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SPECIAL FEATURES OF THE THERMOPHYSICAL MODELING OF INSTRUMENT CUBICLES OF SPACECRAFT

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Mathematical models which allow for the main mechanisms of heat transfer in instrument cubicles of modern spacecraft are presented. Results of numerical modeling of thermophysical processes in a typical module of the instrument cubicle of a communications spacecraft are given. On the basis of an analysis of multidimensional temperature fields we have drawn conclusions on the presence of substantial nonuniformity in the distribution of the temperature field in devices of radioelectronic spaceborne equipment.

At present, communications spacecraft with a large-size nonhermetic instrument cubicle, which is a block-module structure made of flat rectangular honeycomb panels [1] carrying thermally stressed devices of spaceborne equipment, are promising. One problem in designing a communications spacecraft with a long service life in outer space is the provision of certain ranges of thermostability in operation of the devices of spaceborne equipment, since excess over the maximum operating temperature can lead to the appearance of physicochemical processes, which make the elements of radioelectronic equipment inoperative, and decrease the reliability of the entire device. Therefore, the results of the analysis of multidimensional temperature fields in the instrument cubicle can serve as a means for developing measures intended to improve the reliability of operation of the spacecraft as a whole.

The principles of modeling of a combination of interrelated thermophysical processes in the instrument cubicle, which substantially extend the possibilities of prediction of spatial temperature fields, were developed earlier [2]. However, the formulation of the problem did not take into account the real geometry and volumetric heat release of the devices, since it was assumed that their temperature fields are uniform and the heat release is concentrated on the site of installation ("location") of a device [2].

In the present work, we carry out numerical modeling of nonstationary thermophysical processes in the instrument cubicle with account for the real geometry and volumetric heat release of the devices. The problem is considered with the example of a typical Π-shaped module of the instrument cubicle on whose inner side thermally stressed devices of the spaceborne equipment are mounted (Fig. 1). The module is made of panels (1, 2, 3) with a built-in system of provision of a thermal mode; the system is based on low-temperature uncontrolled heat pipes filled with liquid ammonia as a working body. Each panel is a three-layered plate (casing, honeycomb filler, casing). Panels 1 and 3 are open for heat exchange with outer space. The heat released by the devices is transferred through the casing and special "shelves" to the heat pipes and the honeycomb filler. Through the latter, the heat comes to the external casing of panels 1 and 3 and is radiated into outer space in the case where the panel is not illuminated by the sun. If the panel is illuminated, then the heat of solar radiation and that released by the devices of the panel is partially radiated into outer space and partially transferred by the heat pipes to the panel, which is in shadow, and thence it is thrown off to outer space.

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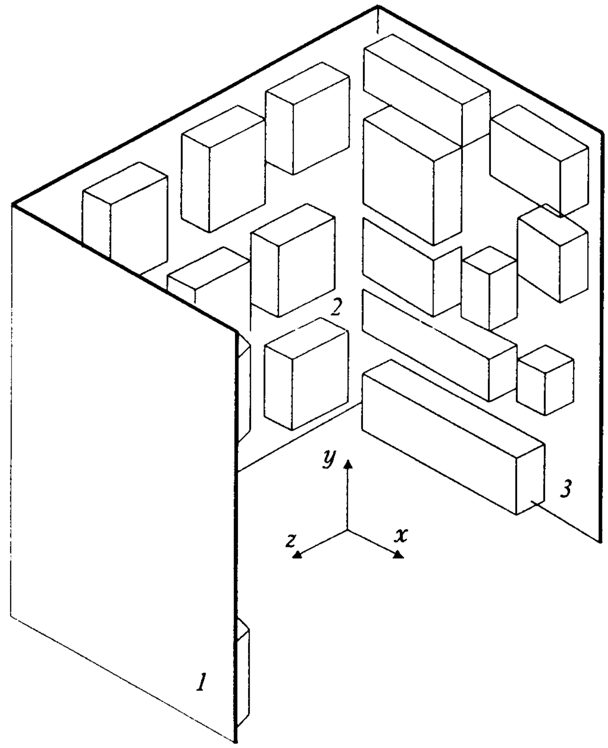

Fig. 1. Overall view of a typical Π-shaped module of the instrument cubicle.

As a device, we considered a typical structure of the cassette-type block of elements of radioelectronic equipment with conductive heat sinks through which the heat is transferred from the plates with micromodules to a cooled base [3]. In such structures, the role of conductive heat sinks is played by heat-removing buses, metallic bases of the plates, and metal screening layers [3, 4]. The metal layer of the printed assembly of the plate is an additional heat sink. In analysis of the thermal mode of a cassette-type block with dense arrangement and a regular internal structure, use is made of the model of a quasihomogeneous heated zone with effective thermophysical characteristics [3, 4]. Here, powers of the sources of heat release are assumed to be uniformly distributed over the regions which have the shape of a parallelepiped and correspond to individual functional elements or groups of elements (multilayer printed-circuit plates) (Fig. 2). In this case, the problem is reduced to solution of the three-dimensional equation of heat conduction for N isotropic parallelepipeds with assigned spatial distribution of internal heat sources:

$$c_i \rho_i \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_{xi} \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_{yi} \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_{zi} \frac{\partial T}{\partial z}\right) + q_{\text{v}} (x, y, z) . \tag{1}$$

According to [2], the system of heat-conduction equations for the casings of the panels, the honeycomb filler, the "shelves," and the bodies of heat pipes has the form

$$c_i \rho_i \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_{xi} \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_{yi} \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_{zi} \frac{\partial T}{\partial z}\right). \tag{2}$$

At all the boundaries at the sites where the casings contact the honeycomb filler and the heat pipes contact the honeycomb filler and the "shelves," the conditions of continuity of the heat fluxes and temperatures are taken [5]:

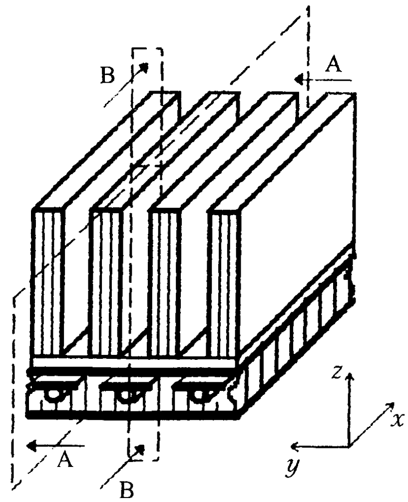

Fig. 2. Physical model of a typical device of spaceborne equipment of cassette-type arrangement with conductive heat sinks which is mounted on the honeycomb panel with a built-in system of provision of a thermal mode.

$$\lambda_{x,i}\frac{\partial T_i}{\partial x}=\lambda_{x,i+1}\frac{\partial T_{i+1}}{\partial x}\,,\quad T_i\,(z,y,t)=T_{i+1}\,(z,y,t)\,;$$
$$\lambda_{y,i}\frac{\partial T_i}{\partial y}=\lambda_{y,i+1}\frac{\partial T_{i+1}}{\partial y}\,,\quad T_i\,(x,z,t)=T_{i+1}\,(x,z,t)\,;\tag{3}$$
$$\lambda_{z,i}\frac{\partial T_i}{\partial z}=\lambda_{z,i+1}\frac{\partial T_{i+1}}{\partial z}\,,\quad T_i\,(x,y,t)=T_{i+1}\,(x,y,t)\,.$$

The boundary conditions which allow for the incident solar-radiation flux [5]

$$A_sS_0\cos\varphi=-\lambda_z\frac{\partial T_i}{\partial z}-\varepsilon_{surf}\sigma T_{surf}^4\tag{4}$$

were taken on the outer edges of panels 1 and 3. On all heat-insulated surfaces of the panels boundary conditions of the type

$$\lambda_{x,i}\frac{\partial T_i}{\partial x}=0\,,\quad \lambda_{y,i}\frac{\partial T_i}{\partial y}=0\,,\quad \lambda_{z,i}\frac{\partial T_i}{\partial z}=0\tag{5}$$

were adopted.

In the present work, we consider the system of provision of a thermal mode of the devices of spaceborne equipment; the system is made on the basis of low-temperature uncontrolled heat pipes with liquid ammonia as a working body which lie inside the honeycomb panels under the devices. Conduction dynamic thermal mathematical models in lumped parameters for uncontrolled low-temperature heat pipes with account for the topography of their arrangement in the honeycomb panels of the module are described in [2] and represent the nonlinear system of ordinary differential equations of heat balance and initial conditions for surface-mean temperatures of each lth element (zones of evaporation, transport, condensation)

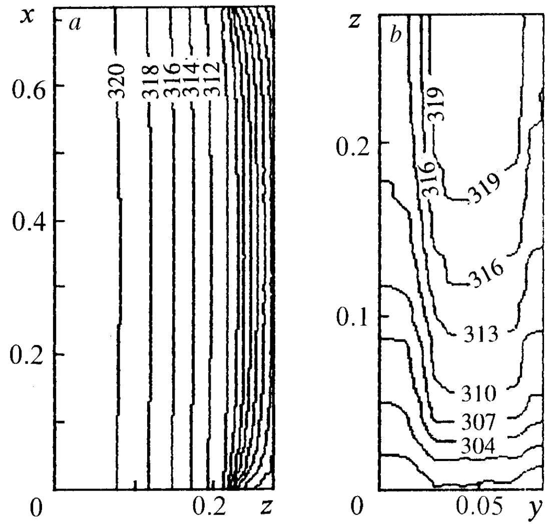

Fig. 3. Position of typical isotherms of the cross-sectional planes A–A (a) and B–B (b) of the element of the device. Figures correspond to the temperature level of typical isotherms. *x*, *y*, *z*, m; *T*, K.

$$\sum_m \alpha_{m,l} (T_m - T_l) = C_l \frac{\partial T}{\partial t} + \sum_n \alpha_{l,n} (T_l - T_n) , \quad T_l (0) = T_0 , \tag{6}$$

where *m* and *n* are the elements which are thermally related to the *l*th element and which participate in the supply and removal of heat.

The mathematical models presented were realized numerically according to the Samarskii additive local one-dimensional scheme [6]. In this scheme, a multidimensional physical process at each time step is a result of successive realization of corresponding one-dimensional processes each of which begins from the distribution of a temperature field which arose after cessation of the previous one-dimensional process. Based on this splitting of the problem by spatial variables, one-dimensional processes are modeled using implicit schemes while the sequential effect of the processes is taken into account explicitly. One-dimensional differential equations along the coordinate axes *x*, *y*, *z* are approximated on a nonuniform grid according to a four-point fully implicit one-step scheme, which is two-layered with respect to time. The boundary conditions for the temperature on the interior and exterior surfaces and at the boundaries between materials are replaced by finite-difference analogs of them according to a scheme which has an order of approximation no lower than at the internal nodes of the grid.

An efficient algorithm and software for calculation in the FORTRAN algorithmic language, which allowed realization of the suggested mathematical models for a rather complex design-arrangement scheme of the instrument cubicle of a spacecraft, have been developed.

In the present work, as an example we present the results of numerical modeling of multidimensional temperature fields of a typical Π-shaped module of a nonhermetic instrument cubicle of a promising communications spacecraft at the point of winter solstice (A_s = 0.26, φ = 66.5°, S_0 = 1440 W/m^2). The total power of heat release of the devices of the spaceborne equipment was 1077 W. The effective coefficients of thermal conductivity of anisotropic elements of the heated zone of the devices of the spaceborne equipment were calculated according to the thermal circuits of an elementary cell of [3, 4]: λ_y = 3.3 W/(m·K), λ_z = 9.3 W/(m·K), and λ_x = 9.3 W/(m·K). The coefficients of thermal conductivity of the honeycomb filler and the parameters of the heat pipes are selected to be adequate to those presented in [2, 5]. The results of

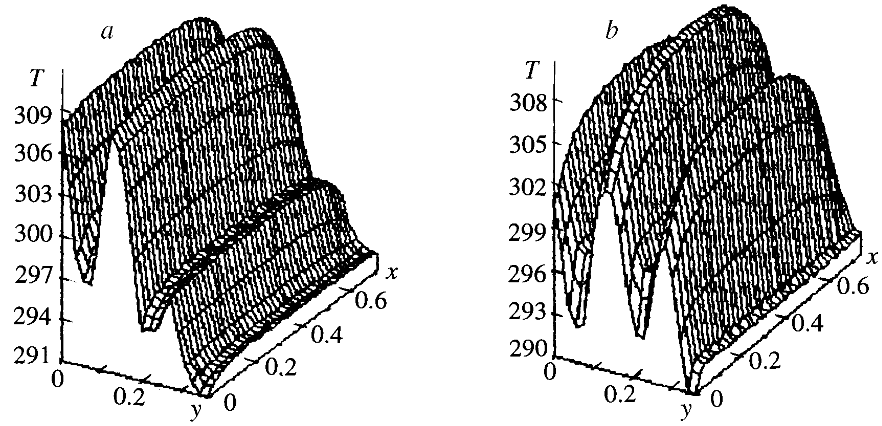

Fig. 4. Temperature distribution over the plane of the "location" of the device. *x*, *y*, m; *T*, K.

numerical calculations were checked by estimating the energy balance on radiator panels 1 and 3 at each time step.

The numerical studies showed that in typical modes of spacecraft operation, we have a substantial nonuniformity of the temperature fields in both individual elements and devices of the spaceborne equipment as a whole. Using the device (with a power of heat release of 160 W) of a typical structure in the form of a block of elements of cassette-type arrangement with conductive heat sinks (Fig. 2), we can see that the maximum temperature difference in one device is 29 K. This can be seen from comparison of the maximum value of the temperature of an element of the device (see Fig. 3a, which shows the position of typical isotherms of the cross-sectional plane A–A of the most thermally stressed element) with the minimum temperature of the location of the device considered (see Fig. 4). Figure 3b shows the position of typical isotherms of the cross-sectional plane B–B of the element indicated. It is evident that operation of the heat pipes also makes the temperature field of the device nonuniform.

A distinctive feature of the problem formulated is taking into account the spatial distribution of the temperature fields both in the honeycomb panels and directly in the devices of the spaceborne equipment. By virtue of this, we carry out numerical calculations using the model presented and the model formulated earlier in [2], where it was assumed that the temperature fields of the device of spaceborne equipment are uniform and the heat release is concentrated on the locations, while the thermal state of the devices was estimated by the so-called maximum temperature of the location. Figure 4a presents the temperature distribution over the plane of the location of the considered device that is calculated within the framework of the mathematical model formulated in the present work. Comparison with a similar temperature distribution calculated without allowance for the real geometry and heat release of the devices, which is presented in Fig. 4b, shows that the values of the maximum temperatures of the devices calculated according to the model which allows for the spatial distribution of temperature over the elements of the device and their volumetric heat release can exceed the values of the maximum temperatures of the corresponding locations by 13 K or more.

The analysis of the results obtained shows that the maximum temperature of the location cannot serve as an accurate estimate (to ±5K), which is necessary for a trustworthy analysis of the reliability of radioelectronic spaceborne equipment, since it is known that an excess of 10 K over the maximum operating temperature of one element can, in some cases, decrease the reliability of the entire device by 50% [7]. The results obtained allow one to draw the conclusion on the insufficient accuracy of methods for calculation of the temperature fields using mathematical models which do not take into account the spatial distribution of temperature over the elements of the devices.

NOTATION

A_s, coefficient of absorption of solar radiation; C, total heat capacity; c, specific heat capacity; q_v, function allowing for the distribution of the power of internal heat sources; S_0, density of the flux of direct solar radiation; t, time; T, temperature; x, y, z, Cartesian coordinates; α, thermal conductivity of the zone of contact between the elements of heat pipes; ε, integral emissivity of the surface; φ, angle between the normal to the surface of the radiator panel and the direction to the sun; λ, coefficient of thermal conductivity; ρ, density; σ, Stefan–Boltzmann constant. Subscripts: i, structural element of a device and a module; l, m and n, element of a heat pipe; s, direct solar radiation; surf, surface of the radiation panel; v, internal heat sources.

REFERENCES

1. V. F. Panin, *Structures with a Honeycomb Filler* [in Russian], Moscow (1982).
2. E. A. Ashurkov, V. A. Burakov, A. G. Kozlov, et al., *Izv. Vyssh. Uchebn. Zaved., Fizika*, **36**, No. 4, 119–128 (1993).
3. G. N. Dul'nev, V. G. Parfenov, and A. V. Sigalov, *Methods of Calculation of a Thermal Mode of Devices* [in Russian], Moscow (1990).
4. G. N. Dul'nev, *Heat and Mass Transfer in Radioelectronic Equipment* [in Russian], Moscow (1984).
5. G. V. Kuznetsov and S. F. Sandu, *Teplofiz. Aéromekh.*, **5**, No. 3, 469–477 (1998).
6. A. A. Samarskii, *Theory of Difference Schemes* [in Russian], Moscow (1983).
7. G. P. Peterson, *Heat Pipe Thermal Control of Electronic Components*, AIAA Pap. No. 85–937 (1985).