MATHEMATICAL SIMULATION OF HEAT EXCHANGE IN A NONHERMETIC INSTRUMENTAL COMPARTMENT OF A SPACECRAFT

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We present physical and dynamic thermal mathematical models in distributed and lumped parameters, calculation algorithms, software, and some results of numerical calculations of radiative-conductive heat exchange in blocks and modules carrying thermally loaded on-board equipment in a nonhermetic instrumental compartment of a proposed durable communication spacecraft with improved mass, size, and energy characteristics improved in comparison with traditional hermetic compartments.

Since the early nineties a new generation of Russian durable competitive communication spacecraft (SC) has been created with a large-scale nonhermetic parallelepiped-shaped instrumental compartment – a block-modular construction built-up on the basis of plane rectangular three-layer honeycomb panels which carries thermally loaded on-board equipment and which simultaneously performs a force function, a thermal function, and a function of protection from ionizing radiations [1]. To ensure the thermal regime of the on-board equipment, a passive thermal control system (PTCS) is used, which is based on optical coatings and uncontrolled low-temperature heat pipes (LTHP) of various outlines and types of profiles in combination with electrical heating systems. One of the design-layout diagrams, nontraditional for Russian communication satellites, of a nonhermetic instrumental compartment that consists, when assembled, of a payload module (PM) and a service-systems module (SSM) (platform) is shown in Fig. 1. The PM consists of a block, which is a П-shaped structure of thermally joined (by means of heat pipes) North panel (an instrument-radiator one), Central panel (an instrument panel which faces the earth and on which an on-board retranslation complex is installed), South panel (an instrument-radiator one), two East and West removable covers, and also a propulsion block panel (PBP) shared with the SSM. The SSM consists of a PBP, an H-shaped information-logical block (ILB) with East and West panels-radiators into which the low-temperature heat pipes are brought out from the instrument panel ILB, and also of a power propulsion block (PPB) that has the form of a П-shaped construction of panels thermally connected by the low-temperature heat pipes: North (an instrument-radiator one), Central (an ordinary panel without instruments), and South (an instrument-radiator one). Taking into account insufficient experience in design and the limited possibilities of experimental data processing in thermovacuum tests, high requirements are imposed on this class of SC as regards the accuracy of design evaluations of the thermal regimes of on-board equipment sensors and the thermal state of construction elements under field conditions in a geostationary orbit (GSO), including the occurrence of emergency situations.

The aim of the present work is to develop further the ideas [2] of mathematical simulation of radiative-conductive heat exchange (RCHE) in blocks and modules that carry thermally loaded on-board equipment in a nonhermetic instrumental compartment of a durable communication SC (see Fig. 1), when it is regularly oriented triaxially to the geostationary orbit in a real physical-time scale.

During the operation in a geostationary orbit [3], basic types of external heat sources [4-6] are preserved, and thermal energy is supplied to the nonhermetic instrumental compartment from heat-generating sen-

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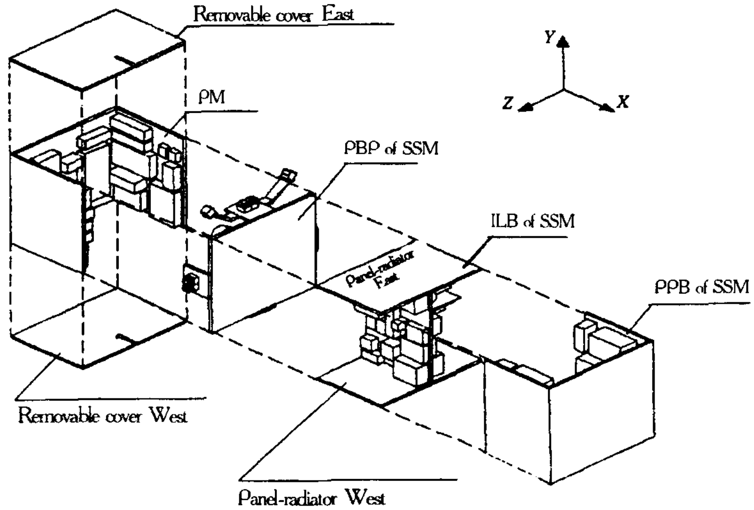

Fig. 1. General block-modular diagram of a nonhermetic instrumental compartment of a durable communication SC

sors of the on-board equipment installed on the internal (instrumental) surfaces of the facings of honeycomb panels, due to the absorption of the flux of direct solar radiation (radiation in the visible spectrum), the reradiation flux (in the infrared spectrum), and the rereflection flux of direct solar radiation from adjacent elements of the construction that can shade separate portions of radiant surfaces. In the internal volumes of the PM and SSM, between nonuniformly heated zones (in the infrared spectrum) radiative heat exchange occurs, which has a self-adjusting character and contributes to the isothermicity of the construction. The heat is also redistributed due to the contact heat exchange in detachable and permanent joints of similar and dissimilar elements of the construction, for example, at the junctions of adjacent honeycomb panels through the elements of their structure (edge former). Excess heat is efficiently removed into the surrounding outer space by applying a special thermocontrolling "optical solar reflector" coating on outer (radiant) surfaces of the facings of honeycomb instrument-radiator panels (North and South ones of PM and SSM), and panels-radiators (East and West ones of SSM). It can be assumed here that all of the heat released by a radiant surface is absorbed by the outer space as by a perfect black body with zero temperature [4]. Uncontrolled LTHPs of PTCS, which are highly efficient heat transmitting devices of evaporation-condensation cycle and which are laid in the very honeycomb instrument-radiator, instrument, and ordinary panels (Central panel of the PPB of SSM), and in radiator panels over inner and outer facings, respectively, make it possible to decrease temperature gradients over the facings, to eliminate disturbances in the thermal regimes of on-board equipment sensors, and to remove excess heat from the Central instrument panel of PM and instrument panel of the ILB of SSM not participating in external heat exchange with the surrounding outer space. It should be noted that a network of uncontrolled LTHPs in the block-modular system of the nonhermetic instrumental compartment can be stretched or contracted depending on the dimensions of instrument-radiator panels. Thus, the most important mechanisms of radiative-conductive heat exchange in blocks and modules of a nonhermetic instrumental compartment of a durable communication SC under field conditions in a geostationary orbit are:

1) external heat exchange on instrument-radiator and radiator panels, and also on removable covers;

2) internal radiative heat exchange;

3) heat release (including that by cyclograms) of the on-board equipment sensors;

4) heat conduction in three-layer honeycomb panels;

5) heat transfer in LTHP with allowance for the special properties of their laying and operation in the panels of PM and SSM;

6) contact heat exchange.

The North and South instrument-radiator panels of PM and SSM are in a periodic semiannual cycle of illumination by the sun. At the point of winter solstice the North panel is constantly shaded, while the South panel is constantly exposed to direct solar radiation. Every six months at the point of summer solstice the panels interchange their positions as regards the illumination by the sun. Without allowance for shadings, rereflections, and reradiations from adjacent elements of the complex construction of communication SC, which require a special, more thorough analysis, the density of the absorbed heat flux from direct solar radiation on the North and South instrument-radiator panels of PM and SSM in a 24-hour cycle is expressed by a lumped constant, and for the East and West panels-radiators of SSM and removable covers of PM this density is expressed by periodic analytical relations that take into account the shaded area of the earth:

$$q_S(t) = \begin{cases} A_S S_0 \cos\theta, & 0 < t \le t_{ES}, \\ 0, & t_{ES} < t \le 24\ \text{h}; \end{cases} \tag{1}$$

$$q_S(t) = \begin{cases} 0, & 0 < t \le 12\ \text{h}, \\ A_S S_0 \sin\theta \sin\left[\dfrac{\pi(24\ \text{h} - t)}{12}\right], & 12\ \text{h} < t \le t_{ES}, \\ 0, & t_{ES} < t \le 24\ \text{h}. \end{cases} \tag{2}$$

The coefficient of absorption of direct solar radiation in (1) and (2) depends on the degree of degradation of the optical solar reflector on its exposure to the action of outer space factors, and it changes, for example, for instrument-radiator panels within the range from 0.08 at the beginning of operation to 0.33 at the end of the active lifetime (AL) [2]. At the point of summer solstice S_0 = 1350 W/m^2, at the point of winter solstice S_0 = 1440 W/m^2, and at the spring and autumnal equinoctial points S_0 = 1400 W/m^2. It is believed that going into and out of the shaded area of the earth occur instantaneously.

The density of the self-radiation flux from the radiant surfaces of the instrument-radiator and radiator panels of PM and SSM is expressed by the Stefan–Boltzmann law. Heat insulation is applied on the outer surfaces of the Central instrument panel of PM and Central ordinary panel of SSM, as a result of which the resultant heat fluxes are assumed here to be equal to zero.

Calculation of internal radiative heat exchange in PM and SSM is carried out using the well-known zone method [7], which is based on the balance of radiant fluxes for each surface with simultaneous introduction of an effective radiant flux consisting of the intrinsic and reflected radiation fluxes. The internal volumes of PM and SSM are considered as closed ones from the viewpoint of radiative heat exchange of the system, and the surfaces bounding them are divided into a finite number of diffuse-gray isothermal area elements, considering that on-board sensors are of zero height (approximation of the mounting seat of a sensor).

In the first stage of implementation of the zone method, mean angular coefficients of radiation between the area elements i and j are calculated by the formula

$$\varphi_{1,ij} = \frac{1}{F_{1,i}} \int_{F_{1,i}} \int_{F_{1,j}} \frac{\cos\varphi_{1,i} \cos\varphi_{1,j}}{\pi r_{1,ij}^2} dF_{1,i}\, dF_{1,j}. \tag{3}$$

In the second stage, at specified temperatures of the area elements the fields of the densities of effective radiation radiant fluxes are determined for each of these elements by solving the system of linear algebraic equations:

$$\sum_j [\varepsilon_{ij} - (1 - \varepsilon_{1,i})\, \varphi_{1,ij}]\, E_{\text{eff}1,j} = \varepsilon_{1,i} \sigma_0 T_{1,i}^4, \quad i = \overline{1, N_{r,1}}, \quad j = \overline{1, N_{r,1}}. \tag{4}$$

In the third stage, the fields of the densities of net radiation radiant fluxes are determined for each area element from the relation

$$E_{r,1,i} = \left(\frac{\varepsilon_{1,i}}{1-\varepsilon_{1,i}}\right)(E_{eff,1,i} - \sigma_0 T_{1,i}^4) , \quad E_{r,1} = \sum_i E_{r,1,i} , \quad i = \overline{1, N_{r,1}} . \tag{5}$$

In calculation of internal radiative heat exchange in a closed system of $N_{r,1}$ rectangular area elements the familiar conditions of closure and the law of conservation of radiant energy

$$\sum_j \varphi_{1,ij} = 1 , \tag{6}$$

$$\sum_i \varepsilon_{1,i} F_{1,i} \sum_j \varepsilon_{1,j} \sigma_0 (T_{1,i}^4 - T_{1,j}^4) \varphi_{1,ij} = 0 \tag{7}$$

must be satisfied.

The main problem to be solved in designing heat-generating on-board equipment in a nonhermetic instrumental compartment of durable communication SC is the removal of excess heat directly from the devices stocked: electroradio components (ERC) and electronics components (EC). Under vacuum only conductive heat supply is efficient. In view of this, the approaches to the design and layout of the on-board equipment must provide for minimum thermal resistance between ERC and EC (the only and main sources of internal thermal loading) and the location of the device. To analyze the thermal regimes of the ERC and EC of thermally loaded on-board equipment, mathematical models have been developed in distributed and lumped parameters of different degrees of complexity [8]. The required thermal regime of the on-board equipment components is decisive for the selection of necessary and sufficient means of thermal control and general approaches to the design and layout of durable communication SC as a whole [1]. However, in the present work, in the first stage of investigations, a simplified approach is used in conformity with which it is assumed that all the heat which was generated during the operation of EPC and EC is supplied to the mounting surface (mounting seat of a device). In this case, the thermal regime of the on-board equipment is predicted from the maximum and minimum temperatures of the mounting seats of devices [2].

Plane rectangular three-layer honeycomb panels [9] (instrument-radiator, radiator, instrument, and ordinary ones), which are efficient as to mass and overall dimensions and which provide the needed strength, heat conduction, and radiative protection, are manufactured in the form of two thin continuous carrying facings of aluminum alloys or composites (carbon or metal-filled plastics) bonded with an anisotropic cellular honeycomb filler of hexagonal structure made of aluminum foil of the required structural depth and made of elements of the structure for mechanical joining in the construction of a nonhermetic instrumental compartment. In instrument-radiator panels the heat coming from the thermally loaded on-board equipment and released by the internal radiant heat fluxes of net radiation propagates by heat conduction over the thin metal facings of the instrument side of the panel in the longitudinal and transverse directions, is removed to LTHP, and, due to conductive heat exchange through the anisotropic honeycomb filler, comes into the metal facings of the radiant side of the panel, where it also propagates in the longitudinal and transverse directions by heat conduction and is emitted to the surrounding outer space. This mechanism of RCHE is also characteristic of other types of the honeycomb panels considered.

A number of works [10-15] have been devoted to simulation of RCHE in three-layer honeycomb panels, but under the conditions of heating that differ substantially from a nonhermetic instrumental compartment. The sole exception is provided by study [16], in which a combinatorial mathematical model of the heat-exchanging panel of SC has been suggested, but the results of its implementation have not been presented.

In mathematical simulation of the processes of conductive heat exchange in instrument-radiator and other types of three-layer honeycomb panels the following main assumptions are made:

1. Nonstationary temperature fields are calculated in each honeycomb panel of the blocks and modules of the nonhermetic instrumental compartment separately in their own local Cartesian coordinate system, with the *OZ* axis being always directed inward.

2. The temperature gradient over the thickness of high-conductive metal facings of honeycomb panels is disregarded (approximation of a thermally thin wall).

3. The temperature gradient over the thickness and height of the structure elements is disregarded.

4. The honeycomb filler is considered as a continuous anisotropic (orthotropic) porous medium with efficient thermophysical characteristics. Radiative heat exchange is not taken into account.

5. The thermophysical characteristics of all the materials used to manufacture a panel are considered to be constant.

6. Heat supply from the thermally loaded on-board equipment to the inner surface of the metal facing of the honeycomb panel is simulated by assigning boundary conditions of the second kind on the mounting seats of devices with allowance for a uniform or nonuniform heat release, including that by cyclograms.

7. Heat removal from thermally loaded on-board equipment to LTHPs along the lines of their laying is simulated by assigning boundary conditions of the third kind in the zone of contact of the LTHPs with the inner surface of the metal facing of the honeycomb panel through an adhesive joint. Here, in determining the temperature head, vapor temperature is taken as the characteristic temperature of the low-temperature heat pipes.

Within the framework of the assumptions made the dynamic thermal mathematical model in distributed parameters of instrument-radiator and other types of three-layer honeycomb panels in the Cartesian coordinate system has the form

$$\frac{\partial T_m}{\partial t} = a_{\rm f}\left(\frac{\partial^2 T_m}{\partial x^2} + \frac{\partial^2 T_m}{\partial y^2}\right) + Q_m , \quad m = 1, 2 , \quad 0 < x < L_x , \quad 0 < y < L_y , \quad 0 \le t \le 24\ {\rm h} ; \tag{8}$$

$$\frac{\partial T_{\rm h}}{\partial t} = a_{{\rm h}.x}\frac{\partial^2 T_{\rm h}}{\partial x^2} + a_{{\rm h}.y}\frac{\partial^2 T_{\rm h}}{\partial y^2} + a_{{\rm h}.z}\frac{\partial^2 T_{\rm h}}{\partial z^2} , \quad 0 < x < L_x , \quad 0 < y < L_y , \quad \delta_{\rm f2} < z < \delta_{\rm f2} + \delta_{\rm h} , \quad 0 \le t \le 24\ {\rm h} ; \tag{9}$$

$$\frac{\partial T_m}{\partial t} = a_{\rm st}\frac{\partial^2 T_m}{\partial \xi^2} + \Phi_m + \Phi_{m.{\rm c}} , \quad m = \overline{3, 6} , \quad 0 < \xi \le 2\,(L_x + L_y) , \quad 0 < t \le 24\ {\rm h} ; \tag{10}$$

$$\left.\frac{\partial T_m}{\partial n}\right|_{\Gamma_m} = 0 , \quad m = 1, 2 ; \tag{11}$$

$$\left.\frac{\partial T_{\rm h}}{\partial n}\right|_{F_{\rm h}} = 0 ; \tag{12}$$

$$-\lambda_{{\rm h}.z}\left.\frac{\partial T_{\rm h}}{\partial z}\right|_{z=\delta_{\rm f2}} = \alpha_{\rm fh}\,(T_2\,(x, y, t) - T_{\rm h}|_{z=\delta_{\rm f2}}) , \tag{13}$$

$$\lambda_{{\rm h}.z}\left.\frac{\partial T_{\rm h}}{\partial z}\right|_{z=\delta_{\rm f2}+\delta_{\rm h}} = \alpha_{\rm fh}\,(T_1\,(x, y, t) - T_{\rm h}|_{z=\delta_{\rm f2}+\delta_{\rm h}}) , \tag{14}$$

$$\left.\frac{\partial T_3}{\partial \xi}\right|_{\xi=0} = \left.\frac{\partial T_6}{\partial \xi}\right|_{\xi=2(L_x+L_y)}, \quad T_3|_{\xi=0} = T_6|_{\xi=2(L_x+L_y)}, \tag{15}$$

$$T_m(x, y, 0) = T_{\text{int}}, \quad m = 1, 2, \quad 0 \le x \le L_x, \quad 0 \le y \le L_y; \tag{16}$$

$$T_{\text{h}}(x, y, z, 0) = T_{\text{int}}, \quad 0 \le x \le L_x, \quad 0 \le y \le L_y, \quad \delta_{\text{f2}} < z < \delta_{\text{f2}} + \delta_{\text{h}}; \tag{17}$$

$$T_m(\xi, 0) = T_{\text{int}}, \quad m = \overline{3, 6}, \quad 0 \le \xi \le 2(L_x + L_y). \tag{18}$$

Thermal model (8)-(18) describes the conductive heat exchange in seven basic elements of a honeycomb panel: carrying metal facings (quasi-two-dimensional equations (8)), an anisotropic honeycomb filler (three-dimensional equation (9)), and elements of the structure (quasi-one-dimensional equation (10)) with boundary conditions (15) characteristic of linear periodic problems.

Formulas for the effective thermal conductivity coefficient of a cellular honeycomb filler of hexagonal structure made of aluminum foil in each of the coordinate directions as a function of the sizes of honeycomb cells, their thickness, and the thermal conductivity coefficient of the foil material are presented in [2].

The thermal model (8)-(18) can be closed by determining the source terms Q_m, Φ_m, and $\Phi_{m.\text{c}}$ in Eqs. (8) and (10) responsible for the external, internal, and contact heat exchange:

$$Q_1 = \frac{\sum\limits_n q_{\text{se},n} + E_{\text{r},1} - q_{\text{cond}} - \sum\limits_k q_{\text{hp},k} - q_{\text{fst1.1}}}{\delta_{\text{f1}}\,\rho_{\text{f}} c_{\text{f}}},$$

$$q_{\text{se}.n}(x, y, t) = \frac{P_{\text{se}.n}(x, y, t)}{F_{\text{se}}}, \quad n = \overline{1, N_{\text{se}}}, \tag{19}$$

$$q_{\text{cond},1}(x, y, t) = \lambda_{\text{h}.z} \left.\frac{\partial T}{\partial z}\right|_{z=\delta_{\text{f2}}+\delta_{\text{h}}}, \quad q_{\text{hp},k}(x, y, t) = \alpha_{\text{fp},k}\,[T_1(x, y, t) - T_{\text{V},k}(t)],$$

$$k = \overline{1, N_{\text{hp}}},$$

$$q_{\text{fst},1} = \alpha_{\text{fst}}\,[T_1(0, y, t) + T_1(x, L_y, t) + T_1(L_x, y, t) +$$

$$+ T_1(x, 0, t) - (T_3 + T_4 + T_5 + T_6)];$$

$$Q_2 = \frac{q_{\text{S}}(t) + q_{\text{cond}} - \varepsilon_2 \sigma_0 T_2^4 - q_{\text{fst}.2}}{\delta_{\text{f2}}\,\rho_{\text{f}} c_{\text{f}}}, \quad q_{\text{cond}.2}(x, y, t) = \lambda_{\text{h}.z} \left.\frac{\partial T}{\partial z}\right|_{z=\delta_{\text{f2}}}, \tag{20}$$

$$q_{\text{fst},2} = \alpha_{\text{fst}}\,[T_2(0, y, t) + T_2(x, L_y, t) +$$

$$+ T_2(L_x, y, t) + (x, 0, t)\,T_2 - (T_3 + T_4 + T_5 + T_6)];$$

$$\Phi_3 = \frac{\alpha_{\text{fst}}\,[T_1(0, y, t) + T_2(0, y, t) - 2T_3]}{h_{\text{st}}\,\rho_{\text{st}}\,c_{\text{st}}}; \tag{21}$$

$$\Phi_{3,c} = -\frac{\alpha_c (\bar{T}_3 - \bar{T}_{m.c})}{\delta_{st}\, \rho_{st}\, c_{st}}; \tag{22}$$

. . . .

$$\Phi_6 = \frac{\alpha_{fst}\, [T_1 (x, 0, t) + T_2 (x, 0, t) - 2T_6]}{h_{st}\, \rho_{st}\, c_{st}}; \tag{23}$$

$$\Phi_{6,c} = -\frac{\alpha_c (\bar{T}_6 - \bar{T}_{m.c})}{\delta_{st}\, \rho_{st}\, c_{st}}. \tag{24}$$

Single-shelf uncontrolled LTHPs of a PTCS, which are built into the anisotropic honeycomb filler over inner and outer facings of the panels, which have small mass in comparison with traditionally used (in hermetic compartments) liquid-contour ones, and which operate on the principle of a closed evaporation-condensation cycle [17, 18], play a decisive role in ensuring thermal regimes of on-board equipment sensors and isothermicity of the panels themselves. The network of LTHPs in the panels of the PM consists of single pipes, two-pipes bundles that thermally connect the instrument-radiator panels and the central panel facing the earth, and three-pipes bundles that thermally connect all the three panels of the PM block and that provide transfer of excess heat through the central panel to the North and (or) South instrument-radiator panels during their half-year periodic illumination by the sun. In the PPB and ILB of SSM only bundles of three and four uncontrolled LTHPs are used. Heat is supplied or removed from them mainly in the zones of the mounting seats of the on-board equipment sensors by means of heat conduction through the uniformly distributed thermal resistance of the adhesive joint of the LTHP shelf with the facing of the panel. The most important features of the operation of LTHPs within honeycomb panels of a nonhermetic instrumental compartment are: multiplicity of the zones of evaporation, transport, and condensation; nonuniformity of heat supply (heat removal) along the perimeter; absence of a perfectly thermally insulated zone of transport; presence of bundles made of several pipes. The main limitations on the operation of LTHPs are attributed to the phenomena of "hydrodynamic choking" and "steaming" of capillary structure [19].

The well-known conductive (without allowance for a detailed analysis of the hydrodynamics and heat- and mass transfer in a vapor channel) dynamic thermal mathematical models of LTHPs in lumped [20] and also distributed parameters with allowance for axial [21] and additionally circumferential thermal conductivity [22] do not take into consideration the noted most important features of operation of LTHPs in the panels of the PM and SSM of a nonhermetic instrumental compartment and therefore call for their further development and refinement.

Mathematical simulation of heat transfer in single-shelf uncontrolled LTHPs, built into an anisotropic honeycomb filler over inner and outer facings of the panels in the PM block, ILB, and PPB of SSM of a nonhermetic instrumental compartment, is carried out within the framework of conductive dynamic thermal mathematical models in lumped parameters of the type of [20] using the following basic assumptions:

1. A single LTHP (or a bundle of pipes) operates in a subcritical regime (absence of hydrodynamic choking, boiling-up, and freezing of the heat-transfer agent).

2. Heat transfer over the constructional elements of an LTHP in the axial direction is not taken into account.

3. Supply (removal) of heat is nonuniform along the perimeter and is limited by the sector $-\varphi_1 \le \varphi \le \varphi_1$.

4. Vapor is in the state of saturation, and its temperature along an LTHP is constant.

5. The evaporation (condensation) zones of an LTHP coincide with the longitudinal dimensions of the mounting seats of the on-board equipment sensors and with the lengths of the zones of connection of two LTHPs in a bundle.

6. Heat-transfer coefficients in the phase transitions of the heat-transfer agent in the evaporation and condensation zones of an LTHP are constant.

Other assumptions are generally known and set out in [20].

Conductive dynamic thermal mathematical models in lumped parameters of single-shelf uncontrolled LTHPs with allowance for the special properties of their laying and operation in the PM and SSM panels of a nonhermetic instrumental compartment represent a system of heat balance equations and initial conditions for each ith element (evaporation, transport, condensation, and vapor zones):

$$\sum_j \sigma_{ji}(T_j - T_i) = C_i \frac{dT}{dt} + \sum_k \sigma_{ik}(T_i - T_k)\,, \quad T_i(0) = T_{i,\text{int}}\,, \tag{25}$$

where j and k are the elements in thermal coupling with the ith element and participating in the supply and removal of heat.

The introduction of a rather realistic (for the conditions considered) additional assumption about the equality, as a first approximation, of the temperatures of the vapor and the transport zone [18] makes it possible to represent the generalized conductive thermal model (25) for a bundle of three LTHPs of the PM block in the form of a system of $7 + N_{\text{se},1} + N_{\text{se},2} + N_{\text{se},3}$ heat-balance equations with the corresponding initial conditions:

$$\sigma_{\text{fp},1n}(\bar{T}_{\text{f},1n} - T_{\text{E},1n}) = C_{\text{E},1n}\frac{dT_{\text{E},1n}}{dt} + \sigma_{\text{E}1,1n}(T_{\text{E},1n} - T_{\text{V},1})\,, \tag{26}$$

$$\sum_n \sigma_{\text{E}1,1n}(T_{\text{E},1n} - T_{\text{V},1}) = C_{\text{V},1n}\frac{dT_{\text{V},1}}{dt} + \sigma_{\text{C},1}(T_{\text{V},1} - T_{\text{C},1})\,,$$

$$\sigma_{\text{C},1}(T_{\text{V},1} - T_{\text{C},1}) = C_{\text{C},1}\frac{dT_{\text{C},1}}{dt} + \sigma_{\text{pp}12}(T_{\text{C},1} - T_{\text{E},2})\,,$$

$$T_{\text{E},1n}(0) = T_{\text{V},1}(0) = T_{\text{C},1}(0) = T_{\text{int}}\,, \quad n = \overline{1, N_{\text{se},1}}\,;$$

$$\sigma_{\text{pp},12}(T_{\text{C},1} - T_{\text{E},2}) = C_{\text{E},2}\frac{dT_{\text{E},2}}{dt} + \sigma_{\text{E},2}(T_{\text{E},2} - T_{\text{V},2})\,, \tag{27}$$

$$\sigma_{\text{fp},2n}(\bar{T}_{\text{f},2n} - T_{\text{E},2n}) = C_{\text{E},2n}\frac{dT_{\text{E},2n}}{dt} + \sigma_{\text{E}2,2n}(T_{\text{E},2n} - T_{\text{V},2})\,,$$

$$\sigma_{\text{E},2}(T_{\text{E},2} - T_{\text{V},2}) + \sum_n \sigma_{\text{fp},2n}(\bar{T}_{\text{f},2n} - T_{\text{E},2n}) = C_{\text{V},2}\frac{dT_{\text{V},2}}{dt} + \sigma_{\text{C},2}(T_{\text{V},2} - T_{\text{C},2})\,,$$

$$\sigma_{\text{C},2}(T_{\text{V},2} - T_{\text{C},2}) = C_{\text{C},2}\frac{dT_{\text{C},2}}{dt} + \sigma_{\text{pp},23}(T_{\text{C},2} - T_{\text{E},3})\,,$$

$$T_{\text{E},2}(0) = T_{\text{E},2n}(0) = T_{\text{V},2}(0) = T_{\text{C},2}(0) = T_{\text{int}}\,, \quad n = \overline{1, N_{\text{se},2}}\,;$$

$$\sigma_{\text{pp},23}(T_{\text{C},2} - T_{\text{E},3}) = C_{\text{E},3}\frac{dT_{\text{E},3}}{dt} + \sigma_{\text{E},3}(T_{\text{E},3} - T_{\text{V},3})\,, \tag{28}$$

$$\sigma_{\text{E},3}(T_{\text{E},3} - T_{\text{V},3}) = C_{\text{V},3}\frac{dT_{\text{V},3}}{dt} + \sum_n \sigma_{\text{C}3,3n}(T_{\text{V},3} - T_{\text{C},3n})\,,$$

$$\sigma_{C3,3n}(T_{V,3}-T_{C,3n}) = C_{C,3n}\frac{dT_{C,3n}}{dt} + \sigma_{fp,3n}(T_{C,3n}-\bar{T}_{f,3n}),$$

$$T_{E,3}(0) = T_{V,3}(0) = T_{C,3n}(0) = T_{int}, \quad n = \overline{1, N_{se,3}},$$

where $N_{se,1}$, $N_{se,2}$, and $N_{se,3}$ are the number of sensors on the line of the laying of LTHP in the South, Central, and North panels, respectively.

The system of equations (26)-(28) can easily be extended to a bundle of two LTHPs and a single LTHP which are also included into the network of pipes in the PM panels.

The generalized conductive thermal model (25) for a bundle of four LTHPs of the ILB of SSM is written in the form of a system of $12 + N_{se,1} + N_{se,2}$ heat-balance equations with corresponding initial conditions, where $N_{se,1}$ and $N_{se,2}$ is the number of sensors in the plane of the laying of LTHPs respectively on both sides of the instrumental panel which does not participate directly in the external heat exchange.

The generalized conductive thermal model (25) for a bundle of three LTHPs of the PPB of SSM is represented by a system of $7 + N_{se,1} + N_{se,3}$ heat-balance equations with the corresponding initial conditions, where $N_{se,1}$ and $N_{se,3}$ is the number of sensors on the line of the laying of LTHPs in the South and North panels, respectively.

Contact heat exchange is important in detachable and permanent joints of homogeneous and inhomogeneous elements of the construction of a nonhermetic instrumental compartment: joints of panels; zones of connection of LTHP through a shelf; shelves of LTHP and facings; honeycomb filler and facings; facings and elements of the structure of the honeycomb panel. All of the listed forms of contact heat exchange are taken into account in boundary conditions (13) and (14) and also in the source terms of Eqs. (19) and (20). The methods used to calculate the coefficients of contact thermal conductivity of certain types of connections are presented in [23, 24]. However, it should be noted that for the actual construction of a nonhermetic instrumental compartment before carrying out field heat-vacuum tests these coefficients are distinguished by considerable uncertainty. According to the classification made in [25], the developed dynamic thermal mathematical models (1)-(25) of RCHE in blocks and modules with thermally loaded on-board equipment in the nonhermetic instrumental compartment of a durable communication SC in the real physical time scale with its regular triaxial orientation in a geostationary orbit relate to second-level thermal models, in which the thermal state of the isolated most important elements of the construction is described in distributed and lumped parameters.

Mathematical simulation of RCHE yields space- and time-dependent spatial temperature fields in all the panels of the blocks and modules of a nonhermetic instrumental compartment, which thereafter are employed to analyze thermal regimes of the on-board equipment sensors by using the maximum and minimum temperatures on mounting seats, thermally elastic stressed-strained state, and solution of other problems.

Numerical implementation of quasi-two-dimensional (8) and three-dimensional (9) nonstationary equations of heat conduction in the carrying facings and anisotropic honeycomb filler is carried out by the finite-difference method following an economical noniterative two-layer scheme of component-by-component splitting (method of fractional steps) with the Yanenko weights [26] on a fixed irregular grid. Numerical implementation of quasi-one-dimensional nonstationary equations of heat conduction in the elements of the structure (10), if they are considered as a closed system, is performed along the marching coordinate by the method of cyclic fitting [27]. The systems of ordinary differential equations of type (26)-(28), which serve for determining the current values of the mean temperatures in the zones of evaporation, transport, and condensation of LTHP, after the reduction to the Cauchy problem, are implemented numerically following an implicit scheme of the first or second order of accuracy. The mean angular emissivities were calculated by double numerical integration over the area of integral (3) with the aid of the formula of rectangles. The system of linear algebraic equations (4) was solved by the Gauss–Seidel iterative method. There is provision for controlling computations on each time layer by checking the overall integrated heat balance in a three-layer honeycomb panel and local heat balances on the mounting seats of all heat generating on-board equipment sensors, integrated heat balance

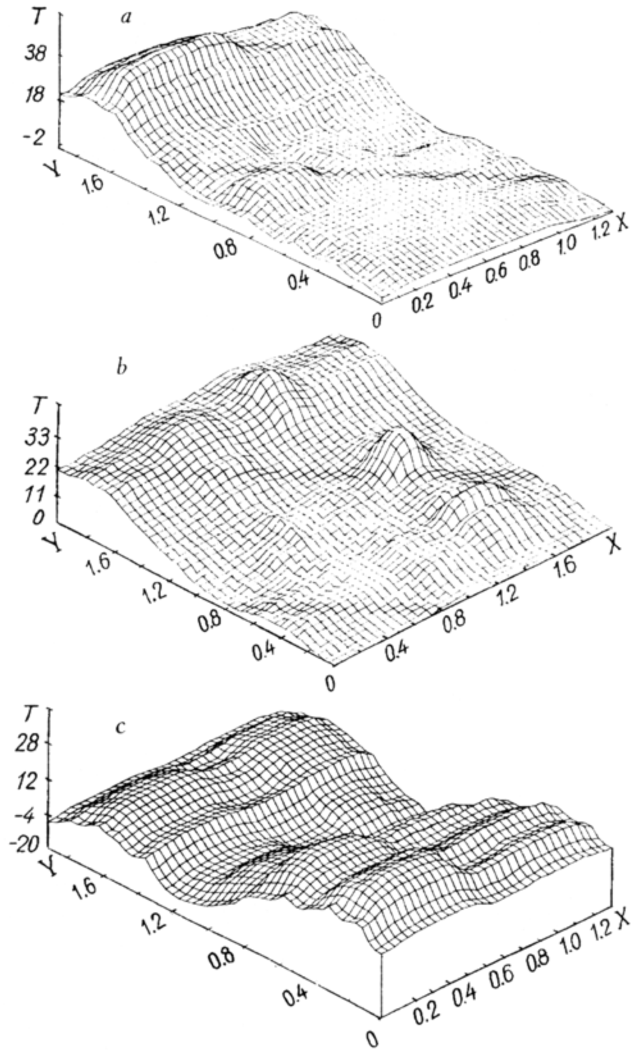

Fig. 2. Three-dimensional distribution of temperature fields over the inner facing of the South instrument-radiator panel of PM (a), Central instrument panel of PM (b), and North instrument-radiator panel of PM (c). T, ^{o}C; X, Y, m.

during the operation of single LTHPs and LTHPs in bundles, and also in calculation of the internal radiative heat exchange.

A procedure of automatic generation of an irregular grid has been devised; it includes the construction of a geometric grid, which, in accordance with the drawing, isolates all the inhomogeneities typical of a given thermal problem (mounting seats of devices, lines of laying of LTHPs, and zones covered with heat insulation) and finer grid to calculate the nonstationary conductive heat exchange and the construction of a system of isothermal area elements to calculate the internal radiative heat exchange by the zone method.

Versions of six structured computer programs (MPPN, ILB, EDB, MPN, MSS, PRO) have been developed in a high-level algorithmic language Visual C++ (v.6.0) for IBM-compatible PCs and working stations. The programs have been blocked into a specialized software system (SSS) COMSTAN (v.1.0) making it possible to simulate nonstationary processes of RCHE in blocks, modules, and over the entire nonhermetic instrumental compartment of a communication SC in all actual regimes of orbital operation in a geostationary orbit, including the occurrence of emergency situations. The results of numerical calculations of nonstationary multidimensional temperature fields in three-layer honeycomb panels and the parameters of LTHPs are processed using up-to-date technologies of graphic and multiplication visualization and also by high-quality color computer animation.

The COMSTAN specialized software system is oriented to a thorough study of the mechanisms of RCHE in rather typical thermally loaded anisotropic structures to be used in outer space. The COMSTAN specialized software system is adapted to the aims and problems of the integrated system GRADIENT for computer-aided design of promising durable communication SC [28].

Within the framework of the COMSTAN specialized software system, under the MPN program, a computational experiment has been carried out to investigate the dynamics of RCHE processes in the PM of a nonhermetic instrumental compartment of a proposed durable communication SC at the point of winter solstice at the end of the active service life (A_s = 0.26; θ = 66.5°). The overall power of heat release was 1072 W. A PTCS was used which was based on a network of uncontrolled ammonia LTHPs of a diameter of $14.5 \cdot 10^{-3}$ m with a grooved capillary structure. Time was reckoned from the start of illumination of the East removable cover and the South panel.

A fundamental picture of the processes and phenomena of RCHE in the PM has been obtained. The spatial distribution of quasi-two-dimensional nonstationary temperature fields over the inner (instrumental) aluminum-alloy facings of the panels in the Π-shaped PM block at the instant t = 6 h is shown in Fig. 2. It is found that the level of temperatures on the mounting seats of the on-board equipment sensors corresponds to their heat-release power, and there is a noticeable orientation of the isotherms along the lines of the laying of operating LTHPs acting as virtually isothermal heat conduits (especially on the shaded North panel). The vapor temperature of the LTHPs was in the range 3.3–28.0°C for the South panel; 2.4–26.3°C for the Central panel, and −10.3–22.2°C for the North panel. Bundles of three LTHPs operated in the regime of excess heat transfer in two directions from the on-board equipment sensors on the panels: South–Central–North and Central–South–North, and a bundle of two LTHPs: Central–South and Central–North panels. Single LTHPs operated only up to the instant of creating isothermal conditions along the lines of their laying. The level of mean internal radiant fluxes of net radiation at the instant t = 6 h was equal to −15, −28, and 18 W/m^2 for the South, Central, and North panels and to 150 and −120 W/m^2 on the East and West removable covers, respectively.

The presented results of numerical calculations on the distribution of spatial temperature fields allow one to make a conclusion about the degree of isothermicity of honeycomb panels and the quality of design for the system of provision of a thermal regime of the on-board equipment sensors of the PM in a nonhermetic instrumental compartment of a proposed durable communication SC.

NOTATION

a, thermal diffusivity; A_S, integrated (total) hemispherical absorptivity; c, C, specific and total heat capacity; E, radiative flux density; Γ, boundary; F, area; h, height; L_x, L_y, linear dimensions of the panel; N_{hp}, N_r, N_{se}, number of the heat pipes, area elements, and sensors of the on-board equipment; P, heat-release power of the sensor; q, heat flux density; Q_m, source term (8); r, distance; S_0, density of direct solar radiation flux; t, time; T, temperature; $\bar{T}$, mean-integral temperature; Φ_m, Φ_{mc}, source terms (10); x, y, z, Cartesian coordinates; α, coefficient of contact thermal conductivity; δ, thickness; δ_{ij}, block function; ε, integrated (total) hemispherical emissivity; θ, angle between the normal to the radiant surface and the direction to the sun; λ, thermal conductivity coefficient; ρ, density; ξ, marching coordinate along the perimeter (structure elements) of the honeycomb panel; σ, thermal conductance; σ_0, Stefan–Boltzmann constant; φ_{ij}, mean angular coefficient of radiation between area elements i and j; φ_1, angle of heat supply (heat removal). Subscripts: c, contact between two honeycomb panels; cond, conductive; C, condensation zone; eff, radiative flux of efficient radiation; ES, shaded area of the earth; E, evaporation zone; f, facing; fst, contact of the facing with the structure elements; fp, contact of the facing with the heat pipe; h, honeycomb filler; hp, heat pipe; int, initial conditions; m, n, ordinal numbers; pp, contact between two heat pipes; r, radiant flux of net radiation; se, on-board equipment sensor; st, structure elements; S, direct solar radiation; V, vapor; 1,2, carrying facings; 3, 4, 5, 6, elements of the structure of a three-layer honeycomb panel. Abbreviations: EC, electronics components; ERC, electroradio components; AL, active lifetime.

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