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THERMAL SIMULATION OF ELECTRICAL DEVICES

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UDC 536.24

A classification of a wide class of electrical instruments is presented, their thermal and mathematical models are formulated, and a "thermal mode" subsystem is considered in a general system of computer-aided design.

The modern development of power engineering, machine construction, radio engineering and other areas of industry requires a greater and greater use of high-power electrical equipment — power and transformer devices, rectifier units, power supplies and other devices based on high-power thyristors, diodes, and transistors. The development of such apparatus involves solving a number of problems, one of which is to ensure the normal thermal operating conditions. The increasing rate of increase in production, the increasing complexity of the construction of the devices, and the reduction in the time available for development require solutions of design problems using computer-aided methods, where the thermal design must be regarded as a subsystem in the overall design system. To set up such a subsystem it is necessary to solve a number of problems of which one of the main ones is to develop thermal and mathematical models for the devices considered and to realize them in practice.

Hierarchical Principle of Layout. For a systematic approach to the design, the individual electrical devices or apparatus are considered as a whole, their characteristic components are distinguished, and the relations between them are studied [1]. Optimum design of the device architecture is carried out with a further stage-by-stage optimization of the constructional units. The systematic approach is based on the hierarchical principle of modeling, which is considered in detail below.

The main circuits and construction of high-power and transformer equipment have been considered fairly completely in [2-7], and analysis of this enables us to distinguish the following hierarchical levels.

The first level includes constructionally completed elements and components of the construction, viz., transistors, thyristors, diodes, and other devices. The devices of the second level are typical replacement elements, the main constructional units (modules), which combine one or several semiconductor elements 1, together with an individual or group 2 of cooling systems. Examples of the use of different forms of cooling — air, liquid, and evaporative, are shown in Fig. 1a [3-7].

Leningrad Institute of Precision Mechanics and Optics. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 40, No. 6, pp. 1062-1069, June, 1981. Original article submitted March 3, 1980.

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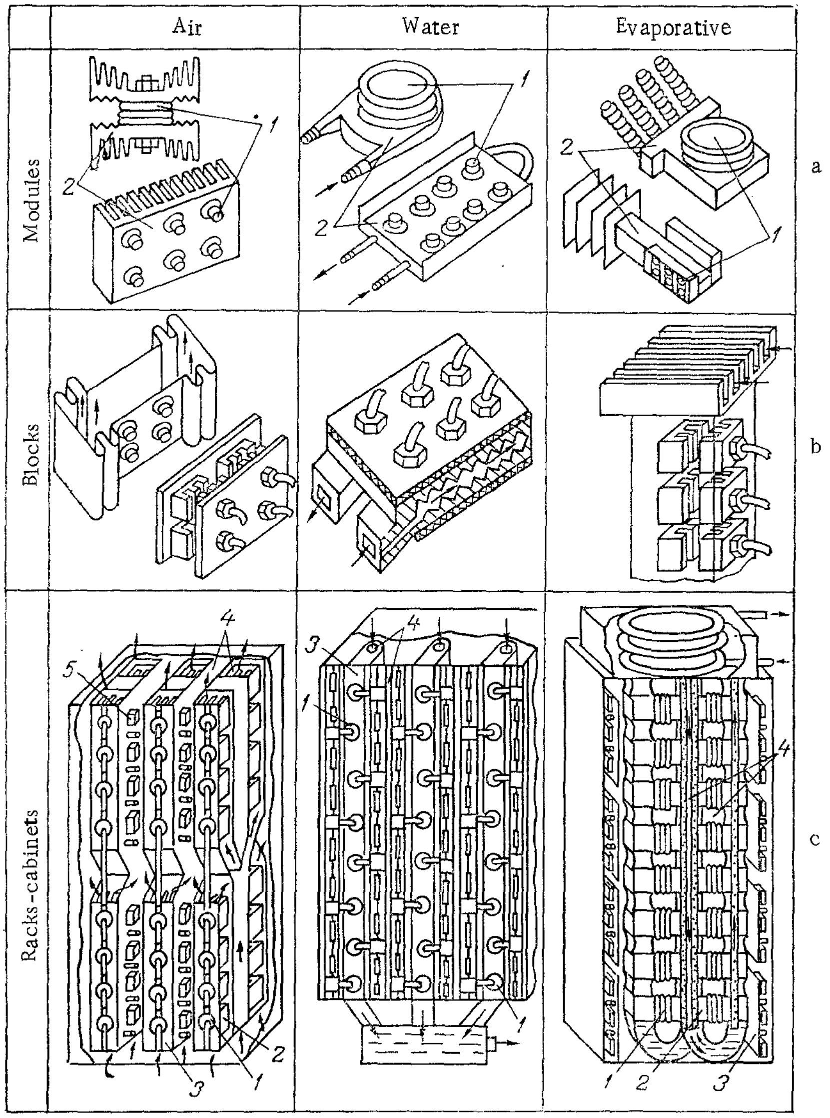

Fig. 1. Classification of the constructions and cooling systems of high-power semiconductor devices: a) modules; b) blocks; c) racks—cabinets.

The third level of the hierarchy consists of units which are a set of cooled modules (Fig. 1b), considered in the second stage. These can be parts of a rack, panels, cabinets, or independent devices. A characteristic feature of the units is the mutual thermal effect on one another of modules close together, and on the heating of the coolant in the channels between them [2].

The fourth level (Fig. 1c) includes racks, cabinets, and panels consisting of several units or modules [2], representing the final construction and which fulfill a certain function.

The modules 3 are arranged inside or on the surface of the channels 4 of the cooling system and dissipate heat to the cooling agents through the surface of the heat exchanger 2, and certain elements 1 can simultaneously exchange heat with several channels.

The more likely loaded elements 5 (Fig. 1c) are cooled by natural convection, internal agitation or by inflow-outflow ventilation set up inside the cabinet or rack. Sometimes a heat exchanger is provided to cool the air inside the cabinet or rack.

A higher, fifth stage of the hierarchy can include rooms and compartments in which the equipment, racks, units and devices are placed.

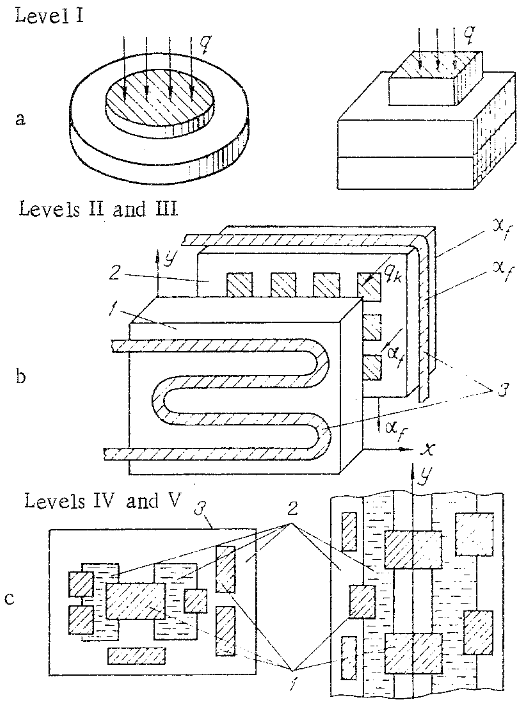

Fig. 2. Thermal models of high-power semiconductor devices: a) the first level — a system of discs or parallelepipeds; b) the second and third levels — plates for complex thermal actions; c) the fourth and fifth levels — a system of arbitrarily arranged bodies which exchange heat with heat carriers in one or several channels.

Thermal and Mathematical Models. A mathematical description of the thermal processes in the electrical devices considered can be given using the principle of stage-by-stage modelling. The following models correspond to the constructions considered above.

For the first stage is a model of the transistors, thyristors, and diodes in the form of a system of several discs, plates, and parallelepipeds [9-11], as shown in Fig. 2a. The thermal model of a system of plates for complex thermal actions corresponds to the second and third levels (Fig. 2b).

To investigate the temperature field of the fifth and fourth levels of construction, we will use a model of a system of arbitrarily situated bodies which exchange heat carriers in one or several channels [1, 8], Fig. 2c.

The model of the fifth and fourth levels is a set of arbitrarily arranged modules 1 (Fig. 2c) which exchange heat with one another and with heat carriers in channels 2. The modules with cooling systems are contained in the case 3 which is generally subjected to different external actions. For a closed cooling system there are heat exchanges inside the channels to cool the heat carriers and to compensate for the vapor in evaporative cooling systems.

We will write the heat-balance equations for all the elements of the rack. The thermal flux, released by the i-th body, goes to increase its heat content and is transmitted to the j-th surrounding bodies and the cooling agents in the F channels in which the i-th body is situated. The thermal flux received by the cooling agent of the f-th channel from bodies which carry away the heat goes to increase the temperature and evaporation (in evaporative cooling) of the cooling agent. If there is a heat exchanger in the f-th channel, the thermal flux received by the cooling agent of the f-th channel is transmitted to it:

$$c_i \frac{dt_i}{d\tau} + \sum_{\substack{j=1 \\ j \neq i}}^{J} \sigma_{ij}(t_i - t_j) + \sum_{f=1}^{F} \sigma_{if}[t_i - t_f(y)] = P_i,\ i = 1 - I, \tag{1}$$

$$\sum_{i=1}^{n} \sigma_{if}[t_i - t_f(y)] = G_{vf}\rho_f c_{pf}\Delta t_f + C_f \frac{d\bar{t}_f}{d\tau} + r_f \frac{dm_f}{d\tau},\ f = 1 - F, \tag{2}$$

$$\sum_{i=1}^{I} \sigma_{if}(t_i - t_f) = P_{\tau f};\ \tau = 1 - T. \tag{3}$$

The boundary and initial conditions are

$$(t_f)_{y=0} = t_{\text{in}},\ (t_i)_{\tau=0} = t_{i0},\ (t_f)_{\tau=0} = t_{f0}. \tag{4}$$

The first group of equations (1) corresponds to the number of bodies in the rack I, and the second group (2) corresponds to the number of channels F in which heat exchange occurs. The equations of group (3) are determined by the number T of heat exchangers in the channels.

To solve this system of equations, it is necessary to find its parameters σ_{ij} and σ_{if}. The thermal conductances between the solids σ_{ij} can be calculated using well-known methods [8] and depend on their thermal properties and mutual positions. Considerable difficulties arise when determining the coefficients σ_{ij}, since they are functions of a large number of factors and primarily of the method of cooling. For air and liquid cooling the heat-exchange parameters are determined by simultaneous solution of the hydrodynamic problems [12, 13] and the heat-exchange problem in channels of complex shape [14].

For an evaporative system the heat-exchange coefficient in the channel will be a complex function depending on many factors [15].

The thermal model of the third and second levels can be represented in the form of mutually connected plates when there are complex thermal actions (Fig. 2b), between which the cooling agent flows. Sources of heat exist on their surfaces. Channels 3 with the heat carriers can be arranged on the periphery and also at the central part. The model is described mathematically using a system of differential equations for the plates with local energy sources and sinks and with heat exchange from the main surfaces and ends:

$$c_1\rho_1 \frac{\partial t_1}{\partial \tau} = \lambda_{x1} \frac{\partial^2 t_1}{\partial x^2} + \lambda_{y1} \frac{\partial^2 t_1}{\partial y^2} + \sum_{i \neq 1}^{n} b_{1i}(t_1 - t_i) + \sum_{1}^{K_1} q_{k1}(x, y),$$

$$c_2\rho_2 \frac{\partial t_2}{\partial \tau} = \lambda_{x2} \frac{\partial^2 t_2}{\partial x^2} + \lambda_{y2} \frac{\partial^2 t_2}{\partial y^2} + \sum_{i \neq 2}^{n} b_{2i}(t_2 - t_i) + \sum_{1}^{K_2} q_{k2}(x, y);$$

where $b^2_{1,2i} = \alpha_{1,2i}/\delta_{1,2}$, 1 and 2 are the plates in the block, and i are the surrounding bodies and media, including plate 2 for plate 1 and vice versa.

The heat exchange of the plate in the channel can be found as follows: the whole thermal flow received by the cooling agent in the f-th channel is carried away by the flow and it is heated or it evaporates if there is an evaporative cooling system:

$$\Sigma\sigma_{1,2}[t_{1,2} - t_f(x, y)] = G_{vf}\rho_f c_{pf}\Delta t_f + C_f \frac{d\bar{t}_f}{d\tau} + r_f \frac{dm_f}{d\tau},$$

where f is the medium in which the heat exchange occurs. The boundary conditions for plate 1 are

$$\frac{\partial t_1}{\partial x} \pm \frac{\alpha_f}{\lambda_x}[t_1 - t_f(x)]_{x=0, L_{x1}} = 0,$$

$$\frac{\partial t_1}{\partial y} \pm \frac{\alpha_f}{\lambda_y}[t_1 - t_f(y)]_{y=0,\ L_{y1}} = 0.$$

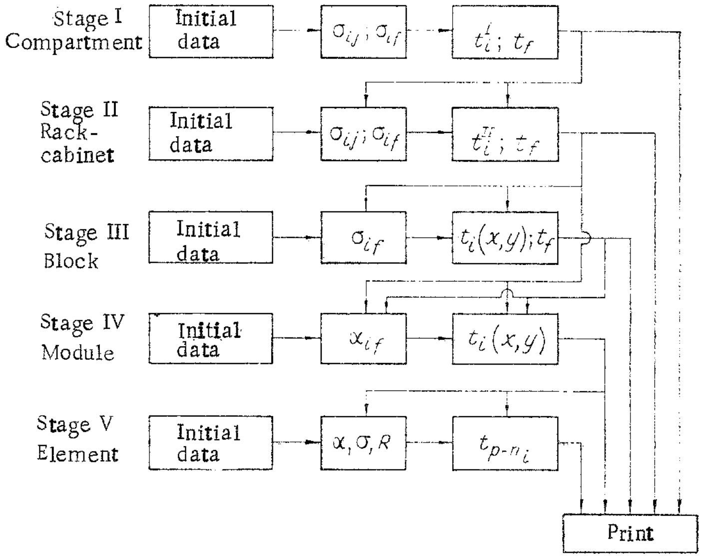

Fig. 3. Block diagram of the algorithm for calculating the thermal fields of electrical devices.

The boundary conditions can be written similarly for plate 2. The initial conditions are

$$t_{1\tau=\tau0} = t_{01}(x, y);\ t_{2\tau=\tau0} = t_{02}(x, y).$$

The model of the element base — transitors, diodes, and thyristors — belongs to level I. Here the temperature field of the device itself and the operating part of its p–n junction, which is a heat-sensitive element, is of interest. The efficiency of the element and of the device as a whole depends on whether the construction and its cooling system ensure that its temperature is not higher than the critical value.

To determine the temperature field of the element, it is necessary to know its internal construction. A description of the construction of semiconductor devices and their thermal models was formulated in [10-12, 16], where the latter were represented by a system of discs (Fig. 2c), plates, or parallelepipeds with lumped or distributed heat sources.

The above systems of equations can be solved by different methods: analytically, numerically, by analog methods, etc. The choice of method is determined by the means available and the specific nature of the problem. Certain special cases are considered in [10, 17, 18].

Block Diagram of an Algorithm for Calculating the Thermal Fields of Electrical Devices. The hierarchical principle of thermal modeling [1] enables one, by considering all the levels successively, to carry out an overall modeling of complex electrical equipment and to take all their energy actions into account beginning from the external — surrounding — medium and including all the heat sources in the crystal of the semiconductor device. This process should be carried out beginning with the last, coarsest level, where the external actions and the arrangement of the elements in the overall structure of the apparatus are taken into account, and then, with the required degree of detail, one considers the heat exchange in the individual devices, i.e., in elements of lower levels. The initial data for analyzing each of the latter levels is information on its construction and the results obtained for the previous stage.

The details of the devices and the number of hierarchical levels are determined both by the complexity of the construction and the required calculation accuracy.

The general procedure for calculating the temperature fields of electrical equipment corresponds to the block diagram in Fig. 3.

In stage I, using model (1)-(4) of "arbitrary arrangement," the mean temperatures t^I of the racks in one room (compartment) are determined, and the temperatures of the heat carriers t_f used to cool them. When preparing the data the thermal conductances σ_{ij} and σ_{if} between the individual devices and the cooling media are determined. The same model is used in stage II to determine the temperature t_i^{II} for blocks and modules inside the rack and the temperature distribution of the heat carriers in the channels t_f (1)-(4). The initial data are the thermal conductances between the elements of the rack, its geometry, and also the thermal actions determined in stage I.

In stages III and IV, to determine the temperature field of the blocks and modules, one finds the temperature field of the plates with local heat sources and also the dependence of the heat-carrier temperature on the coordinates. One first determines the heat-exchange parameters of the modules with the cooling medium and its temperature.

In stage V, using the temperatures obtained above of the points where the devices are connected and of the surrounding medium, one calculates the distribution inside the semiconductor element. The initial data will be the thermal coupling of the device with the substrate and the medium, and the internal thermal resistances.

NOTATION

t_i and t_j, temperature of the i-th and j-th bodies (modules, blocks, plates, elements, casing, etc.); t_f, temperature of the liquid or gaseous medium in the channels; p_i, power of the heat source in the i-th body; σ_{ij}, thermal conduction between the i-th and j-th bodies; σ_{if}, thermal conduction between the i-th body and the medium in the f-th channel; C_i, and C_f, total heat capacity of the i-th body and the cooling agent of the f-th channel; G_{vf}, ρ_f, $c_{\rho f}$, r_f, m_f, volume flow rate, density, specific heat capacity, specific heat of vaporization, and mass of the cooling agent of the f-th channel, respectively; τ, time; p_{Tf}, thermal flux removed by the heat exchanger in the medium of the f-th channel; $q_{k_{1,2}}$, specific power of the local heat sources in the plate; α_f, $\alpha_{f_{1,2}}$, effective heat-exchange coefficients of the plates at the ends and on the main surfaces; λ_{xi}, λ_{yi}, thermal conductivity of the materials of the i-th body; $L_{x_{1,2}}$ and $L_{y_{1,2}}$, dimensions of the plates 1 and 2; $\delta_{1,2}$, thickness of the plates 1 and 2; $\Delta t_f = t_{out} - t_{in}$, temperature drop in the f-th channel; $\bar{t_f} = \frac{1}{y}\int_0^y t_f dy$, mean-volume temperature of the cooling agent of the f-th channel; y, current coordinate in the direction of liquid flow; and n, number of bodies in the part of the f-th channel considered.

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ESTIMATE OF THE ENERGY DISTRIBUTION OF A MULTIMODE uhf FIELD IN RESONATOR SYSTEMS BASED ON HEATING OF A LIQUID DIELECTRIC

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UDC 664.853.56

A method is presented for estimating the results of experimental investigations of the nonuniformity of the energy distribution of an electromagnetic field in the cavity of a "Slavyanka" uhf (microwave) furnace.

In processes of thermal treatment, for the power supply of uhf (microwave) energy as systems connecting sources of electromagnetic energy with the product being treated, use is made of cavity resonators, in which a multimode electromagnetic field is excited [1]. The resulting vector of the intensity of the electric component of the field in an arbitrary element of volume is determined by the vector sum of the intensity of all forms of oscillations at the given point [2]. The value of the resulting field intensity depends on the form of the resonator, the method of excitation of electromagnetic oscillations in it, the frequency of the source of excitation, and the coordinates of the point of observation: the value does not depend on the time. An analytic description of such an inhomogeneous field represents an extremely complicated mathematical problem.

To estimate the nonuniformity of the distribution and the efficiency of the systems being used for "equalizing" the electromagnetic field in the resonator chambers intended for the thermal treatment of the products, it is advisable to apply methods based on the actual absorption of electromagnetic energy at each element of the cavity volume by the material being treated. The main point of one of those methods consists in the determination of the quantity of heat transformed in the liquid enclosed in a calorimeter that is "transparent" to microwaves. (In our case the calorimeter consists of a double cylinder of capacity $125 \cdot 10^{-6}$ m^3, made of plastic.)

The energy absorbed by the liquid (distilled water) in the calorimeter, neglecting phase transformations, is determined by the equation of balance

$$dW = (c_w m_w + c_c m_c)\, d\bar{t}. \tag{1}$$

The diameter of the calorimeter and the thickness of its walls were considered with account of the skin effect and a relation between the mass of the calorimeter and the distilled water for which neglect of the term $c_c m_c$ in Eq. (1) introduces an error that does not exceed 4%.

Moscow Technological Institute of the Food Industry. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 40, No. 6, pp. 1070-1074, June, 1981. Original article submitted January 8, 1980.