equilibrium moisture content of material; \( \lambda, \nu, c, \) thermal conductivity, \( \text{W/(m*K)} \), kinematic viscosity, \( \text{m}^2/\text{sec} \), and thermal diffusivity, \( \text{m}^2/\text{sec} \), of heating agent; \( \lambda_{mt}, \rho_c, \) thermal conductivity \( \text{W/(m*K)} \) and density \( \text{kg/m}^3 \) of material.

LITERATURE CITED


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

N. A. Prudnikov and N. A. Gudko

UDC (621.319.4:621.315,614.6).002.2

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

\[
\frac{\partial \theta}{\partial \text{Fo}} = \frac{\partial^2 \theta}{\partial X^2}, \quad \theta(X, 0) = 1, \quad \frac{\partial \theta(0, \text{Fo})}{\partial X} = -\text{Sk} (\theta_w^0 - \theta_0^0), \quad \frac{\partial \theta(l, \text{Fo})}{\partial X} = 0. \tag{1}
\]

Here \( \theta = T/T_0; \ X = x/L_0; \ \text{Fo} = \alpha x/L_0 b; \ \text{Sk} = \frac{\varepsilon_0 \rho_1 \beta_1}{\lambda 1 + \rho_2 \beta_2}; \ b = (c_1 \rho_1 \beta_1/c_2 \rho_2 \beta_2 + 1) \) 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.

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]:

\[ U = \left( \frac{N_{\text{max}}(n-1)}{W_0 - W_{\text{eq}}} \right)^{1-n} \]  

(2)

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

\[ N_{\text{max}} = \frac{29.5 \cdot 10^{-6}}{L^{0.3}} \cdot \exp \left( \frac{q-181}{0.065q^{1.05}} \right) \cdot \frac{133}{327+P} \cdot \left( \frac{W-W_{\text{eq}}}{W_0-W_{\text{eq}}} \right)^{0.48} \]  

(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 \( N_{\text{max}} \), 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:

\[ q = \frac{\sigma_0^r \rho c_{\text{v}} (T_0^4 - T^4) F_r + \frac{\sigma F_h}{V} (T_0 - T)}{V} \]  

(4)

The area of radiative \( F_r \) and convective \( F_h \) 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):

\[ c_p \frac{dT}{dt} + \rho N_r = \frac{\sigma_0^r \rho c_{\text{v}} (T_0^4 - T^4) F_r + \frac{\sigma F_h}{V} (T_0 - T)}{V} \]  

(5)