ANALYTIC CALCULATION OF DEEP VACUUM DRYING OF MULTILAYER INSULATION ELEMENTS OF HIGH-VOLTAGE TRANSFORMERS

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The isothermal deep drying of electrically insulating elements of transformers in vacuum conditions is considered: A mathematical description of the unsteady moisture-content fields is given and a method of calculating the kinetics of the process is outlined.

In experimental and theoretical investigations of the drying of electrically insulated high-voltage transformers, the usual model for the insulating elements that are the most difficult to dry is a multilayer cylindrical sample with moistureproof ends, prepared by the tight winding of cable paper around a metallic rod [1-7]. Similar models, fitted at various points over the radial thickness of the insulator with thermocouples, internal-pressure sensors, and measuring condensers (intended to record the kinetics of the changes occurring in the course of drying in the electrophysical characteristics of the various layers of the paper), may be used to monitor and regulate the technological process of thermovacuum treatment of real transformers and to determine its optimum length [8]. Data obtained using these models provide a basis for sufficiently accurate judgments of the distribution of temperature and moisture content in the characteristic elements of the insulation (according to [1] the distribution of the moisture content over the layers of the insulation may be determined from the readings of the corresponding thermocouples and internal-pressure sensors using sorption isotherms of the paper [9]). There is a particular interest in data on the moisture content of the most slowly drying inner layers of the insulation in the final stage of vacuum drying, since, knowing the required final moisture content of the insulation, such data can be used as the basis for a decision as to when the thermovacuum treatment of transformers may be ended.

Although there have been several analytic investigations of the internal mass transfer and moisture field in cylindrical elements of cellulose insulation in the course of atmospheric and vacuum drying [4, 6, 10-12], it is practically impossible to use such results for a rigorous quantitative analysis of the moisture distribution in transformer insulating elements in the final stage of deep vacuum drying, since the necessary data on the thermodynamic characteristics and transfer properties of electrically insulating materials in this process are not available. This problem is made worse because the heat- and mass-transfer characteristics of cellulose insulation materials in vacuum conditions depend significantly on the moisture content and temperature of the material. It was evidently just such considerations which led to the attempt in [6] to formulate a mathematical description of the nonsteady moisture-content fields in multilayer cylindrical elements of cellulose insulation during isothermal vacuum drying in the region of relatively low residual moisture content ($W < 1\%$). However, whereas the assumption in [6] that the temperature is equalized over all the layers of the insulating element in the final stage of vacuum drying (when the process parameters are constant) has been confirmed by numerous experimental data [1], the assumption (used as one of the boundary conditions in formulating the problem) that the initial distribution of moisture over the radial thickness of the insulation is uniform does not correspond at all with real conditions and, as a result, there are considerable limitations on the practical use of the resulting analytic solution in obtaining rigorous quantitative estimates on the basis of which appropriate arrangements could be made for the monitoring of technological processes.

A complex experimental investigation of the vacuum drying of multilayer cylindrical models with insulation of various radial thicknesses ($R_1 = 0.8$ cm, $R_2 = 1.8$-4.8 cm) has shown

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that for a sufficiently wide range of the process parameters (t = 100-130°C, P = 0.01-1 mm Hg), after conditions of isothermal drying have been reached (when the temperature drop over the thickness of the insulation does not exceed 3-5°C) and the mean residual moisture content of the sample has been reduced to 1-1.2%, the distribution of the moisture content of the paper over the radius (r) of the model is adequately described by the following empirical relation:

$$W(r)_{\tau_I=0} = W_{eq} + W_{R_1}\{1-\exp[-n(1-r/R_2)]\}. \tag{1}$$

The mean absolute value of n was found to be 3.7 for the investigated ranges of t, P, and $(R_2 - R_1)$ (the winding of the models was of K-120 cable paper).

Equation (1) was used as the initial condition in solving the differential equation of one-dimensional internal moisture transfer for the isothermal drying of a hollow infinite cylinder (modeling a multilayer cylinder of insulation material with moistureproof ends):

$$\frac{\partial W}{\partial \tau_I} = a_m\left(\frac{\partial^2 W}{\partial r^2} + \frac{1}{r}\frac{\partial W}{\partial r}\right). \tag{2}$$

The boundary conditions of the first kind for the symmetrical problem are of the form

$$\frac{\partial W_{(R_1,\tau_I)}}{\partial \tau_I} = 0, \tag{3}$$

$$W_{(R_2,\tau_I)} = W_{eq}. \tag{4}$$

The second of these conditions means that, in the course of final vacuum drying, the moisture content at the external surface of the insulating element has an equilibrium value corresponding to the parameters of the surrounding medium; this assumption is confirmed by the experimental data of [1]. The solution of Eq. (2) with the boundary conditions in Eqs. (3) and (4) (obtained in a linear approximation by the method of integral transforms) is

$$W_{(r,\tau_I)} = W_{eq} + \frac{\pi^2}{2}\sum_{i=1}^{\infty}\frac{m_i^2 V_0(m_i r)\exp(-a_m m_i^2 \tau_I)}{1-\left[\frac{J_0(m_i R_2)}{J_1(m_i R_1)}\right]^2}\times$$
$$\times W_{R_1}\left\{\frac{2}{\pi m_i^2} + \exp(-n)\left[J_0(m_i R_2)\int_{R_1}^{R_2} rY_0(m_i r)\exp\left(\frac{nr}{R_2}\right)dr -\right.\right.$$
$$\left.\left.-Y_0(m_i R_2)\int_{R_1}^{R_2} rJ_0(m_i r)\exp\left(\frac{nr}{R_2}\right)dr\right]\right\}; \tag{5}$$

where $m_i = x_i/R_2$; x_i are the roots of the characteristic equation

$$Y_0(x)J_1(kx) - J_0(x)Y_1(kx) = 0 \qquad (k \leqslant 1); \tag{6}$$

$V_0(m_i r)$ is given by

$$V_0(m_i r) = J_0(m_i r)Y_0(m_i R_2) - J_0(m_i R_2)Y_0(m_i r); \tag{7}$$

$k = R_1/R_2$; J_0, J_1, Y_0, and Y_1 are Bessel functions.

Since, as shown by quantitative estimates, the infinite series in Eq. (5) rapidly converges, the first term of the series may be satisfactory for practical calculations, as follows

$$W_{(r,\tau_I)} = W_{eq} + \frac{\pi^2}{2}\cdot\frac{m_1^2 V_0(m_1 r)\exp(-a_m m_1^2 \tau_I)}{1-\left[\frac{J_0(m_1 R_2)}{J_1(m_1 R_1)}\right]^2}\times$$
$$\times W_{R_1}\left\{\frac{2}{\pi m_1^2} + \exp(-n)\left[J_0(m_1 R_2)\int_{R_1}^{R_2} rY_0(m_1 r)\exp\left(\frac{nr}{R_2}\right)dr -\right.\right.$$

$$-Y_0(m_1R_2)\int_{R_1}^{R_2} rJ_0(m_1r)\exp\left(\frac{nr}{R_2}\right)dr\Bigg]\Bigg\}. \quad (8)$$

The integral expression

$$A=\frac{m_1^2}{1-\left[\frac{J_0(m_1R_2)}{J_1(m_1R_1)}\right]^2}\left\{\frac{2}{\pi m_1^2}+\exp(-n)\left[J_0(m_1R_2)\int_{R_1}^{R_2} rY_0(m_1r)\times\right.\right.$$

$$\left.\left.\times\exp\left(\frac{nr}{R^2}\right)dr-Y_0(m_1R_2)\int_{R_1}^{R_2} rJ_0(m_1r)\exp\left(\frac{nr}{R_2}\right)dr\right]\right\}$$

which appears in Eq. (8) is determined only by the absolute values of the internal and external radii of the hollow cylinder. Computer calculations lead to the following approximate dependence of A on the geometric factor k over the investigated range (0.15 < k < 0.45):

$$A=0.5+k^2. \quad (9)$$

Thus, the nonsteady moisture-content field in the model in the final stage of vacuum drying may be calculated from the fairly simple relation

$$W_{(r,\tau_I)}=W_{eq}+\frac{\pi^2}{2}(0.5+k^2)W_{R_1}V_0(m_1r)\exp(-a_m m_1^2\tau_I). \quad (10)$$

The mean moisture content of the insulation in the model is

$$\overline{W}_{(\tau_I)}=\frac{2}{R_2^2-R_1^2}\int_{R_1}^{R_2} rW_{(r,\tau_I)}\,dr. \quad (11)$$

Appropriate manipulations lead to the result

$$\overline{W}_{(\tau_I)}=W_{eq}+\frac{2\pi W_{R_1}(0.5+k^2)\exp(-a_m m_1^2\tau_I)}{m_1^2(R_2^2-R_1^2)} \quad (12)$$

or

$$\tau_I=\frac{1}{a_m m_1^2}\ln\frac{m_1^2(R_2^2-R_1^2)(\overline{W}_{(\tau_I)}-W_{eq})}{2\pi W_{R_1}(0.5+k^2)}. \quad (13)$$

Equation (13) may be used to calculate the length of isothermal vacuum drying required from the initial monitoring of the moisture content W_{R_1} of the inner layers of the model to the attainment of the required mean moisture content of the insulation. An undoubted advantage of the method is that data on the moisture content and temperature of the inner layers of the cable paper in the sample at any moment during the final stage of isothermal drying are sufficient for the analysis of the unsteady moisture distribution over the cross section of the model and the determination of the necessary duration of the process. These data may be obtained using a model equipped with at least 2-3 thermocouples and one internal-pressure sensor (the hollow rod on which the model is wound may be used for this purpose [13]). It is found that in the conditions under discussion (isothermal vacuum drying) the numerical values given in [6] may be used for the moisture-diffusion coefficient a_m in the multilayer paper models: at t = 110°C, $a_m = 7.5 \cdot 10^{-4}$ cm²/min; at t = 120°C, $a_m = 1 \cdot 10^{-3}$ cm²/min. The discrepancy between the results calculated using Eqs. (10) and (13) and the corresponding experimental curves of the moisture distribution over the layers of the model and the drying curves for the models is small (Figs. 1 and 2). The curves in Fig. 1 and curves 8-10 in Fig. 2, lying in the range of τ corresponding to conditions of isothermal drying, were drawn in accordance with Eq. (10); the points on these curves were obtained on

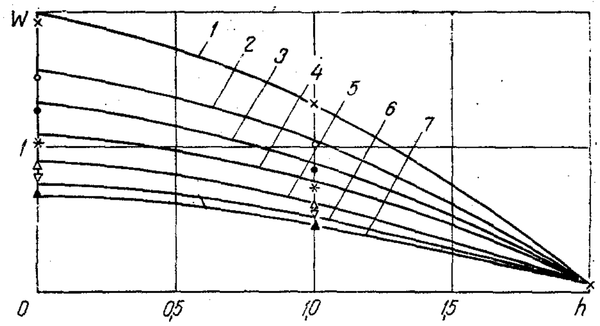

Fig. 1. Distribution of moisture content of paper over the radial thickness of the model (h = 2 cm) in isothermal vacuum drying (t = 120°C, P = 0.1 mm Hg): 1) $\tau_I = 0$ (τ_{tot} = 700 min); 2) 200 (900); 3) 400 (1100); 4) 600 (1300); 5) 800 (1500); 6) 1000 (1700); 7) 1100 min (1800 min). W, %; h, cm.

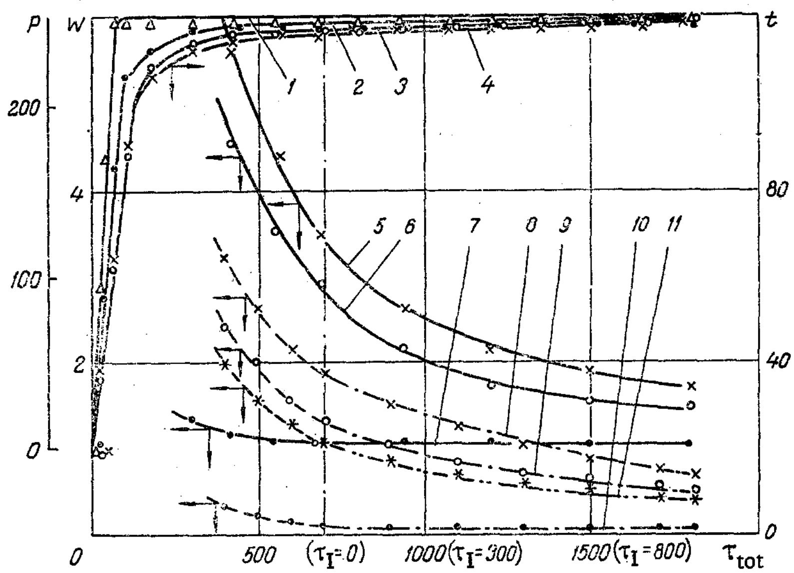

Fig. 2. Drying kinetics of a model with h = 2 cm: curves of the variation in the local pressure, moisture content, and temperature of the insulation at t = 120°C and P = 0.01 mm Hg: 1) temperature of medium; 2-4) temperature of surface, middle, and inner layers of insulation; 5-7) variation of pressure in the inner, middle, and surface layers of the insulation; 8-10) variation in the moisture content of the inner, middle, and surface layers of the insulation; 11) drying curve of the model. P, mm Hg; W, %; τ_{tot}, min.

the basis of experimental measurements of the internal pressure and temperature of the insulation at various points over the radial thickness of the models using the sorption isotherms of K-120 cable paper in vacuum conditions [1, 9]. Curve 11 in Fig. 2 for τ > 700 min was plotted according to Eq. (13); the points on this curve were obtained by averaging over the volume of the cylindrical model the local moisture content of the insulation determined on the basis of experimental data. The good agreement between the calculated and experimental data indicates that the mathematical model adopted is satisfactory and the relations derived from it are correct.

NOTATION

$W_{(r)}$, $W_{(r,\ \tau_I)}$, local moisture content at $\tau_I = 0$ and local value of moisture content in the course of isothermal drying, %; $\bar{W}(\tau_I)$, mean instantaneous moisture, %; W_{eq}, equilibrium moisture content, %; W_{R_1}, moisture content in inner layers of model at $\tau_I = 0$, %; R_1, R_2, inner and outer radii of model, cm; r, radius, cm; $h = (R_2 - R_1)$, insulation thickness of model, cm; a_m, moisture-diffusion coefficient, cm^2/min; τ, time, min; τ_{tot}, length of drying, min; τ_I, length of isothermal drying, min; t, temperature, °C; P, pressure, mm Hg.

LITERATURE CITED

1. I. F. Pikus and L. A. Koshepavo, Inzh.-Fiz. Zh., 30, No. 1 (1976).
2. G. Beer et al., "Transformers," in: The International Conference on Large Electric Systems (CIGRÉ), Vol. 2, Paris (1966).
3. A. Csernatoni-Hoffer, IEEE Trans. Electr. Insul., EI-3, No. 4 (1968).
4. T. Terada and F. Enokubo, J. Inst. Electr. Eng. Jpn., 92A, No. 5 (1972).
5. M. Beyer, Grundlangen der Vakuumtrocknung von Flüssigen Isolierstoffen und Papierisolation, GFR (1966).
6. M. Beyer and H. D. Grossekatthofer, "Berechnung und Optimisierung des Trocknungprozess von Hochspannungs Papierisolation," Elektrotech. Z., A95, No. 8 (1974).
7. S. D. Lizunov, Drying and Degassing Insulation of High-Voltage Transformers [in Russian], Énergiya, Moscow (1971).
8. I. F. Pikus, L. A. Koshepavo, T. B. Zhilyaev, and L. I. Filatova, in: The Electrical Engineering Industry (High-Voltage-Apparatus Series) [in Russian], No. 10 (1976).
9. P. S. Kuts, I. F. Pikus, and L. S. Kalinina, in: Heat and Mass Transfer [in Russian], No. 6, ITMO Akad. Nauk BelorusSSR, Minsk (1972).
10. W. Lampe, Arch. Elektrotech., 53, No. 2 (1969).
11. W. Lampe, Arch. Elektrotech., 53, No. 3 (1969).
12. V. M. Tret'yakov, "Investigation of the technological process of drying of high-voltage cables," Author's Abstract of Candidate's Dissertation, Moscow Power Institute (1968).
13. I. F. Pikus, L. A. Koshepavo, and N. A. Gudko, in: Thermophysics and the Technology of Thermal Drying Processes [in Russian], ITMO Akad. Nauk BelorusSSR, Minsk (1975).

KINETICS OF VARIATION AND UNSTEADY FIELDS OF TRANSPORT POTENTIALS IN HIGH-TEMPERATURE VACUUM DRYING OF HIGH-VOLTAGE CELLULOSE INSULATION

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The results of an analytical investigation are used to analyze the development of temperature fields and internal-pressure fields in high-temperature vacuum drying of cylindrical high-voltage electrical insulation elements.

The cellulose insulation of high-voltage equipment and high-voltage electrotechnical components (the active part of power and measuring transformers, high-voltage lead-ins, cables, etc.) is usually dried to low residual moisture content in a relatively high vacuum (0.1-0.001 mm Hg) at elevated temperature (100-130°C). The characteristic model objects usually chosen for analysis of the drying of high-voltage insulation are the difficult-to-dry multilayer cylindrical elements wound, for example, from cable paper [1-3]. The moisture in electrically insulating cellulose materials is mainly in the adsorption-bound state; in a vacuum at high temperature the mechanism of moisture transfer within the considered insulation elements is determined mainly by filtration—diffusion vapor transport in a radial direction due to the arising pressure gradient [1, 4].

With the adoption of some assumptions an approximate mathematical model of transport processes in high-temperature vacuum drying of cylindrical cellulose insulation elements in generalized variables can be formulated in the following way [5]:

$$\frac{\partial T(X, \mathrm{Fo})}{\partial \mathrm{Fo}} = \frac{1}{1-K}\left[\frac{\partial^2 T(X, \mathrm{Fo})}{\partial X^2} + \frac{1}{X}\frac{\partial T(X, \mathrm{Fo})}{\partial X}\right] + \frac{\mathrm{Bu}}{1-K}\frac{\partial P(X, \mathrm{Fo})}{\partial \mathrm{Fo}}, \quad (1)$$

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