

HYGROSCOPIC PROPERTIES OF CELLULOSE
MATERIALS FOR ELECTRICAL INSULATION

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Results are shown of an experimental study concerning the hygroscopic properties of cellulose materials for electrical insulation under low water vapor pressure.

The few data published by Soviet and foreign authors on the hygroscopic properties of cellulose materials for electrical insulation (cable-grade and capacitor-grade paper, and electrical-grade cardboard) under low water vapor pressures are so contradictory that no quantitative trends in the relation $W_e = f(P, t)$ can be established on their basis. According to the data of most authors, for instance, the $W_e = f(P)_t$ test points for electrical insulation paper under vacuum at different temperatures fit on (or about) straight lines [1, 2, 3].

For electrical insulation paper, according to other authors [4, 5, 6], the sorption isotherms plotted at various temperatures under pressures below 0.01–0.1 mm Hg merge into a single curve, i. e., in the range of low vapor pressures the equilibrium moisture content in electrical insulation materials does not depend on the temperature. As to the moisture content in electrical insulation cardboards under vacuum, there are no data at all available in the technical literature.

The hygroscopic properties of cellulose materials for electrical insulation under low vapor pressures must be known, for the proper selection of their optimum performance parameters and for determining the proper heat–vacuum treatment time in the design of electrically insulating structures. The sorption isotherms of these materials can be used for analyzing the parameters of internal mass transfer and for determining the energy characteristics of interaction between moisture and the matrix material [7, 8].

In view of this, an extensive study was made at the Institute of Heat and Mass Transfer (Academy of Sciences of the BSSR) concerning the sorption characteristics of cellulose materials widely used for electrical insulation in transformers and capacitors. The following materials were selected for test specimens:

TABLE 1

Grade of electrical insulation material	Parameter (c, n)	Temperature, °C			Calculation formula	
		45	70	90		
EMT's cardboard	c	2,0	1,18	0,595	0,26	5,55 exp (– 0,034t) 0,489 – 0,00067t
	n	0,47	0,46	0,442	0,43	
Cardboard A	c	1,58	0,97	0,462	0,225	4,02 exp (– 0,032t) 0,552 – 0,001t
	n	0,523	0,507	0,482	0,462	
Cardboard B	c	1,46	0,82	0,38	0,21	3,74 exp (– 0,032t) 0,063 – 0,0017t
	n	0,586	0,56	0,52	0,485	
Silcon	c	2,25	1,35	0,62	0,31	5,6 exp (– 0,032t) 0,48
	n	0,48	0,48	0,48	0,48	
Terex C-1	c	2,60	1,30	0,432	0,178	9,4 exp (– 0,044t) 0,48
	n	0,48	0,48	0,48	0,48	
Terex C-0,8	c	2,7	1,4	0,50	0,22	8,2 exp (– 0,04t) 0,4 + 0,0011t
	n	0,43	0,45	0,48	0,50	

* For capacitor-grade papers Silcon, Terex C-1, Terex C-0.8 experiments conducted at 26° C.

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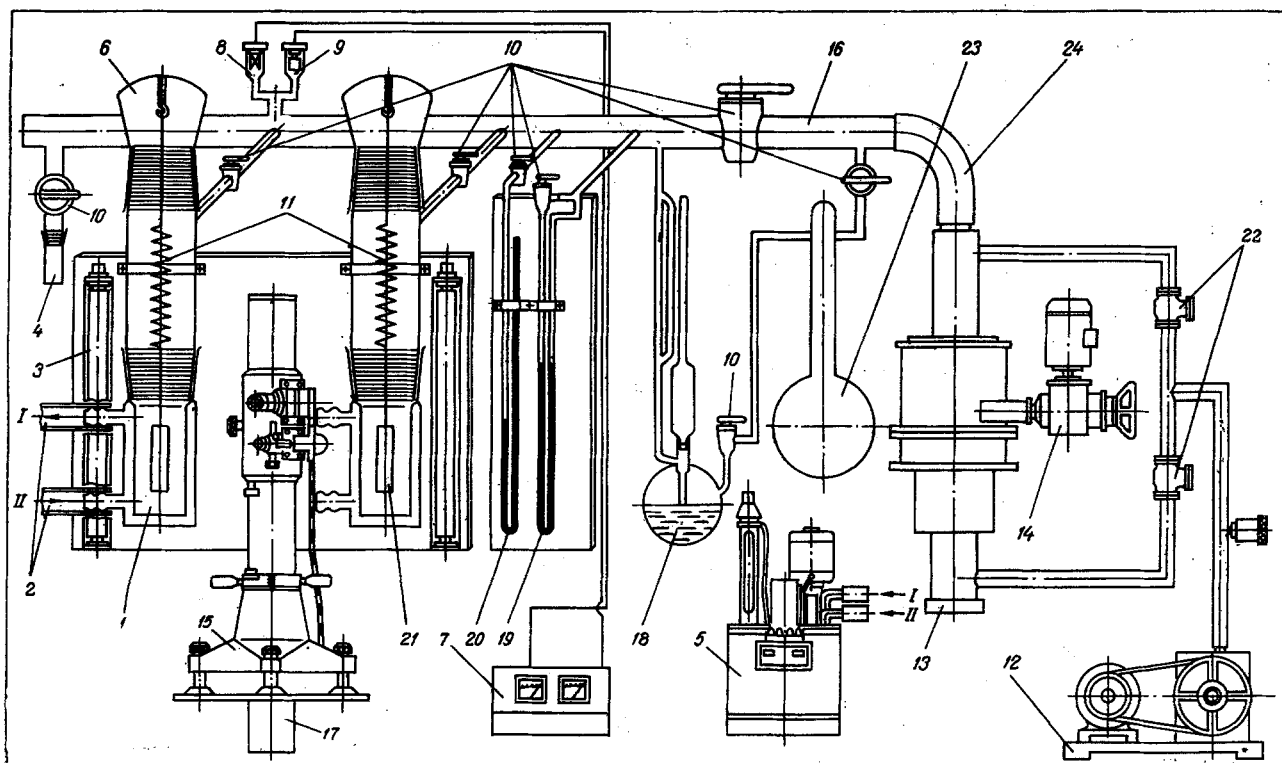


Fig. 1. Schematic diagram of the test apparatus: 1) sorption cylinder, 2) hose, 3) illuminating lamp, 4) sorbate flask, 5) model TL-150 ultraprecision thermostat, 6) upper blade, 7) model VIT-2 vacuometer, 8) model LT-2 lamp, 9) model LM-2 lamp, 10) vacuum tap, 11) quartz springs, 12) model VN-1-2M mechanical pump, 13) model N-IS-2 vapor-oil pump, 14) lock for the vapor-oil pump, 15) model KM-6 cathetometer, 16) collector, 17) cathetometer prop, 18) MacLeod manometer, 19) oil manometer, 20) mercury manometer, 21) specimen, 22) vacuum valve, 23) preliminary bottle, 24) connecting tube.

cable-grade K-120 paper ($\rho = 0.76 \text{ g/cm}^3$), electrical-grade cardboards A ($\rho = 0.93 \text{ g/cm}^3$), B ($\rho = 0.95 \text{ g/cm}^3$), and EMTs ($\rho = 1.05 \text{ g/cm}^3$), as well as capacitor-grade papers KON-II ($\rho = 1.23 \text{ g/cm}^3$), Silcon ($\rho = 1.01 \text{ g/cm}^3$), Terox C-1 ($\rho = 0.998 \text{ g/cm}^3$), and Terox C-08 ($\rho = 0.795 \text{ g/cm}^3$). (The curves of equilibrium moisture content for the paper grades K-120 and KON-II had been given in our earlier article [9]).

The tests were performed in a special-purpose vacuum-sorption apparatus shown schematically in Fig. 1. The gravimetric method was used with a MacBane balance, making it feasible to conduct these tests under low vapor pressures (0.01-10 mm Hg) and over a wide temperature range (20-90°C).

The basic operating components of the apparatus were sorption cylinders 1 made of glass with removable lids 6 ground on top. The latter were fastened to sorption balances 11 comprising fine springs of fused quartz. Batches 21 of test material were hung onto the quartz springs with glass thread.

The quantity of sorbed moisture was recorded with a model KM-6 cathetometer 15 responding to the deflection of the helical quartz springs inside the sorption cylinders.

An elongation of a spring corresponded to a change in the weight of the respective test specimen. The sorption balances were very sensitive and yielded readings accurate to within $5 \cdot 10^{-6} \text{ g}$.

The two-stage vacuum-suction system consisted of a model VN-1-2M mechanical prevacuum pump 12, a model VA-01-1 high-vacuum aggregate with a model N-IS-2 vapor-oil diffusion pump 13 as the main component, a set of connecting tubes with a nitrogen trap, and vacuum valves 22 with taps. All joints were hermetic and had been designed for producing and maintaining a vacuum within 10^{-3} to 10^{-5} mm Hg .

The necessary vapor pressure for testing the process was established by releasing some amount of water vapor from flask 4 containing bidistillate. The air dissolved in this distillate had been removed by passing the latter through three freezing cycles.

The manometric part of the vacuum-sorption apparatus consisted of a U-tube mercury manometer

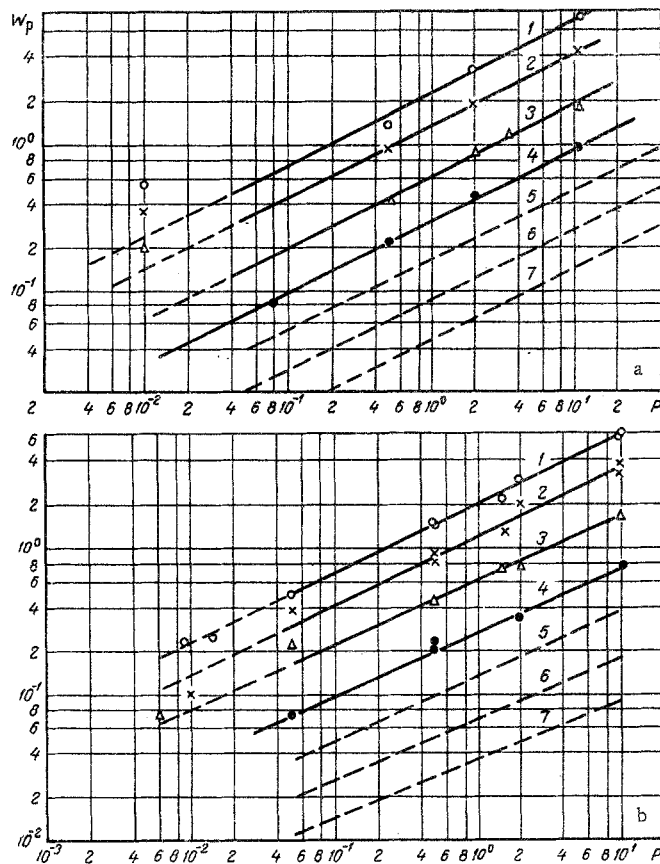


Fig. 2. Sorption isotherms of (a) capacitor-grade Silicon paper and (b) electrical-grade EMTs cardboard, at various temperatures: 1) 26°C for (a) and 29°C for (b), 2) 45°C, 3) 70°C, 4) 90°C, 5) 110°C, 6) 130°C, and 7) 150°C.

20, a U-tube silicone fluid manometer, a model VKZh-4 manometer 19, a model VIT-2 ionization-thermocouple vacuumeter 7 in combination with manometer probes LT-2 (8) and LM-2 (9), and a MacLeod compression gage 18.

The sorption cylinders were wrapped in jackets through which water was circulated from a model TL-150 ultraprecision thermostat 5 for maintaining the required temperature inside the cylinders. For checking the performance of the thermostatizing system, copper-constantan thermocouples had been installed into the active zone of the sorption cylinders.

The temperature inside the sorption cylinders deviated from the reference level by not more than $\pm 0.5^\circ\text{C}$ throughout the experiment.

Control tests were performed to establish the effect of the vapor temperature and pressure as well as the effect of the testing time on the deflection of the quartz springs. These tests were performed on specimens of a hydrophobic material (Teflon). According to these control tests, the vapor pressure P had no effect on the spring elongation. Temperature changes had some effect on the spring deflection. Such a thermal deflection of springs usually depends on the sensitivity, the length, and the diameter of the spring coils. In order to account for this error, temperature corrections were added before and after each test in the calculation of the moisture content. The effect of the testing time on the spring sensitivity was determined by calibrating each spring before and after the experiment.

As the absolutely dry weight of a specimen in these tests was regarded, the weight of a specimen after desiccation at a 90–95°C temperature and under a 10^{-4} – 10^{-3} mm Hg pressure, before the readings of the quartz-spring balance had been stabilized.

For calibration against the absolutely dry weight, the initial moisture content in a test specimen was determined by the Fischer method.

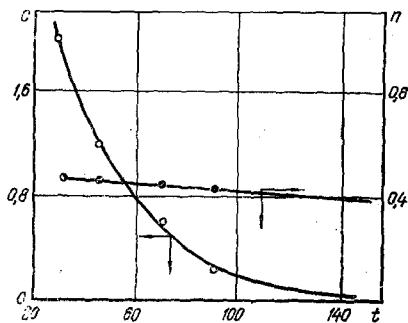


Fig. 3. Parameters c and n as functions of the temperature t ($^{\circ}\text{C}$) for the electrical-grade EMTs cardboard.

As a specific example, in Fig. 2a and 2b are shown curves of equilibrium moisture content in electrical-grade EMTs cardboard and in capacitor-grade Silicon paper.

According to Fig. 2, a rise in the vapor pressure at a constant temperature is accompanied by an increase in sorbed moisture. Thus, for example, a change of pressure from 0.1 to 10 mm Hg is followed by an increase in the equilibrium moisture content from 0.66 to 5.9% in grade EMTs cardboard at 29°C and from 0.72 to 7.0% in Silicon paper at 26°C . As the temperature rises, the equilibrium moisture content drops. This effect of the temperature on W_e is particularly pronounced under higher vapor pressures.

Thus, a temperature rise from 29 to 90°C under $P = 10$ mm Hg is accompanied by a drop in the equilibrium moisture content from 5.9 to 0.7% in grade EMTs cardboard and from 7.0 to 0.93% in Silicon paper.

The equilibrium moisture content in grade EMTs cardboard and in Silicon paper, as a function of the vapor pressure under vacuum, has been plotted in Fig. 2 in logarithmic coordinates and the data fit closely enough on a set of straight lines within the test ranges of both P and t .

The sorption isotherms of all the other tested materials have a similar trend.

Thus, within this pressure range, the relation $W_e = f(P)_t$ for cellulose materials used as electrical insulation is parabolic and can be accurately described by Freundlich's empirical equation [10] $W_e = cP^n$, where c and n are constants whose values depend on the physicochemical properties of the material and on the temperature of the sorption process.

A quantitative evaluation of the sorption isotherms in our study involved calculating c and n in this equation as well as finding the empirical relations $c = f(t)$ and $n = f(t)$ for each tested material. The results of this evaluation are given in Table 1.

The numerical values of exponent n for the capacitor-grade Silicon and Terox C-1 papers are the same and equal to 0.48, for the capacitor-grade Terox C-0.8 paper n increases linearly with the temperature t , and for the electrical-grade cardboards n decreases linearly as the temperature increases.

For illustration, n and c as functions of the temperature are shown graphically in Fig. 3 for the grade EMTs cardboard.

Thus, the universal equations for calculating the equilibrium moisture content in cellulose materials for electrical insulation, as a function of the vapor pressure and the temperature, are:

for grade EMTs cardboard

$$W_e = 5.55 \exp(-0.034t) P^{0.489-0.00067t}, \quad (1)$$

for grade A cardboard

$$W_e = 4.02 \exp(-0.032t) P^{0.552-0.001t}, \quad (2)$$

for grade B cardboard

$$W_e = 3.74 \exp(-0.032t) P^{0.063-0.0017t}, \quad (3)$$

for capacitor-grade Silicon paper

$$W_e = 5.6 \exp(-0.032t) P^{0.48}, \quad (4)$$

for capacitor-grade Terox C-1 paper

$$W_e = 9.4 \exp(-0.044t) P^{0.48}, \quad (5)$$

for capacitor-grade Terox C-0.8 paper

$$W_e = 8.2 \exp(-0.04t) P^{0.4+0.0011t}, \quad (6)$$

The validity range of these equations is evidently limited to the following range of vapor pressure: 0.05 to 10 mm Hg. Below this pressure range, the equilibrium moisture content in the capacitor-grade

papers measured at $P < 0.05$ mm Hg is somewhat above the sorption isotherms described by the respective equations. Unfortunately, in the entire technical literature there is only one reference (by N. Foote [11]) with data on the equilibrium moisture content in capacitor-grade papers under vapor pressures below 0.05 mm Hg (the author there has obtained these data at a temperature of 27°C).

Our values of equilibrium moisture content in the capacitor-grade papers under low pressures P agree closely enough with Foote's data, and the data for higher pressures are also in a satisfactory agreement.

Thus, according to [11], at a temperature of 27°C we have $W_e = 0.4\%$ under a pressure $P = 0.05$ mm Hg, $W_e = 0.7\%$ under $P = 0.1$ mm Hg, and $W_e = 0.2\%$ mm Hg; the values of equilibrium moisture content obtained for the Silicon paper under the same pressures at a temperature of 26°C are respectively 0.54, 0.72, and 1.0%.

By extrapolation of the universal equations into the range of higher temperatures, we have obtained sorption isotherms for the test materials at 110, 130, and 150°C under vacuum (in Fig. 2 these isotherms are indicated by dashed lines). S. Dushman [12] has demonstrated the validity of thus extrapolating the sorption test data for cellulose materials under low vapor pressures. The reliability of the sorption isotherms above 100°C, calculated for the given materials according to those equations, has been confirmed by a comparison of the calculated values with those few published data [11, 13] on the equilibrium moisture content in cellulose materials.

As a result of this experimental study, we have thus determined the equilibrium moisture content in cellulose materials for electrical insulation over sufficiently wide and practically important ranges of vapor pressure and temperature; we have also derived empirical relations for calculating the equilibrium moisture content, as a function of the pressure and the temperature, for all the tested materials.

NOTATION

W_e	is the equilibrium moisture content, kg/kg of dry material, · 100%;
P	is the water vapor pressure, mm Hg;
t	is the temperature, °C;
ρ	is the density of the material, g/cm ³ .

LITERATURE CITED

1. A. Chernatoni-Hoffer, *Electrotechnica* [Italian], No. 10 (1968).
2. E. B. Franklin, *Newsbrief in Electrical Machinery and Apparatus* (Trans. IEEE) Nos. 33-34 (1965).
3. G. Bier, G. Gasparini, et al., *Trans. Internatl. Research Comm. CIGRÉ* (1966).
4. H. P. Moser, *ETZ-A* [German], 81, No. 2, 41 (1960).
5. D. Bingelli et al., *Trans. Internatl. Research Comm. CIGRÉ* (1966).
6. W. Vidmann, *AEГ Mitteil.* [German], 55, 17 (1965).
7. A. V. Lykov, *Desiccation Theory* [in Russian], Izd. Énergiya, Moscow (1968).
8. L. M. Nikitina, *Thermodynamic Parameters and Mass Transfer Coefficients of Moist Materials* [in Russian], Izd. Énergiya, Moscow (1968).
9. P. S. Kuts, I. F. Pikus, and L. S. Kalinina, *Heat and Mass Transfer* [in Russian], Minsk (1972), Vol. 6.
10. S. Brunauer, *Adsorption of Gases and Vapors* [Russian translation], Izd. Inostr. Lit. (1948).
11. N. M. Foote, *Industr. and Engrg. Chemistry*, 39, No. 12, 1642 (1947).
12. S. Dushman, *Scientific Principles of Vacuum Technology* [Russian translation], Izd. Mir (1964).
13. D. S. Varshavskii, *Methods of Improving the Quality of Power Capacitors* [in Russian], Izd. TsINTI (1963).