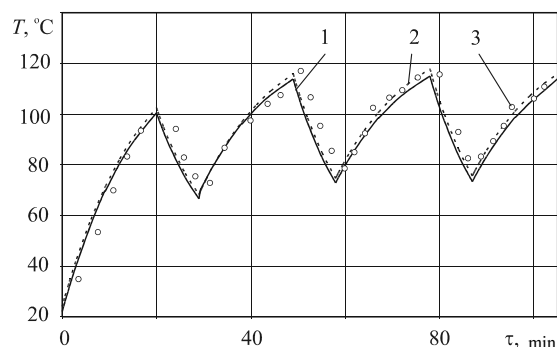perature for the given type of electric insulation. Otherwise, it is necessary to turn to intermittent work with the period of current load $\tau_н$ and the pause $\tau_о$ alternation.

Figure. *The time change of betatron winding peak temperature in the point X=0,5: 1) exact analytical solution; 2) approximate calculation; 3) experimental data [3]*

Winding temperature conditions of PMB – 6 type betatron with a lattice pole is estimated by concrete examples [2]. The results of calculations of the betatron winding peak temperature are shown in the Figure.

The highest deviation value of the peak temperature computed by the approximate calculation relative to the exact solution achieves 10 % during the first cycle of heating and cooling. During the last cycles this value is not more than 4 %. The solution obtained in this way allows investigating the temperature conditions of this winding in the wide range of geometrical and electrophysical parameters change.

Conclusion

For the first time, the approximate dependences for calculating transient temperature in betatron winding with the limited number of heating – cooling cycles are obtained. They may be used only for estimating thermal condition of electromagnet devices which specific electric losses in magnetic circuit is significantly less than in the winding. The calculated dependences are checked-up by comparing with the experimental data from scientific literature.

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TECHNIQUES OF ANALYSING HEAT CONDITIONS IN ELECTRON DEVICES OF SPACECRAFT

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On the bases of thermal macrolevel models of electron device and construction elements the technique of analysing heat conditions of unpressurized electron spacecraft equipment has been developed. The technique involves formation of electric loss sequence diagram for connected thermal and electric analysis, which makes possible to increase the accuracy and reliability of heat analysis for the device and its elements.

The required stage in engineering process of space craft (SC) electron devices (ED) is the analysis of heat conditions by the results of which the ED working capacity is estimated. The analysis of heat conditions of ED elements is the most urgent at its arrangement outside of pressure container and increase of SC required active life to 10 and more years.

The characteristic property of electron devices aboard SC is their operation in dynamic conditions when electron devices of power supply systems, orbit coordination and others operate by turns depending on SC orbital position. Heat release power and temperature fields in ED nodes and blocks change respectively that requires the investigation of dynamic heat conditions of ED and its elements.

This problem may be solved only using advanced manufacturing sciences of multidisciplinary calculations. In this case it is a connected electric and heat analysis allowing us to take into consideration the interference of electric and heat conditions of ED [1–6].

The available at present software (BETASoft, Ansys, Nastran, T-Flex, ABAQUS, CosmosWorks etc.) does not allow carrying out the connected electric and heat analysis in one package with the possibility to determine three-dimensional temperature fields by ED con-

struction and temperature on heat loaded elements of the device [5, 6].

At the same time the modern packages of circuit simulation allow studying transient and steady-state processes of ED electric networks and calculating the dynamic of heat release at circuit elements on the bases of macrolevel models. However, the technique of forming the equivalent network of ED thermal model is not formalized in them and there is no the functional of reciprocal data transmission between electric and thermal models as well as the question of calculation accuracy is still open. Therefore, the development of thermal models of electro-radio products (ERP) and the device construction elements and the technique of heat conditions analysis, allowing us to solve the problems of connected analysis, is urgent.

Thermal models may be presented by mathematical models of micro- and macrolevel [2, 7]. The model of microlevel is described by differential heat conduction equation in partial derivatives with edge condition. The number of jointly studied different mediums in practically used models of microlevel can not be large due to computational complexity. It is possible to decrease the computational costs entering the assumption on space discretization that gives an opportunity to pass to the models of macrolevel (macromodels). The mathematical models of macrolevel are the systems of algebraic and ordinary differential equations. On the bases of these models the technique allowing analyzing ED thermal conditions subject to heat load ERP integration has been suggested.

The component and topological equations serve as initial data for macrolevel models formation. Properties of elements (components) are described by the component equations and their interactions in analyzed system are described by the topological ones. The identical notation of mathematical ratios which describe electric and thermal processes stipulate formal analogy of their component and topological equations and equivalent schemes. This gives an opportunity to investigate thermal conditions, setting transition coefficients, by means of the package of circuit simulation and carry out the connected electric and thermal analysis of ED in one package that is not realized at the moment in packages using component-topological models [7].

The suggested technique allows forming a mesh by ED construction similar to finite-element one and connecting ERP models without mesh changing that can not be done using the finite-element method. ERP models are connected with the equivalent circuit through thermal resistances included between the node in which the average temperature of ERP mounting surface is determined and the nodes of triangular elements of ED construction mesh. Owing to this fact the simplified models of ERP may be constructed and stored in the library of models that is a certain advantage of the given approach.

To ascertain the quantitative connection between thermal and electric parameters the following coefficients are entered: $k_C=1$ °C·F/J; $k_R=1$ Wt·Ohm/°C; $k_t=1$ V/°C; $k_q=1$ A·s/J. the following parameters are connected by these coefficients: $C_e=k_C C_т$ is the thermal capacity and electric capacity; $R_e=k_R R_т$ is the electric and thermal resistance; $\varphi=k_t t$ is the electric potential and temperature; $I=k_q q$ is the electric and heat current.

For ED completed outside the pressure container the assumption about absence of temperature gradient along the thickness of the construction elements is true (Fig. 1, a) as their linear sizes exceed significantly the
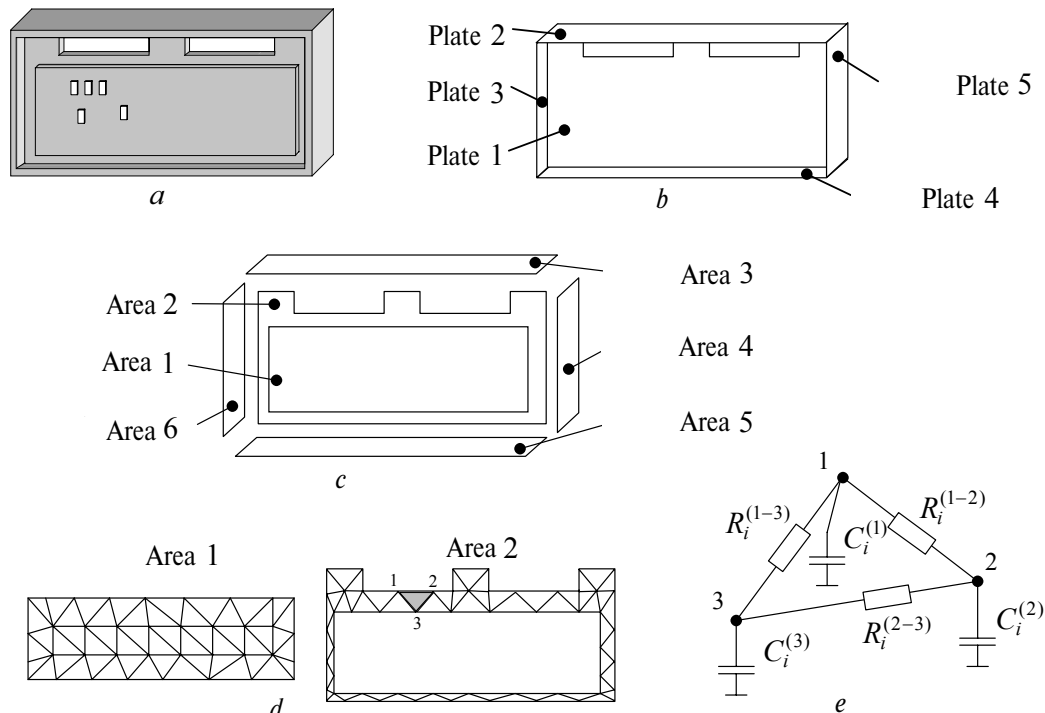
Fig. 1. Stages of forming thermal model equivalent circuit: a) solid model; b) construction presented in the form of thin plates; c) areas are defined on thin plates; d) areas divided into triangular elements; e) a part of the equivalent circuit of area 2

thickness [4]. The accepted assumption allows representing the thermal models of the construction elements in the form of thin planes set (Fig. 1, *b*). At such approach the ED equivalent circuit is formed by the following algorithm:

1. On the obtained thin-wall plates in interactive mode the areas are extracted (Fig. 1, *c*). For each area the thermaphysical properties of material and sampling increment are set.

2. The triangular mesh (Fig. 1, *d*) meeting the Delone criterion is constructed automatically in each area according to the specified sampling increment [3, 8]. According to this criterion other nodes of this mesh should not occur inside the circle circumscribed around any triangular element. After this the continuous numbering of triangular mesh nodes is carried out.

3. Each *i* triangular element of the mesh is specified by three nodes (vertices) which are also the nodes in the equivalent circuit (Fig. 1, *e*). Heat capacities $C_i^{(1)}$, $C_i^{(2)}$, $C_i^{(3)}$ which are connected by thermal resistances $R_i^{(1-2)}$, $R_i^{(2-3)}$, $R_i^{(1-3)}$ are installed into these nodes for imitating thermal processes persistence. The given resistances imitate conduction heat-transfer along the device construction. Their magnitudes for *i* triangular element are calculated by the formulas:

$$\begin{cases} R_i^{(1-2)} = \dfrac{4S}{\delta\lambda((y_2-y_3)(y_3-y_1)+(x_3-x_2)(x_1-x_3))}; \\[3mm] R_i^{(2-3)} = \dfrac{4S}{\delta\lambda((y_3-y_1)(y_1-y_2)+(x_1-x_3)(x_2-x_1))}; \\[3mm] R_i^{(1-3)} = \dfrac{4S}{\delta\lambda((y_2-y_3)(y_1-y_2)+(x_3-x_2)(x_2-x_1))}, \end{cases}$$

where $R_i^{(1-2)}$, $R_i^{(2-3)}$, $R_i^{(1-3)}$ are the thermal resistances between the nodes of triangular element, °C/Wt; δ is the thickness of the element, m; $\{x_1, y_1\}$, $\{x_2, y_2\}$, $\{x_3, y_3\}$ are the coordinates of triangular element vertices, m; λ is the heat conductivity coefficient of element material, Wt/(m·°C); S is the area of the triangular element, m².

In its turn, $S=0{,}5[(x_2-x_1)(y_3-y_1)-(x_3-x_1)(y_2-y_1)]$.

The values of heat capacities $C_i^{(1)}$, $C_i^{(2)}$ and $C_i^{(3)}$ are calculated by the formula

$$C_i^{(1)} = \frac{c_{sp}\rho S\delta}{3},$$

where $C_i^{(1)}=C_i^{(2)}=C_i^{(3)}$ are the heat capacities in the nodes of the triangular element, J/°C; δ is the thickness of the element, m; c_{sp} is the specific heat capacity of element material, J/(kg·°C); ρ is the specific density of element material, kg/m³.

4. Owing to nodes continuous numbering the development of area equivalent circuit comes to connecting the triangular element subcircuit to the proper nodes of the triangular mesh on which the area is divided. Due to the common nodes located on the boundary of areas the automatic joining of areas equivalent circuits occurs, as a result of which the ED equivalent circuit is formed.

5. The main radiating areas are singled out for accounting heat exchange by radiation in interactive conditions. After this in automatic mode the first triangle is selected from the first area and from the second one such triangle is selected which allows obtaining the least distance between them. Then nonlinear thermal resistance R_i which imitates the heat exchange by radiation is connected in the nodes of two subcircuits of triangular elements. All triangles of singled out areas are searched by this algorithm.

Nonlinear thermal resistance R_i, °C/Wt is determined by the formula

$$R_n = K_R \frac{t_1 - t_2}{\left(\dfrac{t_1+273}{100}\right)^4 - \left(\dfrac{t_2+273}{100}\right)^4},$$

where t_1, t_2 are the average temperatures of triangular elements, taking part in heat exchange, °C; $K_R=(5{,}67\varepsilon\varphi S)^{-1}$ is the coefficient depending only on body geometrics and conditions of heat exchange by radiation, °C⁴/Wt; ε is the emissivity; φ is the irradiance coefficient.

The value of irradiance coefficient φ of two mutually parallel situated triangular elements depending on distance between them is calculated by the formula [1]

$$\varphi = 0{,}837\left(1 - e^{\frac{-0{,}452a}{h}}\right),$$

where a is the side of the triangular element, m; h is the average distance between two triangular elements, m.

6. The areas participating in convective heat transfer in the conditions of free convection are singled out in interactive mode. Then between the node where the ambient temperature is specified and the nodes of areas triangular elements in which the average temperature of the element is defined the nonlinear thermal resistance R_{con} imitating heat exchange by convection is connected in automatic mode [1]

$$R_{con} = \frac{1}{NAS\left(1{,}662 - 0{,}0031\left(\dfrac{t+t_{amb}}{2}\right)\right)(t-t_{amb})^{1/3}},$$

where N is the coefficient allowing for surface orientation; A is the coefficient allowing for physical medium parameters, Wt/(m²·°C^{1/3}); t is the average temperature in triangular element, °C; t_{amb} is the ambient temperature, °C.

Thus, thermal models of the device construction elements are formed if the form of equivalent circuits the magnitudes of element parameters of which are calculated by the presented formulas.

As it is enough to determine average temperature of REA element body for analyzing its thermal conditions in this connection the model of the element is simplified (Fig. 2).

The equivalent circuit of such model consists of thermal resistance R_c imitating conduction heat transfer along ERP body and mount, nonlinear thermal resistan-

ces R_n and R_{con} imitating heat exchange by radiation and convection heat transfer, heat capacities C_e and source of heat release I. The elements in the equivalent circuit are connected according to Fig. 2. The value of thermal resistance R_c, °C/Wt is calculated by the formula

$$R_c = \frac{b}{\lambda_e S_s},$$

where b is the thickness of the layer between ERP and a site, m; λ_e is the effective coefficient of layer material heat conductivity, Wt/(m·°C); S_s is the area determined by the surface of ERP contact with its site, m².
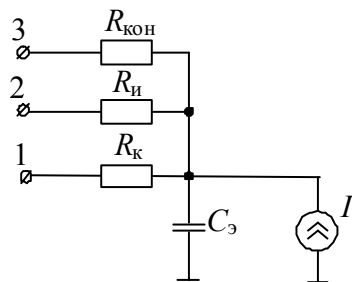

Fig. 2. *Simplified thermal model of construction element*

The presented thermal model of ERP allows using the values of thermal resistances R_c and heat capacity C_e specified in technical conditions or obtained experimentally that increases its accuracy and sufficiency.

To specify thermal loads at carrying out connected thermal and electric analysis the technique is developed. At the first stage of this technique the modes of operation (T_i, P_i) cyclogram defining the sequence of ED modes of operation is formed (Fig. 3) where T_i is the duration of ED operating conditions, s; P_i is the load power, Wt; $i=1...N$ is the number of modes. Then the electrical modeling where each mode is studied at time slice τ corresponding to the time of transients establishment in the circuit is carried out.

Then by the results of electric modeling of each mode of operation of the device the array $(i,P_1,...,P_j,...,P_M)$ is produced. In this array $j=1...M$ is the number of accountable heat release sources; P_j is the value of electric losses at j heat release source which is extrapolated to the time T_i of ending a certain mode of operation
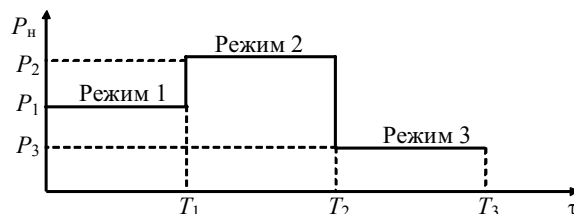

Fig. 3. *Cyclogram of ED modes of operation (Режим – Mode)*

Thermal conditions are analyzed with the use of circuit simulation package Spice on ED thermal model and calculated magnitudes of electric losses that allows computing accurately average and peak temperature values at ED elements.

The developed technique of analyzing SC ED thermal conditions performed outside of pressure container is based on macrolevel models that gives an opportunity to carry out the connected thermal and electric analysis in one package, acquire the library of typical construction elements and ERP, use thermal parameters of ERP or construction elements specified in technical conditions and obtained experimentally. The technique includes the formation of electric losses cyclograms for carrying out the connected thermal and electric analysis that allows increasing the accuracy and adequacy of the analysis of device thermal conditions and its elements. The application of suggested technique for analyzing ED thermal condition of power supply system in satellite system «Glonass» allowed decreasing overheats at the device elements, increase reliability and improve their dynamic indices.

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