THERMOPHYSICAL CHARACTERISTICS OF A MULTILAYER CAPACITOR-TYPE DIELECTRIC

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Results are shown of an experimental study concerning the thermophysical characteristics of multilayer specimens made from various grades of capacitor paper.

The thermophysical properties of composite multilayer systems such as capacitor-type dielectrics are, generally, functions of many variables. It is important not only to establish the entire complex of these characteristics at certain complete defined conditions but also to reveal the dependence of the thermophysical properties on such determining factors as the density of the capacitor paper, the degree of its compression, its temperature, and its moisture content.

An experimental study was made using multilayer specimens of the following grades of capacitor paper: Terox C-08, Terox C-I, Silcon-I, and KOH-II (the sheet thicknesses and the densities of the capacitor paper are listed in Table 1).

The basic principles of the method and the test procedure with the specially built apparatus have been described in detail in [1].

It is to be noted here that the apparatus has made it possible to determine in a single test the thermal diffusivity and the thermal conductivity of a capacitor-type dielectric in the direction perpendicular to the material layers under given test conditions, and also to examine the material over a rather wide and practically important range of temperatures (10-160°C) as well as compression factor (0.8-1.0).

The advantages of this setup included also the relative simplicity of the measuring instruments and the short testing time, the small size and the easy preparation of specimens, and the facilities for determining the thermophysical characteristics of a capacitor-type dielectric at various moisture contents in the material.

The tests have shown that the value of the compression factor has an appreciable effect, with other conditions unchanged, on the effective thermal conductivity of a capacitor-type dielectric. Indeed, according to Fig. 1, even a small change in the compression factor is followed by a change in thermal conductivity λ: namely, a change in K causes a large decrease in effective thermal conductivity. Moreover, $\lambda = f(K)$ is a power-law relation for all tested grades of capacitor paper. It is characteristic that, as the tests have revealed, this functional relation is (within the range $K = 0.8$-1.0) almost independent of the temperature and the moisture content.

The thermal conductivity of multilayer capacitor paper increases rapidly with a higher compression factor, because the contact between sheets in a stack improves and the amount of air contained between them decreases.

The results of this experimental study, which has yielded a functional relation between the thermophysical properties of multilayer capacitor paper and the moisture content in the material, are shown in Figs. 2 and 3. The tests were performed according to a special procedure, by first plotting the nominal "drying curve" for a control specimen clamped between "coolers" [1].

The initial moisture content in the material was determined by sampling and analyzing for moisture content, by both the distillation and the Fischer method. In some tests the specimens were first dried in a

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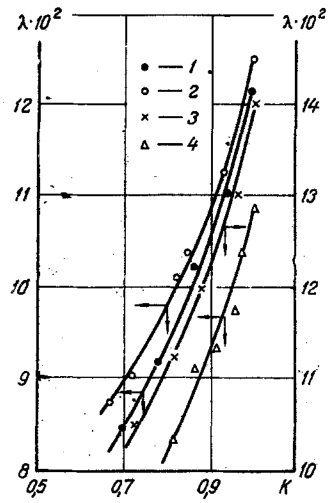

Fig. 1

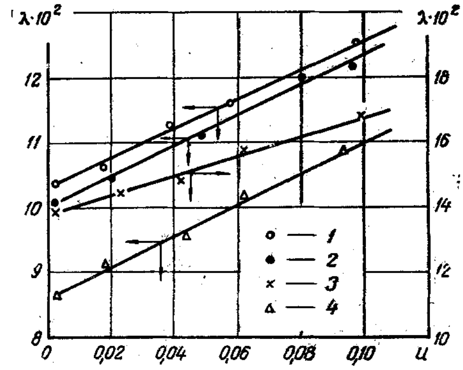

Fig. 2

Fig. 1. Effective thermal conductivity λ of a capacitor-type dielectric as a function of the compression factor K, at t = 20°C: 1) Terox C-I with u = 0.096 kg/kg; 2) Silcon-I with u = 0.098 kg/kg; 3) KOH-II with u = 0.003 kg/kg; 4) Terox C-08 with u = 0.093 kg/kg.

Fig. 2. Effective thermal conductivity λ as a function of the moisture content u in capacitor paper, at t = 20°C and K = 1: 1) Silcon-I; 2) Terox C-I; 3) KOH-II; 4) Terox C-08.

vacuum oven down to the required moisture level, and then quickly placed in the clamp of the test apparatus. In order to reduce the errors arising from likely variations in the moisture content during a test, the exposed end surfaces of specimens were moisture insulated with epoxy resin. The moisture in capacitor paper was varied during this test series from 0.09-0.1 kg/kg (corresponding to equilibrium moisture in a capacitor-type dielectric under room conditions) down to 0.002-0.003 kg/kg; the compression factor was assumed constant and equal to unity.

The studies have shown that the effective thermal conductivity of all grades of capacitor paper decreases with decreasing moisture content in the material. This is so because the thermal conductivity of the solid phase in a cellulose structure is much lower than that of water and, moreover, dehydration of the material is followed by the entrance of air, whose thermal conductivity is even lower, into the pores in the place of water.

According to Fig. 2, the relation λ = f(u) is linear for all grades of material tested here and it can be expressed more explicitly as follows:

$$\lambda = \lambda_c(1 + \delta u),$$

with λ_c denoting the thermal conductivity of a multilayer stack of dry capacitor paper and δ denoting the increment of thermal conductivity during a change in the moisture content by 1 kg/kg dry material.

At a given compression factor, the magnitude of λ_c depends on the grade of capacitor paper and on the temperature of the material. The tests have shown that changing the temperature does not affect the relation λ = f(u) and the magnitude of δ is determined only by the physicochemical as well as the structural properties of the system.

Numerical values of δ obtained by an evaluation of test data for the model material (with K = 1) are shown in Table 1. According to these data, the increment of thermal conductivity δ decreases with higher density of the capacitor paper. In other words, a change in the moisture content affects the thermal conductivity λ more in the case of a multilayer capacitor-type dielectric whose density is low. A similar λ = f(u) applies to organic materials with a fibrous structure [2, 3, 4].

According to Fig. 3, the thermal diffusivity of a multilayer capacitor-type dielectric increases smoothly with decreasing moisture content over its entire test range. Such an a = f(u) relation is governed by the moisture-dependence of all the factors making up the thermal diffusivity (λ, c, and ρ). Thus, one

TABLE 1. Thermophysical Characteristics of a Multilayer Capacitor-Type Dielectric

Name of the capacitor paper	Density ρ, g/cm³	Thickness, μ	δ $(K=1)$	ψ $(K=1)$	λ_c^0, W/m·°C (K = 1)	c_0, J/kg·°C	n
Terox C-08	0,795	9,6	2,75	$0{,}01\cdot10^{-3}$	0,085	1220	$2{,}9\cdot10^3$
Terox C-1	0,998	9,9	2,32	$0{,}1\cdot10^{-3}$	0,098	1200	$3{,}0\cdot10^3$
Silcon-I	1,01	10,1	2,18	$0{,}1\cdot10^{-3}$	0,101	1220	$3{,}0\cdot10^3$
KOH-II	1,23	9,8	2,05	$0{,}045\cdot10^{-3}$	0,137	1320	$2{,}9\cdot10^3$

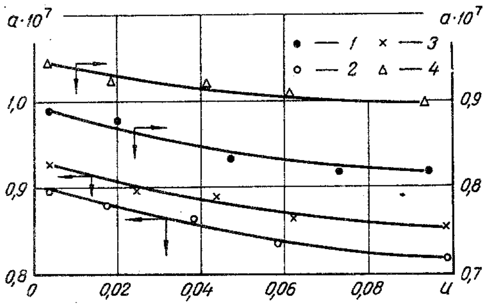

Fig. 3. Effective thermal diffusivity of a capacitor-type dielectric a as a function of the moisture content u in the material, at t = 20°C and K = 1: 1) Terox C-I; 2) Silcon-I; 3) KOH-II; 4) Terox C-08.

must consider here that the density of a capacitor-type dielectric decreases somewhat during drying. As to the specific heat, it also decreases during dehydration, inasmuch as the specific heat of dry cellulose is approximately one third the specific heat of water.

Despite the reduced thermal conductivity of specimens, therefore, it is quite probable that the thermal diffusivity of the material will increase with decreasing moisture content (in the considered range of variation of u) because of the simultaneous even larger decrease in the specific heat per volume of material.

An evaluation of test data has revealed the following relation between the specific heat of multilayer capacitor-paper specimens and their moisture content. The specific heat c was calculated according to

$$c = \frac{\lambda}{a\rho}. \tag{1}$$

The relation c = f(u) appears linear for all tested materials over the 10-160°C temperature range, with the test points distributed on the family of curves

$$c = c_0 + nu, \tag{2}$$

c_0 denoting the specific heat of dry capacitor paper and n denoting an empirical coefficients. Values of c_0 and n are given in Table 1.

Calculations have shown a close agreement between the test values of n and those based on the superposition equation.

Results of the experimental study concerning the effect of temperature on the effective thermal conductivity of a capacitor-type dielectric (with K = 1) are shown in Fig. 4. In order to eliminate the effect of moisture content on the trend of the $\lambda = f(t)$ characteristic here, the test results were evaluated in terms of the referred effective thermal conductivity $\lambda_c = \lambda/(1 + \delta u)$ as a function of the temperature. One may conclude from the graph that, at various densities of the capacitor paper, $\lambda_c = f(t)$ is linear over the rather wide 10-160°C temperature range. The increase in the thermal conductivity of multilayer capacitor paper with increasing temperature is due to the corresponding change in the molecular thermal conductivity of all components (cellulose, water, and air) in this multiphase system, also due to the higher fraction of radiative per total heat transfer. The test data in Fig. 4 were evaluated in terms of the relation

$$\lambda_c = \lambda_c^0 + \psi t, \tag{3}$$

with λ_c^0 denoting the effective thermal conductivity of a dry multilayer capacitor-type dielectric at t = 0°C, ψ denoting an empirical factor characterizing the grade of paper and numerically equal to the slope of the $\lambda_c = f(t)$ lines with respect to the t-axis. Numerical values of λ_c^0 and ψ are given in Table 1.

It is to be noted that the values of ψ are the same here for capacitor paper grades Silcon-I and Terox C-I but only about half as high for KOH-II and Terox C-08 paper. This can be explained by ψ being a function of many factors, which include the material density and structure, the pore size, the arrangement of cellulose fibers, the chemical composition of the material, etc. In the final analysis, all these factors determine how the temperature will affect the basic modes of heat transfer in the studied materials.

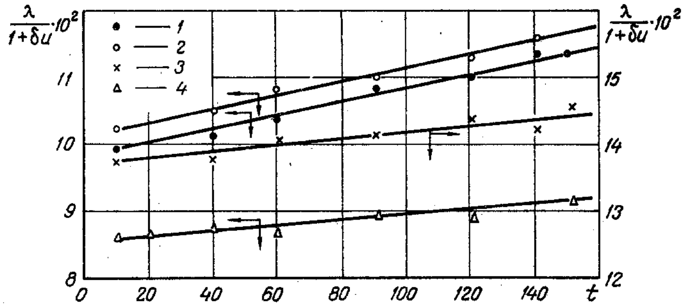

Fig. 4. Relation $\lambda_c = f(t)$ with K = 1: 1) Terox C-I; 2) Silcon-I; 3) KOH-II; 4) Terox C-08.

It appears from Table 1 that a higher density of the capacitor paper, with all other conditions unchanged, results in a higher effective thermal conductivity.

Thus, the universal equation for the effective thermal conductivity of a multilayer capacitor-type dielectric as a function of the temperature and the moisture content (with K = 1) is

$$\lambda = (\lambda_c^0 + \psi t)(1 + \delta u). \qquad (4)$$

In conclusion, we note that the results of our study concerning the effect of compression on the thermal conductivity of a capacitor-type dielectric and also the calculated values of the effective thermal conductivity of multilayer grade KOH-II capacitor paper agree closely with the data published earlier by other authors [5, 6].

NOTATION

λ is the effective thermal conductivity, W/m·deg;
K is the compression factor;
u is the moisture content, kg/kg;
ρ is the density of capacitor-type dielectric, kg/m^3;
c is the specific heat, J/kg·deg;
a is the thermal diffusivity, m^2/sec;
t is the temperature, °C.

LITERATURE CITED

1. I. F. Pikus and V. D. Kononenko, in: Heat and Mass Transfer in Drying and Heating Processes [in Russian], Nauka i Tekhnika, Minsk (1971).
2. A. V. Lykov, Theoretical Principles of Structural Thermophysics [in Russian], Izd. AN BSSR (1961).
3. A. F. Chudnovskii, Thermophysical Characteristics of Disperse Materials [in Russian], GIFML (1962).
4. B. I. Kaufman, Thermal Conductance of Structural Materials [in Russian], Gosstroiizdat (1955).
5. D. S. Varshavskii, Izv. Vuzov, Énergetika, No. 4 (1967).
6. I. R. Chekhovskii, Élektrotekhnika, No. 12 (1970).