per second through the column cross section; N(z), power per unit length of arc; σ, ρ, h, S_1, ε, electrical conductivity, density, enthalpy, heat-conduction function, and integrated volume radiation density; ζ, radius of the column referred to R; S_*, value of S_1 on the column boundary; $\sigma_S = \partial\sigma/\partial S$; $h_S = \partial h/\partial S$; $\varepsilon_S = \partial\varepsilon/\partial S$; $S = S_1 - S_*$; q_ζ, q_ε, energy losses per unit length of the positive column per unit time for the heat conduction and the radiation.

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THERMAL MODE OF A LAMP OPERATING IN THE PULSE MODE

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UDC 536.2

A method of computing the thermal modes of lamps is proposed and the passage to the analysis of thermooptical distortions occurring in their active elements is realized.

The effective conversion of pumping energy into heat causes optical inhomogeneity of the active elements. In turn, the optical inhomogeneity results in the appearance of a thermal lens, birefringence, divergence of the radiation. Hence, an analysis of these parameters is one of the fundamental problems occurring in the production of lamps.

In numerous papers devoted to the analysis of the thermal modes of lamps, the thermal state of just the active element is examined as a rule, without taking into account its relation to the other elements in the system [1-6]. At the same time, the thermal analyses do not permit a judgment about the quality of system operation. This is explained by the indirect influence of the thermal effects. Papers devoted to the investigation of thermooptical distortions in the active element are either based on a known temperature field, or are experimental in nature [7-10]. In this connection, the problem of developing thermal and mathematical models of lamps, the production of methods of analyzing their thermal mode, and the passage to an analysis of the thermooptical distortions in the active element is quite urgent.

This paper is devoted to the production of a method of analyzing the thermal mode of a lamp. The thermal mode of the active element is investigated in greatest detail, and the thermooptical distortions that occur are determined. The sequence presented below for the analysis is common to a broad class of constructions of lamps operating in the pulse mode.

Let us examine the example of analyzing the thermal mode of the lamp displayed schematically in Fig. 1. It consists of the following main elements: a cylindrical active element 1 fabricated from glass; two pumping lamps 2 operating in the single pulse mode; a reflecter 3, and a housing 4.

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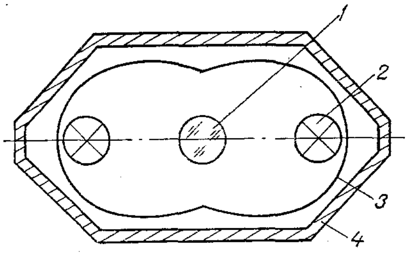

Fig. 1. Schematic diagram of the lamp construction.

In order to produce the thermal model of the lamp, let us simplify the construction, and let us also make some assumptions idealizing the nature of the thermophysical phenomena resulting. We list the main ones:

1) The volume under consideration is bounded by the housing. The domains indicated in Fig. 1 enter into the thermal model.

2) Extraction of the thermal energy in the lamp elements because of plasma radiation energy absorption will be considered the result of the action of internal heat sources.

3) In the first stage of the analysis we consider the internal sources to be distributed uniformly, and the temperature fields of the separate elements to be uniform also.

4) The thermophysical parameters are constant and independent of the temperature.

5) The heat transfer between the separate elements of the lamp is characterized by the mean values of the heat transfer coefficients within the limits of each surface.

Let us examine the thermophysical processes occurring in the lamp elements. Heating the elements at the time of pumping pulse action can be considered adiabatic since its time of action is small. The ultimately allowable pulse time during which adiabatic heating occurs can be determined from the relationships in [2]. In this case the temperature of the i-th element is determined by the power of the internal heat sources and the specific heat of the material, and is not dependent on the heat conductivity of the material and the intensity of the heat transfer with the surrounding elements [2]:

$$t_i = t_{\mathrm{p}} + \frac{P_i \tau_{\mathrm{p}}}{C_i}\,. \tag{1}$$

Formula (1) assumes the heat source to be constant during the pulse action. The internal heat sources in the separate elements can be determined on the basis of a numerical integration of the radiation and absorption spectra by the method elucidated in [11]. For this lamp construction, the values of these sources turn out to equal: $P_1 = 0.07P_{\mathrm{el}}$; $P_2 = 0.3P_{\mathrm{el}}$; $P_3 = 0.35P_{\mathrm{el}}$.

Knowing the internal heat sources, and the complete specific heats of the elements, we determined the mean values of the temperatures of all the elements to the end of the pumping pulse from (1): $t_1 = 34$; $t_2 = 131$; $t_3 = 80$°C.

The thermal mode of the lamp elements after pulse termination is described by the system of equations [12]

$$\begin{cases} C_i \dfrac{dt_i}{d\tau} + \sum\limits_{j=1}^{4} \sigma_{i,j}(t_i - t_j) = 0, \\ i = 1,\ 2,\ 3,\ 4,\ i \neq j. \end{cases} \tag{2}$$

The heat transfer process between separate elements is characterized for the system under consideration by convective–conductive, conductive, and radiant heat conductivities which can be determined by known relationships [12-14].

Values of the heat conductivities turn out to equal $\sigma_{1.2} = 0.09$ W/K; $\sigma_{1.3} = 0.13$ W/K; $\sigma_{1.4} = 0.08$ W/K; $\sigma_{2.3} = 0.2$ W/K; $\sigma_{3.4} = 0.88$ W/K.

The system of ordinary differential equations (2) can be solved either numerically on an electronic digital computer, or by an approximate analytic method developed in [15]. The following nonstationary values of the mean temperatures (Fig. 2) are obtained as a result of a computation.

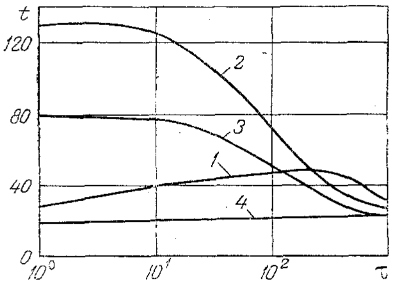

Fig. 2

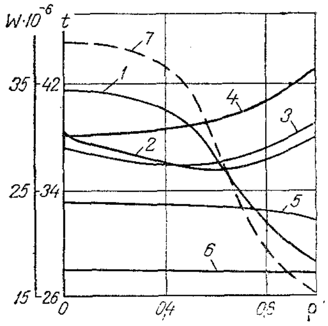

Fig. 3

Fig. 2. Mean nonstationary temperatures of the lamp elements (see Fig. 1) after termination of the pumping pulse. t, °C, τ, sec.

Fig. 3. Temperature field of the active element at different times and power distribution of the internal heat source in the active element: 1) $\tau = \tau_p$; 2) $\tau = 9$ sec; 3) 12; 4) 30; 5) 600; 6) 900 sec; 7) $W = W(\rho)$. W, W/m³.

We investigate the temperature field of the active element in more detail in the next step of the analysis. To do this we reject the assumption 3) about the uniformity of the temperature field and the internal heat source in the active element. The nonuniformity of the distribution of the internal heat source is caused by attenuation of the radiation in the active medium, as well as by the focusing property of the cylindrical surface. We compute the nonuniformity of the distribution by the formulas [16]

$$q(\rho) = \begin{cases} \dfrac{n^3}{\pi} \displaystyle\int_0^{\pi} d\varphi \int_0^{\xi_{pr}} G(\xi, \varphi)\, d\xi, & \rho < \dfrac{1}{n}, \\ \dfrac{n^3}{\pi} \left\{ \displaystyle\int_0^{\varphi_1} d\varphi \int_0^{\xi_{pr}} G(\xi, \varphi)\, d\xi + \int_{\varphi_2}^{\pi} d\varphi \int_0^{\xi_{pr}} G(\xi, \varphi)\, d\xi \right\}, & \rho \geqslant \dfrac{1}{n}, \end{cases} \tag{3}$$

$$G = \frac{(1-R)\cos i}{L_1^2} \exp(-kr_0 L_1), \quad L_1^2 = L_2^2 + \xi^2,$$

$$L_2^2 = 1 + \rho^2 - 2\rho\cos\varphi, \quad \cos i = \frac{1 - \rho\cos\varphi}{L_1},$$

$$\xi_{pr} = \sqrt{(1-\rho\cos\varphi)^2/\cos^2 i_{pr} - L_2^2}, \quad \cos i_{pr} = \sqrt{1 - n^{-2}},$$

$$\varphi_{1,2} = \arccos \frac{1 \pm \sqrt{(n^2-1)(n^2\rho^2-1)}}{n^2\rho}.$$

Formulas (3) are valid only for the monochromatic component of the radiation. However, active elements are ordinarily exposed to radiation of a broad spectrum band, and the material of the active element has selective absorptive properties. Consequently, it is first necessary to determine the relative nonuniformity of the internal heat source for each monochromatic component, and afterwards to integrate over the whole radiation spectrum.

By knowing the nature of the internal heat source nonuniformity as well as the total energy absorbed by the active element, the absolute values of the internal sources can be determined by the following formulas

$$W(\rho) = F' q(\rho),$$
$$F' = \frac{P_1}{2\pi l r_0^2 \int_0^1 q(\rho)\, \rho\, d\rho}. \tag{4}$$

Results of computing the nonuniform internal heat source in the active element are presented in Fig. 3.

Therefore, we have the information necessary to determine the temperature field of the active element during the pumping pulse [2]

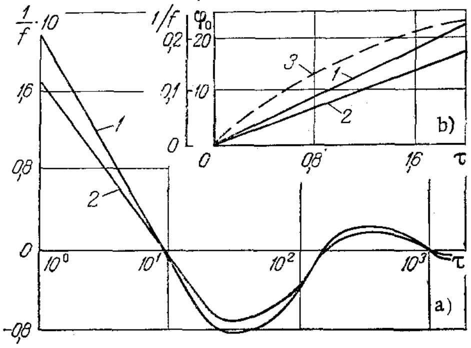

Fig. 4. Dependence of thermooptical distortions in an active element on the time: a) optical intensity of a thermal lens after termination of the pumping pulse (1 – radial, and 2 – tangential polarization); τ, sec; $1/f, m^{-1}$; b) optical intensity of the thermal lens and divergence of radiation during the pumping pulse (1 – radial, 2 – tangential polarization, 3 – $\varphi_0 = \varphi_0(\tau)$). τ, msec; φ_0, min.

$$t_1(\rho, \tau) = t_p + \frac{\pi l r_0^2}{C_1} \int_0^{\tau_p} W(\rho, \tau)\, d\tau. \tag{5}$$

We consider the heat source constant during the pulse, i.e., $W(\rho, \tau) = W(\rho)$. The temperature field of the active element during the pulse is presented in Fig. 3.

Now, let us investigate the temperature field in the active element after termination of the pulse. Since the length of the active element considerably exceeds the diameter and heat transfer with the endfaces is negligible, then the following equation can be used to compute the nonstationary temperature field of the active element

$$\frac{\partial^2 t(r, \tau)}{\partial r^2} + \frac{1}{r} \frac{\partial t(r, \tau)}{\partial r} = \frac{1}{a} \frac{\partial t(r, \tau)}{\partial \tau} \tag{6}$$

with the initial

$$t(r, 0) = t(r)\big|_{\tau=\tau_p} \tag{7}$$

and boundary conditions

$$-\lambda \frac{\partial t(r_0, \tau)}{\partial r} + q'(\tau) = 0, \quad \frac{\partial t(0, \tau)}{\partial r} = 0. \tag{8}$$

The temperature field of the active element at the time of pulse termination $\tau = \tau_p$ (Fig. 3) is taken as initial conditions (7). On the basis of the energy conservation law, the heat flux on the surface of the active element is determined thus in the boundary conditions (8):

$$q'(\tau) = \{2\sigma_{1,2}[t_2(\tau) - t_1(\tau)] + \sigma_{1,3}[t_3(\tau) - t_1(\tau)] + \sigma_{1,4}[t_4(\tau) - t_1(\tau)]\}/S.$$

Values obtained from solving the system (2) (see Fig. 2) are taken as the temperature $t_i(\tau)$. Therefore, the thermal interaction between the active element and the other bodies of the system is taken into account in the boundary conditions (8). Solution of the problem (6)-(8) is obtained numerically on a digital computer. The results of computing the temperature field of an active element at different times are represented in Fig. 3.

Let us examine the thermooptical distortions induced in a cavity by an active element. The theoretical and experimental investigations show that the active element subjected to a radial temperature gradient will be converted into a lens with two focal lengths, which are determined approximately by the following formulas [7]:

$$f = \frac{1}{nlb_2}, \qquad b_2 = \frac{2(N \pm Q/2)}{nr_0^2} \Delta t, \qquad N = 25 + 0.17t_0, \; Q = 6 + 0.03t_0, \tag{9}$$

where the ± signs are for radial and tangential polarization, respectively.

Since the temperature drop Δt is a function of the time, the focal length of the thermal lens therefore will also depend on the time. The results of computing the dependence of the optical force of the lens on the time are presented in Fig. 4. It is seen from the dependences obtained that a positive lens, whose optical intensity increases during the action of the pumping pulse (Fig. 4b), is formed at the time of the pulse in the active element. After termination of the pulse, the optical intensity of the thermal lens decreases in proportion to the temperature gradient Δt, and the sign of the lens is already opposite at the ninth second. Furthermore, as all the lamp elements cool down, the lens again becomes positive (Fig. 4a).

The presence of a lens within a plane resonator results in an increase in the radiation divergence calculated by the formula [7]

$$\varphi_0 = \sqrt{\frac{2\Delta h}{L}} = \sqrt{\frac{2l}{L}\left(N + \frac{Q}{2}\right)_0 \Delta t}\ . \tag{10}$$

Results of computing the radiation divergence during the pulse are presented in Fig. 4b.

To verify the validity of the sequence developed for the computation, experimental investigations were performed to determine the focal length of the thermal lens in the active element after termination of the pumping pulse. The results of this verification exhibited satisfactory agreement between the experimental and computed data.

The computation method proposed already permits determination of the allowable temperature levels of the separate elements in the design stage, also the development of the form and parameters of the cooling system, the investigation of the thermooptical distortions in the active element, the development of means to cancel these distortions, the analysis of the influence of separate factors, and the determination of the allowable pulse repetition rate.

NOTATION

t_i, temperature of the i-th element; t_p, initial temperature of the active element; t_0, temperature of the center of the active element; Δt, temperature drop between the center and the side surface of the active element; P_i, internal heat source intensity in the i-th element; P_{el}, energy delivered per pumping lamp; C_i, total specific heat of the i-th element; τ_p, pumping pulse operation time; $\sigma_{i,j}$, thermal conductivity between elements i and j; k, spectral coefficient of absorption of the active element; n, index of refraction of the active element; R, Fresnel reflection coefficient; r_0, l, S, radius, length, heat eliminating surface of the active element, respectively; $\rho = r/r_0$, relative radius; W, intensity distribution of the internal heat source in the active element along the radius; λ, a, heat conduction and diffusivity coefficients of the active element; φ_0, angular divergence of the radiation; L, resonator length; Δh, maximal difference in the optical lengths between the center and the side surface of the active element.

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ANALYSIS OF THE THREE-DIMENSIONAL SELECTIVE RADIATION FIELD IN A COMBUSTION CHAMBER USING MATHEMATICAL MODELING

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UDC 536.3

Using the zonal method, the spectral structure of radiation fluxes over the height of furnace baffles in the BKZ-320-140 PT steam generator, appearing with the combustion of lignite in the combustion chamber, is investigated.

Improving furnaces that are presently in operation and designing new efficient furnaces, as well as optimizing their thermal operation, impose increasingly stringent requirements on the accuracy and detail of heat-exchange calculations. Of special significance in this connection is the determination and analysis of the temperature distribution and the heat-flux distribution in combustion chambers with the help of zonal methods taking into account the actual radiation properties of the media and bodies participating in heat exchange.

In the present work, using the zonal method, we analyze heat transfer in the combustion chamber of the BKZ-320-140 PT steam generator burning lignites from the Kansk–Achinski coal field. In so doing, we investigate for the first time the spectral structure of the radiation field under the conditions of three-dimensional multizone systems with a complex configuration, filled with a thermally and optically inhomogeneous medium having real radiation characteristics, using a computational method applicable to furnaces. The spectral structure is important for determining the effect of the radiation properties of the furnace medium and of the heat-absorbing surfaces on indicators of local and total heat transfer in the combustion chamber.

In the calculations, we investigated the multizone mathematical model of heat transfer [1]. The geometric volume of the combustion chamber and the vertical surfaces of the baffles were represented as seven computational regions, each of which consisted of two volume regions (near-wall region and the core of the flow) and three surface (lateral, frontal, and rear baffles) regions. We calculated the heat exchange for coal consumption of 51,606 tons/h. The mathematical model and the scheme for separating the combustion chamber into zones are presented in [1].

Taking into account the nonuniformity of the vertical thickness distribution of ash deposits on the furnace baffles in the combustion chamber is important for studying the local values of temperature and radiation fluxes. Starting from the assumption that the thickness of the deposits varies linearly with the height of the cooling chamber, the magnitudes of the thermal resistance R_i in the computational region i were found from the relation

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