3) for a series of values of τ from (8) the drying curve can be constructed for data for specific conditions;

4) the curve for heating of parts is calculated from the formula (10); and,

5) if the results obtained do not agree with the given results, then some conditions of the process must be measured and the calculation must be repeated.

The proposed method is extremely simple, and can be carried out with the help of a pocket calculator or a slide rule. At the same time, it enables taking into account all the basic parameters of the process, such as the temperature level and the conditions of heating, the geometry of the parts, the thermophysical properties of the parts, the pressure in the chamber, etc.

NOTATION

ε, reduced emissivity; $\sigma_0 = 5.67 \cdot 10^{-8}$ W/(m^2·deg^4), Boltzmann's constant; τ, time, sec; W, moisture content, kg of moisture/kg of the material; L, size, m; g, specific heat liberation, W/m^3; P, pressure in the chamber, Pa; F, area, m^2; P, volume of the part, m^3; T, temperature, °K; N, rate of drying, kg of moisture/(kg of the material·C); a, thermal diffusivity, m^2/sec; λ, thermal conductivity, W/(m·deg); ρ, density, kg/m^3; c, heat capacity, J/(kg·deg); α, heat-transfer coefficient, W/(m^2·deg); and K, a coefficient. Indices: w, wall; e, surrounding medium; 0, starting values; eq, equilibrium value.

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THERMOOPTICAL PROCESSES IN MIRROR—LENS OBJECTIVES. II. STEPWISE MODELING OF THERMOOPTICAL PROCESSES

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The synthesis of mirror lens telescopes on the basis of a joint study of optical and thermal processes is proposed. A method of calculating the temperature fields of an optical system is considered and the values of thermooptical aberrations are refined.

A method of synthesis of a thermostable optical system was discussed in the preceding paper [1] on the example of the mirror—lens objective of the VEGA television camera. In the first stage (Fig. 1), on the basis of the experience of previous developments, the technical assignment of the optical characteristics and image quality, the operating conditions, and the restrictions imposed on the weight and size, the basic optical scheme 1 is chosen, the main types of which are given in [2], its parameters are calculated, and the materials of the optical and structural elements 2 are chosen. The restrictions of the technical assignment (TA) determine the possibility of the use of active and passive temperature regulation 4. On the basis of an analysis of thermal aberrations 5, the allowable temperature drops between optical elements 6 are determined, as well as the radial and axial drops in the main elements. A joint analysis 7 of the instrument's operating conditions, thermal aberrations, and allowable temperature drops enables one to decide whether the optical system satisfies the TA, and whether active temperature regulation, a change of materials, or a change in the basic optical scheme is required.

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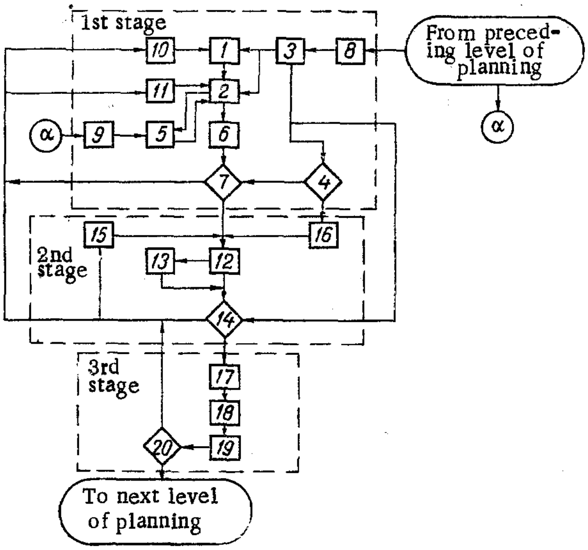

Fig. 1. Block diagram of planning.

In the case of a positive solution in the first stage, one proceeds to the next stage – the development of the construction 12. The latter is accomplished on the basis of the requirements of the technical assignment simultaneously with an analysis of the thermal regime 13 and a comparison 14 with the allowable values of the temperatures and drops obtained in the first stage. If a positive solution cannot be obtained by constructive measures, one must return to the preceding stage. The first two stages were discussed in detail in [1].

In the present paper we dwell on the third stage – the refined calculation of the temperature fields 17, thermal deformations 18, and aberrations 19, which is done after the completion of construction and enables one to decide 20 whether the objective developed accords with the technical assignment.

So, let us proceed to calculate the temperature fields of the television camera depicted in Figs. 1 and 2 in [1]. On their basis we can propose the scheme for the telescope mounted on the VEGA spacecraft (Fig. 2), in which we distinguish the primary 1 and secondary 2 mirrors, sections 3-5 of the blind, 6-8 of the objective housing, the lenses 9-12, the electronics units 13 and 14, the detector unit 15, the platform 16, and the ambient medium 17 (Fig. 1).

The fullest mathematical description of the temperature fields of such a complicated device as a telescope is reduced to a system of differential equations of heat conduction for the solid bodies with the appropriate boundary and initial conditions. The realization of such a mathematical model in the majority of cases proves to be difficult or impossible even using modern computers. In this case it is advisable to use the method of stepwise modeling, the grounding for which is given in [3, 5]. The essence of the method comes down to the fact that in the initial stage one analyzes the system as a whole, with a minimum degree of detailing, while in subsequent stages one analyzes heat exchange in individual units and elements of the instrument with the required degree of detailing. Into the boundary conditions at the surfaces one substitutes not the local values but the averaged values of the heat fluxes and temperatures of the surrounding bodies found from the preceding stages of calculation. The errors arising from this can be determined analytically [4] or experimentally.

Stepwise modeling is based on the hierarchical principle of the planning of optical instruments [5]. For example, the television camera under consideration is mounted on a platform along with other instruments. Therefore, in the first stage of the investigation of the thermal regime the platform with the instruments mounted on it was analyzed and its average temperature was determined. The estimates showed that the temperature of the platform in the various regimes of operation in space varies in the range from –20 to +40°C. In this stage of planning, along with data on the thermal regime, we determined other requirements of the technical assignment on the development of the television camera, such as the overall and adjusting dimensions, etc.

In the second stage the thermal regime of the television camera itself was analyzed: The average temperatures and drops in its individual units and elements were determined. This was done on the basis of two values of the platform temperature, –20 and +40°C. The refined

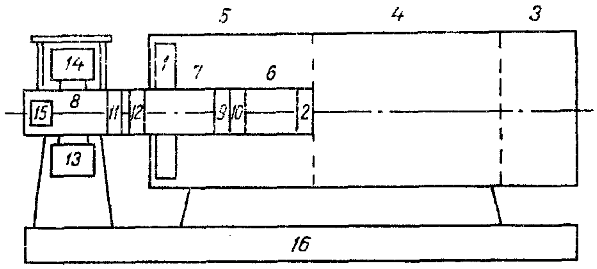

Fig. 2. Diagram of telescope construction.

calculation of the temperatures and thermooptical aberrations comprises the content of the third stage of the planning of the optical system being discussed in this paper.

The results obtained were also used to analyze the thermal regime of the detector unit. This unit is part of the television camera and is fastened to the housing of the optical system, the temperature of which was assumed to be known from the preceding stage. The calculation enabled us to assure a normal thermal regime for the unit, in which the sensitivity of the radiation receivers and the thermal noise correspond to the requirements of the technical assignment. The procedure and results of the calculation are given in [6].

Let us examine the second stage of the calculation of the thermal regime in more detail and take the temperature fields of mirrors 1 and 2 and lenses 9-12 as one-dimensional and varying along the radii of these regions (Fig. 2). We take the temperature fields of the housing sections 6-8 as one-dimensional, varying along the axis, and the temperature fields of the sections 3-5 of the blind as two-dimensional, varying along the axis and angularly (in the cylindrical coordinate system). The temperature drops over the thickness of the enumerated regions can be neglected. We take the temperature fields of the electronics and detector units as uniform and the temperatures of the ambient medium (space) and the platform as given and equal to −269°C and −20 to +40°C, respectively.

The heat sources are the electronics and detector units, as well as solar radiation entering the blind 3.

Heat exchange between regions of the instrument takes place by radiation and heat conduction. The thermophysical properties of the materials and the heat-transfer coefficients within each region were assumed to be independent of the coordinates of these regions and were determined by their average temperatures.

With allowance for the formulated assumptions, the mathematical statement of the problem consists of a system of algebraic and differential energy equations [6]:

$$T_i \sum_j^{17} \sigma_{ij} - \sum_j^{17} T_j \sigma_{ij} = P_i, \quad i = 13,\ 14,\ 15; \tag{1a}$$

$$\frac{d^2 T_k}{dz^2} - b_k^2 (T_k - \tilde{T}_k) = 0, \quad k = 6,\ 7,\ 8; \tag{1b}$$

$$\frac{d^2 T_r}{dr^2} + \frac{1}{r}\frac{dT_r}{dr} - b_r^2 (T_r - \tilde{T}_r) = 0, \quad r = 1,\ 2,\ 9,\ 10,\ 11,\ 12; \tag{1c}$$

$$\frac{\partial^2 Tl}{\partial z^2} + \frac{1}{r^2}\frac{\partial^2 T_l}{\partial \varphi^2} - b_l^2 (T_l - \tilde{T}_l) = -W_l/\lambda_l, \quad l = 3,\ 4,\ 5; \tag{1d}$$

$$T_s = \text{const}, \quad s = 16,\ 17; \tag{1e}$$

$$b_n^2 = \sigma_{\Sigma_n}/(\lambda_n V_n), \quad n = k,\ r,\ l;$$

$$\tilde{T}_n = \sum_j^{17} T_j \sigma_{n,j}/\sigma_{\Sigma_n}, \quad \sigma_{\Sigma_n} = \sum_j^{17} \sigma_{nj}. \tag{1f}$$

Equations (1a) correspond to uniformly heated regions (the radiator and the electronics units), (1b) correspond to sections of the housing whose temperature varies along the axis, (1c) correspond to mirrors and lenses with radial temperature fields, (1d) ocrrespond to sections of the blind with two-dimensional temperature fields, and finally, Eqs. (1e) are written for regions having assigned temperatures: the platform, the radiation receivers, and the ambient medium.

The system (1) is supplemented by the boundary conditions.

An exact solution of such a system of equations is practically impossible, while a numerical solution is associated with large expenditures of work and time on the development and debugging of a program allowing for the peculiarities of the specific construction.

The problem can be simplified considerably, since heat exchange between the regions can be characterized by the average temperatures of the individual surfaces: the end and cylindrical surfaces of sections of the blind and the housing and the ends and plane surfaces of disks that model the mirrors and lenses. In this case, the heat flux P_i released in the i-th region is transferred to other bodies of the system, $\sum_{i}^{17}\sum_{k}\sum_{l}\sigma_{ij}(T_{ik}-T_{jl})$, i.e.,

$$\sum_{j}^{17}\sum_{k}\sum_{l}\sigma_{ij}(T_{ik}-T_{jl})=P_i,\ i=1,\ \ldots,\ 15. \tag{2}$$

The number of equations equals the number of bodies in the system. The number of unknowns equals the number of surfaces of all the bodies and exceeds the number of equations. To close the system (2), we must write equations connecting the average temperatures of the individual surfaces of each body. Such equations are obtained by an exact (for one-dimensional regions) or approximate (for two- and three-dimensional ones) analytic solution of the corresponding equation of heat conduction and have the form

$$\begin{aligned}(T_0-T_l)\sigma_{0l}+(T_0-T_v)\sigma_{0v}&=Q_0,\\(T_l-T_0)\sigma_{0l}+(T_l-T_v)\sigma_{lv}&=Q_l.\end{aligned} \tag{3}$$

The parameters σ_{0l}, σ_{0v}, σ_{lv}, Q_0 and Q_l are given in [7, 8].

The thermal conductivities and the powers of heat release in the regions comprise the initial information for the analysis of the thermal regime. The procedure for calculating these parameters is given in [6].

Calculations of the thermal regime of the television camera were made using a program developed in the Fortran IV language for an ES computer. The program provides for the automatic compiling and solution of the system of algebraic equations (2) and (3). The calculation was made by the method of successive approximations with refinement of the nonlinear parameters [the radiative conductivities and the coefficients σ_{0l}, σ_{0v}, and σ_{lv} in Eqs. (3)]; in each approximation the system of equations was solved numerically by the Gauss method; the algorithm and a block diagram of the program are given in [6].

We studied four regimes of operation of the television camera, differing in the platform temperature and in the presence or absence of heat-release power in the blind. The results of the calculations, given in [6], showed that the temperatures of elements of the optical system differ insignificantly from the platform temperature. The maximum temperature drop between mirrors of the optical system is 2.8°K. The temperature drops over the radii of the primary and secondary mirrors do not exceed 0.08 and 0.01°K, respectively. The temperature drop over the housing of the objective lies in the range of 2.3-8.9°K.

An aberration calculation of the system was made on the basis of the refined values of the temperatures. For this the radii of the mirrors and lenses, the air gaps, the thicknesses of the lenses, and the indices of refraction were determined from formulas given in [9] with allowance for the temperature of each element of the system. With the same temperature for all the elements, the maximum defocusing was only 1 μm, and in a refined calculation with allowance for the nonuniform temperature distribution of the optical system we obtained a defocusing of 19 μm.

The maximum temperature drop over the radius of the primary mirror is 0.08°K, on account of which the radius R of the mirror varies by $\Delta R = 8\cdot 10^{-4}$ mm.

Let us estimate approximately the maximum size of the gap between surfaces whose radii differ by the indicated amount. Differentiating the well-known formula [9] connecting the sagitta δ with the height h on a surface with a radius of curvature R, we obtain

$$\delta=h^2/2R,\ \Delta\delta=h^2\Delta R/2R^2. \tag{4}$$

Substituting h = 120, R = −1258, and $\Delta R = 8 \cdot 10^{-4}$ mm into (4), we obtain the size of the gap between the surfaces, $\Delta\delta = 4 \cdot 10^{-6}$ mm. The wave aberration arising in this case is $8 \cdot 10^{-6}$ mm (λ/60, where λ is the radiation wavelength). In accordance with the Rayleigh criterion, this aberration must not exceed λ/4. Consequently, the deformation of the wave front due to the temperature drop over the mirror can be neglected. In addition, this allows us to not make a more detailed analysis of the temperature distribution in the individual optical elements with allowance for their complicated configuration and the local thermal connections. In other cases, when the aberrations caused by the nonuniformity of the temperature field of an optical element are pronounced, while the demands on the image quality are high, such an analysis is necessary. This also holds for more precise calculations of thermal deformations and thermooptical aberrations [10]. The number of stages of the thermal calculation increases in this case.

Thus, our calculations of temperature fields and thermooptical aberrations allow us to conclude that the construction measures adopted assure the normal thermal regime of the optical system of the television camera, in which the sizes of the thermooptical aberrations do not exceed the tolerances. This allows us to conclude the planning of the optical system and proceed to the next level of construction — the creation of the detector unit [6].

If the refined calculation shows that the thermal aberrations exceed the tolerances, then additional measures must be taken (a change in the construction, materials, or optical scheme) to improve the thermal regime and reduce the thermal aberrations.

The method of synthesis of mirror—lens telescopes on the basis of a joint study of optical and thermal processes discussed in these papers can also be used in the planning of other optical systems. Other connections between individual subsystems may develop and new subsystems may appear in this case, but the general approach evidently will not undergo significant changes.

NOTATION

T_i, T_j, average surface temperatures of the i-th and j-th regions; σ_{ij}, thermal conductivity between these regions; P_i, heat flux released in the i-th region; λ_n and V_n, thermal conductivity and total volume of the n-th region; W_l, specific power of heat release in the l-th region; T_{ik} and T_{jl}, temperatures of the k-th surface of the i-th body and of the l-th surface of the j-th body; T_0 and T_l, temperatures of the ends of a body; T_V, volumetric-average temperature of a body.

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