ACCELERATED THERMOCOUPLE METHOD OF MEASURING THERMAL CONDUCTIVITY

L. F. Yankelev and V. S. Roife

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Means for accelerated measurement of the thermal conductivity of building materials are described. Most of the operations involved may be performed automatically.

In known methods for determining thermal conductivity using a linear heat source, the heater and thermometer are separate elements. Attempts to use a resistance thermometer simultaneously as a linear heat source introduce a number of errors, since the average temperature along the thermometer is obtained rather than the temperature at one point. Moreover, in dense materials the hot wire may become pinched, so that the resistance of the thermometer may be influenced by strain effects as well as by temperature.

In the method described here, special butt-welded thermocouples serve as the heat source or sink. If the thermocouple is used as a heat source, the thermocouple heating current must be separated from the direct current that it generates. This allows simultaneous heating of the thermocouple with alternating current and measurement of the generated thermal emf, i.e., the simultaneous measurement of temperature during the heating process. If the thermocouple is used as a linear heat sink, no electrical filter is required for separating the current supplied to the thermocouple from the direct current generated by it. After the thermocouple has been heated by an electric current, its cooling process is observed.

The resistances of the thermocouple electrodes must be as close to each other as possible, and the electrodes must be arranged coaxially. Accordingly, the thermocouples are butt-welded without a bead.

Before testing, the specimens are placed in a temperature-controlled environment at the temperature at which the thermal conductivity is to be measured.

If the power of the linear heat source is constant, then the temperature in the specimen is

$$t = -\frac{q}{4\pi\lambda} E_i\left(-\frac{r^2}{4a\tau}\right).$$

In our experiments r^2 was small ($\sim 4 \cdot 10^{-8}$ m), since the temperature is measured at the surface of the heat source, and for small values of the argument $r^2/4a\tau$

$$E_i\left(-\frac{r^2}{4a\tau}\right) = \gamma + \ln\frac{r^2}{4a\tau} - \frac{r^2}{4a\tau} + \frac{1}{4}\left(\frac{r^2}{4a\tau}\right) + \ldots$$

Therefore the difference between temperatures recorded at two different times is

$$t_2 - t_1 = \frac{q}{4\pi\lambda}(\ln\tau_2 - \ln\tau_1)$$

or

$$\lambda = \frac{q}{4\pi}\,\frac{\ln(\tau_2/\tau_1)}{t_2 - t_1}.$$

At time $\tau = \tau_0 \gg r^2/4a$ let the supply of electrical energy to the thermocouple be cut off. This moment marks the commencement of operation of a heat sink of power q. Therefore, for the cooling process ($\tau > \tau_0$)

$$t = \frac{q}{4\pi\lambda}\int\limits_{r^2/4a\tau}^{\infty}\frac{\exp(-u)}{u}\,du - \frac{q}{4\pi\lambda}\int\limits_{r^2/4a(\tau-\tau_0)}^{\infty}\frac{\exp(-u)}{u}\,du,$$

whence

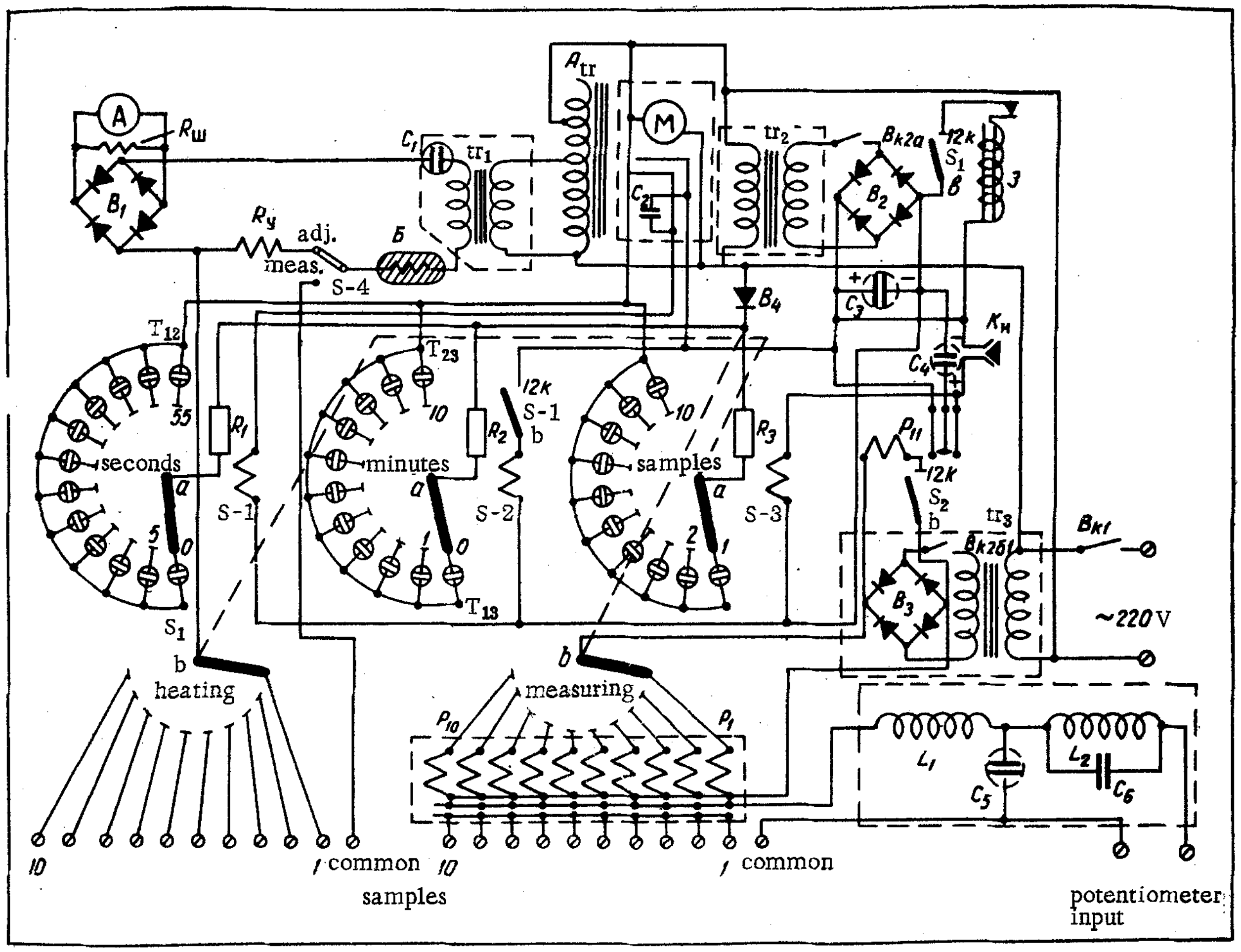
$$t = \frac{q}{4\pi\lambda}\ln\frac{\tau}{\tau-\tau_0}, \quad \tau - \tau_0 \gg \frac{r^2}{4a}$$

or

$$\lambda = \frac{q}{4\pi} \ln \frac{\tau}{\tau - \tau_0} \Big/ t,$$

where the value of t relates to the initial state, i.e., to the temperature before the source is switched on. Thus, the thermal conductivity is determined from a single reading of time and temperature after commencement of cooling. This serves as a reliable check on the results.

It must be possible to heat the thermocouple with alternating current and simultaneously measure the thermal emf. Alternating current may not pass from the heating circuit to the measuring circuit (potentiometer input), since this would not permit measurement of the thermal emf and might damage the measuring instruments. Likewise, the direct current generated by the thermocouple may not pass to the heating circuit; otherwise it would not be possible to measure the true value of the thermal emf. Therefore in designing the device (see figure) a compound LC filter was inserted in front of the potentiometer. This filter creates a dc resistance of the order of 300 Ω, in series with the input resistance of the potentiometer. The alternating current at 50 cps is attenuated by the filter by approximately 120 dB (10^6 times). The thermocouple heating circuit includes a high-capacity condenser to eliminate possible shorting of the thermal emf.



Block diagram of device for determining thermal conductivity.
a) seconds; b) minutes; c) samples; d) heating; e) measuring; f) samples; g) potentiometer input.

Measurement of one sample takes 10 min. Then, after a two-minute interval the thermocouple of the following sample automatically begins to heat and the potentiometer input is switched over. These operations are controlled by the switching unit.

The basic elements of the switching unit are 11-position electromagnetic step-by-step selector switches. Three of these switches were used, two for reading and indicating time and the third for switching the heating and measuring circuits and for indicating the number of the sample being tested. As start-pulse pickup for the first selector switch (seconds) we used a small ac Warren motor. One revolution of the shaft (after reduction) takes 5 sec. The thermocouple is cut directly into the heating circuit across the selector contacts, and into the measuring circuit across an intermediate relay. The use of intermediate relays in the measuring circuit reduces impulse noise.

The device was designed to test ten samples in one experiment. For simultaneous testing of a larger number of samples it is necessary to use another type of selector switch, for example, a 25-contact ShI-25, and to increase the number of relays correspondingly.

In practice testing samples of different shapes and sizes have to be dealt with. Accordingly, thermocouples varying in both length and cross section may be used. To avoid changing the heating current during testing, provision for presetting has been included. Additional regulation is not required during the test, since a current stabilizer is incorporated in the heating circuit.

Particular attention was paid to protecting the measuring circuit from every kind of interference. With this aim, shielded conductors were mainly employed. Components generating electromagnetic fields (transformers, switches, relays, etc.) were screened with steel housings. The various units and components are mounted in two compartments. The power pack is accommodated in the lower compartment and the components of the switching and indicating units in the upper.

Since during the heating period the thermocouple serves both as a heat source and as a thermometer, a separate heater is not required. In particular, errors caused by the introduction of a second wire are eliminated, while the dimensions of the sample may be much less than in other variants of the method based on a linear heat source. However, the most important feature of the proposed method is its speed. The test will be shorter, the thinner the thermocouple, because the Fourier number is greater and, consequently, the formulas for calculating the thermal conductivity become applicable sooner. For example, with a thermal electrode diameter of 0.5 mm any building material can be tested in no more than a few seconds.

Values of the Thermal Conductivity for Different Materials

Material	Volumetric weight of dry material, kg/m³	Absolute moisture content, %	$\lambda \cdot 1.163^{-1}$ W/m · degree at 25° C
Arbolit from wood waste	550	0	0.079
		14.5	0.145
		23.2	0.176
	600	0	0.080
		16.0	0.150
		27.5	0.189
Dense Portland-cement	1900	0.70	1.03
		8.7	1.3
	2100	0.75	1.06
		3.4	1.44
Cellular concrete	600	15	0.17
	1000	15	0.38
Cellular cinder concrete	600	20	0.16
Gypsum plaster	1600	1	0.56
Petroleum bitumen mark 3	990	0	0.14
Expanded clay	600	1	0.121
	650	1	0.126
Pumice	400	0	0.069
	630	0	0.076
Foamed concrete	400	20	0.16
	800	20	0.34
Perlite	290	0	0.058
	400	0	0.065
Stramit	190	8	0.08
	180	8	0.065
			(at —4)

A significant advantage of the method described is that it gives the thermal conductivity not only of dry materials but also of moist materials with high accuracy, since the temperature change and heating time are quite small, so that the moisture distribution in the material does not change appreciably.

The device was used to investigate concretes of various density and moisture content, light aggregates, and insulating materials. For dry materials a comparison was made with the results of parallel determinations by the steady-state heat conduction method, and for moist materials by the regular regime method. Values of the thermal conductivity obtained with the device are presented in the table.

NOTATION

t – temperature of thermocouple; q – quantity of heat released by source per unit time per unit length; λ – thermal conductivity; r – distance from axis of source to point at which temperature is measured; a – thermal diffusivity; τ – time.

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Institute of Building Physics,
Moscow