RADIATION CHARACTERISTICS OF HEAT PROTECTIVE MATERIALS OF THE BURAN ORBITAL SPACECRAFT

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Some features of investigations of the temperature dependence of the integrated and spectral emissivity of erosion-resistant coatings on a low-thermal conductivity fibrous heat insulation are discussed. Results are provided for the standard "black" and "white" coatings. A study is made of the influence of repeated attacks of the high-temperature dissociated air on the integrated emissivity of the "black" coating. Data are obtained on the radiation characteristics of this coating after full-scale tests during the Buran orbital spacecraft flight.

To provide themal designs of the heat protection of an orbital spacecraft of a reusable space system, it is necessary to know the radiation characteristics of erosion-resistant boron silicate coatings on a quartz or alumosilicate fibrous heat insulation. These data are required for calculations of combined radiative-conductive heat transfer (RCHT) in fibrous materials since the thermoradiative properties of the outer coatings enter in the boundary conditions. The integrated emissivity ε_t determines heat release by radiation on entry into the earth's atmosphere. The spectral emissivity ε_λ enters directly in the boundary conditions for RCHT inside the heat insulation and allows calculation of spacecraft heating by solar radiation when the spacecraft is in orbit. Moreover, the spectral emissivity helps one to understand and interpret the nature of the absorption and radiation of the coatings. Its knowledge allows the prediction of changes in the radiation characteristics as the coating composition changes and proper implementation of noncontact pyrometric measurements of temperature in bench and full-scale tests.

Investigating the temperature dependence of the radiation characteristics of coatings on a fibrous heat insulation presents a very difficult problem. Heat insulation is a low-heat-conducting material, partially transparent to thermal radiation, which makes the heating of a coating to the working temperatures impossible on the side of the heat insulation. In heating the coating on the opposite side by different methods, it is difficult to eliminate the influence of the reflected radiation of the heating source, to provide a uniform heating, and to measure the coating temperature. Therefore, the majority of the radiation characteristics of various coatings developed for spacecraft of the Space Shuttle system were calculated based on measurement results for the spectral reflectivity at room temperature. The values of ε_t calculated in this way can markedly differ from those obtained at high temperatures. Within the framework of the Space Shuttle program some high-temperature studies were also carried out. In [1], heating was accomplished by an arc plasmatron; the radiation of the plasma fluxes reflected from the sample could influence the measurements of the radiation characteristics and temperature. Moreover, the coating of the test sample could be contaminated by the evaporation products of the electrodes. In [2], the sample was heated in a furnace for approximately 60 sec, then it was rather slowly (within several seconds) displaced to the water-cooled window, through which its radiation was measured. In so doing, it was assumed that the temperature remained unchanged. Neglect of cooling led to overestimation of the temperature and underestimation of the emissivity. Cooling of the coatings in measurements is a bottleneck in investigating the radiation characteristics because of the low thermal conductivity and the low density of heat insulation.

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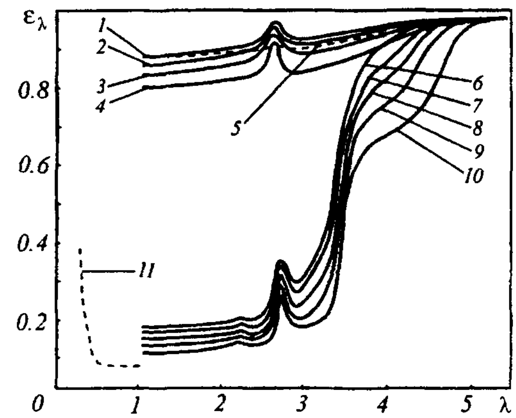

Fig. 1. Spectral normal emissivity of the standard "black" (1-5) and "white" (6-10) coatings: 1) 1490 K; 2) 1195; 3) 1009; 4) 746; 5) 1520, the coating after full-scale tests; 6) 1554 K; 7) 1400; 8) 1190; 9) 790; 10) 633; 11) recalculation based on the results of reflectivity measurements in the short-wavelength region at room temperature. λ, μm.

To obtain reliable data on the radiation characteristics of coatings on a low-thermal conductivity heat insulation, at the Institute of High Temperatures (IHT) of the Russian Academy of Sciences a new fall-furnace method based on high-speed recording both of the spectrum and of the total radiation flux was developed and experimental setups for its implementation were manufactured. At the first stage the setup described in [3, 4] was created and pioneering emissivity measurements by the fall-furnace method were carried out. The experience gained in using this setup allowed the creation of a new experimental setup [5, 6], in which the main drawbacks of the first setup were given proper weight and the procedure was advanced.

At the IHT in the context of the Buran project a large complex of studies of the emissivities of different boron silicate coatings on TZMK-10 quartz heat insulation was carried out, which were developed in the course of creation of the heat protection of the orbital spacecraft. In the present work, consideration is given to the results obtained only for the standard "black" and "white" coatings.

Figure 1 shows some results for the spectral and temperature dependence of the emissivities of the "black" and "white" coatings of the heat protection of the Buran spacecraft. As is seen, ε_λ of the "black" coating (curves 1-5) is rather high and has an emission band at $\lambda = 2.72$ μm, which is caused by the presence of hydroxyl groups in the structure of the coating. As a whole, the character of change in the ε_λ of the "black" coating with wavelength is, apparently, determined both by the silica base and the dye agent (silicon tetraboride) additives. Here, the observed increase in ε_λ with temperature is typical for silica, while the high values in the entire spectrum investigated starting from 1 μm and even shorter are the result of the influence of silicon tetraboride. This coating as well as quartz glass at the wavelengths approaching 5 μm possess a high emissivity of 0.96, practically independent of temperature. The influence of silicon tetraboride is so substantial that the emission band initiated by the presence of the OH groups does not manifest itself much against the background of the generally high ε_λ of the "black" coating.

For the "white" coating (curves 6-10) in the investigated spectrum ε_λ changes from 0.1 at $\lambda = 1$ μm to its limiting value of 0.96 typical for quartz glass at the beginning of the nontransparency region where the emissivity is determined only by the surface reflectivity, since the coating itself is optically infinite. Therefore the wavelength range of approximately 5 to 6 μm should be considered as the best spectral range that can be used in pyrometry to measure the temperature of the "white" coatings. In this range, the brightness temperature measured will be very close to the true one and the influence of possible foreign reflected fluxes (for instance, from the plasmatron arc or the heating furnace) will be minimum. In the entire semitransparency region, the emissivity of the "white" coating increases with temperature. However, this increase is different in the spectrum and at $\lambda > 4.8$ μm the isotherms merge into one curve. The behavior of the spectral emissivity in the region of

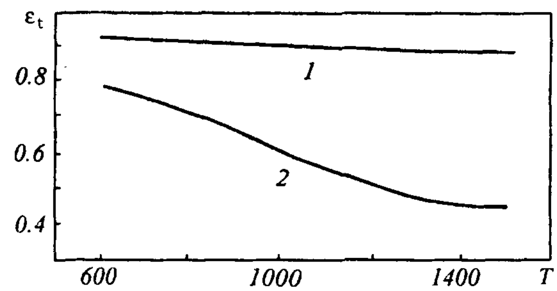

Fig. 2. Integrated emissivity of the "black" (1) and "white" (2) coatings. T, K.

wavelengths smaller than 3.5 μm depends substantially on the presence of OH hydroxyl groups in the glass and the fibrous heat insulation. It is the internal stretching vibrations of the OH groups and their combinations with the vibrations of the tetrahedron of the silica skeleton that are responsible for the emission bands at 2.72 and 2.22 μm. As is seen from the experimental data, the character of the spectral dependence of the δ_λ of the "white" coating is similar to quartz glass containing a large amount of OH groups. The increased ε_λ values of the coating within the spectrum $\lambda < 2.5$ μm as compared to the quartz glass testify to the influence of boron oxide and to a possible presence of optical inhomogeneities in the coating and the substrate material. The intensity of the emission bands of the OH groups in the "white" coating turns out to be weaker than in the quartz glass or dense quartz ceramics, which is explained by the small coating thickness.

The dashed curve 11 in Fig. 1 denotes the spectral semispherical emissivity of the "white" coating obtained using the data on the reflectivity at room temperature in the shortwave spectrum.

Figure 2 shows the results of direct measurements of the integrated emissivity ε_t for the "black" and "white" coatings. It is seen that for the "black" coating within the range 600–1500 K ε_t remains very high. Its minimum value at 1500 K is 0.89. For the "white" coating ε_t decreases with increasing temperature, which is attributed to the shift of the maximum of the Planck function to the short-wavelength region and to the small ε_λ in this region.

Figures 1 and 2 clearly demonstrate the difference in the emission characteristics of the "black" and "white" coatings. The "black" coating possesses a high ε_t, which provides intense heat release by radiation and works well in the most thermostressed slabs of the heat protection system. As a whole, the "white" coating radiation in the wavelength range from the visible region to 2.5 μm, on which practically the entire energy of solar radiation falls, is low because of the low absorption of quartz and borosilicate glass and the high scattering coefficient of the substrate, i.e., TZMK-10 heat insulation. Correspondingly, the reflection of the "white" coating in this spectral region will be high, which provides good heat insulating properties of the heat protection of the upper surfaces of the orbital spacecraft when it is in orbit. We have measured the ratio of the absorption coefficient of solar radiation to the integrated emissivity at room temperature and found it to be 0.16.

An important problem for heat protection of a reusable spacecraft is a possible decrease in the emissivity of the "black" coating after the next flight of the spacecraft. This decrease occurs due to the action of high-temperature dissociated air flow. To study this problem, three academic institutes, namely, the Institute of Mechanics Problems, the Institute of Chemical Physics, and the Institute of High Temperatures in cooperation with the Science and Production Association "Molniya" have joined their efforts to carry out special studies of changes in radiation characteristics in cyclic tests of heat protective slabs on a VGU-3 high-frequency air plasmatron under conditions simulating conditions of orbital-spacecraft entry into the earth's atmosphere.

An investigation was made of several samples cut from slabs subjected to repeated cyclic actions differing in number: 10, 30, 47, and 100 cycles. Figure 3 shows data obtained for the standard "black" coating on the dependence of the integrated emissivity at three different temperatures on the number of cycles of action. Each cycle took 10 min; the coating temperature was 1520 K. It is seen that ε_t decreases as the number of cycles of action increases and this decrease is most pronounced in the first cycles. The maximum decrease in

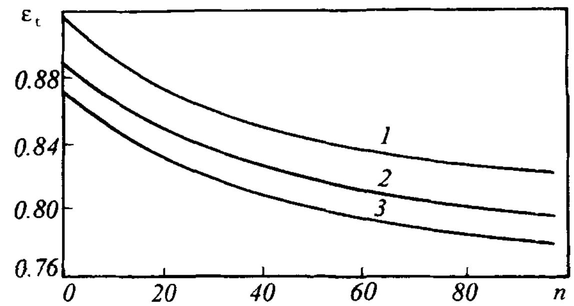

Fig. 3. Plot of ε_t of the "black" coating at different temperatures versus the number n of cycles of the dissociated air flow action: 1) 1200 K; 2) 1400; 3) 1520.

ε_t after 100 cycles of action, as compared to the initial one, amounts to 12% and is weakly dependent on temperature. The more substantial decrease in ε_t in the initial cycles of the tests is explained by the abrupt decrease in the silicon tetraboride content in the surface layer of the coating, which was confirmed by direct measurements of the relative boron concentrations. After several tens of cycles the boron content is stabilized. Morphological studies of the coating and its chip have shown that already after the first cycle of tests, macroscopic relief changes occur on the surface which increase with the number of cycles. After 100 cycles one-third of the thickness of the coating surface layer (about 100 μm) changes. The dense coating layer beneath retains its properties. In the thin surface layer an insignificant amount of the crystalline phase is formed but this is not accompanied by cracking. Despite the decrease in the boron content and other changes in the "black" coating, the results obtained testify to a comparatively small change in ε_t and confirm the possibility of heat-protection operation under the action of high-temperature dissociated air flows during 100 cycles.

However, tests on a plasmatron cannot, of course, give exhaustive information on the possible changes in the radiation characteristics of the coatings under actual flight conditions. In this connection, the results of investigating the emissivity of the standard "black" coating cut from a thermostressed slab of the Buran orbital spacecraft after its return to earth deserve attention. In Fig. 1, dashed curve 5 shows the spectral dependence of ε_λ for this coating sample at a temperature of 1520 K. It is seen that the spectral emissivity has not undergone strong changes after the spacecraft flight; it has only slightly decreased. It can be assumed that this is related to the decrease in the boron concentration within the short-wavelength region, while in the neighborhood of 2.72 μm with the decrease in the amount of OH groups. As a whole, after the first flight the emissivity remained very high, which fully meets the requirements for the "black" coating reused as part of the orbital-spacecraft heat protection.

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