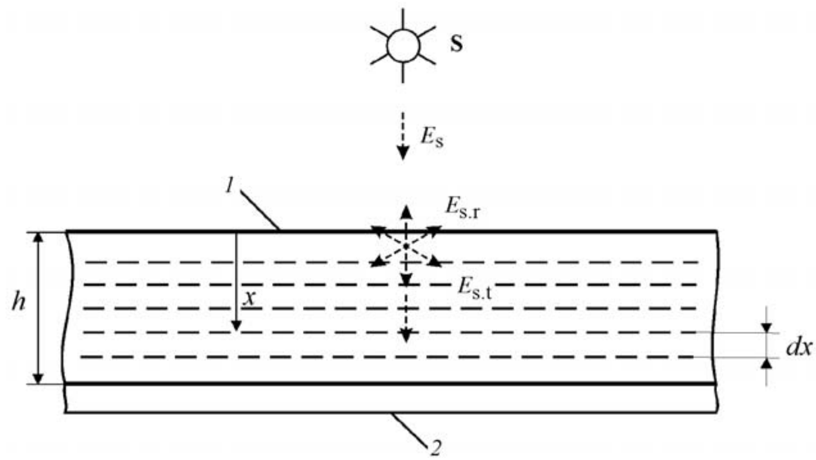

Fig. 3. Scheme of the model of the heat-shield fragment: 1) face of the fragment; 2) metal plate of the fragment.

$(\delta T) \leq 0.25\%$, and $[\delta\alpha_s/\varepsilon)] \leq 2.25\%$, and the error in determining the characteristics of the investigated samples in which we are interested does not exceed $\delta\tau_s \leq 5.6\%$, $\delta\rho_s \leq 7\%$, and $\delta\alpha_s \leq 9\%$.

In the first series of tests, we investigated nine samples differing in thickness made from a fibrous heat insulator based on silicon oxide: two samples each of thickness 0.002, 0.004, and 0.006 m, one sample of 0.01 m with no coating, and two samples of thickness 0.002 m with a silicon-oxide-based white coating. In the testing process, the solar radiant power was equal to 1400 W/m^2. The equipment on which the tests were carried out had the following parameters: the diameter and length of the vacuum chamber were 0.8 and 1.5 m, respectively; the absorptivity of the black shield was 0.99, and in the testing process it was cooled to a temperature $T = 77$ K; the solar radiant flux diameter was 0.6 m.

The results of the tests are given in Fig. 2. They confirmed the transparence of the investigated material and the coating. The experimental points 1 pertain to samples without a coating, points 2 to samples with a coating, points 3 and dashed lines show the mean values of τ_s, ρ_s, and α_s for uncoated samples of equal thickness, and vertical lines show the dispersion of the data obtained for these samples. In considering the data, it is seen that the τ_s values of the samples without a coating decrease from 0.127 at a thickness of 0.002 m to 0.06 at a thickness of 0.1 m. From comparison of the τ_s values for the samples with and without a coating, it follows that the coating is equivalent to an increase in the thickness of the material sample without a coating by 1 mm. The reflectivity ρ_s of all samples is practically the same and equals 0.845. The absorptivity α_s of the uncoated samples increases from 0.032 at a thickness of 0.002 m to a value of 0.105 at a thickness of 0.01 m.

Experimental Study of the Influence of Transparence of the Heat-Insulating Material on the Thermal Regime of the Model of a Heat-Shield Fragment. Figure 3 schematically represents the model of the heat-shield fragment. It consists of a layer of the heat-insulating material pasted to the metal plate initiating the protected construction. Two test series (the second and third ones) were carried out for samples representing models of heat-shield fragments with varying thickness of the heat-insulating layer also from a silicon-oxide-based material over the range $h = 0.005$–0.02 m. A black coating with radiative characteristics $\varepsilon = \alpha_s = 0.92$ was applied to either side of the metal plate of the samples, and the temperature of each plate was controlled by the two thermocouples mounted on it. Tests were carried out on the above-mentioned facility and under the same conditions inside the vacuum chamber as in the previous tests. In the process of testing, the samples were heated by radiant fluxes of constant density from the initial temperature to the temperature at which the steady-state regime was reached. In the second series of tests, the samples were heated by a solar flux with $E_s = 1400$ W/m^2. In the third test series, the samples were irradiated with an infrared radiation flux from the heated black metal plate with a controlled temperature $T_b = 400$ K set parallel to the sample. The heated plate surface facing the sample has an effective radiating capacity $\varepsilon_{ef} = 0.96$ due to the application of artificial roughness in the form of v-shaped grooves and the above-mentioned black plate. The test data are presented in Fig. 4 in the form of the dependences $\sigma T_p^4/(1-\rho)E = f(h)$, where T_p is the temperature of the metal plate of the sample upon its going to the steady-state thermal regime. Comparing the results obtained in the second and third test

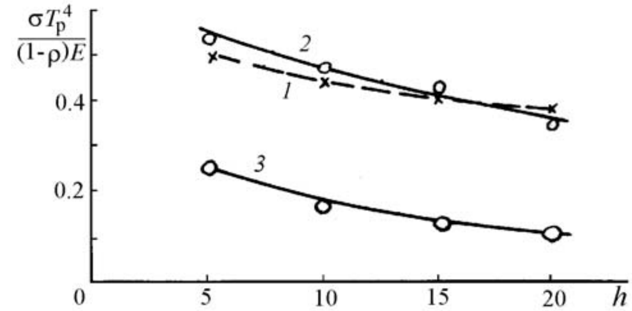

Fig. 4. Results of the calculations and tests of the model of the heat-shield fragment: 1) calculations; 2) second series of tests; 3) third series of tests. h, mm.

series, it should be noted that due to the transparence of the heat-insulating layer of the samples, the temperature of their metal plates has increased by about 25%.

Computational Investigation of the Influence of the Transparent Outer Heat-Insulating Layer on the Thermal Regime of the Protected Construction. The computational investigation was carried out for a solar-flux-irradiated flat fragment of the heat shield consisting of a layer of a semitransparent heat-insulating material 1 fixed to a metal plate 2 (Fig. 3). In so doing, from the viewpoint of the one-dimensional model of heat propagation in the heat-insulating material it was assumed that the intrinsic infrared radiation of the heat-insulating material and the metal plate inside the fragment, as well as the thermal resistance of the contact between the heat-insulating material and the metal plate, is negligibly small. In this case, the thermal state of the fragment is determined by solving the following differential equation:

$$c_{\text{t.m}} d_{\text{t.m}} \frac{\partial T}{\partial t} = \lambda_{\text{t.m}} \frac{\partial^2 T}{\partial x^2} - \frac{\partial E_{\text{s}}(x, t)}{\partial x} \tag{4}$$

with account for the boundary conditions

$$x = 0: \quad -\lambda_{\text{t.m}} \frac{\partial T}{\partial x} = \alpha_{\text{i}_\text{e}}(t) - \varepsilon_{\text{f}} \sigma T_{\text{f}}^4 , \tag{5}$$

$$x = h: \quad -\lambda_{\text{t.m}} \frac{\partial T}{\partial x} = c_{\text{p}} d_{\text{p}} \delta_{\text{p}} \frac{\partial T_{\text{p}}}{\partial t} - \alpha_{\text{s.p}} E_{\text{s}}(t, h) \tag{6}$$

and the initial condition

$$t = 0: \quad T(x) = T_0 , \quad T_{\text{p}} = T_0 . \tag{7}$$

The function $E_{\text{s}}(x, t)$ was determined in two stages. First we calculated the radiant fluxes $E_{\text{s}}(0, t)$ and $E_{\text{e}}(0, t)$ incident on the fragment surface depending on the time and position in the orbit by the method described in [6]. Then, by means of interpolation of the experimental dependence $\tau_{\text{s}} = f(\delta)$ given in Fig. 2, we determined the function

$$E_{\text{s.t}}(x, t) = 0.145 E_{\text{s}}(0, t) \exp(-115x) . \tag{8}$$

Calculations were made for three circular circumterrestrial orbits of height H = 200 m above the Earth's surface. The plane of the first orbit coincides with the direction of the Sun, the plane of the second orbit is inclined by 45^{o} with respect to the direction of the Sun, and that of the third orbit is perpendicular to the direction of the Sun. In each orbit, the fragment orientation corresponded to the maximum values of the solar radiant fluxes incident on it. Calculations were made for the following parameters of the fragment: h = 0.02, 0.04 m, $c_{\text{t.m}}$ = 900 J/(kg·K), $d_{\text{t.m}}$ = 150 kg/m^3, $\lambda_{\text{t.m}}$ = 0.025 W/(m·K), $c_{\text{p}} d_{\text{p}} \delta_{\text{p}} = 4 \cdot 10^9$ J/(m^2·K), $\alpha_{\text{s.p}}$ = 1, ε_{f} = 0.8, and T_0 = 323 K.

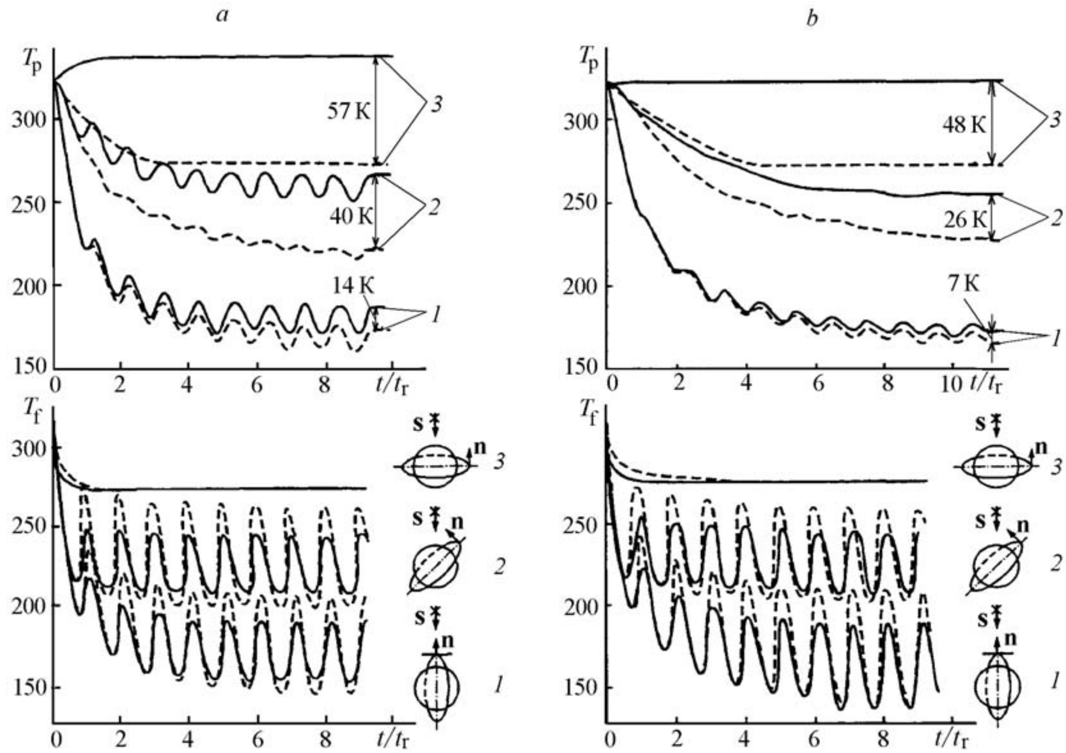

Fig. 5. Temperatures of the metal plate and the face of the heat-shield fragment depending on time at a thickness of the heat-insulating layer h = 0.02 m (a) and 0.04 m (b): 1, 2, 3, numbers of circular orbits around Earth. T, K.

Then, for comparison, similar calculations were made for an analogous fragment of a heat shield with an opaque heat-insulating material having identical thermal characteristics and an absorption coefficient of the solar radiation of the outer surface of $\alpha_s = 0.145$. In this case, instead of Eq. (4) and the boundary conditions (5), (6) we used the following expressions:

$$c_{\text{t.m}} d_{\text{t.m}} \frac{\partial T}{\partial t} = \lambda_{\text{t.m}} \frac{\partial^2 T}{\partial x^2}, \tag{9}$$

$$x = 0: \ -\lambda_{\text{t.m}} \frac{\partial T}{\partial x} = \alpha_i E_e(t) + 0.145 E_s(t) - \varepsilon_f \sigma T_f^4, \tag{10}$$

$$x = h: \ -\lambda_{\text{t.m}} \frac{\partial T}{\partial x} = c_p d_p \delta_p \frac{\partial T_p}{\partial t}. \tag{11}$$

The initial condition (7) remains unaltered.

Calculations of the nonstationary heat-conduction equations were carried out up to the instant of time at which the temperatures inside the insulator and the metal plate during consecutive flights around Earth with numbers m and $m+1$ became equal. The results of the calculations are presented in Fig. 5 in the form of dependences of the temperatures of the plate and the face of the fragment on the ratio t/t_0, where t_0 = 5400 s is the revolution period of the space vehicle in the considered orbits. On these graphs, the solid and dashed lines pertain to the fragments with a transparent and an opaque heat-insulating material, respectively. It can be seen that the time–temperature dependences pertaining to the first and second orbits are periodic and those pertaining to the third orbit stabilize at a constant level after several flights adequately to the incident radiant fluxes. Comparing the obtained results, one should pay attention to the discrepancy, due to the transparence of the heat-insulating material, between the temperature dependences in all variants of geometric parameters of fragments and orbits. First of all, one should note the considerable increase in the metal-plate temperature, reaching 57, 40, and 14 K for orbits 3, 2, and 1, respectively, when the insulator thickness is equal to 0.02 m. Analogous temperature increases reach 48, 47, and 7 K when the insulator thickness is equal to 0.04 m.

Comparison of the temperature dependences of the faces of the fragments shows that as a consequence of the transparence of the heat-insulating material the amplitude of variation in temperature ΔT decreases from 60–70 K to 40–50 K in orbits 1 and 2.

Moreover, we performed calculations corresponding to the second series of tests in which the models of heat-shield fragments were irradiated with a constant-density solar flux E_s = 1400 W/m^2. Thus, the functions $E_s(x)$ in Eq. (4) and the function $E_s(h)$ in the boundary condition (6) are time independent, and the function $E_e(t) = 0$ in the boundary condition (5). The results of the calculations presented in Fig. 4 (curve 1) are in good agreement with the experimental data obtained in the second series of tests (curve 2).

Conclusions. A method and an experimental facility for estimating the influence of transparence to external radiation of the heat-resistant material on the thermal regime of the construction have been described. A computational procedure has been presented and calculations of the influence of transparence to solar radiation of the fibrous heat-resistant material based on silicon oxide on the thermal regimes of heat-resistant structures of space vehicles in circular circumterrestrial orbits have been made. From the analysis of the results obtained, it follows that transparence of heat-resistant materials to external radiant fluxes has a strong effect on the thermal regimes of heat-resistant structures and protected constructions of aerospace vehicles.

NOTATION

c, heat capacity of the material, J/(kg·deg); *d*, density of the material, kg/m^3; *E*, radiant flux, W/m^2; *h*, thickness of the heat-insulating layer on the heat-shield fragment, m; **n**, normal vector to the sample face; *P*, air pressure in the chamber, Pa; **s**, vector of the solar radiant flux; *T*, temperature, K; *t*, time, s; α, absorptivity; δ, sample thickness, m; ε, integral semispherical radiating capacity; λ, heat-conductivity coefficient, W/(m·K); ρ, reflectivity; $\sigma = 5.67 \cdot 10^{-8}$, Stefan–Boltzmann constant, W/(m^2·K^4); τ, transmission capacity. Subscripts: b, black plate; f, sample face; e, Earth radiation; i, infrared radiant flux; r, revolution; p, metal plate on the heat-shield fragment; s, solar radiant flux; ef, effective; i.b, infrared radiant flux of the back side of the sample; i.f, infrared radiant flux of the face of the sample; s.p, solar radiant flux absorbed by the metal plate of the heat-shield fragment; s.r, solar reflected radiant flux; s.t, solar transmitted radiant flux; s.a, solar absorbed radiant flux; t.m, heat-insulating material; 1, 2, black and white temperature sensors, respectively; I, II, III, IV, numbers of temperature sensors.

REFERENCES

1. H. E. Clarc and D. G. Moor, Method and Equipment for Measuring Thermal Emittance of Ceramic Oxides from 1200 to 1800, SP-55, 241–258 (1964).
2. T. A. Hughes, R. M. F. Linford, R. I. Schmidt, and N. I. Christensen, Radiant heat transfer in reusable surface insulation, *NASA TMX-2719*, 197–226 (1972).
3. A. Saboonchi, W. H. Sutton, and T. J. Love, Direct Determination of Gray Participating Thermal Radiation Properties of Insulating Materials, *J. Thermophys. Heat Transfer*, **2**, No. 2, 97–103 (1988).
4. J. T. Howe, M. J. Green, and K. C. Weston, Thermal shielding by subliming volume reflectors in convective and intense radiative environments, *AIAA J.*, **11**, No. 7, 989–1000 (1973).
5. R. Siegel and J. R. Howell, *Thermal Radiation Heat Transfer*, 2nd ed., Hemisphere Publishing Corp., New York (1981).
6. A. I. Dennison, Illumination of a space vehicle surface due to sunlight reflected from Earth, *ARS J.*, **32**, No. 4, 635–637 (1962).