of volatiles per unit volume of wood. Subscripts; e, during moisture evaporation; i, ignition delay; w, body surface; s, solid; v, volatile; V, parameters per unit body volume; m, moisture (water); *, combustion zone in boundary layer. Superscripts, R, λ, c, radiant, conductive, and convective thermal flux components; *, solid fuel ignition condition; S_w, evaporation surface area.

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THERMAL AND MATHEMATICAL MODELING OF OPTOELECTRONIC DEVICES

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Mathematical models describing the thermal regime of optoelectronic devices are substantiated, and a method for realizing such models is proposed — stage by stage modeling.

1. Formulation of the Problem. Optoelectronic devices (OED's) are complex systems consisting of component parts such as optical and mechanical parts, radiation detectors and sources, electronic circuits, etc. The thermal regime of an OED has an effect on both quality and reliability of operation of the individual components and the device as a whole.

A number of studies have analyzed the thermal regime of individual OED elements (mirror, lens, radiation detector) [1-4].

Below we will consider optoelectronic devices as a whole and offer a method for their thermal modeling, which permits analysis of temperature fields of individual OED elements with consideration of external effects and basic thermal linkages.

2. Heirarchical Principle of OED Composition. A detailed description of OED construction can be found in [5-7]; analysis of the literature permits us to classify the following structural levels.

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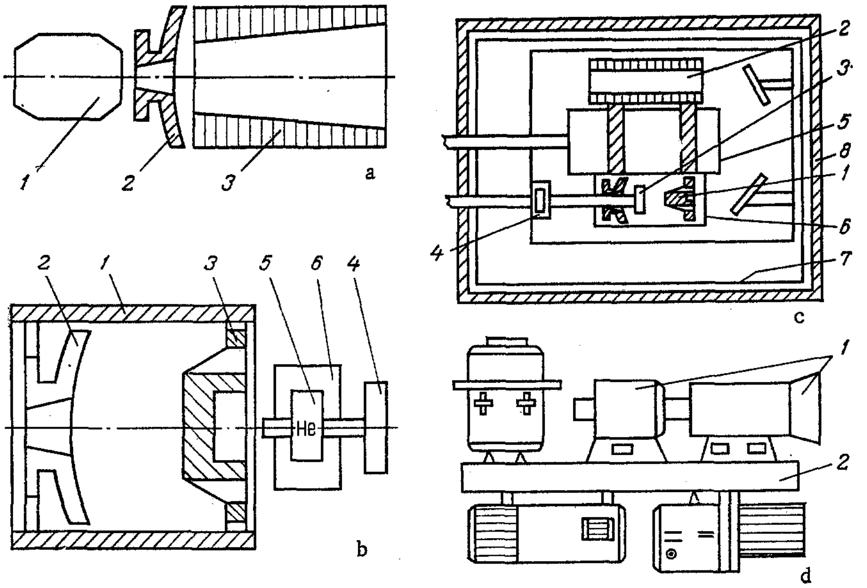

Fig. 1. OED construction levels: a) elements; b) modules; c) functioning device.

The lowest level consists of individual elements: parts of the device which cannot be divided further without destroying their integrity, for example, optical system parts (mirrors, lenses, prisms, couplers, etc.), mechanical parts (leads to scanning and tracking systems, various converters, modulators), radiation sources (laser, gas-discharge tube, incandescent lamp, and LED components), etc.

Figure 1a shows some individual OED components: mirrors 1 and 2, coupler 3.

At the second level, we have modules composed of first level elements: optical, mechanical, and electrical modeules, radiation sources and detectors. As a rule these modules have their own chassis, and in a number of cases, provisions for regulating their thermal regimes.

Cryostats are used to cool the individual system, coupled to the volume to be cooled by heat exchangers, thermal bridges, or thermal tubes, thermoelectric batteries, choke-type heat exchangers, or vortex tubes [8-10]. For devices operating under space conditions radiant cooling is used; various heaters are used to supply heat [7, 11].

Figure 1b shows an OED objective, consisting of a chassis 1, two mirrors 2, 3, radiation detector 4 with an individual cooling system, consisting of helium cryostat 5, surrounded by screen 6.

The third construction level is the optoelectronic device itself, consisting of individual second level modules and first level elements with a common cooling system. The device is a complete construction which performs some definite function. The modules are combined into a device using brackets, cards, guide and carrier rods, chasses, etc. [5]. Cryostats, thermobatteries, refrigeration devices, and radiators are used for cooling with heaters to supply heat [7-11].

Figure 1c shows the construction of an OED composed of objective 1, coupler 2, radiation detector 3 with individual cooling system 4. The coupler and objective are cooled by contact with nitrogen vessel 5. The coupler, objective, and nitrogen container are surrounded by two screens 6, 7. The entire device is located within a chassis 8.

On the fourth structural level we may consider groups of devices 1, located in one instrument compartment or on one platform 2 (Fig. 1d).

3. Stage-by-Stage Modeling of Optoelectronic Devices. In the general case the thermal model of the OED consists of a large number of regions with complex configuration arbitrarily arranged in a space with heat sources and sinks. These regions exchange heat with each other, with the surrounding medium, and with the cooling agent. The most complete mathematical description of the temperature fields of such systems consists of a system of differential equations for thermal conductivity of the solid bodies, and equations of motion, continuity, and state for the cooling agent flows with corresponding boundary and initial conditions.

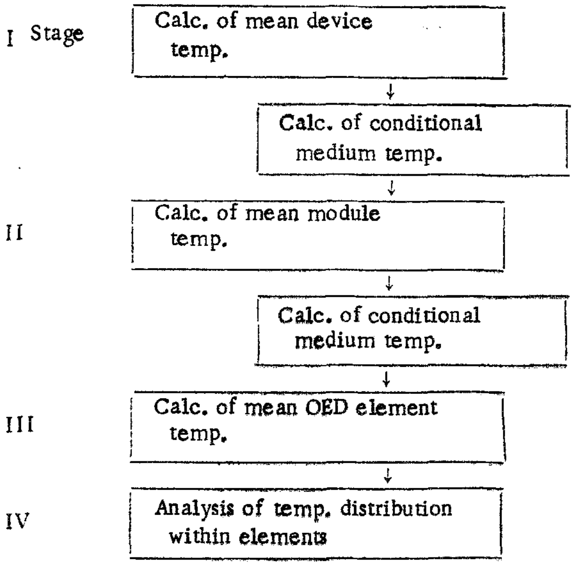

Fig. 2. Block diagram of stage-by-stage OED calculation.

In the majority of cases realization of an OED mathematical model is difficult or impossible even with the aid of modern computers. Moreover, this approach is also unsuitable because of imprecise knowledge of the input information required for the calculation (heat liberation coefficients, thermophysical properties of the bodies, cooling agent flow rates, etc.).

Attempts to calculate thermal regimes of various complex electrical, electronic, and energy-production devices have demonstrated the effectiveness of the approach which is called stage-by-stage modelling [12, 13]. The essence of this method is the following. The thermal regime of the complex system is calculated in several stages using various thermal and mathematical models. In the initial stage the system is considered as a whole with minimum attention to details, considering external influences and the location of the devices within the general structure of the object. In subsequent stages, using the required degree of detail, heat exchange in individual devices, modules, and finally, individual elements is analyzed. Averaged values of thermal flux or temperatures of surrounding bodies found in previous calculation stages are substituted in the boundary conditions on the body surfaces.

Model construction in the stage-by-stage method consists of consolidating the original model, combining its individual parts for calculation of certain averaged characteristics, followed by decomposition — singling out individual elements or groups thereof for more detailed analysis. Consolidation methods and techniques for combining individual system elements into a subsystem may vary, and are determined by the structure of the object [13, 14] and the method used for analysis of temperature fields [15]. In the most general case with arbitrary object structure consolidation methods are very complex. Therefore it is most appropriate to undertake consolidation and detailization in accordance with some heirarchy determined by the particular structure in question.

Mathematical models of the thermal regime of an optoelectronic device correspond to the various levels of the structural heirarchy and permit calculation of: mean temperatures of details and devices located in one compartment or on one platform; mean temperatures of individual modules (optical, electronic, mechanical, etc.), and temperature fields of individual elements.

In the general case the number of stages in the calculation may vary, and is defined by the complexity of the construction under study and the accuracy required. A diagram of the stage-by-stage model construction process is shown in Fig. 2.

We will now consider the individual stages, corresponding thermal and mathematical models, and possible methods for their realization.

4. Thermal and Mathematical OED Models. Stage I — Calculation of Mean Surface Temperatures of Devices in the Compartment. We will consider a group of devices and mechanisms located within a single compartment or on a single platform. The components exchange heat with

each other, the compartment walls or platform surface, and also with the surrounding medium. This heat exchange is accomplished by conduction, radiation, and convection under atmospheric conditions, or by conduction and radiation under space conditions. The heat sources are those devices in which heat liberation occurs and external sources, for example, solar radiation. We will consider the temperature fields of the individual components to be uniform at this stage. In this case the mathematical formulation of the problem reduces to a system of ordinary differential equations [15]:

$$c_i \frac{dT_i}{d\tau} + \sum_j^N (T_i - T_j)\sigma_{ij} = P_i - Q_i - (T_i - T_c)\sigma_{ic},$$
$$T_c = \text{const}, \quad i = 1, 2, \ldots, N, \tag{1}$$

with initial conditions

$$T_i|_{\tau=0} = T_{i0}. \tag{2}$$

Expressions for calculation of the thermal flux Q_i removed from a device by a thermal tube, thermobattery, or refrigerator are presented in [8-10].

To move to the following stage, analysis of the thermal regime of individual devices, the temperatures $\tilde{T}_i$ of nominal media are calculated for each device, i.e., heat exchange between the i-th body and surrounding bodies with temperatures T_j ($j = 1, 2, \ldots, N$) and with the medium is replaced by heat exchange with a nominal medium with temperature $\tilde{T}_i$ defined in the following manner [15]:

$$\tilde{T}_i = \Big(\sum_j^N \sigma_{ij}T_j + \sigma_{ic}T_c\Big)\Big/\Big(\sum_j^N \sigma_{ij} + \sigma_{ic}\Big). \tag{3}$$

The temperature of the nominal medium for all device surfaces is considered constant and independent of coordinate. This assumption and also the assumption of temperature field uniformity within the devices in the first calculation stage are justified by the principle of local effect: any perturbation is of a local character [16]. The errors produced by this technique can be evaluated analytically or experimentally.

The system of ordinary differential equations can be solved by one of the numerical methods or approximation.

<u>Stage II — Calculation of Mean Module Temperatures.</u> In this stage we consider the thermal regime of the optoelectronic device, commencing from heat exchange with a nominal medium. The goal of the calculation is determination of nominal media temperatures for individual modules. The thermal model for this stage is a system of regions arranged in no special order (the modules), which exchange heat with each other, the device body, and the nominal medium. Heat exchange is accomplished by radiation, conduction, and convection in heat exchangers.

The temperature fields of the individual regions (bodies of objectives, collimator, coupler, screens, etc.) can be considered one-dimensional and variable over length in this stage. Analysis reveals that temperature change over element thickness may be neglected.

Temperature change over length of the regions usually does not exceed several degrees,* so that the thermophysical properties of the materials and heat liberation coefficients may be considered coordinate-independent, and heat exchange can be characterized by the mean temperatures of the individual surfaces. Then the thermal flux P_i, liberated in the i-th region increases the enthalpy of that region $c_i dT_{vi}/d\tau$, is transferred to other bodies of the system $\sum_k \sum_j \sum_l \sigma_{ij}(T_{ik} - T_{jl})$ to the nominal medium $\sum_k \sigma_{ik,c}(T_{ik} - \tilde{T}_i)$ and is also removed by the thermal tube, thermobattery, or refrigerator Qi:

$$C_i \frac{dT_{vi}}{d\tau} + \sum_k \sum_j \sum_l \sigma_{ij}(T_{ik} - T_{jl}) = P_i - Q_i - \sum_k (T_{ik} - \tilde{T}_i)\sigma_{ic}. \tag{4}$$

System (4) is supplemented by equations relating the mean volume and mean surface temperatures of the bodies [17]:

*Satisfaction of this condition is necessary for normal operation of the optical system.

$$\sum_j (T_{1i}-T_j)\sigma_{ij}+\sigma_{1vi}(T_{1i}-T_{vi})+\sigma_{12i}(T_{1i}-T_{2i})=0,$$
$$\sum_j (T_{2i}-T_j)\sigma_{ij}+\sigma_{2vi}(T_{2i}-T_{vi})+\sigma_{12i}(T_{2i}-T_{1i})=0, \qquad (5)$$
$$i=1,\ 2,\ \ldots,\ N,$$

where $T_{1i} = T_i(z)|_{z=0}$; $T_{2i} = T_i(z)|_{z=L_i}$. Expressions for calculation of the coefficients σ_{12}, σ_{1v}, and σ_{2v} are presented in [17, 18].

Convective heat exchange in thermal tubes and system heat exchangers will be characterized by a heat liberation coefficient α. Estimation of the Brun criterion [19] indicates that it is significantly less than 0.1. In this case the error produced by this approach does not exceed 5% as compared to solution of the conjugate problem [20].

Liquid temperature and pressure changes over the length of the heat exchangers and thermal tubes in each region are insignificant, so that the thermophysical properties and liquid flow rate can be considered coordinate-independent.

The heat capacities of cryogenic liquids and their vapors is much less than the heat capacity of the solid portions of the construction. In light of this fact the terms caused by transient heat exchange processes can be neglected in the equations for the liquid. Then the thermal flux $\alpha_{if}\pi D_e(T_i - T_f)$ entering the liquid form the heat exchanger walls is expended in increasing liquid enthalpy $G_\rho c_p dT_f/dz$ and evaporating liquid Q_f:

$$\pi D_e \alpha_{if}(T_i-T_f)=G_\rho c_p \frac{dT_f}{dz}+Q_f. \qquad (6)$$

The boundary conditions for Eq. (6) are determined by the configuration of the cooling system. Thus, for example, with a serial system, in which at the input to section f + 1 liquid arrives at the temperature of the output of the previous section f, we have

$$T_{f+1}|_{z=0}=T_f|_{z=L_i}. \qquad (7)$$

Integrating Eq. (6) over the length of section f of the heat exchanger, we obtain

$$\sigma_{if}(T_{vi}-\overline{T}_f)=G_\rho c_p(T_{fl}-T_{f0})+\overline{Q}_f, \text{ where}$$
$$T_{vi}=\frac{1}{L_i}\int_0^{L_i} T_i(z)\,dz; \quad \overline{T}_f=\frac{1}{L_i}\int_0^{L_i} T_f(z)\,dz; \qquad (8)$$
$$\overline{Q}_f=\frac{1}{L_i}\int_0^{L_i} Q_f(z)\,dz; \quad T_{f0}=T_f|_{z=0}; \quad T_{fl}=T_f(z)|_{z=L_i}.$$

The relationship between the liquid temperatures T_{fl}, T_{f0} and $\overline{T}_f$ can be obtained by simultaneous solution of the thermal conductivity equations for the channel walls and Eq.(6) for the liquid, or by assuming a linear

$$\overline{T}_f=0.5\,(T_{f0}+T_{fl}) \qquad (9)$$

or logarithmic law of liquid temperature distribution [21]:

$$\overline{T}_f=T_{vi}(m+\exp(-m)-1)/m+T_{f0}(1-\exp(-m))/m,$$
$$T_{fl}=\overline{T}_f\,\frac{(1-\exp(-m))\,m}{m-1+\exp(-m)}+T_{f0}\,\frac{\exp(-m)(1+m)-1}{m(1-\exp(-m))}, \qquad (10)$$
$$m=\sigma_{if}/G_\rho c_p.$$

Thus, in the second stage, the mathematical formulation of the problem reduces to solution of a system of ordinary differential equations (1) and (4) with algebraic equations (5), (8)-(10), with initial conditions (2). The temperatures obtained in the second stage are used to calculate a nominal medium temperature with Eq. (3).

Stage III — Calculation of Mean Temperatures of OED Elements. Here we consider individual OED modules surrounded by a nominal medium. The goal of this stage is definition of the temperatures which will appear in the boundary conditions in analysis of temperature fields of individual elements. The thermal and mathematical models for this stage are determined by the construction of the unit whose thermal regime is under study.

Thermal and mathematical models of electronic modules have been considered in [15]. Models are presented for certain types of radiation sources and receivers in [4, 22].

In the present study we will limit ourselves to consideration of optical systems. The thermal models of these, as in the preceding cases, are systems of unordered bodies (mirrors, lenses, chassis, etc.) exchanging heat with each other and with the nominal medium. Heat exchange occurs by radiation and by conduction through mounting elements. It is appropriate to consider the temperature fields of the regions one-dimensional and variable along the axis (for chasses, couplers) or along radius (mirrors and lenses). Evaluation of the Biot criterion shows that the temperature changes over element thickness can be neglected. As in the preceding case, the thermophysical properties of the materials and heat liberation coefficients will be considered coordinate-independent, while heat exchange between regions will be characterized by mean temperatures of individual surfaces.

With consideration of these assumptions the mathematical formulation of the third stage problem is a system of ordinary differential (4) and algebraic (5) equations.

Stage IV — Analysis of Temperature Distributions in OED Elements. In this stage we consider individual OED elements, surrounded by bodies of known temperatures. As in the preceding case, we limit ourselves to optical system elements: mirrors, lenses, prisms, etc. Thermophysical properties of materials and heat liberation coefficients will be considered coordinate-independent.

In this case the mathematical models are ordinary thermal conductivity equations [23]

$$\nabla^2 T = \frac{1}{a}\frac{\partial T}{\partial \tau} \tag{11}$$

with boundary conditions of the third sort and initial conditions:

$$T(0, \varkappa_i) = T_0(\varkappa_i), \quad \varkappa_i = x,\ y,\ z,\ r. \tag{12}$$

Equation (11) with corresponding boundary and initial conditions can be solved by analytical "exact" or approximate methods, or numerically. Choice of a method is determined by the region studied and the accuracy required.

The results of temperature field analysis may be used to calculate noise levels, tracking or measurement errors, and to calculate thermodeformations and the corresponding thermoaberrations. The initial data to be used are the mean temperatures of the individual elements (for calculation of noises and noise errors), as well as the temperature distribution in the regions (for calculation of thermodeformations).

NOTATION

T_i, T_j, temperatures of bodies i and j; T_c, temperature of surrounding medium; C_i, P_i, total heat capacity and heat power liberated in body i; σ_{ic}, σ_{ij}, thermal conductivity of body i to medium and body j; N, number of bodies in system; τ, time; T_{vi}, mean volume temperature of body i; T_{ik}, T_{jl}, mean temperature of surface k of body i and surface j of body l; T_f, liquid temperature in section f of heat exchanger; σ_{if}, thermal conductivity from heat exchanger wall to liquid; G_ρ, c_p, mass flow rate and specific heat of liquid; D_e, effective diameter; a, thermal diffusivity.

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METHOD OF CALCULATING TEMPERATURE PROFILES IN TWO-PHASE ANNULAR FLOWS

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On the basis of the energy equation, a method of calculating temperature profiles in a liquid film and in the surrounding gas flow is given.

Experimental measurement of local temperatures in the cross section of a thin liquid film is technically very difficult, and does not provide the required accuracy. In this connection, analytical methods of investigation are expedient.

Temperature profiles in two-phase films are determined by the physical properties of the components, the conditions at the inlet, and at the phase boundaries, and also the hydrodynamics of the flow, the parameters of which are unknown [1]. Thus, the problem reduces to solving the energy equation [2]

$$w_l \frac{\partial T_l}{\partial x} = -(a_l + a_{lT}) \frac{\partial^2 T_l}{\partial y^2} + \left(\frac{a_l + a_{lT}}{R-y} - \frac{\partial a_{lT}}{\partial y} \right) \frac{\partial T_l}{\partial y} \quad (1)$$

with the initial conditions

$$T_1 = T_{10}(y), \quad T_2 = T_{20}(y) \text{ for } x = 0 \quad (2)$$

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