RECONSTRUCTION OF THE MODEL SPECTRUM OF THERMAL EMISSION OF A PLANET IN EXPERIMENTAL EQUIPMENT

A. V. Kolesnikov

UDC 629.78.018

The radiative characteristics of an ideal coating for discrete emitters of simulators of the self-radiation of planets and the possibilities of correcting their emission spectra using special coatings are determined.

In the calculation and expermental modeling of external heat exchange of a spacecraft one uses models of planets in which the spectra of the self-radiation of the planets is taken as similar to the emission spectrum of an absolutely black body with a temperature equal to the average radiation temperature of the region of the planet under consideration, while the spectral composition of the solar radiation reflected from planets is taken as the same as the spectral composition of the direct flux of thermal emission of the sun. Advances in the development of light technology and optics make it possible to reproduce the thermal part of the solar emission spectrum sufficiently precisely in ground based experimental apparatus. Using high-pressure and very-high-pressure arc lamps filled with xenon or mercury-xenon, for example, in optical devices with correcting filters, one can reproduce the spectral composition of solar thermal emission with an acceptable accuracy for practical work [1-3]. The incorporation of such optical devices into the construction of a simulator of the field of solar radiation reflected from a planet is associated only with technical difficulties, but not with difficulties of a fundamental character. Owing to the fact that the intensity of solar radiation reflected from the planets is hundreds of thousands of times lower than the intensity of direct solar radiation and about as many times lower than the intensity of the plasma emission in the arcs of the radiant-flux sources used to model solar radiation, the required spectral composition and density of solar radiation reflected from planets can be reproduced in ground based experimental apparatus using systems of discrete emitters that are essentially point sources. This, in turn, creates favorable conditions for providing, by means of the appropriate optical devices, the required solid angle of emergence of the radiation emitted into the working zone.

The intensity of the self-radiation of a planet can be taken as equal to the intensity of the radiation of an absolutely black body with a temperature corresponding to the radiation temperature of the planet being simulated. When the self-radiation fields of planets are reproduced with emitters having radiation characteristics close to the characteristics of an absolutely black body, the discreteness of the emitters inevitably leads to disparity between the radiation spectra of the simulator and the model planet. The disparity will be the greater, the higher the level of discreteness of the emitters, and hence, the higher their temperatures. Since the overwhelming majority of the materials and coatings used in space technology are nongray, the difference between the spectra leads to errors in the amount of radiation flux from the simulator absorbed by elements of the test object — spectral errors.

In Fig. 1 we present the results of calculations of the relative values of the spectral errors for the various materials and coatings in use with known radiation characteristics in the infrared region of the spectrum. The information encountered in the literature on the spectral absorptivity (A_λ) pertains, as a rule, to a relatively narrow spectral range, and so in the calculation we used literature data [1-6] expanded into the middle- and far-infrared part of the spectrum, on the basis of information on the values of the integral emissivity at normal temperatures. The relative spectral error $\overline{\Delta q}$ was defined by the expression

$$\overline{\Delta q} = (A - A^0) / A^0. \qquad (1)$$

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 50, No. 2, pp. 324-329, February, 1986. Original article submitted October 17, 1984.

0022-0841/86/5002-0247$12.50

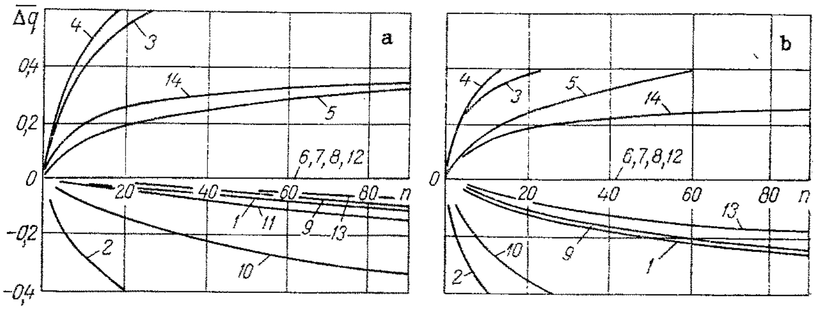

Fig. 1. Dependence of the spectral errors on the degree of discreteness of the black emitter: 1) white enamel; 2) anodized aluminum; 3) titanium alloy; 4) stainless steel; 5) aluminum; 6) silver; 7) chromium; 8) gold; 9) white fiber glass; 10) quartz glass; 11) ceramic coating; 12) AMG-6 alloy; 13) green enamel; 14) oxidized stainless steel. a) T_0 = 253°K; b) 400.

According to [4],

$$A = \frac{\int_0^\infty A_\lambda \varepsilon_\lambda \frac{2\pi C_1}{\lambda^5 (\exp\,(C_2/\lambda T) - 1} d\lambda}{\sigma T^4}, \tag{2}$$

$$A^0 = \frac{\int_0^\infty A_\lambda \frac{2\pi C_1}{\lambda^5 (\exp (C_2 / \lambda T_0) - 1)} d\lambda}{\sigma T_0^4}. \tag{3}$$

The graphs presented in Fig. 1 correspond to the cases of the reception of the self-radiation of the earth with a radiation temperature T_0 = 253°K and simulation of the radiation of the most heated section of the moon (the subsolar section), for which the solar zenith angle equals while $T_0 \approx 400°$. The results of the calculations indicate the strong dependence of Δq on n for some of the materials and coatings in use. For n > 10 the errors are so large in a number of cases that it becomes a question of the feasibility of achieveing a high accuracy of reproduction of the intensity field of planetary self-radiation using a simulator with discrete emitters.

In connection with the fact that the level of spectral errors is high when black discrete emitters are used, one must consider the problem of the correction of the spectrum of discrete emitters. In solving this problem one must, first, formulate a concept of the character of the wavelength dependence of the spectral emissivity of an ideal coating for a discrete emitter such that it could assure the similarity of the radiation spectrum of the simultator and the model spectrum of self-radiation of a planet when there is a considerable difference between the emitter tempratures and the radiation temperature of the planet, and second, to analyze the radiation characteristics of the known materials and coatings in order to determine their degree of correspondence to the ideal and to choose the most suitable among them.

The condition of similarity of spectra can be written as

$$I_\lambda / I_\lambda^0 = B, \tag{4}$$

where B is a constant not dependent on the radiation wavelength.

Using the Planck function, we write the condition (4) in the form of a relation among ε_λ, B, λ, T, and T_0:

$$\varepsilon_\lambda = B\,\frac{\exp\,(C_2/\lambda T) - 1}{\exp\,(C_2/\lambda T_0) - 1}. \tag{5}$$

The quantity B can be expressed through the integral emissivity (ε) of the emitter and the temperature ratio T/T_0:

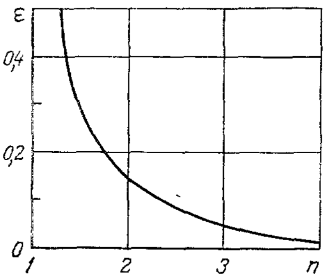

Fig. 2

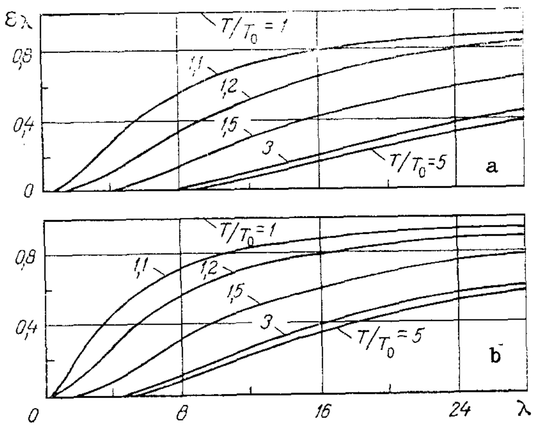

Fig. 3

Fig. 2. Integral emissivity of an ideal emitter as a function of its degree of discreteness.

Fig. 3. Dependence of ε_λ on λ for an ideal emitter. λ, μm.

$$\int_0^\infty \pi I_\lambda d\lambda = B \int_0^\infty \pi I_\lambda^0 d\lambda, \quad \varepsilon\sigma T^4 = B\sigma T_0^4, \quad B = \varepsilon (T/T_0)^4$$

or

$$\varepsilon = B (T_0/T)^4. \tag{6}$$

For λ satisfying the condition $C_2/\lambda T_0 \ll 1$, and hence the condition $C_2/\lambda T \ll 1$, the exponential term in the expression for the Planck function can be linearized [7]. In this case Eq. (5) is simplified and takes the form

$$\varepsilon_\lambda = B \frac{C_2/\lambda T}{C_2/\lambda T_0} = B\, T_0/T. \tag{7}$$

From Eq. (7) it follows that for large λ such spectra are provided for with a constant ε_λ, e.g., with $\varepsilon_\lambda = 1$. In this case

$$B = T/T_0. \tag{8}$$

By defining B in this way, we can also uniquely define the function $\varepsilon_\lambda = f(\lambda)$.

From (5) and (8) it follows that

$$\varepsilon_\lambda = \frac{T}{T_0} \frac{\exp (C_2/\lambda T_0 \cdot T/T_0) - 1}{\exp (C_2/\lambda T_0) - 1}, \tag{9}$$

where the ratio T/T_0 is a parameter dependent on the degree of discreteness n of the emitters.

By its essence $n = \varepsilon\sigma T^4/\sigma T_0^4 = \varepsilon(T/T_0)^4$, and hence

$$n = B = T/T_0. \tag{10}$$

Replacing B in (6) by its expression from (10), we obtain

$$\varepsilon = (T/T_0)^3. \tag{11}$$

The relations (9) and (11) define the spectral and integral emissivities of an ideal emitter coating.

The function $\varepsilon = \varphi(n)$ is shown in Fig. 2. The results of a calculation of $\varepsilon_\lambda = f(\lambda)$ for $T_0 = \{253, 400\}$°K and $T/T_0 = \{1.1, 1.2, 1.5, 3, 5\}$ are presented in Fig. 3.

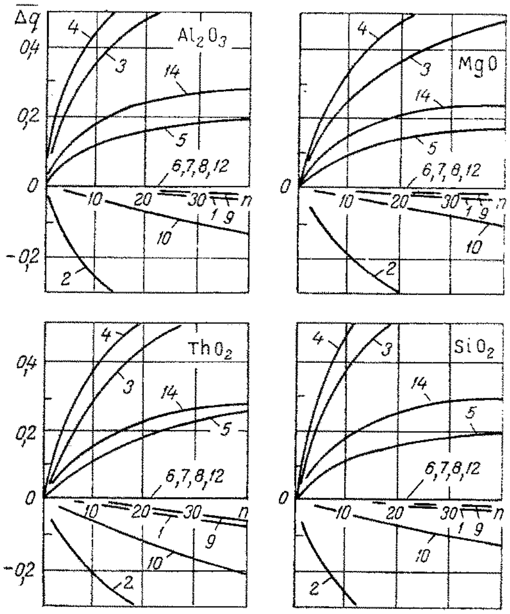

Fig. 4. Dependence of the spectral errors on the degree of discreteness of the emitters. The numbering of the curves corresponds to the numbering of Fig. 1.

A characteristic feature of the radiation characteristics of an ideal emitter coating is the strong dependence of ε_λ and ε on temperature, and hence on the discreteness of the emitters, as well as the extremely low and practically unrealizable value of ε for $n > 3$. Attention is also drawn to the fact that, with regard to providing the required level of discreteness, the possibilities of an ideal emitter coating are very limited because of the linear character of the dependence of n on T/T_0, whereas for black emitters n is proportional to the fourth power of the ratio T/T_0. Nevertheless, the functions $\varepsilon_\lambda = f(\lambda, T, T_0)$ and $\varepsilon = \varphi(n)$ obtained are not only of theoretical but also of practical interest. On the basis of these functions one can determine the class of coatings which make it possible, in principle, to correct the radiation spectra of simulators with discrete emitters.

The dependences of ε_λ on λ for a number of dielectrics — some metal oxides, SiO_2, and certain oxides of rare-earth elements — correspond to a certain extent to the ideal qualitative character of the wavelength distribution of the spectral emissivity. Sufficiently complete data on the dependence of ε_λ on λ are presented in the literature [1-6] for certain materials for which ε_λ grows with an increase in λ. They were used to estimate the dependence of the spectral errors $\overline{\Delta q}$ on the degree of discreteness of emitters having Al_2O_3, MgO, ThO_2, and SiO_2 as coatings. The results of the calculations, made in accordance with Eqs. (1)-(3) for the case of $T_0 = 253°K$, are presented in Fig. 4.

In comparing these results with the calculated results for black emitters, one can see a decrease in the spectral errors due to the use of coatings having a spectral emissivity that grows with an increase in λ. A cardinal decrease in the level of the spectral errors cannot be achieved, however. Here it must also be noted that the use of coatings radiating poorly, and hence reflecting well, in the short-wavelength region, especially the visible region, also has negative consequences, consisting in worsening of the quality of simulation of the ideal absorptive properties of cosmic space. With allowance for the latter, we can conclude that the use of black emitters is advisable in practice.

NOTATION

T, emitter temperature; T_0, radiation temperature of the planet; $\overline{\Delta q}$, relative error in the amount of radiation flux from the simulator absorbed by the heat-sensing element (relative spectral error); λ, radiation wavelength; ε_λ, ε, spectral and integral emissivities, respectively, of the emitter; A_λ, spectral absorptivity of the coating of the heat-sensing element; A, A^0, integral absorptivities of the heat-sensing elements with respect to the radiation of the emitter proper and the model planet; n, degree of discreteness of the emitters, determined by the ratio of the surface area of the layout to the total area of the emitting elements; I_λ^0, spectral intensity of the radiation of an absolutely black body having the temperature T_0; I_λ, spectral intensity of the radiation of an ideal coating with the temperature T; $C_1 = 5.9544 \cdot 10^{-17}$ W·m²; $C_2 = 1.4387 \cdot 10^{-2}$ m·°K; $\sigma = 5.6699 \cdot 10^{-8}$ W/(m²·°K⁴).

LITERATURE CITED

1. L. V. Kozlov, M. D. Nusinov, et al., Modeling of the Thermal Regimes of a Spacecraft and the Medium Surrounding It [in Russian], Acad. G. I. Petrov (ed.), Mashinostroenie, Moscow (1971).
2. V. V. Andreyanov, V. V. Artamonov, et al., Automatic Planetary Stations [in Russian], Nauka, Moscow (1973).
3. Simulation of the Thermal Conditions of Cosmic Space for Tests of Spacecraft [Russian translation], from materials of the foreign press for 1960-1966, Survey, Byull. Nauchno-Tekh. Inform., Tsentr. Aerogidridin. Inst., No. 197 (1966).
4. A. E. Sheindlin (ed.), Radiative Properties of Solids (Handbook) [in Russian], Énergiya, Moscow (1974).
5. V. A. Petrov, Emissivities of High-Temperature Materials [in Russian], Nauka, Moscow (1969).
6. D. Ya. Svet, Thermal Emission of Metals and Certain Substances [in Russian], Metallurgiya, Moscow (1964).
7. R. Siegel and J. R. Howell, Thermal Radiation Heat Transfer, McGraw-Hill, New York (1971).