BASIC LAWS OF THE VACUUM DRYING PROCESS APPLIED TO CELLULOSE MATERIALS FOR ELECTRICAL INSULATION

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Results are shown of an experimental study concerning the vacuum drying of cellulose materials for electrical insulation by a combined convective–radiative heat supply. A semi-empirical generalized equation is given by which the drying time down to the desired final moisture content in typical materials can be determined.

The service life of cellulose insulation in transformers is determined, essentially, by the rate of its aging processes, which depend largely on the moisture content in the material. Furthermore, the moisture content in the insulation also determines the electrical characteristics of the latter (loss tangent, breakdown voltage, and insulation resistance).

Although the subject is quite relevant, very little is found in the literature about the optimization of the drying process applied to transformer insulation. Phenomena which occur during this process have remained almost entirely unexplored.

In this article we present the results of an experimental study concerned with the heating and drying kinetics in insulation specimens for active transformer components exposed to a combination of convective and radiative heat under vacuum.

The tests were performed on specimens of electrical insulation cardboard grades A (density 0.93 g/cm^3, thickness 2, 2.5, and 3 mm), grade V (density 0.95 g/cm^3, thickness 3 mm), and grades ÉMTs (density 1.05 g/cm^3, thickness 1.5 and 3 mm).

The operating parameters were varied over a wide range: the pressure of the vapor–air mixture in the chamber from 0.1 to 300 mm Hg, the temperature from 90 to 120°C.

The test apparatus consisted of two hermetically connected vacuum chambers, the lower chamber serving as a repository for a model VLTK-500 scale with 0.1 g graduations. The test specimens were placed on a special pad rigidly joined to the load pan in the upper operating chamber. Scale readings were taken visually through a system of mirrors and a viewing glass in the lid of the lower chamber. In order

TABLE 1. Values of the Empirical Coefficients a, b for Various Electrical Grades of Cardboard Insulation

Cardboard grade	ρ, g/cm^3	h, mm	a	b
A	0,93	2,0	0,1050	0,00068
		2,5	0,1022	0,00098
		3,0	0,1000	0,00124
V	0,95	3,0	0,0900	0,00240
EMTs	1,05	1,5	0,0540	0,00610
		3,0	0,0300	0,00900

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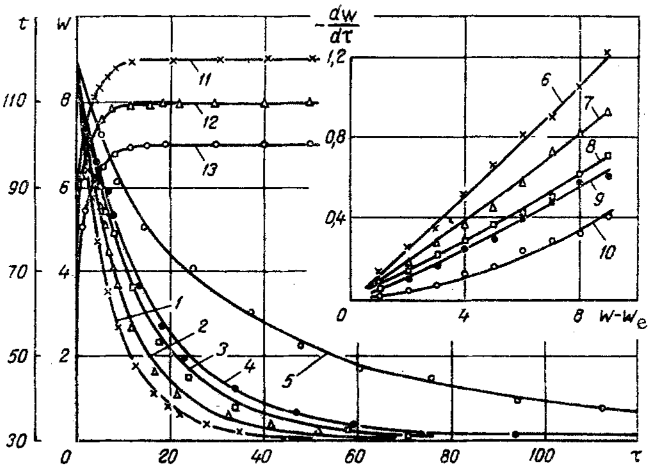

Fig. 1. Drying curves (1-5), drying-rate curves (6-10), and heating-kinetics curves (11-13) for electrical-grade cardboards: grade A cardboard h = 3 mm at t = 120°C and p = 1.5 mm Hg (1, 6, 11), grade A cardboard h = 3 mm at t = 110°C and p = 1.5 mm Hg (2, 7, 12), grade A cardboard (3, 8), grade V cardboard (4, 9, 13), grade ÉMTs cardboard (5, 10); h = 3 mm, t = 100°C, and p = 1.5 mm Hg for 3-5, 8-10, and 13.

to avoid errors due to a likely effect of the thermocouples weight on the scale readings, on a special cantilever beam inside the operating chamber we suspended similar additional cardboard specimens for studying the heating kinetics. The temperature of the specimens and also the ambient temperature in the operating chamber were measured with copper–constantan thermocouples (electrode wires 0.15 mm in diameter) assembled with a model ÉPP-09 24-point electronic potentiometer.

The heat sources were electronic nichrome elements mounted into the housing of the operating chamber. A specified ambient temperature in the chamber was maintained automatically by means of a model ÉPV-2 electronic indicating–recording potentiometer.

The suction system in this apparatus included two VN-IMG pumps, nitrogen-cooled traps for freezing the water vapor, drains for maintaining the required pressure in the chamber, vacuum valves, and piping. The chamber pressure was measured with a U-tube mercury vacumeter and with a VT-3 thermocouple vacumeter.

Specimens had been prepared in the form of rectangular pieces weighing 100-200 g and first held for several days in a desiccator with a definite moisture content. The initial moisture content was determined by two methods in parallel: by drying in a vacuum oven and by distillation.

During the test we measured the following quantities: ambient temperature and pressure in the chamber, temperature of the material, and weight of the specimens to be dried. The measurements were made at 1 min intervals (at the beginning) increasing to 5-10 min (at the end). A test was completed when the weight of the specimen became stable without change for 3-4 h under conditions of the experiment.

The test results are shown in the form of drying curves $W = f(\tau)$ referred to the initial moisture $W_1 = 9\%$ and drying-rate curves $-dW/d\tau = f(W - W_e)$ (Fig. 1). A correction was introduced here to account for a short period (3-7 min) of temperature and pressure stabilization in the drying chamber at the beginning of the test.

An analysis of the drying and the drying-rate curves has shown that they do not pass through a critical point, i.e., that the vacuum-heat treatment of cellulose insulation proceeds under a decreasing drying rate. According to Fig. 1, the temperature of dried specimens rose fast and, after a short time interval, became equal to the ambient temperature in the chamber. From the beginning of the process, the moisture content followed an intricate trend asymptotically approaching the equilibrium level W_e.

It may be stated that the internal heat and mass transfer has a decisive effect on the drying rate in vacuum, the process rate being limited by the slow transfer of generated vapor from the evaporation zone through dry layers to the surface of the material [1, 2].

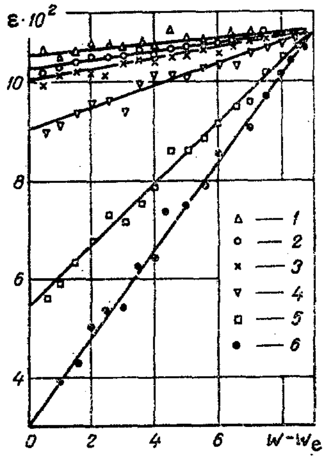

Fig. 2. Maximum referred drying rate $\varepsilon = -(dW/d\tau)/N(W-W_e)$ as a function of the instantaneous excess moisture content $(W-W_e)$, %, for electrical-grade insulating cardboards: grade A cardboard h = 2 mm (1), grade A carbdoard h = 2.5 mm (2), grade A cardboard h = 3 mm (3), grade V cardboard h = 3 mm (4), grade ÉMTs cardboard h = 1.5 mm (5), grade ÉMTs cardboard h = 3 mm (6).

An analytical solution of the intricate problem of compounded internal and external heat and mass transfer is mathematically very difficult. Besides, there are no published data available on the heat and moisture transfer coefficients which would apply to this particular process. For this reason, in order to establish a specific relation for insulating cardboard between the vacuum-drying process time and the basic process factors, we analyze the test data directly.

As can be seen in Fig. 1, the drying-rate curves for all test specimens at various operating conditions are bent toward the moisture-content axis of abscissas and their shape corresponds to a power function.

An evaluation of the test data has yielded the following generalized equation for the drying-rate curves:

$$-\frac{dW}{d\tau} = N[a(W-W_e) + b(W-W_e)^2]. \tag{1}$$

The empirical coefficients a, b in Eq. (1) do not depend on the process parameters (temperature t and vapor–air pressure p in the operating chamber), but are determined only by the thickness of any given material. The effect of external factors on the process kinetics in drying electrical-grade cardboard insulation is manifested in the change of N – the maximum drying rate corresponding to a given initial moisture content in the material ($W_1 = 9\%$).

The validity of expression (1) is well illustrated in Fig. 2, where the relative referred drying rate has been plotted as a function of the instantaneous excess moisture content $(W-W_e)$ in the material:

$$\varepsilon = -\frac{dW/d\tau}{N(W-W_e)}.$$

Indeed, as can be seen here, the test points for each grade and gage of cardboard lie quite close to the straight line

$$\varepsilon = a + b(W-W_e) \tag{2}$$

over the entire range of process parameter values.

The functional relation

$$\varepsilon = -\frac{dW/d\tau}{N(W-W_e)} = a + b(W-W_e) \tag{3}$$

obtained directly from the drying-rate curves may be useful for deriving a universal relation between the vacuum-drying time and the specimen thickness for cardboard insulation under actual operating conditions [3].

Equation (3) will be rewritten as follows:

$$d\tau = -\frac{1}{N} \cdot \frac{dW}{(W-W_e)[a+b(W-W_e)]}. \tag{4}$$

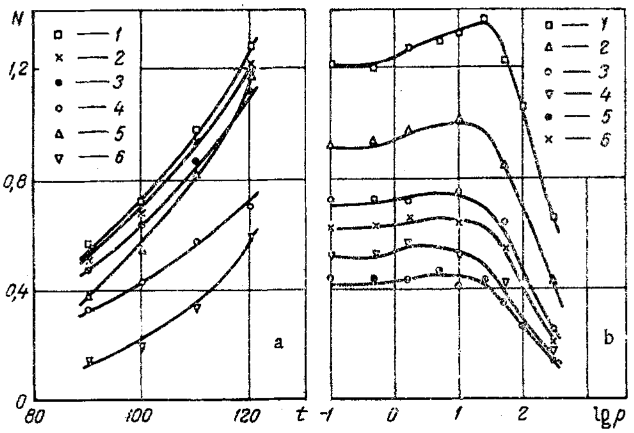

Fig. 3. Maximum drying rate N (%/min) as a function of the temperature t (°C) (a): grade A cardboard h = 2 mm at p = 1.5 mm Hg (1), grade A cardboard h = 3 mm at p = 1.5 mm Hg (2), grade V cardboard h = 3 mm at p = 1.5 mm Hg (3), grade ÉMTs cardboard h = 3 mm at p = 1.5 mm Hg (4), grade A cardboard h = 3 mm at p = 50 mm Hg (5), grade V cardboard h = 3 mm at p = 300 mm Hg (6); as a function of logp (b): grade A cardboard h = 2 mm at t = 120°C (1), grade A cardboard h = 2 mm at t = 110°C (2), grade A cardboard h = 2 mm at t = 100°C (3), grade A cardboard h = 2 mm at t = 90°C (4), grade ÉMTs cardboard h = 3 mm at t = 100°C (5), grade V cardboard h = 3 mm at t = 100°C (6).

Integrating (4) from W_1 (initial moisture content) to W_2 (final moisture content) yields

$$\tau = \frac{1}{aN} \ln \frac{[a + b(W_2 - W_e)](W_1 - W_e)}{[a + b(W_1 - W_e)](W_2 - W_e)}. \tag{5}$$

In order to evaluate the effect of basic parameters on the kinetics of vacuum drying, we have processed the test data for electrical-grade cardboards quantitatively by the method of successive tracking of the function N = f(t, p, h, ρ); we have also established how the coefficients a, b depend on the specimen thickness of the various cardboard grades.

For this purpose, we systematized all the drying curves with respect to each governing factor. A subsequent analysis of those curves showed that the vacuum drying of the test specimens had been appreciably accelerated by a temperature rise under constant other process conditions.

The maximum drying rate N has been plotted in Fig. 3a as a function of the temperature t.

It is evident here that the relation N = f(t) is of the same type for all test specimens (at a given pressure in the drying chamber) and is, in fact, a power function

$$N \sim t^n, \tag{6}$$

where the exponent n does not depend on the specimen thickness but is determined solely by the vapor–air pressure in the chamber. Within the range of test pressures p the value of n ranges from 2.87 to 5.27.

The fact that n is greater than unity indicates that, as the temperature rises, its effect on the drying rate of insulation cardboards under vacuum increases. Apparently, this is due to the increasing fraction of heat absorbed by the material through radiation at higher temperatures as well as due to the increasing rate of internal heat and mass transfer.

A complete analysis of the N = f(t) relation based on all tests over the entire range of chamber pressures has yielded the following empirical equation:

$$n = 2{,}1 \lg (p + 23). \tag{7}$$

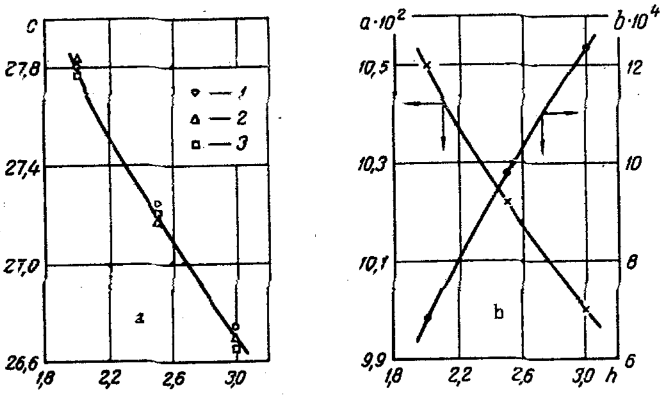

Fig. 4. Maximum referred drying rate $C = N(p + 29)^5/t^n$ as a function of the specimen thickness h (a) for grade A cardboard: p = 0.1 mm Hg and t = 110°C (1), p = 10 mm Hg and t = 90°C (2), p = 50 mm Hg and t = 120°C (3). Empirical coefficients a, b as functions of the specimen thickness h (b) for grade A cardboard.

Thus, the exponent n (i.e., the effect of the temperature on the rate at which cardboard insulation is vacuum dried) increases with the chamber pressure. This is obviously a result of a higher rate of heat supply to a dried material under a higher pressure, mainly because of the increasing role played by convective heat transfer in an increasingly denser medium [1, 2].

An important aspect of this process is that the vapor–air pressure inside the drying chamber affects not only the rate of heat supply to a dried specimen (which is reflected in the functional relation $n = f(p)$) but also determines the evaporation rate of the moisture as well as the mechanism of heat and mass transfer inside the dried material.

The results of the test data evaluation for the purpose of revealing the effect of pressure on the rate of vacuum drying, in the case of electrical-grade cardboard insulation, are presented graphically in terms of the maximum drying rate N as a function of log p.

According to Fig. 3b, the relation $N = f(p)$ at a constant temperature is of the same type for all test specimens. As the vapor–air pressure is dropped below atmospheric, the drying rate increases considerably owing to improved mass transfer conditions. At a pressure in the 1-20 mm Hg range (depending on the temperature level) N reaches its maximum value. A further reduction of pressure results in a low drying rate, which can be explained primarily by the radical change in the mechanism of internal mass transfer and then by the greatly inhibited convective heat transfer within this pressure range.

It is to be noted that a similar trend in the relation between the evaporation rate of moisture and the pressure has been observed also by other authors during the sublimation of ice [4] as well as in the vacuum drying of gelatine and porous water-impregnated ceramics [1, 5].

An analysis of the test data has also shown that, for any given specimen, the critical point of the $N = f(p)$ curve corresponding to maximum N shifts toward lower pressures as the temperature decreases. This can be explained as follows. When the pressure decreases, evidently, the molecular-viscous mode of heat and mass transfer gradually transforms into a purely molecular transfer with the quantity $p_v/\sqrt{T}$ rather than the partial pressure becoming the vapor transfer potential [1]. It follows from here that at a higher temperature the molecular flow of vapor begins under a higher partial vapor pressure.

An evaluation of the test data for each specimen in the form of graphs representing the maximum referred drying rate N/t^n as a function of log p has yielded the following universal relation for N as a function of the pressure and the temperature:

$$N = \frac{Ct^n}{(p + 29)^5}, \tag{8}$$

with C denoting a coefficient independent of the process parameters and determined for each cardboard grade by the specimen thickness only.

An analysis of the drying curves for specimens of various thicknesses (other conditions equal) has shown that the rate of vacuum-heat treatment is inversely proportional to the thickness h of the dried material. This is so, because the material thickness determines the path length through which vapor and moisture are transferred from the inside layer to the body surface. A deepening of the evaporation zone during the dehydration of a specimen increases the resistance of the capillary system through which vapor has to be removed and, in this way, the drying rate is decreased [1, 6].

The test data for grade A cardboard have also been evaluated, as shown in Fig. 4a, in terms of a relation between coefficients C and the specimen thickness h. The test points lie adequately close to a curve which fits the following equation:

$$\frac{N(p+29)^5}{t^n} = \frac{29{,}8}{h^{0{,}1}}. \tag{9}$$

For all tested grades of cardboard we have an analogous relation

$$C = \frac{C_1}{h^{0{,}1}}. \tag{10}$$

An analysis of the test data has shown, furthermore, that the value of coefficient C_1 does not depend on the process parameters and on the specimen thickness but only on the grade of material. Since the physicochemical properties of all grades in this experiment are close, it may be assumed – to the first approximation – that the value of C_1 depends only on the material density.

An analysis of all test data covering the entire range of operating conditions and specimen thicknesses in terms of the coefficient

$$C_1 = \frac{N(p+29)^5 h^{0{,}1}}{t^n}$$

as a function of the density ρ has yielded a curve which fits the following equation:

$$C_1 = \frac{1470}{\exp(4{,}2\rho)}. \tag{11}$$

In this way, the universal equation for the maximum drying rate, in the case of electrical insulation cardboard grades A, V, and ÉMTs under a combined convective–radiative heat supply, is

$$N = \frac{1470 t^{2{,}1 \lg(p+23)}}{\exp(4{,}2\rho)\, h^{0{,}1} (p+29)^5}. \tag{12}$$

As has been mentioned earlier, the thickness and the density of insulating cardboard affects this process not only through the maximum drying rate but also through the values of the empirical coefficients a, b, in Eq. (5).

The values of those coefficients, based on the data in Fig. 2 for all test specimens, are given in Table 1.

It is evident here that for any given grade coefficient a decreases and coefficient b increases as the specimen becomes thicker. In Fig. 4b are shown the curves of $a = f(h)$ and $b = f(h)$ for grade A cardboard, which fit the following equations:

$$a = \frac{2{,}53}{h^{1{,}1} + 22}; \tag{13}$$

$$b = 0{,}0124 - \frac{0{,}28}{h^{1{,}1} + 22}. \tag{14}$$

A comparison of numerical values obtained for various cardboard specimens of the same thickness shows that coefficient a increases and coefficient b correspondingly decreases as the density of the material becomes higher. According to Table 1, furthermore, the effect of thickness on the magnitude of these coefficients becomes stronger as the density of the cardboard material increases.

A generalization of the test data has yielded a rather simple formula to be recommended for calculating the vacuum-drying time of electrical insulation cardboard grades A, V, and ÉMTs:

$$\tau = \frac{0{,}68\cdot 10^{-3} h^{0{,}1} (p + 29)^5 \exp(4{,}2\rho)}{a t^{2{,}1 \lg (p+23)}} \ln \frac{[a + b(W_2 - W_e)](W_1 - W_e)}{[a + b(W_1 - W_e)](W_2 - W_e)}\,. \tag{15}$$

The values of coefficients a, b in Eq. (15) for cardboard grades A, V, and ÉMTs are given in Table 1.

The drying curves calculated according to Eq. (15) agree closely with the test data. Equation (15) is obviously applicable only to the tested range of process parameters and cardboard thicknesses.

NOTATION

W, W_1, W_e	are the instantaneous, initial, and equilibrium moisture content in a specimen respectively, %;
τ	is the time, min;
$dW/d\tau$	is the drying rate, %/min;
N	is the maximum drying rate at a given initial moisture content in the material, %/min;
t, T	is the temperature, °C and °K respectively;
p	is the pressure, mm Hg;
p_v	is the partial pressure of vapor, mm Hg;
h	is the thickness of material, mm;
ρ	is the density of specimen with initial moisture content, g/cm^3;
a, b, C, C_1	are the empirical coefficients.

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