DETERMINING THE THERMAL DIFFUSIVITY OF PYROELECTRIC MATERIALS

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UDC 536.219

Formulas are derived for the thermal diffusivity of pyroelectric materials made in the shape of plane-parallel plates. The thermal diffusivity of grade TsTS-19 pyroactive piezoceramic was measured. The test results are shown here.

Pyroelectric materials include dielectrics in which spontaneous polarization occurs during a change of their thermal state [1]. Pyroelectric materials have found many applications in various branches of modern engineering. Particular attention is paid to segnetoelectrics in this class of materials, which are widely used in radio engineering as well as in electroacoustics and hydroacoustics, also in computer technology, etc. [2].

The use of pyroelectrics under conditions of variable temperature requires reliable and simple methods of determining their thermophysical ties, including the thermal diffusivity. The thermal diffusivity of pyroelectrics can be determined by well known methods applicable to solid materials in general as, for example, by measuring the transient temperature field with heat probes.

On the basis of the pyro effect, it is possible to determine the thermal diffusivity of a pyroelectric without the use of heat probes. The necessary information about the thermal state of a test specimen is furnished here by the built up electric charge and the corresponding voltage difference which appears between the electrodes on the specimen.

Theory of the Method. We consider the equation of an electric circuit which consists of a pyroelectric element connected to a recording instrument [3]. With the instrument input resistance R_{in} and input capacitance C_{in}, the current equation for this electric circuit is

$$C\frac{dV}{d\tau}+\frac{V}{R}=\frac{d\bar{P}_s}{d\tau}, \tag{1}$$

where $\bar{P}_s$ denotes the mean-integral polarization of the pyroelectric element, V denotes the voltage difference between the electrodes, and τ denotes time,

$$C=C_{in}+C_p;\quad R=\frac{R_{in}R_p}{R_{in}+R_p}.$$

Here C_p and R_p denote respectively the capacitance and the resistance of the pyroelectric element. Integrating Eq. (1) with the initial conditions $\tau_0 = 0$ and $V_0 = 0$ yields

$$V=\frac{1}{C}\exp\left(-\frac{\tau}{RC}\right)\int\frac{d\bar{P}_s}{d\tau}\exp\left(\frac{\tau}{RC}\right)d\tau. \tag{2}$$

The spontaneous polarization $\bar{P}_s$ is generally determined by many factors such as the geometry, the physical properties, the state of the pyroelectric element, etc. If we confine this analysis to pyroelectric elements in the shape of plane-parallel plates and assume that their physical properties remain independent of the temperature, then its mean-integral spontaneous polarization may be expressed as

$$\frac{d\bar{P}_s}{d\tau}=A\gamma\frac{d\bar{T}}{d\tau}, \tag{3}$$

D. I. Mendeleev All-Union Scientific-Research Institute of Measurements, Leningrad. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 26, No. 4, pp. 738-741, April, 1974. Original article submitted May 31, 1973.

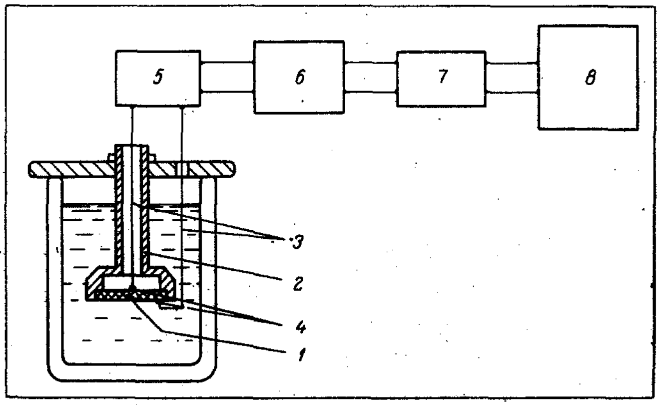

Fig. 1. Schematic diagram of recording the pyroelectric voltage: 1) pyroelectric element; 2) water mixed with snow; 3) contact tabs; 4) electrodes; 5) capacitive voltage divider; 6) model U1-2 instrument voltage amplifier; 7) resistive voltage divider; 8) model ÉPP-09 MZ potentiometer.

where $\bar{T}$ denotes the mean-integral temperature of the pyroelectric element, A denotes its surface area, and γ denotes the pyroelectric factor. The mean-integral temperature of a plane-parallel plate with the thickness δ and with boundary conditions of the first or the third kind with respect to the temperature at one surface is determined according to the well known relation [4]

$$\frac{\bar{T}-T_a}{T_0-T_a}=1-\sum_{n=1}^{\infty} B_n \exp\left(-\mu_n^2 \frac{a\tau}{\delta^2}\right), \tag{4}$$

where a denotes the thermal diffusivity, B_n and μ_n are coefficients in the n-th term of the series, T_0 denotes the specimen temperature, and T_a denotes the ambient temperature.

We insert the values from (3) and (4) into (2), then integrate under the summation sign, and obtain

$$V=\frac{A\gamma a}{C\delta^2}(T_c-T_0)\sum_{n=1}^{\infty} B_n \frac{\exp\left(-\mu_n^2 \frac{a\tau}{\delta^2}\right)-\exp\left(-\frac{\tau}{RC}\right)}{\frac{1}{RC}-\mu_n^2\frac{a}{\delta^2}}. \tag{5}$$

Expression (5) uniquely relates the voltage across the electrodes on a pyroelectric plate to the physical properties of that plate.

In this case, when the voltage during the period of a temperature change in the pyroelectric plate is known, Eq. (5) can serve as a basis for determining one of the parameters.

The thermal diffusivity can be determined, to the first approximation, from either one or two terms of the series. The high-accuracy criterion here is $RC \gg 1$ and $a/\delta \ll 1$. Equating the derivative of the first term to zero, we obtain the time for the voltage across the electrodes on a plane-parallel plate to reach its maximum

$$\tau_m=\frac{\ln \frac{\mu_1 a}{\delta^2} RC}{\mu_1^2\frac{a}{\delta^2}-\frac{1}{RC}}. \tag{6}$$

Using two terms of the series, we find this time from the expression

$$\frac{\exp\left(-\mu_1^2\frac{a\tau_m}{\delta^2}\right)\left(-\mu_1^2\frac{a}{\delta^2}\right)-\exp\left(-\frac{\tau_m}{RC}\right)\left(-\frac{1}{RC}\right)}{\frac{1}{RC}-\mu_1^2\frac{a}{\delta^2}} + \frac{\exp\left(-\mu_2^2\frac{a\tau_m}{\delta^2}\right)\left(-\mu_2^2\frac{a}{\delta^2}\right)-\exp\left(-\frac{\tau}{RC}\right)\left(-\frac{1}{RC}\right)}{\frac{1}{RC}-\mu_2^2\frac{a}{\delta^2}}=0. \tag{7}$$

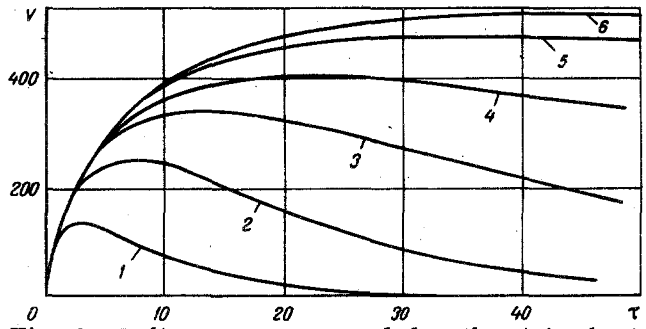

Fig. 2. Voltage curves recorded on the strip chart of a model ÉPP-09 MZ instrument: 1) RC = 3 sec; 2) RC = 10 sec; 3) RC = 30 sec; 4) RC = 100 sec; 5) RC = 300 sec; 6) RC = 1000 sec; voltage V (V), time τ (sec).

If τ_m is known from tests, then the thermal diffusivity of a pyroelectric material can be found from either (6) or (7), depending on the required accuracy. It is to be noted that relations (6) and (7) may be used for determining the thermal diffusivity of specimens in the shape of plane-parallel plates as well as in the shape of hollow bodies with a uniform thickness (hollow cylinder, hollow sphere, etc.). On the other hand, these relations also make it possible to estimate the effect of thermal noise on the performance pyroelectric transducers, this effect being a function of the time constant RC.

Experiment. The thermal diffusivity was measured for the grade TsTS-19 pyroactive piezoceramic, a segnetoelectric material. The test specimen was prepared in the shape of a round disk 50 mm in diameter and 1.9 mm thick, with electrodes in the form of an electrically conductive silver coating. The thickness of the latter did not exceed 5 μ and was disregarded in the determination of the thermal diffusivity. The tests were performed under stepwise temperature changes at one piezoceramic surface. Such a stepwise temperature change was effected by immersing the pyroelectric disk, inside a hollow case, into a water and snow mixture. The temperature jump amounted here to 20 ± 1°C. The voltage across the electrodes on that disk was plotted on a strip chart of a model ÉPP-09 MZ recording instrument during 1 sec travel time of the pen drive. The high output impedance of the piezoceramic element and the low input impedance of the recording instrument were matched through a model U1-2 instrument voltage amplifier. The generated voltage level was reduced by means of a scaling capacitor at the amplifier input and a resistive voltage divider at the amplifier output. The total voltage reduction scale was 10^5. The operation of recording the pyroelectric voltage is shown schematically in Fig. 1.

The tests were performed with the electrical time constant (RC) of the input circuit set to various lengths, namely 3, 10, 30, 100, 300, and 1000 sec. The curves recorded on the ÉPP-09 MZ strip chart are shown in Fig. 2, each corresponding to a different value for the time constant of the input circuit. A peak in the voltage variation is quite evident here, and the time till its occurrence may be used for determining the thermal diffusivity. Calculations according to Eq. (7) with τ_m found by tests have yielded for the grade TsTS-19 material a thermal diffusivity of $5.8 \cdot 10^4$ m²/h. This value is at most 5% higher than that calculated according to Eq. (6). The differences between the values of thermal diffusivity based on RC = 1000, 300, 100, and 30 sec respectively do not exceed 8%. The deviation becomes larger with RC = 10 sec, or even more so with RC = 3 sec. Then, apparently, the inertia of the model ÉPP-09 MZ instrument plays a more significant role.

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