THERMOPHYSICAL PROPERTIES OF A MULTILAYER CAPACITOR DIELECTRIC UNDER VACUUM

I. F. Pikus and V. P. Kononenko

UDC 536.21

Results are presented of an experimental investigation of the coefficient of thermal conductivity in a multilayer cellulose capacitor dielectric under vacuum conditions.

The drying and degassing of the insulation of power capacitors are carried out under vacuum conditions (here the magnitude of the remanent pressure of the steam–gas mixture in the drying chamber reaches a value of the order of 1 to 10^{-2} N/m^2). Therefore it is of interest to investigate the thermophysical characteristics of a cellulose capacitive dielectric under conditions which hold for thermovacuum treatment of capacitors (i. e., over a wide and practically significant range of pressures extending from normal pressure to 10^{-2} N/m^2).

The experiments were performed on multilayered samples of dry capacitor paper of various technical grades and various densities having a sheet thickness of about 10μ. (The characteristics of the investigated capacitor materials are given in [1].) The principal foundations of the chosen method of investigation and the procedure used for handling the experimental data have been described in detail in [2].

The experimental bench, whose schematic is displayed in Fig. 1, consists of the following principal sections: the measurement section, the thermostating section, the vacuum-exhaust section, and the auxiliary section. The measurement section, which is designed to create and record a time varying temperature field in the investigated sample, includes an automatic recording photoelectronic millivoltmeter 32 of the N-37 type, a differential copper–constantan thermocouple 23 with electrodes having a diameter of 0.1 mm; a hollow cylindrical refrigerator-clamp 3, 6 between whose plates the investigated multilayer sample 4 is placed; a flat heater 5 having the dimensions 60 × 60 × 0.1 mm which is fabricated from constantan wire having a diameter of 0.08 mm; a stabilized power supply 42 of the UIP-1 type from which a constant electric power measured by means of a multirange M-106 voltmeter 41 and a multirange M-104 milliammeter 40 is fed to the heater.

The thermostating section consists of the two ultrathermostats 15 and 30 of the I-10 type which are designed for feeding a liquid coolant with a rigorously stipulated temperature into the clamp (in experiments performed at temperatures up to 90°C distilled water was used as the liquid coolant, while glycerine was used at higher temperatures), and a system for automatically maintaining the required temperature under the glass cover. This system includes two heating elements 2 (KI-1000-220 lamps serve as these elements) and an automatic control block based on a contact thermometer 7, an intermediate relay with a spark-quenching device 19, and an autotransformer 18.

The required degree of pressurization of the capacitor dielectric is ensured by a specially developed electropress 1 which acts on the refrigerator-clamps 3, 6 between which the investigated sample is situated. The stipulated pressurization factor is set by means of a precision indicator head of the clock type 22 with a division size of 0.001 cm and a micrometer screw 27 which are rigidly attached to the refrigerator-clamps.

In order to perform investigations in a vacuum the clamps containing the investigated sample are placed under a glass cover 8 having a diameter of 600 mm which is mounted on a plate 28 fabricated from stainless steel and having a thickness of 30 mm. The cover was sealed by means of a profiled cover washer 9. The input leads of the electrical conductors and thermocouples, as well as the insertion of the pipelines

Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 26, No. 1, pp. 26-34, January, 1974. Original article submitted September 26, 1972.

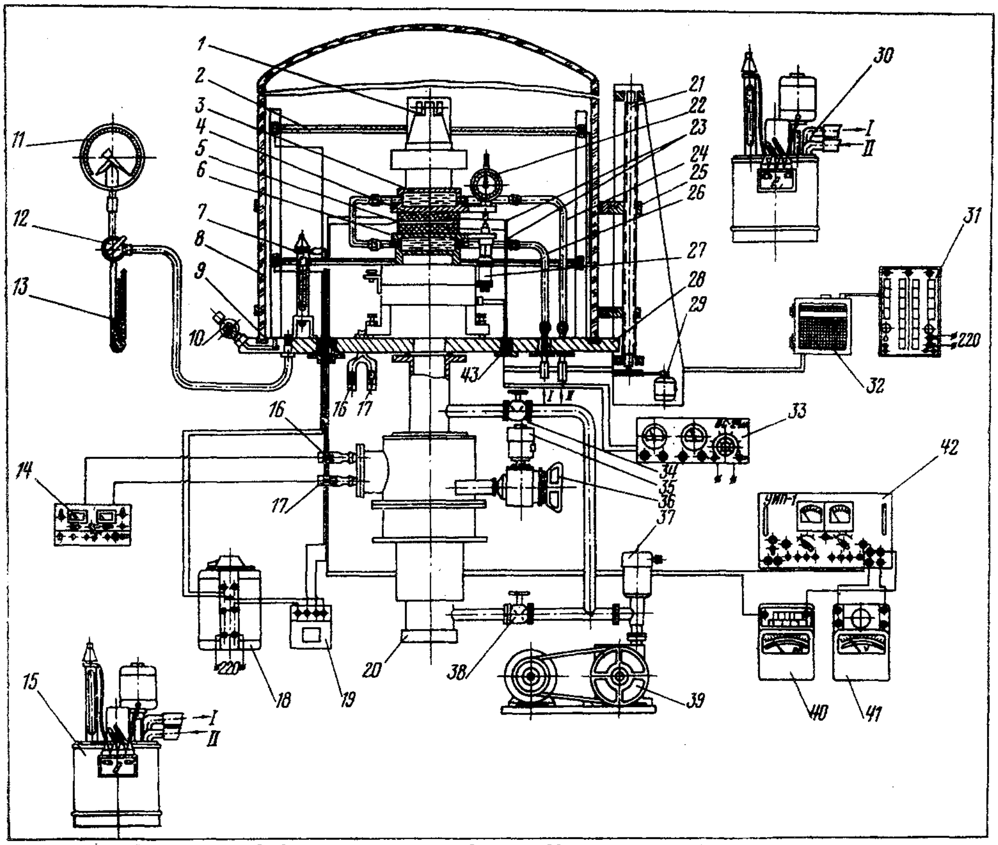

Fig. 1. Schematic of the experimental installation: 1) electropress; 2) heating element; 3, 5) refrigerator clamps; 4) sample; 5) heater; 7) electrocontact thermometer; 8) glass cover; 9) washer; 10) bleeder needle valve; 11, 13, 14) vacuum gauges; 12) tap; 15, 30) ultrathermostat; 16, 17) manometric tubes; 18) autotransformer; 19) relay; 20) diffusion pump; 21) cover jack; 22) indicator; 23) differential thermocouple; 24, 26) tube; 25) screw; 27) micrometer; 28) plate; 29) electric motor of the jack; 31) amplifier; 32) automatic-recording millivoltmeter; 33) rectifier; 34, 38) vacuum rectifiers; 35, 36) vacuum shut-offs; 37) solenoid valve; 39) mechanical pump; 40) milliammeter; 42) stabilized power supply; 41) millivoltmeter; 43) vacuum-tight input lead.

for feeding the circulating liquid coolant into the clamp, is accomplished by means of special vacuum-tight fittings 24, 26, and 43. A needle-valve bleeder designed for admitting atmospheric air and accomplishing pressure regulation in the system is mounted on the plate, and a fitting is also provided to connect the block for measuring the magnitude of the remanent pressure (this includes the U-shaped mercury vacuum-gauge 13, an electrocontact vacuum-gauge 11, and manometric pickups of the VIT-1 thermocouple-ionization vacuum-gauge 14).

In order to create and maintain the rarefaction under the cover a two-stage vacuum-exhaust system is provided which consists of a VN-2MG 39 prevacuum pump, a high-vacuum steam—oil aggregate 20 of the VA-05-4 type, and pipelines for a vacuum-tight shut-off armature 34, 38 and a magnetic valve 37 of the MK-50 type which is aggregated with an electrocontact vacuum-gauge 11. The installation is equipped with a special screw cover jack 21 with an electric drive.

The described experimental installation allowed a complex investigation of the thermophysical characteristics (coefficient of thermal conductivity and coefficient of thermal diffusivity) of the capacitor dielectric to be carried out over a wide range of variation of the temperature of the material (10 to 160°C), the compression factor of the multilayer sample (0.8 to 1) and the magnitude of the gas-filler pressure.

The heat transfer in fibrous materials is usually considered on the assumption of some kind of orderly laying of the fibers. The structure of a multilayer capacitor dielectric is very complex: the cellulose consists of individual fibers oriented in different directions, while the pores and capillaries between fibers

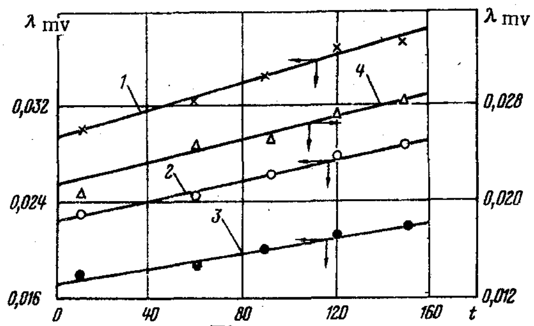

Fig. 2

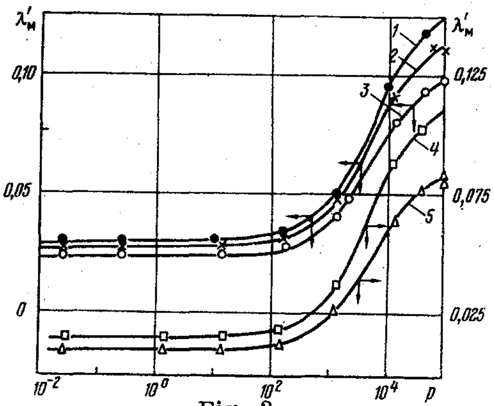

Fig. 3

Fig. 2. Dependence of the coefficient of thermal conductivity of the samples of capacitor paper under vacuum on temperature for $p = 2.66 \cdot 10^{-2}$ N/m², K = 1: 1) KON-II; 2) Silicon; 3) Terox S-0.8; 4) Terox S-1.

Fig. 3. Dependence $\lambda'_m = f(p)$ for a Silicon capacitor paper; K = 1: 1) 150°C; 2) 90; 3) 10; 4) K = 0.9, t = 150°C; 5) K = 0.86, t = 10°C. λ, W/m·°C; p, N/m².

have the most varied shapes and sizes. It is a characteristic feature that the cellulose fibers proper are penetrated by a complex system of micropores. In analyzing the heat transfer in such a heterogeneous system we should take into account the fact that in a multilayer capacitive dielectric the violation of the continuity of the cellulose framework is violated even for a pressurization factor equal to unity, and the thermal flux is transferred from sheet to sheet predominantly due to contact conductivity through thermal bridges between cellulose fibers and the molecular thermal conductivity of the gas filler.

In the first approximation it may be assumed that a completely pressurized capacitor dielectric (for K = 1) constitutes a two-phase system with uniformly distributed and identically oriented filler elements having a cubic shape, the direction of the thermal flux being perpendicular to one of the faces of the cube. By analogy with [3] the effective coefficient of thermal conductivity of such multilayer samples is determined by the expression

$$\lambda_M = \alpha\lambda_{pa} + \beta\lambda'_{pa}, \tag{1}$$

where

$$\lambda_{pa} = \lambda_c \left[1 - m\frac{\frac{\lambda_c}{\lambda_p} - 1}{1 + m^{1/3}\left(\frac{\lambda_c}{\lambda_p} - 1\right)}\right];$$

$$\lambda'_{pa} = \lambda_p \left[1 - (1-m)\frac{\frac{\lambda_p}{\lambda_c} - 1}{1 + (1-m)^{1/3}\left(\frac{\lambda_p}{\lambda_c} - 1\right)}\right]$$

are the values of the coefficient of thermal conductivity of the idealized model of the dielectric for the respective cases in which the continuous phase of the heterogeneous system is first assumed to be cellular and the filler of the air, and then the cellular structure is treated as the filler while the air filling the pores is treated as a continuous phase; $m = 1-\rho/\rho_c$ is the porosity of the capacitor paper.

The coefficients α and β (note that $\beta = 1-\alpha$) are the structural characteristics of the multilayer samples and, as the handling of the experimental data shows, in the investigated range of variation of the definitive factors the values of these coefficients do not depend on the density of the capacitor paper, the temperature of the material, and the degree to which the system is evacuated; for a given thickness of the paper sheets they are determined solely by the magnitude of the pressurization factor of the samples. The experimentally determined dependence of the coefficient α on the pressurization factor of the samples is described by the following equations for all of the investigated types of capacitor paper

$$\alpha = 0.2K^{4.72}. \tag{2}$$

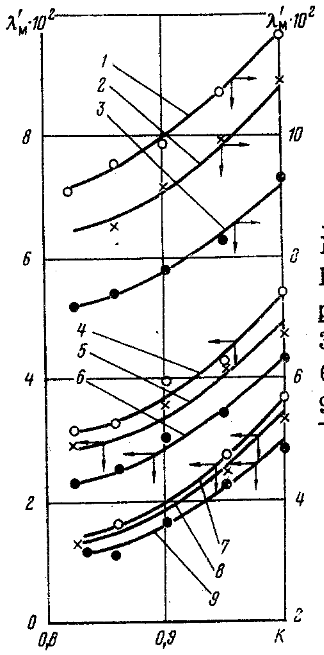

Fig. 4. The dependence $\lambda'_m = f(K)$ for multilayer samples made of KON-II capacitor paper: 1-3) p = 13.3 kN/m^2; 1) 150°C; 2) 90; 3) 10; 4-6) p = 1.33 kN/m^2; 4) 150°C; 5) 90; 6) 10; 7-9) p = 13.3 N/m^2; 7) 150°C; 8) 90; 9) 10. λ, W/m·°C.

Figure 2 displays the temperature dependence of the effective coefficient of thermal conductivity of multilayer elements made of capacitor paper of the investigated types for a pressurization factor equal to 1 under conditions of a high vacuum ($p = 2.66 \cdot 10^{-2}$ N/m^2) when, as will be shown below, the quantity λ_m does not depend on the pressure of the gas filler and is determined solely by the conductive heat transfer along the cellular structure and by radiant heat exchange. (Note that, as shown by the calculations according to the relationships presented in [4], for such a fibrous material as cellulose the contribution of the radiant component of the effective coefficient of thermal conductivity is negligible and even at a temperature of the material equal to 160°C does not exceed 1 to 3% of λ_M.)

From Fig. 2 it is evident that the experimental values of the coefficient of thermal conductivity of the pressurized capacitor dielectric subjected to a high vacuum satisfactorily fit a straight line in the coordinates $\lambda_{mv} = f(t)$ i.e.,

$$\lambda_{mv} = \lambda^0_{mv} + Rt, \tag{3}$$

where λ^0_{mv} corresponds to the conductivity via the solid cellular framework of the multilayer capacitor dielectric at 0°C; the quantity Rt corresponds to the increase in molecular thermal conductivity of the cellular structure and the conductivity via radiation for an average temperature of material equal to it.

Handling of the data obtained from the experimental investigation in order to obtain the generalized dependence of the effective coefficient of thermal conductivity of pressurized (K = 1) samples of capacitor dielectric which have been subjected to a high vacuum on the temperature of the material and the density of the capacitor paper led to the following relationships:

$$\lambda_{mv} = 0.022\,\rho^{1.6}\,(1 + 1.9 \cdot 10^{-3} t). \tag{4}$$

At the same time it follows from (1) that under conditions of a high vacuum the quantity λ_{mv} can be described by the following equation for $\lambda_p \cong 0$:

$$\lambda_{mv} = \alpha \lambda_c (1 - m^{2/3}). \tag{5}$$

Taking account of the fact that for K = 1, $\alpha = 0.2$, and extrapolating Eq. (4) to the value ρ corresponding to the density of the cellulose cellular framework ($\rho_c = 1.56$ g/cm^3), we obtain the following dependence of the coefficient of thermal conductivity of the cellular structure of electrical insulation celluloses on temperature from Eq. (5) for m = 0:

$$\lambda_c = 0.225 + 0.43 \cdot 10^{-3} t. \tag{6}$$

It is appropriate to note that for t = 30°C the value of λ_c calculated according to Eq. (6) ($\lambda_c = 0.238$ W/m·deg) is in good agreement with the value of this coefficient obtained by D. Varshavskii and associates ($\lambda_c = 0.241$ W/m·deg) [5].

Experiments showed that the effective coefficient of thermal conductivity of multilayer samples depends essentially on the gas pressure in the pores and in the interlayers between sheets. The heat transfer via the thermal conductivity of the air in the pores of the cellulose is determined in a wide range of variation of p from atmospheric pressure to a high vacuum (i.e., under conditions which hold for the thermovacuum treatment of a capacitor dielectric) by the ratio of the average mean free path of a gas molecule to the distance between the surfaces involved in the heat exchange process (i.e., to the size of the pores [6]).

The results of the experimental investigation which we performed are evidence of the fact that for all of the investigated grades of multilayer capacitor dielectric the dependence $\lambda_m = f(p)$ in semilog coordinates has a S-shaped character of the type over a wide range of variation of the temperature of the material (10-160°C) and of the degree of pressurization of the sample (K = 0.8-1.0).

As a specific example, Fig. 3 shows such a dependence for multilayer samples made of capacitor paper of the Silicon type. From this figure it is evident that even for small rarefactions the effective thermal conductivity of the samples increases abruptly with a lowering of the gas pressure. Beginning at a pressure of 10^2–10^3 N/m^2 the decrease in the quantity λ_m with increasing vacuum slows up, and the onset of a region of free-molecular flow (Kn > 1) occurs where the thermal conductivity of the system under vacuum is practically independent of the pressure of the gas filler and is determined solely by the conductivity via the solid framework of the cellulose and by the radiant thermal conductivity.

Note that the variation of the density of the capacitor paper, the temperature of the material, and the degree of pressurization of the multilayer sample affect only the absolute values of the effective coefficient of thermal conductivity; the character of the curves $\lambda_m = f(p)$, however, remains unchanged.

With a certain approximation it may be assumed that the capacitor dielectric contains pores of two sizes: macropores corresponding to the average dimensions of the vacuoles between the fibers and sheets of the capacitor paper, and micropores in the fibers. The conductivity of such a system of pores which have an arbitrary shape may be expressed as follows [7]:

$$\lambda_p = \frac{\lambda_p^0}{1 + \dfrac{2\gamma L}{pd_1}} + \frac{\lambda_p^0}{1 + \dfrac{2\gamma L}{pd_2}}. \qquad (7)$$

Since the size of the micropores in the fibers of the capacitor paper is very small, it may be assumed that the second term in Eq. (7) is directly proportional to the magnitude of the pressure of the gas filler — i.e.,

$$\lambda_p = \frac{\lambda_p^0}{1 + \dfrac{B}{p}} + \lambda_p' p. \qquad (8)$$

Here B and λ_p' are constants which are determined mainly by the physicochemical properties and structure of the capacitor paper. An analysis of the experimental data on an investigation of the effect of the air pressure in the pores of the thermal conductivity of the capacitor dielectric shows that in the investigated range of variation of t and K the values of these constants do not depend on temperature or on the pressurization factor of the sample. The numerical values of these constants as functions of the density of the capacitor paper may be determined from the empirical relationships

$$B = 3.6 \cdot 10^3 \rho^{0.5} (1.56 - \rho)^{-1.6}, \qquad (9)$$

$$\lambda_p' = 2.1 \cdot 10^{-8} \rho^4 (1.56 - \rho)^{0.1}. \qquad (10)$$

It should be noted that in calculating the effective coefficient of thermal conductivity of the capacitor dielectric under vacuum according to Eq. (1) by replacing λ_p with the numerical values of the thermal conductivity coefficient of the air in the pores as determined according to Eq. (8) it is necessary to take account of the temperature dependence of λ_p^0.

It is well known that the effective coefficient of thermal conductivity of a capacitor dielectric depends substantially on such a structural parameter as the pressurization factor of the sample [1, 8].

Experiments have shown that a reduction in the degree of pressurization of the dielectric is accompanied by a reduction of the quantity λ_p throughout the entire investigated range of variation of the temperature of the material and the magnitude of the gas pressure in the system, the character of the dependence

$\lambda'_m = f(K)$ having been found to be identical for all of the investigated capacitor papers (as an example, Fig. 4 shows the experimentally obtained dependence $\lambda'_m = f(K)$ for KON-II paper for t = 10, 90, 150°C and p = 13.3, 1330, and 13,330 N/m²).

The effect of the degree of pressurization of the samples on the magnitude of the coefficient of thermal conductivity is especially noticeable in the range of low air pressure where the transfer of heat by the conductivity of the gas in the intersheet gap is negligibly small.

The results of our experimental investigations showed that in order to calculate the effective coefficient of thermal conductivity of a capacitor dielectric under vacuum for a pressurization factor $K \leq 1$ one may use the parallel equivalence circuit according to which

$$\lambda'_m = \lambda_m K + \lambda_p (1 - K). \tag{11}$$

Under these conditions λ_m is calculated according to Eq. (1) with substitution of the corresponding numerical values of the coefficients α and β which in turn depend on the value of K. The comparison of the values of λ'_m calculated according to Eq. (11) and from the experimental data is evidence of the acceptibility of the derived formula for calculating the effective coefficient of thermal conductivity of a dry multilayer capacitor dielectric under vacuum over a wide range of variation of the definitive factors (the curves in Fig. 3 and 4 were plotted according to (11) with allowance for the density of the capacitor paper, the temperature of the material, the magnitude of the pressure of the gas filler, and the degree of pressurization of the samples; the points correspond to the experimental data). This allows the conclusion to be drawn to the effect that the adopted assumptions and the procedure for handling the experimental data are correct. At the same time one should keep in mind the fact that the empirical relationships given above were obtained on the basis of the experimental data, and therefore the range of application of the proposed generalized equation for calculating the effective coefficient of thermal conductivity of a capacitor dielectric under vacuum must evidently be restricted to those limits of variation of the definitive parameters within which the investigations were performed, namely: $\rho = 0.8$–1.23 g/cm³ (for a thickness of the sheets of capacitor paper equal to 10 μ), t = 10–160°C, $p = 10^{-2}$–10^5 N/m², and K = 0.8–1.

Along with an investigation of the coefficient of thermal conductivity of the dielectric under vacuum, we likewise determine the coefficient of thermal diffusivity of the sample and calculated the specific heat of the material.

NOTATION

- λ_c, λ_p are the coefficients of thermal conductivity of the cellular framework of the cellulose and the air filling the pores, in W/m·°C;
- λ_m, λ'_m are the values of the effective coefficient of thermal conductivity of the capacitor dielectric for K = 1 and K < 1, respectively, in W/m·°C;
- λ_p^0 is the coefficient of thermal conductivity of the air at atmospheric pressure, W/m·°C;
- K is the pressurization factor;
- p is the pressure, in N/m²;
- L is the mean free path of the air molecules at a pressure of 1 N/m², in mm;
- γ is a constant which is equal to 1.6 for diatomic gas;
- d_1, d_2 are respectively the average size of the macropores and micropores, in mm;
- ρ_c, ρ are the density of the cellular framework and of the capacitor paper, in g/cm³;
- t is the temperature of the material, °C.

LITERATURE CITED

1. I. F. Pikus and V. D. Kononenko, Inzh. Fiz., 23, No. 8 (1972).
2. I. F. Pikus and V. D. Kononenko, in: Heat and Mass Transfer in Drying and Thermal Processes [in Russian], Minsk (1971).
3. A. Misnar, Thermal Conductivity of Solids, Liquids, and Gases and Their Compositions [Russian translation], Moscow, Mir (1968).
4. S. P. Vnukov, V. A. Ryabov, and D. V. Fedoseev, Inzh. Fiz. Zh., 21, No. 5 (1971).
5. D. Varshavskii, V. Chekhovskii, and V. Chebakov, Élektrotekhnicheskaya Promyshlennost', No. 2 (1971).
6. A. V. Lykov, Heat- and Mass-Transfer Handbook [in Russian], Énergiya, Moscow (1972).

7. M. G. Kaganer, Thermal Insulation in Low-Temperature Engineering [in Russian], Mashinostroenie, M(1964). 1966).
8. D. Varshavskii, Izv. VUZ. Énergetika, No. 4 (1967).