6. A. I. Ol'shanskii and E. L. Brom, Izv. Vyssh. Uchebn. Zaved., Tekhnol. Legkoi Prom-sti, No. 4 (1975).
7. K. D. Makarenko, in: Questions of Intensification of Heat and Mass Transfer in Drying and Thermal Processes [in Russian], Nauka i Tekhnika (1967).
8. I. F. Pikus, in: Questions of Intensification of Heat and Mass Transfer in Drying and Thermal Processes [in Russian], Nauka i Tekhnika (1967).
9. G. A. Bocharov, "An investigation of drying of baker's yeast by the combined method," Author's Abstract of Candidate's Dissertation (1973).
10. A. S. Ginzburg and V. A. Rezchikov, in: Current State and Ways of Development of Grain-Drying Techniques, Elevator Industry Series [in Russian], Moscow (1967).

CERTAIN LAWS APPLICABLE TO THE VACUUM DRYING OF ELECTRICAL INSULATION ELEMENTS IN AN INERT HEAT-TRANSFER VAPOR

I. F. Pikus, I. A. Gubskii, and A. M. Zverev

UDC 66.047.2

Results are given from an experimental study of the heating and drying kinetics of model laminated samples of electrical insulation in petroleum-product vapor.

One of the most progressive and least studied methods for the drying of insulation used in high-voltage electrical equipment (transformers in particular) is the so-called method of vacuum drying in a "vapor phase" atmosphere, i.e., in the vapor of an inert heat-transfer agent (for example, a petroleum product) whose physicochemical and technological properties are compatible with those of insulating materials and liquid impregnating dielectrics [1, 2].

We have carried out an experimental investigation of the vacuum drying of laminated insulation elements in an inert heat-transfer vapor, using a specially designed test stand, the details of which are described in [2]. The investigated objects are cylindrical model samples made from rolled-up type K-120 cable paper with moisture-insulated ends, simulating the most difficult-to-dry elements of electrical insulation structures. The samples are prepared by means of a special device that rolls paper strip of width 160 mm tightly around metal rods with a diameter of 16 mm. For moisture insulation the ends of the cylinder and the free ends of the paper strip in the model samples are coated with an epoxy compound, and then the ends of the cylinder are further packed with bushings of gasoline-resistant rubber by means of a four-bolt clamping mechanism. During fabrication of the model samples the electrodes of a copper — Constantan thermocouple and internal pressure gauges in the form of hypodermic needles connected via thin impulse tubes to the vacuometric system are inserted at one end between the layers of cable paper at various points along the radius. Also, the model samples are fitted with the brass mesh electrodes of local measuring capacitors designed for determining the layer-by-layer values of the dielectric characteristics of the cable paper as they vary during the experiment (these measurements are performed only in the final stage of vacuum drying of the insulation). The testing and measuring equipment and experimental procedure are described in [2]. The thicknesses of the laminated insulation of the model samples are 20, 30, and 40 mm. A typical cyclic schedule of the experiments is planned with regard for the actual technological process of insulation drying in an inert heat-transfer vapor and comprises the following:

a) heating and drying of the (pre-evacuated) samples in petroleum-product vapor for prescribed and strictly regulated regime parameters (temperature level of the process, pressure in the working chamber,

A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk.
Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 32, No. 6, pp. 1015-1023, June, 1977. Original article submitted May 4, 1976.

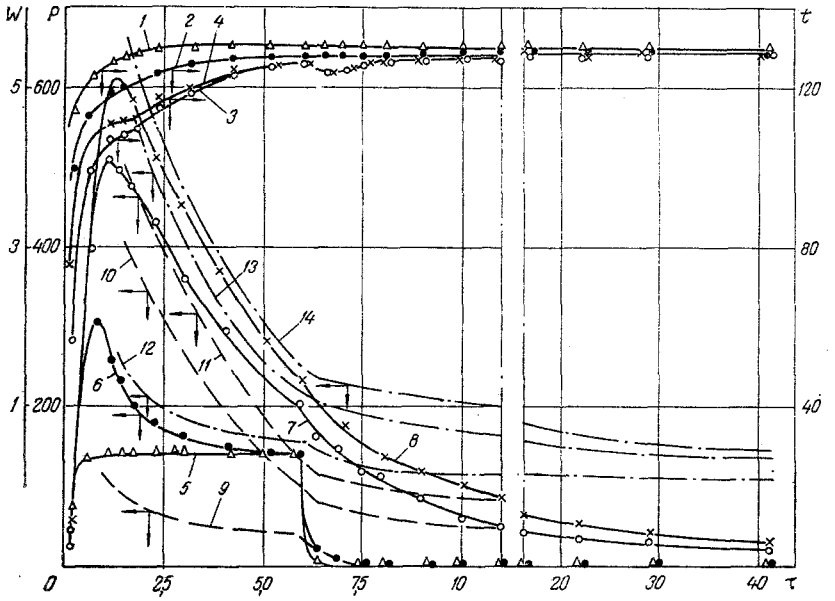

Fig. 1. Kinetic curves for heating and drying of a model sample, h = 20 mm at t = 130°C, P = 140 mm Hg, G = 2 kg/h. 1-4) Temperatures of the medium and of surface, middle, and interior insulation layers; 5) pressure variation in working chamber; 6-8) variation of total pressure in surface, middle, and interior layers of the model sample; 9-11) variation of the partial pressure of water vapor in surface, middle, and interior insulation layers; 12-14) variation of layer-by-layer moisture content of surface, middle, and interior insulation layers of the model sample; τ, h; t, °C; W, %.

and mass flow of the petroleum-product vapor); this period lasts 6 to 17 h, depending on the thickness of the insulation;

b) vacuum heat treatment in the transition regime (with the vaporizer off and the condenser fully open) for 0.5 h;

c) final vacuum drying of the insulation at a given temperature level of the process and a given residual pressure in the working chamber, say 0.1 to 0.5 mm Hg; this period varies between 30 and 73 h in length.

The defining regime parameters of the investigated process are varied in the following ranges: temperature level from 110 to 140°C; total pressure of the vapor mixture in the working chamber in the "vapor-phase" period from 110 to 170 mm Hg (the partial pressure of the petroleum-product vapor in the working chamber is a constant 100 mm Hg in all the experiments); mass flow of petroleum-product vapor into working chamber during drying period in the "vapor-phase" regime from 0.5 to 2 kg/h. The results of the measurements are plotted in graphs of superimposed kinetic curves for heating of the insulation and curves of the internal vapor pressure versus time in different zones throughout the thickness of the model sample (Fig. 1). These data are used to plot layer-by-layer drying curves for the cable paper. It is assumed here that the total internal pressure in any zone of the sample (as measured by a secondary pressure gauge) after the experimental curve $P_{in} = f(\tau)$ passes through its maximum can be taken as equal to the sum of the internal partial pressure of the petroleum-product vapor (corresponding to the saturation pressure at the instantaneous temperature in the given zone) and the internal partial pressure of the water vapor; the partial pressure of the water vapor in any zone of the sample corresponds to the equilibrium value for the instantaneous state parameters (temperature and moisture content) of the cable paper in the measurement zone [3]. The applicability of these assumptions is supported by control experiments in which the layer-by-layer moisture content of the cable paper in model samples heat-treated in petroleum-product vapor is determined by random sampling and direct analysis of the moisture content by the method of K. Fisher.

By analogy with the procedure described in [3] the instantaneous local moisture content of the insulation is calculated and analytical layer-by-layer drying curves plotted (dot-dash curves in Fig. 1) according to the generalized equation for the water-vapor sorption isotherms of K-120 cable paper under vacuum conditions [4]

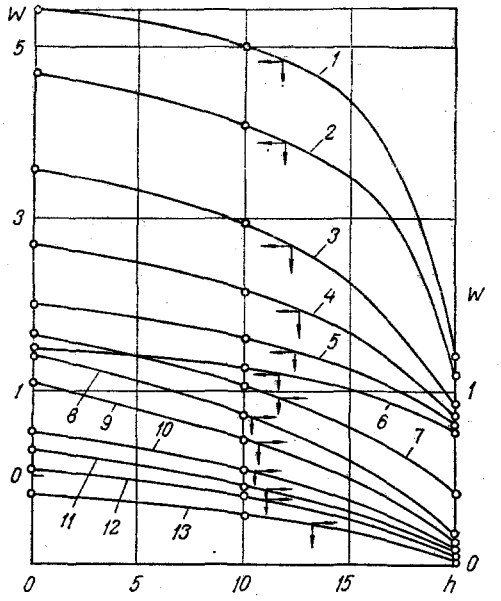

Fig. 2. Instantaneous radial moisture distribution of insulation in the dried-out model sample, h = 20 mm at t = 130°C, P = 140 mm Hg, G = 2 kg/h, and various drying times, including the initial 45-min preheating operation: 1) 1.5; 2) 2; 3) 3; 4) 4; 5) 5; 6) 6; 7) 6.5; 8) 8; 9) 10; 10) 16; 11) 22; 12) 29; 13) 41 h.

on the basis of the kinetic curves obtained for the variation of the local internal pressure of the water vapor with regard for the first of the stated assumptions (these curves are shown dashed in Fig. 1) and the kinetic curves for heating of the corresponding insulation layers. Under the conditions of the transition period and the beginning of the vacuum-drying period we have conducted special control experiments on predried model samples, recording the variation of the internal local pressure of the petroleum-product vapor in different radial zones of the dry insulation (saturated with this vapor and heated to the regime temperature) after connection of the drying chamber to the condenser as well as during subsequent evacuation of the system and maintenance of a residual pressure of 0.1 to 0.5 mm Hg in it. These control experiments show that after evacuation for 3 to 8 h (depending on the radial thickness of the insulation) the internal pressure of the petroleum-product vapor becomes commensurate with the pressure of the surrounding medium even in the innermost layers of the model samples.

Layer-by-layer drying curves for the insulation in the transition period and in the period of final vacuum drying of the model samples are also plotted on the basis of data from measurements of the internal vapor pressure in the insulation and the layer-by-layer temperature curves. To determine the weighted-mean instantaneous moisture content of the insulation and to plot the drying curve for the whole model sample graphs of the radial moisture distribution in the dried-out model insulation sample are plotted (Fig. 2) for each experiment from the calculated layer-by-layer insulation drying curves. The mean moisture content of the insulation at any time is calculated from the curves obtained for the moisture distribution in the cable paper (along the radius with regard for the real configuration of the model sample as a hollow cylinder with inside diameter of 16 mm). These calculated values of the weighted-mean instantaneous moisture content of the insulation are plotted in coordinates (W, τ), and the points thus obtained are used to plot drying curves for the model samples in the investigated process (Fig. 3). It is important to note that the given procedure is clearly the best suited to kinetic analysis of the vacuum drying of insulation in an atmosphere of vapor of a condensed inert heat-transfer agent, where the conventional weighing method is totally inapplicable for plotting of the drying curves for the model samples.

A quantitative analysis of the drying curves shows that they can be described in the "vapor-phase" period by means of the generalized equation for the duration of vacuum drying of cylindrical model insulation samples with combined convective and radiative heat transmission [3]:

$$\tau = \frac{1}{aN} \ln \frac{[a + b(W - W_e)](W_1 - W_e)}{[a + b(W_1 - W_e)](W - W_e)}, \quad (1)$$

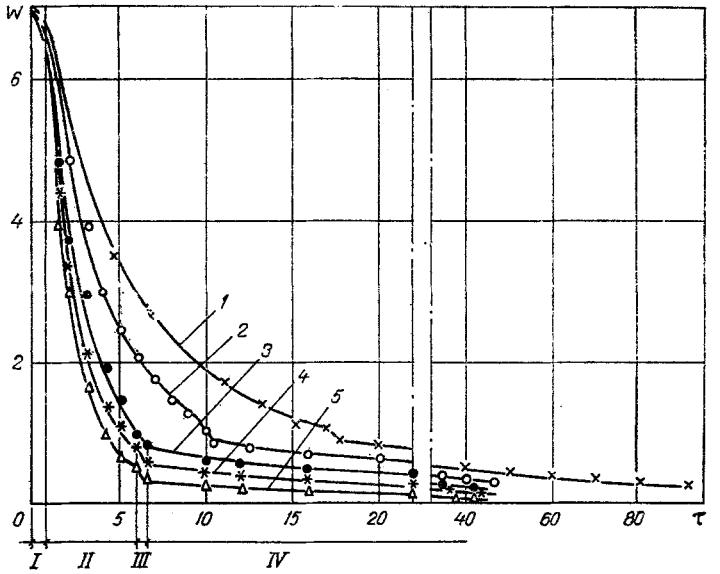

Fig. 3. Kinetic curves for drying of model samples: 1) h = 40 mm, t = 130°C, P = 140 mm Hg, G = 2 kg/h; 2) h = 30, t = 130, P = 140, G = 2; 3-5) h = 20, P = 110, G = 2, t = 120, 130, and 140, respectively; I) preheating period; II) drying in petroleum-product vapor; III) transition regime; IV) final vacuum drying period.

where a and b are empirical coefficients that do not depend on the regime parameters of the process or the thickness of the sample; the absolute values of these coefficients turn out to be roughly the same for all the investigated model samples: $a = 0.067$; $b = 0.011$. The influence of the regime parameters and sample thickness on the rate of the dehydration process for the insulation in the given process is manifested in the absolute values of the maximum drying rate N and equilibrium moisture content W_e of the cable paper (the latter quantity depends only on the temperature and partial pressure of the water vapor in the drying chamber). The results of processing of the experimental data by the method of successive estimation of the functional dependence N = f(t, P, G, h) are given in Fig. 4; for the investigated ranges of variation of the regime parameters and the quantity h this functional dependence is described by the empirical relation

$$N = 10^{-5} t^{2.7} h^{-1.6} (1.24 + 0.69 G^{0.22}). \quad (2)$$

The fact that the power exponent of t in the resulting parametric relation is much greater than unity indicates the ever-increasing influence of the temperature (as the temperature level of the process is raised) on the drying rate of the insulation in petroleum-product vapor (see Fig. 4). It is noted, apropos, that the influence of the temperature factor on the drying rate of the model samples in the investigated process turns out to be less than under the conditions of vacuum drying with combined convective and radiative heat transmission [3]. This disparity is attributable to the fact that the heat transmission into the material due to the heat of phase conversion of the condensing petroleum-product vapors, though appreciable, depends very little on the temperature level of the process (in the investigated range of variation of the regime parameters). Moreover, under the "vapor-phase" conditions the relative contribution of the radiative component to the total quantity of heat transmitted into the model sample becomes less pronounced, thereby diminishing further the influence of the temperature factor on the drying rate.

Numerical processing of the experimental data to highlight the influence of the pressure of the vapor mixture in the drying chamber on the dehydration kinetics of the model samples shows that any variation of P (within the interval from 110 to 170 mm Hg) is not reflected in the absolute values of the maximum drying rate N; the influence of this parameter on the drying time of the insulation in petroleum-product vapor, all other conditions being equal, is manifested in the dependence of W_e in expression (1) on the partial pressure of the water vapor in the drying chamber (as mentioned, this dependence is given in [4]).

It follows from the graphical dependence of the maximum reduced drying rate $N/t^{2.7}$ on G (Fig. 4) that in the interval G < 0.5 to 1 kg/h an increase in the mass flow of petroleum-product vapor into the chamber is accompanied by an abrupt increase in the drying rate. For G > 1 kg/h the variation of this regime parameter does not yield a significant change in the intensity of the process.

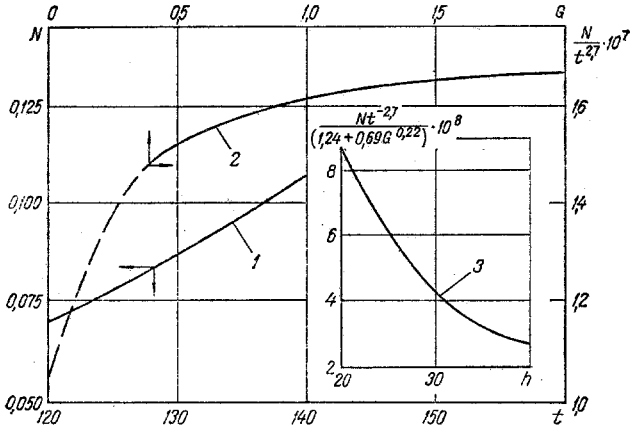

Fig. 4. Maximum drying rate N (%/min) versus process regime parameters and radial thickness of the insulation: 1) $N = f(t)$ for a sample with h = 20 mm at P = 110 mm Hg, G = 2 kg/h; 2) $(N/t^{2.7}) \cdot 10^7 = f(G)$ for h = 20, P = 110 to 140, t = 120 to 140; 3) $Nt^{-2.7} \cdot 10^8/(1.24 + 0.69G^{0.22}) = f(h)$ for P = 110 to 170, G = 0.5 to 2, t = 120 to 140.

Control experiments have shown that increasing the influx of heating vapor into the chamber causes the formation of an "excess" of petroleum product, which condenses onto the relatively "cold" surfaces and runs off into the lower part of the chamber, where it is again vaporized. This secondary "natural" circulation of the inert heat-transfer vapor at a certain level of G can exert a dominant influence on the external heat- and mass-transfer processes associated with heating and drying of the model insulation samples in a confined volume. All of the foregoing promotes circumstances whereby, beginning with a certain level G = 0.5 to 1 kg/h, an increase in the amount of petroleum-product vapor fed into the drying chamber is felt less and less in the rate of heat transmission into the insulation, even though the total quantity of heat input to the system increases. Conversely, in the interval of small values of G (less than 0.5 kg/h) the quantity of heating vapor supplied from the vaporizer into the working chamber can with decreasing G become commensurate with the quantity of petroleum product condensed on the model sample and passed through the chamber into the condenser, so that in the final analysis a situation can be created in the chamber such that the heat input into the insulation due to phase transition of the petroleum-product vapor becomes relatively small. As should be expected, the rate of the insulation drying process in petroleum-product vapor falls off appreciably as the radial thickness of the samples is increased (Fig. 4).

The experiments show that an increase in the quantity h (in the investigated interval h = 20 to 40 mm) is not reflected in the behavior of the sample drying curves and does not affect the functional dependence of the maximum drying rate on the regime parameters of the process. In using relation (1) to describe the vacuum drying curves for the model samples in petroleum-product vapor it is necessary to take account of the length of the preheating period, which in the given experiments is 45 min on the average.

It is essential to note that the lower limit of the interval of variation of the mean final moisture content of the insulation for the analytical relation (1) to be valid must clearly be dictated by the values W_2 occurring in the given experimental study (W_2 = 0.5 to 1%).

During the half-hour transition drying period the reduction in the mean moisture content of the insulation is 0.15 to 0.25% for all the experiments (see Fig. 3). As for the final vacuum-drying period, numerical processing of the experimental data shows that the generalized semiempirical relation derived in [3] can be used to describe the insulation drying curves in this stage of the process.

We now examine certain characteristics exhibited for the heating kinetics of electrical insulation elements in the investigated process. As is apparent from Fig. 1, in the vacuum heat treatment of the model samples under conditions of combined convective and radiative heat transmission and additional heat input from petroleum product vapor condensed on the surface of the samples all the insulation layers are strongly heated. In the initial drying period lasting several hours a considerable temperature differential is observed in the sample, particularly between the surface and middle layers. This result is chiefly due to rather vigorous heat transmission toward the surface of the model sample due to all components of the complex heat-transfer process in conjunction with the comparatively large thermal resistance of the pre-evacuated laminated cellulose insulation.

Moreover, the substantial temperature gradient in the model samples at the beginning of drying is to a certain extent attributable to the characteristic laws of the mechanism of moisture evaporation and internal mass transfer in the investigated process. Under conditions of strong heat transmission into dried-out samples the moisture evaporation and evacuation of water vapor from the surface layers of the cable paper take place extremely rapidly, so that the temperature of the insulation in this zone of the model sample asymptotically approaches the temperature of the surrounding medium along a generally monotonic curve. The moisture evaporation in the middle and interior layers and the migration of water vapor therefore are inhibited mainly by the ever-increasing resistance to the filtration-diffusion flow of vapor through the outer dried-out layers of cable paper as the drying process progresses; typically, the stronger the drying process of the model sample as a whole, the more pronounced will be the nonuniformity of the radial moisture distribution in the insulation, and this trend will necessarily be accompanied by a redistribution of the heat expended in moisture evaporation and heating of the material in any given insulation layers. Thus, the vacuum heat treatment of insulation in petroleum-product vapor is characterized, on the one hand, by a high rate of heating (and, hence, of drying) of the insulation and, on the other, by the presence of strong temperature gradients throughout the thickness of the insulation elements in the preheating stage.

Another typical attribute of the heating kinetics of the model samples in the given process is an abrupt decrease in the heating rate of the insulation (predominantly the interior layers of cable paper) after the material reaches a temperature of order 105 to 115°C. This experimentally established fact can be explained as follows. In the indicated interval of variation of the instantaneous temperature of the material the quantity of heat input to the sample (which decreases as the temperature of the model sample rises due to the reduction of the temperature differential) becomes commensurate with the heat loss in moisture evaporation from the insulation. Thus, as is evident from Fig. 1, the given temperature interval of the material corresponds to vigorous drying of the insulation. The experiments show that the mean moisture content of the insulation at the end of this characteristic period is 3 or 4%, regardless of the process regime parameters or the sample thickness (in the investigated intervals of variation of t, P, G, and h).

Another factor that tends to slow down the heating of the insulation in the given stage of the drying process for the model samples is clearly the reduction in the rate of condensation of the petroleum-product vapor. This effect is related not only to the increase in temperature of the surface layers of cable paper to a level quite close to the saturation temperature of the petroleum-product vapor (corresponding to the partial pressure of this vapor in the working chamber), but also to the evolution of an extreme excess water-vapor pressure in the interior of the model samples, which prevents penetration of the vapor and condensed petroleum product into the insulation. As a result, the heat transmission into the insulation by phase conversion of the petroleum vapor is diminished. After completion of the given characteristic stage of the heating kinetics of the insulation samples in petroleum-product vapor the temperature of the cable paper increases in every layer of the model sample along exponential curves, and at the end of the "vapor-phase" period it comes closest to the temperature level of the process in the present experimental study.

NOTATION

W, W_1, W_e, instantaneous, initial, and equilibrium moisture contents of insulation, %; τ, time, min; N, maximum drying rate at initial moisture content of the model sample, %/min; t, temperature, °C; P, total pressure of vapor mixture in the working chamber, mm Hg; h, radial thickness of model sample, mm; G, mass flow of petroleum-product vapor into the working chamber, kg/h; a, b, empirical coefficients; in (subscript), internal.

LITERATURE CITED

1. S. D. Lizunov, Drying and Degassing of High-Voltage Transformer Insulation [in Russian], Énergiya, Moscow (1971).
2. I. F. Pikus, I. A. Gubskii, and L. A. Koshepavo, in: Problems of Drying and Heat Treatment [in Russian], ITMO Akad. Nauk BelorusSSR, Minsk (1976).
3. I. F. Pikus and L. A. Koshepavo, Inzh.-Fiz. Zh., 30, No. 1 (1976).
4. P. S. Kuts, I. F. Pikus, and L. S. Kalinina, in: Heat and Mass Transfer [in Russian], Vol. 6, ITMO Akad. Nauk BelorusSSR, Minsk (1972).