equilibrium moisture content of material; λ, ν, a, thermal conductivity, W/(m•K), kinematic viscosity, m²/sec, and thermal diffusivity, m²/sec, of heating agent; λ_{mt}, ρ_0, thermal conductivity W/(m•K) and density kg/m³ of material.

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METHODS FOR PERFORMING ENGINEERING CALCULATIONS OF THE PROCESS OF VACUUM DRYING OF HEAVY-DUTY CAPACITORS

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A method is proposed for calculating the instantaneous average values of the temperature and moisture content of the insulation of capacitors as a function of the parameters of the drying process.

Heavy-duty capacitors, as objects of heat treatment, are complicated structures. The process of their thermovacuum drying is also quite complicated from the physical viewpoint. All these characteristics are responsible for the great complexity of the physical and mathematical modeling of these processes and the fact that there do not exist reliable engineering methods for calculating them. At the same time, such methods are required not only by designers of such electrothermal equipment, but also by manufacturers.

We shall first study the thermophysical model of a capacitor (Fig. 1). The presence of a foil interlayer 1 substantially affects the thermal conductivity of the system as a whole. We assume that at the lower boundary we have the most general case — boundary conditions of the second kind, and in addition the heat flux is time dependent. To a first approximation the heat expended on the evaporation of moisture in the insulation can be neglected. Since the thermal conductivity of the system along the X axis is several orders of magnitude higher than the thermal conductivity in the transverse direction we shall study the one-dimensional problem. In so doing we assume that the temperature gradient in the transverse direction within one layer of paper will be vanishingly small. Then, the energy expended on heating the paper adjacent to the foil can be taken into account as the draining of heat from the foil, and heat conduction along the foil only can be studied. This approach is fully justified, since heat transfer by conduction along the paper is several orders of magnitude weaker than along the foil

$$\frac{\partial\theta}{\partial \mathrm{Fo}}=\frac{\partial^2\theta}{\partial X^2},\quad \theta(X,\ 0)=1,\quad \frac{\partial\theta(0,\ \mathrm{Fo})}{\partial X}=-\mathrm{Sk}(\theta_w^4-\theta^4),\quad \frac{\partial\theta(1,\ \mathrm{Fo})}{\partial X}=0. \tag{1}$$

Here $\theta = T/T_0$; $X = x/L_0$; $\mathrm{Fo} = a\tau/L_0^2 b$; $\mathrm{Sk} = \varepsilon\sigma_0 T_0^3/\lambda$; $b = (c_1\rho_1\delta_1/c_2\rho_2\delta_2 + 1)$ is a coefficient that takes into account the additional heat lost to heating the paper or film adjacent to the foil.

Equation (1) was represented in an implicit difference form, which was highly stable, and was solved by the straight iteration method.

The calculations show that the difference of the temperatures at the outer and inner layers does not exceed 1°C. These results are confirmed by the experimental data of [1], where large temperature gradients also were not recorded, which gives a basis for neglecting in further calculations the internal heat conduction in heavy-duty capacitors.

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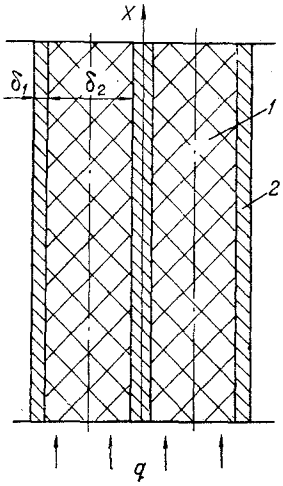

Fig. 1. Thermophysical model of the capacitor: 1) insulation; 2) foil.

We shall now study the process of heating and drying of capacitors. Experimental studies established that these processes are described well by an equation of the type [1]:

$$U=\left[\frac{N_{\max}\tau(n-1)}{W_0-W_{\mathrm{eq}}}+1\right]^{\frac{1}{1-n}}, \tag{2}$$

where $U = (W - W_{\mathrm{eq}})/(W_0 - W_{\mathrm{eq}})$ is the integral relative excess moisture content; $n = 1.6$;

$$N_{\max}=\frac{29.5\cdot 10^{-6}}{L^{0.3}}\exp\left(\frac{q-181}{0.665q^{1.05}}\right)\frac{\lg\dfrac{327+P}{133}}{\left(\dfrac{327+P}{2330}\right)^{0.48}}\left(\frac{W-W_{\mathrm{eq}}}{W_0-W_{\mathrm{eq}}}\right). \tag{3}$$

The data obtained by calculations based on Eq. (3) are compared with the experimental data in Fig. 2. As one can see, the deviation does not exceed 2%. For convenience the expression (3) was represented in the form of a nomogram (Fig. 3). Thus the integral moisture content of the capacitors as a function of time is calculated without a direct coupling with the temperature field. This coupling is realized indirectly through the quantity $N_{\max}$, which depends on the maximum specific energy liberation q.

The determination of q appearing in the formula (3) presents some methodical difficulties, so that we shall study this question in greater detail. In the general case the heat flux to the parts can be convective (from air, vapor, or oil) and radiative; we shall then write the formula for calculating it in the following form:

$$q=\left[\frac{\sigma_0\varepsilon_{\mathrm{red}}}{V}(T_{\mathrm{w}}^4-T^4)F_r+\frac{\alpha F_k}{V}(T_e-T)\right]. \tag{4}$$

The area of radiative F_r and convective F_k heat transfer must be determined from the specific conditions, and is calculated as a sum, equal to the total area of the capacitor (for the case of heating with hot oil, wetting part of the surface of the capacitor, and radiation for the rest of the surface) or double the total surface area (for the case when the entire surface of the capacitor is heated by a radiant flux without screening together with simultaneous wetting of the entire surface by hot diametral gas). Under conditions of heating by radiation and significant screening the sum of the radiative and convective heat-transfer surfaces can also be less than the total surface area of the capacitor.

To calculate the rate of heating we shall construct the integrated balance equation, in which we take into account the heat loss to evaporation of moisture using the expression (2):

$$c\rho\frac{dT}{d\tau}+\rho Nr(w)=\frac{\varepsilon\sigma_0F_r}{V}(T_{\mathrm{w}}^4-T^4)+\frac{\alpha F_h}{V}(T_e-T), \tag{5}$$

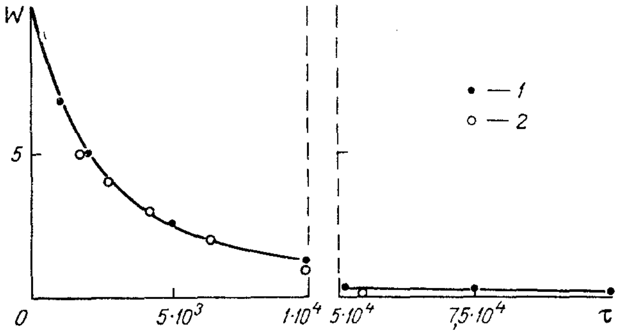

Fig. 2. Comparison of the computed and experimental data on the kinetics of drying of capacitors for the conditions P = 15 Pa, T = 393 K, and L = 0.3 m: 1) calculation; 2) experiment. W, %; τ, sec.

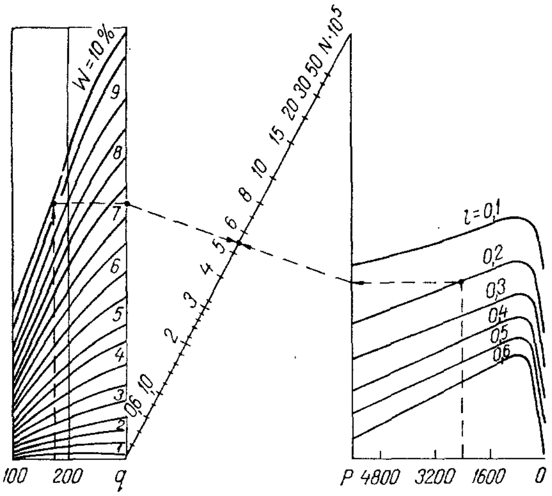

Fig. 3. Nomogram for calculating the maximum drying rate. q, kW/m³.

where r(w) is the specific heat of drying, including the heat of evaporation and desorption and depending on the moisture content [2]:

$$r(w) = 2500 + K\exp(-23.5\,w),$$

$$N = N_{\max}\left[1 + \frac{N_{\max}\tau(n-1)}{W_0 - W_{\mathrm{eq}}}\right]^{\frac{1}{1-n}}. \tag{6}$$

Substituting the expressions for r(w) and N into (5) and taking into account the nonlinearity on the right side of the balance equation, this equation could not be solved in quadratures. We shall therefore perform a transformation. We shall represent the product Nr(w) in the form of an approximate function, described by the equation

$$Nr(w) = f(\tau) = N_{\max}K\exp(-m\tau). \tag{7}$$

In addition, for the standard types of heavy-duty capacitors, the coefficients in the approximation have the following values: $m = 3.015 \cdot 10^{-4}$; $K = 1.16 \cdot 10^{14}$. In addition, we approximate the nonlinear term on the right side according to the type of equation by a straight line in segments. Then we have

$$T_{\mathrm{W}}^4 - T^4 = K_n(T_{\mathrm{W}}^4 - T_0^4)\left(1 - \frac{T - T_0}{T_{\mathrm{W}} - T_0}\right), \tag{8}$$

where K_n = 1.05-1.1 is a correction facotr, which reduces the error in the main section of the approximation ($T \leq 140$°C), which in this case constitutes:

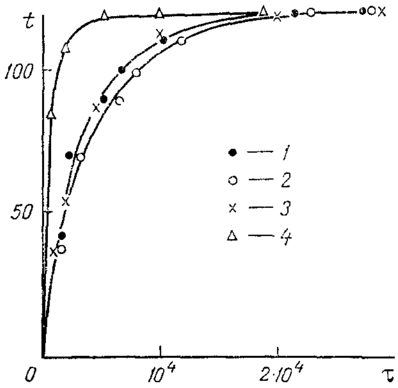

Fig. 4. Kinetics of heating of parts in the process of drying under the following conditions: P = 15 Pa, T = 393°K, L = 0.3 m; 1, 2) temperature of the outer and inner sections (experiment); 3) average temperature (calculation); 4) average temperature neglecting heat losses to evaporation (calculation). t, °C.

T	325	350	375	400
%	−0.4	−8	−2	0

Substituting (7) and (8) into (5), we obtain

$$\frac{dT}{d\tau}+LT=g(\tau), \tag{9}$$

where

$$L=\frac{\varepsilon\sigma_0F_r(T_W^4-T_0^4)K_n}{c\rho V(T_W-T_0)}+\frac{\alpha F_k}{c\rho V};$$

$$A=\frac{\varepsilon\sigma_0F_rK_n(T_W^4-T_0^4)}{c\rho V}\left(1+\frac{T_0}{T_e-T_0}\right)+\frac{\alpha F_kT_e}{c\rho V};$$

$$P=\frac{N_{\max}K}{c},\quad g(\tau)=A-P\exp(-m\tau).$$

We solve Eq. (9) by the method of variation of constants

$$T=\frac{A}{L}+\exp(-L\tau)\left(T_0-\frac{A}{L}\right)+\frac{P}{L-m}[\exp(-L\tau)-\exp(-m\tau)]. \tag{10}$$

The data obtained from calculations using the formula (10) are compared in Fig. 4 with the experimental data. The disagreement between them does not exceed 2%. At the same time, neglecting the heat loss to evaporation of moisture (curve 4) would have increased the error up to 35%.

Thus the engineering method for calculating the drying of capacitors can be formulated as follows:

1) for a fixed temperature of the wall of the vacuum chamber T_W (exceeding by 2-5°C the maximum admissible drying temperature), the specific liberation of heat is determined using the formula (4);

2) using the formula obtained from (2) the time required for drying parts to the required moisture content is determined:

$$\tau=(U^{n-1}-1)\frac{W_0-W\mathrm{eq}}{N_{\max}(n-1)};$$

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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