2. N. I. Gel'perin, V. G. Ainshtein, and A. V. Zaikovskii, Khim. Neft. Mashinostr., No. 3, 17-20 (1968).
3. V. N. Korolev and N. I. Syromyatnikov, Inzh.-Fiz. Zh., 37, No. 5, 829-835 (1980).
4. A. M. Xavier and J. F. Davidson, in: Proc. Second Engineering Foundation Conference, Cambridge Univ. Press, London—New York (1978), pp. 333-336.
5. Yu. G. Epanov, A. I. Tamarin, and S. S. Zabrodskii, Fuel Combustion with Minimum Harmful Flare-Ups [in Russian], Tallin (1978), pp. 13-14.
6. V. V. Matsnev, I. N. Shteiner, and B. I. Gorelik, Teploénergetika, No. 4, 10-13 (1983).
7. B. I. Gorelik, "Improvement of the operational reliability and efficiency of solid-fuel combustion in furnaces with a low-temperature fluidized bed," Authors's Abstract of Candidate's Dissertation, Engineering Sciences, Leningrad (1986).
8. N. V. Antonishin and S. S. Zabrodskii, Inzh.-Fiz. Zh., 5, No. 2, 10-14 (1962).
9. S. S. Zabrodskii, High-Temperature Fluidized-Bed Apparatus [in Russian], Moscow (1971).

MODELING THERMAL REGIMES OF OBJECTIVES IN OPTOELECTRONIC DEVICES

G. N. Dul'nev, V. V. Barantsev,
and V. G. Parfenov

UDC 536.24

A numerical method is proposed for calculating the temperature field of objectives in optoelectronic devices, based on use of the stage-by-stage modeling method. A set of programs realizing the technique are described.

The thermal regime of optoelectronic devices has a significant effect on the quality and reliability of their operation. An important part of the mathematical modeling of such a device used for design purposes is modeling of the thermal regime. An optoelectronic device is a complex system, including varied optical, mechanical, and electronic components.

The basic method for designing complex systems is the block-hierarchical method, in which the system is successively considered at different hierarchy levels with a gradually increasing degree of detail. The stage-by-stage method of mathematical modeling of heat transport processes, the general principles of which are presented in [1], is most satisfactory for the block-hierarchical method. A hierarchy of component levels for optoelectronic devices for thermal modeling purposes was proposed in [2], with four levels of detail being distinguished. On the first level we have individual elements: mirrors, lenses, reflectors, etc.; on the second level we have optical, mechanical, and electronic devices: lasers, objectives, servolines, etc.; on the third, optoelectronic devices; and on the fourth, groups of devices located in one compartment or one chassis. Such a level structure agrees with the hierarchy of optoelectronic device description used in designing such devices [3].

An essential feature of modeling heat exchange processes is the necessity of considering a process of one and the same physical nature for the entire optoelectronic device with consideration of thermal coupling between elements of the first hierarchical level which belong to subsystems of the second hierarchical level having different physical natures. Therefore, the most complete model of an optoelectronic device thermal regime consists of a system of multidimensional differential thermal conductivity equations for elements of the first hierarchical level and energy equations for the fluxes of heat transport agents with boundary conditions of the first, second, or third sort, or with matching conditions on boundary surfaces. Realization of such a complete model is difficult even with use of modern computers, since the number of elements at the lowest hierarchical level exceeds several hundreds or thousands. The difficulties which occur are related both to the problem of choosing a solution method and the volume of machine time required, and with the volume of initial data appearing in a full model. Moreover, optoelectronic device construction is performed in accordance with the four-level hierarchy described above. Analysis of the thermal regime at

---

Precision Mechanics and Optics Institute, Leningrad. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 54, No. 6, pp. 995-1002, June, 1988. Original article submitted March 18, 1987.

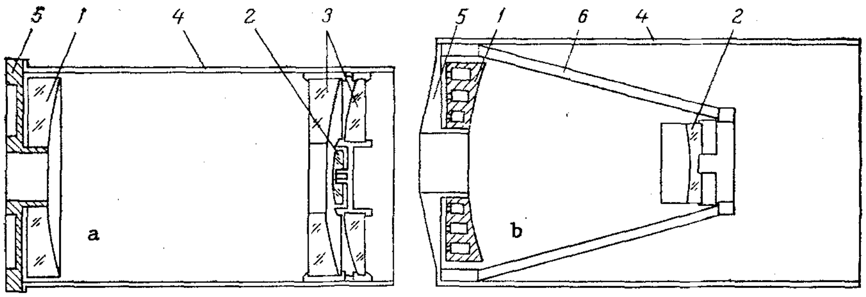

Fig. 1. Construction of mirror-lens (a) and mirror (b) objectives: 1) main mirror; 2) secondary mirror; 3) lenses; 4) tube; 5) main mirror holder; 6) struts.

any higher hierarchical level must be performed under conditions where the internal structure of subsystems at this level has yet to be clarified. Therefore, in the higher stages of design the full model cannot be used because of lack of information.

With the stage-by-stage method, thermal regime modeling is performed by successive use of mathematical models corresponding to different hierarchy levels. At any level except the first, those characteristics of subsystem temperature fields (for example, mean volume temperatures of individual regions, mean temperatures of various surfaces) are determined which are needed for determination of the construction parameters corresponding to this level. The internal structure of the subsystems is considered by means of generalized integral characteristics appearing in these construction parameters. Use of such a method is justified by the fact that the features of subsystem internal structure corresponding to a low hierarchical level have an insignificant effect on the characteristics of the temperature fields used in design at this level. For example, the features of microcircuit arrangement on a card in any electronic circuit have little effect on the temperature field of a tube located in the objective module. This fact can be used in analysis of the thermal regime of subsystems of the following hierarchical level. It is obvious that in performing such an analysis it is desirable to use the characteristics of temperature fields of higher level subsystems already found in previous design stages.

Thus, modeling of the optoelectronic device thermal regime will be performed stage by stage with a gradual transition from an upper hierarchical level, including a group of devices, to a lower one, including the simplest subsystems – individual elements which cannot be divided without disrupting their integrity [3]. The problem of calculating the objective thermal regime arises at the third stage. In its solution the conditions of external heat exchange of the objective with the surrounding medium, surrounding bodies, or cooling fluids are considered defined in previous stages of the calculation. These are specified by space–time distributions of thermal fluxes, heat liberation coefficients, and temperatures of the surrounding medium, bodies, and cooling agents. This problem of the third stage has two special features which distinguish it from analogous problems of previous stages. First, the objective is a subsystem with a relatively small number of "primary" elements at the very lowest hierarchical level, which lack any internal structure. Second, for the majority of objective elements it is necessary to define multidimensional spatial temperature fields. The effect of the thermal regime on device characteristics is determined on the basis of those fields.

Therefore, in analyzing the objective thermal regime, it is necessary to provide the possibility of using various variants of the stage-by-stage method. For example, in the approach usually used at preceding hierarchical levels, mean temperatures of elements are calculated first, and then used to analyze temperature distributions in individual elements [2]. The unique feature of other variants is solution of a system of equations including ordinary differential equations for the mean temperatures as well as one or several multidimensional equations for the temperature fields of the various elements.

The present study will consider questions of developing physical and mathematical models of heat exchange processes in objectives, methods for their numerical realization and corresponding programs for realization of the stage-by-stage modeling method.

Thermal and Mathematical Models. At present, lens, mirror-lens, and mirror objectives are used, which vary from one another in the elements of which they are composed and their construction form. Typical objective constructions are shown in Fig. 1. The optical elements – lenses and mirrors – are suspended by holders within tubes having cylindrical internal surfaces which are symmetric about the tube axis. The secondary mirror is attached to the tube or main mirror holder by struts. To protect the optical elements from the action of the surrounding medium and interference, transparent protective elements, filters, covers, and hoods are used. Lenses and protective elements have an axisymmetric form, while mirrors are usually nonaxisymmetric. In the general case, we can distinguish the following sources of thermal action on the optical elements:

sources of radiation entering the optical unit through the optical channel, being made up of the sum of the desired signal and parasitic components;

radiation sources incident on the external surfaces of optical unit elements;

the surrounding medium;

bodies located near the optical unit and exchanging heat therewith;

cooling fluids of the systems which ensure a normal thermal regime, stabilizing the temperatures of optical unit elements.

The distributions of temperatures, heat liberation coefficients, thermal fluxes, and volume sources of external heat liberation describing external thermal actions may be dependent on time and spatial coordinates and lack axial symmetry.

The thermal model of the objective is a system of thermally related bodies in which heat propagation occurs by thermal conductivity. The form of the objective elements is considered axisymmetric. Provision is made for consideration of both three-dimensional and lower dimensional temperature fields. The thermal model considers temperature dependence of thermal conductivity and specific heat.

In the process of device operation volume and surface absorption of radiation from external sources occurs in the objective elements, described by multidimensional distributions of volume and surface thermal flux density. In many cases the objective thermal regime is significantly nonstationary. For example, for objectives used in laser technology, this is caused by transient processes occurring during pulsed laser operation.

Heat transport between objective elements is accomplished by thermal conductivity, convection, and radiation. The contribution of each mechanism to total heat exchange depends on the construction of the objective, the temperature stabilization system used, and use conditions.

Heat transport by thermal conductivity produces a significant contribution to heat exchange between elements in objectives used in the presence of a gaseous medium, when convection is absent in any existing gaps. Such a condition is satisfied, in particular, for some interlens spaces. To consider this heat exchange a multidimensional thermal conductivity equation for the immobile gaseous medium is used. Heat exchange of lenses and mirrors with surrounding tubes through holders is described by corresponding thermal resistances.

Radiant heat exchange between elements plays a major role in objectives operating in vacuo. To consider this contribution the element surfaces are regarded as grey, diffusely reflecting and radiating. In the case of presence of specularly reflecting surfaces the spatial distribution of coefficients describing radiant heat exchange is considered known and introduced as initial data. Provision is made for description of radiant heat exchange in cavities of complex form in a three-dimensional approximation.

To consider free convection in cavities of complex form either known criterial relationships are used, or in their absence, calculations of resultant convective thermal fluxes are carried out on the basis of relationships for heat liberation coefficients for heat exchange in an unbounded space, while the temperature of the gaseous medium which appears in the expressions is found from the thermal balance equation, considering all segments into which the element surfaces are divided.

The mathematical model is then a system of nonlinear multidimensional nonsteady-state thermal conductivity equations for regions of first level componentry:

$$\rho_i c_i (T_i) \frac{\partial T_i}{\partial \tau} = \operatorname{div} (\lambda_i (T_i) \operatorname{grad} T_i) + q_{vi} (\bar{x}, \tau), \tag{1}$$

$$T_i|_{\tau=0} = T_{0i}(\bar{x}), \quad i = 1, 2, \ldots, m. \tag{2}$$

The boundary conditions for Eq. (1) have the form

$$-\lambda_i(T_i)\frac{\partial T_i}{\partial n}\Big|_{\Gamma_i} = \sum_{\substack{\nu=1\\ \nu\neq i}}^{m} \alpha_{c\nu}(\bar{x}_i, T_1, T_2, \ldots, T_m)(T_i - T_\nu) + \\ + \sum_{\substack{\nu=1\\ \nu\neq i}}^{m} \sigma \int_{A_\nu} \beta_{ri\nu}(\bar{x}_i, \bar{x}_\nu)(T_i^4 - T_\nu^4)\,dA_\nu + \sum_{\nu=m+1}^{M} \alpha_\nu(\bar{x}_i, T_i, T_\nu)(T_i - T_\nu) + q_{si}(\bar{x}, \tau), \tag{3}$$

where the last sum on the right describes the external thermal actions on objective elements.

Numerical Solution Method and Program Package Structure. By generalizing data of computer experiments on analysis of uncertainties of numerical solutions a mixed method [4] was chosen for modeling the objective thermal regime, with the temperature field of each element being found by an implicit method, and information on thermal interaction of elements being taken from the preceding time step. Use of this method permits realization of the modular principle in creating calculation programs for concrete objectives. In the given case, this is the most desirable technique, since because of the variety of possible objectives and constructions, techniques in which a new program must be created for each objective are unusable. The program developed consists of three types of modules.

The first type realized implicit methods for solution of the thermal conductivity equations corresponding to individual objective elements – lenses, mirrors, protective elements, filters, tubes, all using various spatial grids. A uniform step is used along the angular coordinate. As for the remaining spatial coordinates, for bodies of arbitrary cylindrical form (protective elements, filters, tubes) a nonuniform rectangular grid is used, while for other bodies (lenses, mirrors) an incorrect triangular grid is used. When the incorrect triangular grid is used the spatial operators of the thermal conductivity equations are approximated using the finite element method [5].

Temperature fields of cylindrical-form elements are calculated by a locally one-dimensional method [6]. For lenses and mirrors splitting is performed over the angular coordinate only.

The mixed method employed is constructed by considering relationships between elements in the form of flux values from the preceding time step, since for the majority of such relationships the estimates presented in [4] are satisfied. However, such an approach is ineffective for intense thermal couplings, which can occur, for example, in the case of thermal interaction of a lens or mirror with a tube through a holder. These relationships are considered by simultaneous solution of difference equations for the holder and a portion of the tube and difference equations for the lens or mirror.

The second type of module realizes algorithms for calculation of thermal fluxes in the prededing time step for typical thermal relationships between the objective elements. We will consider, for example, thermal relationships in an interlens space. In the approximation of diffuse radiation and reflection the resultant radiant thermal flux $q_{k\ell}{}^{ij}$ between the ℓ-th and k-th sections of the surfaces of elements i and j (lenses or tube and lens) is calculated with the equation

$$q_{kl}^{ij} = \sigma\beta_{kl}^{ij}((T_k^i)^4 - (T_l^j)^4)A_k^i. \tag{4}$$

The coefficients $\beta_{k\ell}{}^{ij}$ are found either by solution of the corresponding system of equations for all the segments, or by solution of a simpler system for two surfaces of the lens and internal tube surface. In the latter case $\beta_{k\ell}{}^{ij}$ are constant for all segments of the given element surface. The input data for the corresponding program module are variables which permit calculation of the number of division points of the element surfaces and their coordinates, the emissivity of the surfaces, and an attribute which specifies the method for calculation of the coefficients $\beta_{k\ell}{}^{ij}$. In the presence within the objective of specularly reflecting surfaces the coefficients defining the radiant heat exchange $\beta_{k\ell}{}^{ij}$ can be calculated separately using the Monte Carlo method [7], and then used as input data. The output data produced are resultant thermal flux values, which, in turn, act as input for modules of the first type for calculation of lens and tube temperature fields. The resulting convective thermal fluxes between surfaces of complex form are found from the expression

$$q_k^i = \alpha_{ki}(T_k^i - T_c)A_k^i, \tag{5}$$

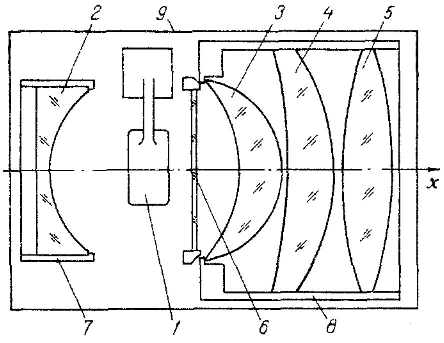

Fig. 2

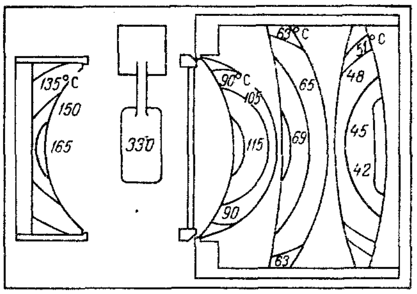

Fig. 3

Fig. 2. Thermal model of condenser objective: 1) lamp; 2) mirror; 3) lens I; 4) lens II; 5) lens III; 6) filter; 7) mirror holder; 8) tube; 9) condenser body.

Fig. 3. Condenser steady-state temperature field.

where T_c is calculated from the system

$$\sum_{i=1}^{m}\sum_{k=1}^{N(i)}\alpha_{ik}\left(T_k^i - T_c\right)A_k^i = 0. \tag{6}$$

Values of α_{ik} for cavity surfaces are found from criterial relationships for heat liberation coefficients in an unbounded space [8, 9]. The input data for the corresponding program module include attributes specifying the form of the criterial expressions.

The modules of the third type automatically perform some steps of the transition from objective parameters to input data for type one and two modules. As an example of such a module, we may consider a program which enumerates elements and spatial division points for a lens or mirror.

We will note that the modular principle by which the program package is constructed allows and simplifies expansion by inclusion of new modules of all three types, based on other variants of spatial grids and difference methods, reflecting thermal relationships between objective elements more complex than those of the model realized, making the use of the package simpler and more convenient for design purposes. Further studies will be performed in these directions to improve the program package.

Calculation Results. As an example of thermal regime modeling carried out by the program package described, we will present results of a calculation of the nonsteady-state axisymmetric temperature field of a condenser objective, the thermal model of which is shown in Fig. 2.

The lamp 1 is installed between mirror 2, held in holder 7, and a lens system, consisting of lenses 3, 4, 5, attached to tube 8. To reduce thermal loads on the lens system the filter 6 is installed between it and the lamp. The mirror holder and tube are installed in the condenser body 9. The power of the radiation source is 200 W. The condenser is located within a medium at a temperature of 20°C. At the initial time all elements have a temperature equal to that of the surrounding medium. The condenser objective axis x is parallel to the force of gravity. In modeling the thermal regime of the condenser objective two variants of the stage-by-stage method were used.

In the first, a simultaneous solution was performed of the system of nonsteady state multidimensional thermal conductivity equations for the objective elements. The given system consisted of four two-dimensional thermal conductivity equations for lens and mirror with holder, two one-dimensional equations for filter and tube (along axes r and x, respectively), as well as two ordinary differential equations for the lamp envelope and objective body, the temperature fields of which were assumed uniform. The corresponding program package consisted of four type one modules, which solved the thermal conductivity equations for the axisymmetric elements and the elements with one-dimensional temperature field, as well as a module for simultaneous solution of the difference equations for the optical element with holder; three type two modules for calculation of radiant and convective heat exchange and heat exchange in the planar interlayer within a cavity of complex form (the cavity between mirror and filter), and a number of type three modules.

The spatial grid for the condenser objective contained 215 points. The steady-state temperature field is shown in Fig. 3.

The calculation time required for exit to a steady-state regime on an ES-1040 computer comprised 15 min.

For the second variant of the stage-by-stage method the condenser objective thermal regime was calculated in two steps. In the first, the time dependences of mean temperatures of the objective elements were found. Then in the second step, based on these dependences, individual modules of the complex described above were used to find temperature distributions in the optical elements.

Values of mean element temperatures and axial and radial temperature changes within the optical elements obtained by this variant differed by 10-15% from the values found previously. This difference is essentially caused by the assumption used in the second variant of equality of mean volume and mean surface temperatures of the objective elements. In connection with this, the problem of choosing a variant of the stage-by-stage modeling method should be resolved with consideration of the complexity of the objective construction, temperature requirements imposed on the objective, and the degree of nonuniformity of the temperature fields within the elements.

The results obtained permit recommendation of the complex developed for use in designing objectives for optoelectronic devices.

NOTATION

T_i, temperature fields of objective elements; c_i, λ_i, ρ_i, specific heat, thermal conductivity, and density of element materials; $\bar{x}(x_1, x_2, x_3)$, spatial coordinate; τ, time; q_{vi}, q_{si}, specific volume and surface energy sources (drains); α_{cv}, convective heat liberation coefficient between elements; β_{riv}, coefficient defining radiant heat exchange between elements; T_k^i, mean temperature of k-th segment of element i; $q_{k\ell}^{ij}$, $\beta_{k\ell}^{ij}$, radiant thermal flux and coefficient defining radiant heat exchange between segments of elements; σ, Stefan–Boltzmann constant; $\phi_{k\ell}^{ij}$, angular coefficient between k-th segment of element i and ℓ-th segment of element j; A_k^i, area of k-th segment of element i; T_c, temperature of surrounding medium in cavity; q_k^i, convective thermal flux to cavity surface.

LITERATURE CITED

1. G. N. Dul'nev and A. V. Sigalov, Inzh.-Fiz. Zh., 45, No. 4, 651-656 (1983).
2. G. N. Dul'nev and E. D. Ushakovskaya, Inzh.-Fiz. Zh., 46, No. 4, 659-666 (1984).
3. L. P. Lazarev (ed.), Automation of Optoelectronic Device Design [in Russian], Moscow (1986).
4. V. I. Egorov, A. E. Mikhailov, and V. G. Parfenov, Choice of a Difference Method for Solution of Thermal Conductivity Equation Systems. 2. Mixed Method [in Russian], Moscow (1986), Dep. VINITI, No. 1577.
5. O. Zenkevich, The Finite Element Method in Technology [in Russian], Moscow (1975).
6. A. A. Samarskii, Theory of Difference Methods [in Russian], Moscow (1977).
7. R. Siegel and J. Howell, Radiant Heat Exchange [Russian translation], Moscow (1975).
8. G. N. Dul'nev, Heat-Mass Transport in Radioelectronic Equipment [in Russian], Moscow (1984).
9. A. I. Leont'ev (ed.), Heat-Mass Transport [in Russian], Moscow (1979).