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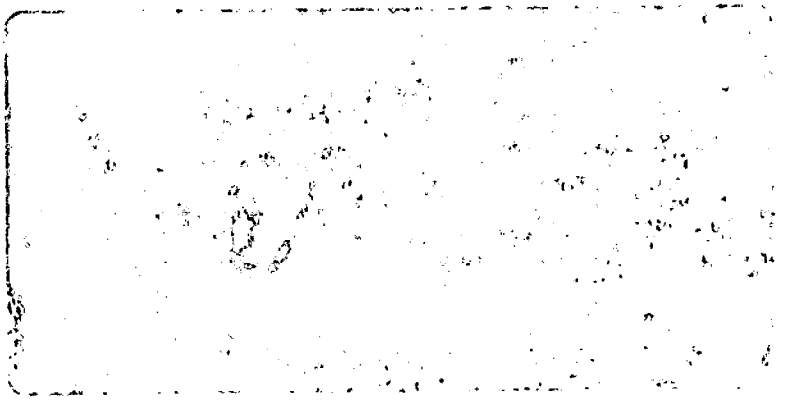

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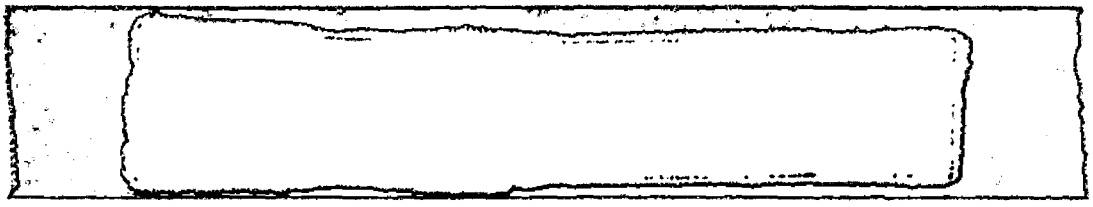

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ABSTRACT

A theoretical technique for measuring extremely small temperature changes by means of a pyroelectric device is described. The sensing element is a short, thin rod of polarized barium titanate ceramic with electrodes on the ends. The electric charges produced by changes in temperature are to be measured by a vibrating-reed electrometer. The device appears to be sensitive to temperature changes as small as 2×10^{-7}°C, and modifications can be made to achieve much greater sensitivity. The system is extremely free of ordinary theromometric errors. Preliminary experiments confirm the theoretical sensitivity of the device. A number of calorimetric and noncalorimetric applications for the device are suggested.

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INTRODUCTION

Pyroelectricity is the manifestation of the temperature dependence of the spontaneous polarization of certain anisotropic solids. If a piece of pyroelectric material is held at a constant temperature for a period of time, it becomes electrically neutral, due both to the acquisition of free electric charges from the surrounding media by its surface and to internal conduction of free charges. If the temperature of the material is raised a small amount, the material becomes electrically polarized. Conversely, if the temperature of the material is lowered by the same amount, the magnitude of the polarization is the same, but the direction of polarization is reversed.

The phenomenon of pyroelectricity was first observed in Europe in 1703 by Dutch traders who had acquired tourmaline crystals in Ceylon for gemstones. The traders noticed that the tourmaline, when placed in a fire, first attracted ashes and then repelled them. Pyroelectricity and its sister phenomenon, piezoelectricity (polarization due to mechanical stress), have been studied extensively.[1] Piezoelectricity saw its first practical use during World War I in Langevin's studies on the detection of underwater objects. Since then, piezoelectricity has found myriads of uses in transducers and in crystal resonators. Pyroelectricity, on the other hand, has not fared as well. Aside from its recent uses as a nondestructive means for measuring the polarization of ferroelectric materials[2] and as a measuring device for large heat fluxes,[3] it has remained a laboratory curiosity.

This work proposes a means for using pyroelectric devices to measure extremely small changes in temperature. The change in the polarization of the device is measured by a dynamic condenser electrometer. The sources of error in the system are analyzed, and the pyroelectric device is compared with other temperature-measuring devices. Several preliminary experiments are described. Finally, possible calorimetric and noncalorimetric applications for such a device are discussed.

OCCURRENCE AND CAUSE OF PYROELECTRICITY

It can be shown from the tensor equations describing pyroelectricity and piezoelectricity that of the 32 crystal classes only 10 lack enough elements of symmetry to be pyroelectric. These 10 classes both lack a center of symmetry and have a single, unique polar axis. The mineral tourmaline is the oldest and, until recently, the best-known example of a pyroelectric material. But lately, a new class of solid materials has been studied which exhibits pyroelectricity only within definite temperature limits. These are the ferroelectric materials--materials which are spontaneously polarized within temperature limits known as Curie points and whose direction of polarization can be reversed by the application of a strong electric field.

Three general classes of ferroelectrics, based on differences in interatomic bonding, are recognized. Rochelle salt and potassium dihydrogen phosphate are typical representatives of the first two classes. The third and most important class contains materials having a perovskite structure, the most important representative being barium titanate. At temperatures above 120°C, barium titanate has a cubic structure and is not polarized. Below the 120°C Curie point, the structure of barium titanate changes to tetragonal and the material becomes spontaneously polarized. If the barium titanate is cooled below its

Curie point in the absence of an electric field, it exhibits random domain structure and has little or no net polarization. However, if barium titanate ceramic is cooled through its Curie point while being subjected to a very intense electric field, sufficient domains are oriented in the same direction to give a strong net spontaneous polarization. This polarization is permanent and can be removed only by either raising the temperature of the barium titanate above its Curie point or by subjecting the material to an extremely strong reverse electric field at lower temperatures. Because of their widespread use as ultrasonic transducers, polarized barium titanate ceramics are commercially available in a variety of shapes and sizes.

TEMPERATURE-CHANGE MEASUREMENT

The discussion of the use of pyroelectric devices for measuring extremely small changes in temperature is based upon the use of polarized barium titanate ceramic as the pyroelectric material. This choice was made because barium titanate ceramic is one of the most intensely pyroelectric materials of those thus far described in the literature. Barium titanate becomes unsuitable for temperature-change measurements above 100°C, and other materials must then be used (as described below).

The barium titanate ceramic discussed has the physical properties listed in Table I. In this section of the paper, a temperature-sensing device having the shape of a disk as shown in Fig. 1 (a) is described. The disk is cut from ceramic so that the direction of polarization is normal to the flat surfaces. It has a cross-sectional area of 1 cm^2 and a thickness of 1 mm. Silver electrodes are deposited on the flat surfaces and electrical leads are attached to the electrodes.

Table I. Properties of barium titanate ceramic

Property	
Density	5.3 g/cm^3 (a)
Relative dielectric constant	1200 (a)
Resistivity	10^{14} ohm cm (a)
Thermal conductivity	2.5×10^{-3} cal cm/sec ^{o}C cm^2 (a)
Heat capacity	0.12 cal/g^{o}C (b)

(a) From Gulton Industries, Inc. Bulletin X-103.

(b) Reference 2.

Examine the temperature behavior of this disk. Under the conditions of constant applied stress and electric field, the tensor equations of pyroelectricity and piezoelectricity[4] can be integrated to

$$\frac{\Delta Q}{A} = p \Delta T, \qquad (1)$$

where $\Delta Q/A$ is the change in electric charge per unit area in coul/cm^2, ΔT is the change in temperature in ^{o}C, and p is the pyroelectric coefficient in coul/cm^2 ^{o}C. A plot of the absolute value of the pyroelectric coefficient (at zero applied stress) versus temperature is given in Fig. 2. Note that p is relatively constant between -70 and -10^{o}C and between 20 and 60^{o}C. The value of p at 25^{o} C is approximately 2×10^{-8} coul/cm^2 ^{o}C. If the disk is short-circuited at a given temperature and then its temperature is changed 1^{o}C,

an electric charge of 2×10^{-8} coul is produced upon it. The disk also behaves as a capacitor, and, based on the parallel-plate formula, has a capacitance of 1×10^{-9} farad. From the formula for voltage on a charged capacitor, $E = Q/C$, it is seen that a ΔT of $1^{\circ}C$ has produced a voltage across the disk of 20 volts. By contrast, a thermocouple produces a voltage of 20 to 60 microvolts with a $1^{\circ}C$ temperature difference between its junctions. At first glance, the pyroelectric device seems to have almost a million times the sensitivity of a thermocouple.

An immediate problem arises in the measurement of this voltage. The voltage is large, but the amount of charge is minute. Further, charge is produced only by a change in temperature. Once the charge is removed, the device is again electrically neutral. A possible method of measuring such a voltage is by means of an electrostatic instrument such as the Hoffman Electrometer. This technique has one serious objection. As is seen below, the primary use for a pyroelectric thermometer is in calorimetry. If a period of time elapses between the moment at which the device is electrically neutral and the moment at which its charge is read, some of the charge may leak through the device itself. The device has a resistance of 10^{13} ohms, which gives an RC time constant of 10^{4} seconds. However, 10% of the charge can leak off in 20 minutes, and this error is too large to tolerate in accurate calorimetric work.

The solution to the problem lies in the dynamic condenser electrometer, an instrument which can measure the charges as they are produced on the pyroelectric device. The particular model of a dynamic condenser electrometer discussed here is the Cary Model 31 Vibrating Reed Electrometer manufactured by the Applied Physics Corporation. This instrument can detect currents of 1×10^{-17} amp, charges of 5×10^{-16} coul, and potentials of 2×10^{-5} volt.

The electrometer measures small currents by the rate-of-charge method by behaving as such a large capacitor that, during an experiment, insufficient voltage is produced on the electrometer to impede the flow of current in the external circuit. The electrometer converts the small voltage imposed across it to alternating current by means of the vibrating reed so that it may be amplified on an amplifier having a very stable zero. A recorder may be used to give a permanent record of the voltages indicated on the electrometer scale. A circuit can be constructed that will discharge the electrometer capacitors and momentarily short-circuit the external circuit either at the end of a fixed period of time or whenever the voltage as read on the electrometer exceeds a certain value.

The use of a vibrating-reed electrometer in continuously measuring a pyroelectric current can now be investigated. If the electrometer is connected with the pyroelectric disk, an equivalent circuit diagram can be drawn, as shown in Fig. 3. The pyroelectric device behaves as a charge generator in parallel with its own capacitance and resistance. These three elements are connected in parallel with the vibrating-reed electrometer. For the purposes here, the electrometer acts as a stationary capacitor of capacitance C_c and a vibrating-reed capacitor of capacitance C_v.[6] When a voltage E is imposed across the input and feedback terminals of the electrometer, the negative feedback characteristics cause a voltage distribution on the circuit as shown in Fig. 3. These voltages are related by the equation $E = E_f + E_v = E_f + E_f / G$, where G is the over-all amplification of the electrometer. By means of a rate-of-charge balance on this circuit, one can ascertain the effect of leakage in the device, derive a simple expression for the change in temperature as a function of the voltage on the electrometer, and determine the sensitivity of the pyroelectric device. Charge is produced in the circuit of Fig. 3 at a rate determined by the time derivative of Eq. (1), and distributes itself on the pyroelectric capacitor,

the pyroelectric resistance, and the electrometer according to

$$\frac{dQ}{dt} = p A \frac{dT}{dt} = \frac{dQ_p}{dt} + \frac{E}{R_p} + \frac{dQ_E}{dt} \quad . \qquad (2)$$

Here dQ_p/dt and dQ_E/dt are the rates of charge accumulation on the pyroelectric device and on the electrometer respectively, and E/R_p represents leakage current flow through the device resistance. The amount of charge on the vibrating-reed electrometer at any time is expressed by

$$Q_E = C_v E_v + C_c (E_v + E_f) .$$

The capacitances, C_c and C_v, are 10μμf and 25 μμf, respectively, and the amplification, G, is 1000. The above relations are substituted in Eq. (2) and the result is written as a function of E_f (which is the voltage read on the vibrating-reed electrometer or on an attached recorder). Then

$$\psi \; p \; A \; \frac{dT}{dt} = \phi \; E_f + \frac{dE_f}{dt} \quad , \qquad (3)$$

(i) (ii) (iii)

where $$\psi = \left(\frac{C_v + C_c + C_p}{G} + C_c + C_p \right)^{-1} \approx 10^9 \text{ farads}^{-1} ,$$

$$\phi = \frac{\psi}{R_p} \left(\frac{G+1}{G} \right) \approx 10^{-4} \text{ sec}^{-1} .$$

Here C_p is the capacitance of the pyroelectric device, about 10^{-9} farad. Any external, grounded capacitance such as a shielded cable connecting the pyroelectric device to the electrometer will contribute an added capacitance to C_v,

but this added capacitance will cause an almost negligible effect on the value of ψ if the cable is short. Note that, if E_f can always be kept sufficiently small, Term (ii) of the equation can always be kept much smaller than Term (i), and, thus, Term (ii) can be dropped, creating an error of known magnitude. As mentioned above, the vibrating-reed electrometer circuit can always keep E_f below a certain value by discharging the circuit when E_f reaches a preset value. It can be seen that Term (ii) is always less than 0.1% of Term (i) if the time between discharges is 10 seconds, by inserting the appropriate numerical values in Eqs. (1) and (3). Dropping Term (ii) of Eq. (3) and integrating with respect to time, one has

$$\Delta T = \frac{E_f}{p\psi A} , \qquad (4)$$

where ΔT is the temperature change since the time at which E_f was equal to zero (last time of discharge). This derivation has shown that the effect of leakage is negligible if the circuit is discharged periodically. The relation between temperature change and electrometer voltage is given by Eq. (4). If values are inserted for p, A, and ψ, a voltage of 2×10^{-5} volt on the electrometer -- its minimum readable deflection -- corresponds to a temperature change of $1 \times 10^{-6}\ ^{o}C$.

For precise work, it would be desirable to calibrate an entire pyroelectric thermometer-electrometer setup, because of the difficulty of measuring p, C_p, and the correction for a shielded cable. A platinum resistance thermometer could be used to indicate a small temperature change, say $0.1\ ^{o}C$, and the corresponding pyroelectric charge produced by the device could be measured. Thus the product $p\psi A$ could be determined at desired temperature intervals.

INCREASE IN SENSITIVITY

The sensitivity of the pyroelectric device can be increased greatly in three ways:

1. The shape of the pyroelectric sensing element can be optimized. The denominator of the right-hand side of Eq. (4) can be defined as the sensitivity,

$$\theta = p \psi A = \frac{pA}{\alpha + \frac{\beta K A}{d}} , \tag{5}$$

where $$\alpha = \frac{C_v + C_c}{G} + C_c = 1.0035 \times 10^{-11}$$

and $$\beta = \frac{1}{36\pi} \times 10^{-11} \left(\frac{G+1}{G} \right) .$$

Here β includes the constant in the parallel-plate capacitor formula, and an electrometer amplification factor, and K is the relative dielectric constant of the pyroelectric material. The sensitivity can be maximized with respect to the electrode area, A, and the thickness, d, by setting $\frac{\partial \theta}{\partial A} = 0$ and $\frac{\partial \theta}{\partial d} = 0$. The optimum values of A, d, and θ are found to be

$$A = \left(\frac{\alpha V}{\beta K} \right)^{1/2} ,$$

$$d = \left(\frac{\beta K V}{\alpha} \right)^{1/2} ,$$

$$\theta_{\frac{p}{2}} = \left(\frac{V}{\alpha \beta K} \right)^{1/2} , \tag{6}$$

where V is the element volume.

A sensing element of barium titanate ceramic having a volume of 0.1 cm^3

(the same volume as that of the disc element in Fig. 1 (a)) should have an electrode area of about 0.1 cm^2 and a length of about 1 cm. This rod-shaped element, shown in Fig. 1(b), is about five times as sensitive as the disc element and therefore should detect a temperature change of about 2×10^{-7}°C. Note also that the sensitivity of a rod-shaped element is proportional to the square root of its volume.

2. Materials having a higher pyroelectric coefficient or a lower dielectric constant (or both) can be used as sensing elements. Alternately, pyroelectric devices can be used at temperatures closer to the Curie point where the pyroelectric coefficient is larger, with the disadvantage that the dielectric constant is also larger. Many ferroelectric materials, some of which may be far more sensitive than those listed below, are currently being studied, although few measured or calculated pyroelectric coefficients have been published. Several of the more sensitive pyroelectric materials are listed in Table II. The sensitivities are based on the optimum rod-shaped sensing element having a volume of 0.1 cm^3.

Table II. Sensitivity of various pyroelectric materials.

Material	T°C	p	K	θ	θ/θ^* (a)
$BaTiO_3$ ceramic	25	2×10^{-8} (b)	1200 (c)	97	1
	100	6×10^{-8} (b)	1600 (c)	252	2.6
$BaTiO_3$ single-domain	25	2×10^{-8} (d)	160 (d)	265	2.7
crystal	100	2×10^{-7} (d)	530 (c)	1460	15.1
91%$BaTiO_3$ 9% $CaTiO_3$ ceramic	25	3.5×10^{-8} (e)	1200 (e)	170	1.8
Rochelle salt	18	1.3×10^{-8} (c)	400 (c)	109	1.2

(a) θ^* is θ for $BaTiO_3$ ceramic at 25°C.

(b) Fig. 2.

(c) Reference 4.

(d) Reference 2.

(e) Reference 7.

3. A number of sensing elements can be connected in series to give a a larger over-all voltage. The usual error of heat loss along the leads of a thermopile does not occur here because the sensing elements and their interconnecting leads are all at the same temperature. The sensitivity of n elements in series is

$$\theta = \frac{pA}{a + \frac{\beta KA}{dn}}$$

The optimum shape of a single element can be described by

$$A = \left(\frac{aVn}{\beta K}\right)^{1/2}$$

$$d = \left(\frac{\beta K V}{an}\right)^{1/2}$$

and the optimum sensitivity for all the elements in series is

$$\theta = \frac{p}{2}\left(\frac{Vn}{a\beta K}\right)^{1/2}$$

Note that n elements in series, each having volume V, are as sensitive as a single optimum-shaped element of volume $V' = Vn$. However, because of the smaller element size, the elements in series achieve thermal equilibrium much more rapidly than a single large element. A single rod-shaped element 3.2 cm long and 0.32 cm^2 in cross section has the same sensitivity as 10 elements in series, each 1.0 cm long and 0.10 cm^2 in cross section. The sensitivity is about 6×10^{-8} °C.

ANALYSIS OF PYROELECTRIC DEVICE

There are three main sources of electrical error in the circuit:

1. Some error is inherent in the vibrating-reed electrometer. A more or less steady background current is produced by contact potentials, thermoelectric potentials, insulation strain, etc. This background noise corresponds to less than 6×10^{-16} coul and is relatively reproducible. It can be determined from a blank run and a correction can be made for it.[6]

2. Contact and thermoelectric potentials can be made very small if precautions are taken to eliminate dissimilar metal contacts and to use homogeneous leads. Further, since very small temperature changes are being measured, these potentials change little with time. Since all voltages that enter into Eq. (3) are differentiated with respect to time (with the exception of the second term, which is very small), contact and thermoelectric potentials cause negligible error.

3. Johnson noise, which may be produced in the pyroelectric device itself, manifests a root-mean-square voltage proportional to the square root of the resistance. In this circuit, the Johnson noise is of the order of the sensitivity of the electrometer and can be neglected. Since virtually no current flows through the pyroelectric element, current noise is also absent.

The major inaccuracy in the measurement of temperature changes, then, would appear to be a calibration error. With care, this source of error can be made very small, and therefore a pyroelectric device is potentially capable of both great sensitivity and great accuracy.

A pyroelectric thermometer can be compared with other types of thermometers as follows:

1. No other temperature-sensing device in use has the sensitivity of a pyroelectric thermometer. It would require a thermopile containing many thousand thermocouples to achieve this sensitivity, but such a thermopile would be difficult to construct and probably highly inaccurate. To measure a temperature change of 10^{-3} °C with a platinum resistance thermometer requires measurement of a resistance within several parts per million. A thermistor is 10 to 100 times as sensitive as a platinum resistance thermometer, which is still far below the sensitivity of a pyroelectric device. Furthermore, both the platinum resistance thermometer and the thermistor require the input of electrical energy for measurement of their resistance. This input is an additional source of error in accurate calorimetric measurements.

2. The operation of a pyroelectric thermometer is not restricted to the use of a barium titanate ceramic as a sensing element. Operation of a pyroelectric thermometer above about 100° C would require a material having a higher Curie point than barium titanate. Many materials having the perovskite structure of barium titanate are being studied, and some have been found with a larger pyroelectric coefficient than that of barium titanate. $PbNb_2O_6$ has a Curie point of 570°C,[7] and barium zirconium metaniobate has

a Curie point higher than 1400°C.[8] Thus it appears possible to extend the use of pyroelectric thermometers to very high temperatures. Low-temperature pyroelectric thermometry may be possible with materials such as colemanite, which has been reported to be pyroelectric from -6°C down to the temperature of liquid helium.[9]

3. The barium titanate rod in Fig. 1(b), if enclosed in a protective sheath, has a calculated thermometric time lag, in a well-stirred calorimeter, of about 0.8 second. The thermometric time lag is defined as the time required for a thermometer to respond to within 1/e of the initial temperature difference between it and an isothermal bath into which it is plunged. An instrument with a more rapid response could be made, but with proportional loss in sensitivity, by reducing the size of the device.

PRELIMINARY EXPERIMENTS

Several simple experiments to confirm the theoretical sensitivity of a pyroelectric thermometer and to verify Eq. (4) were performed. A barium titanate ceramic element was placed in a 3-in. cavity within a 9-in. cubical wooden block. The wooden block was to damp out rapid fluctuations of room temperature and thus have the pyroelectric element sensitive only to slow drift in room temperature. A spherical shell-shaped element having $\theta = p\psi A = 58.5$ and a mass of 25.8 g was used because it was readily available at the time. The electrical leads of the element were connected to the terminals of a vibrating-reed electrometer. A 3/4-in. hole was drilled through the side of the wooden cube. Precautions were taken to insure that the electrical lead from the pyroelectric element to the electrometer input terminal (which was at 10^{19} ohms impedance to ground) was well insulated and shielded. These precautions were not necessary on the lead connected to the low-impedance feedback terminal.

Thermal energy was supplied to the pyroelectric device by shining a 2-cell flashlight through the hole in the side of the box. This was done in a fully lighted room. A voltage immediately began building up on the electrometer. When the light was turned off, the voltage began to decrease. It has been shown that this is not a photoelectric effect.[2] Therefore one can conclude that the pyroelectric element has absorbed a portion of the incident radiation as heat. It was convenient to observe the initial time derivative of the voltage change, $(dE_f/dt)_0$, as a measure of the initial time derivative of the temperature change. Initially, E_f increased linearly with time. The derivatives $(dE_f/dt)_0$ were approximated by dividing a small increase in E_f by the corresponding time increment. The values of $(dE_f/dt)_0$ varied inversely as the square of the distance of the flashlight from the pyroelectric device, as shown in Fig. 4(a). When the flashlight was less than 100 cm from the device, the rate of voltage increase was so rapid that the recorder was unable to keep up with the electrometer, causing these values of $(dE_f/dt)_0$ to appear to be somewhat low. Inaccuracy in the differentiation was responsible for the scatter in the data.

The experimental setup was roughly calibrated by placing an accurate platinum resistance thermometer in a similar enclosure and by observing its response to the flashlight. The platinum resistance thermometer, which was sensitive to a change of $2 \times 10^{-4}\,^{\circ}C$, showed no immediate response to the flashlight when it was more than 23 in. away. On the other hand, the pyroelectric device responded strongly when the flashlight was ten feet away. Values of $(dT/dt)_0$ as a function of flashlight distance were measured for the platinum resistance thermometer as shown in Fig. 4(b). The inverse square law which is obeyed here is reasonable, because the flashlight beam spreads out as a diverging cone.

Because $(dE_f/dt)_0$ and $(dT/dt)_0$ each vary inversely as the square of the flashlight distance, ΔT must be a linear function of E_f as predicted by Eq. (4). Further, the temperature change of the pyroelectric element can be calculated from an extrapolation of the $(dT/dt)_0$ line for the platinum resistance thermometer and heat capacity data for both thermometers. If the reasonable assumption that the barium titanate sphere (which had a tarnished silver surface) has a radiation absorption coefficient of five times that of the platinum thermometer is made, the calculated value of $p\psi A$ agrees exactly with the theoretical one.

It should be exphasized that these were not accurate experiments and that much careful work must still be performed. However, these experiments definitely confirm that temperature changes of the order of magnitude described in this paper can be measured by a pyroelectric thermometer.

USES

The list of possible uses for a pyroelectric thermometer in measuring small temperature changes is almost endless. Calorimetric measurements might include heats of mixing, heats of dilution, heats of adsorption, heats of wetting, heats of radioactive decomposition, heats of setting of cements, heats of mechanical strain, etc. Measurement of the molecular weights of high-molecular-weight compounds by boiling-point elevation or freezing-point depression requires accurate and sensitive thermometry. Pyroelectric materials could be used as sensing elements in the class of infrared detectors known as thermal devices. The devices currently in use utilize thermocouples or resistance elements (bolometers) to measure a temperature change caused by incident infrared radiation. These devices are usually limited in their ultimate sensitivity by Johnson noise when a thermocouple is used as a sensing element, and by Johnson and current noises when a resistive element is used. The ultimate

attainable level of sensitivity of a thermal device is the level set by thermal noise (small random temperature fluctuations about the mean temperature of a body in thermal equilibrium with its surroundings). As mentioned previously, a pyroelectric device is not limited in its ultimate sensitivity by Johnson or current noises. Because of its very great response to a small change in temperature, a pyroelectric element in a thermal device may be limited only by thermal noise.

Another series of possibilities can be seen from a time differentiation of Eq. (1),

$$I = \frac{dQ}{dt} = p A \frac{dT}{dt} \tag{7}$$

The current I produced by a pyroelectric device is directly proportional to the time derivative of the temperature change. If the current measured by a vibrating-reed electrometer is large enough, an accurate large resistor can be connected across the electrometer terminals and the voltage drop across the resistor measured. If the value of the resistance is 10^8 ohms or less, the effective RC time constant of the pyroelectric device– electrometer circuit is very small and the electrometer almost immediately reads the voltage drop across the resistor. An analysis similar to that used in deriving Eq. (4) shows

$$\frac{dT}{dt} = \frac{E_f}{RpA} , \tag{8}$$

where R is the value of the resistor placed across the electrometer terminals. Often, in heat-transfer measurements, the values of dT/dt at a number of points are of greater interest than precise values of the temperature at the points. A series of pyroelectric sensing elements could be placed at various points on the object being studied. All the elements could be wired into a

multiple switch so that they could be connected alternately to a vibrating-reed electrometer. Thus, time derivatives at a number of points could be measured directly rather than by difficult and often erroneous differentiation of temperature data. Perls has measured large heat fluxes by a similar technique.[3]

SUMMARY

Temperature changes can be measured by a method involving a relatively obscure physical phenomenon--pyroelectricity. This technique is unique in its high sensitivity, accuracy, and lack of certain types of electrical noise. For these reasons the number of effects and phenomena that can be studied by means of a pyroelectric temperature-sensing device is almost unlimited.

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FIGURE CAPTIONS

Fig. 1. Pyroelectric devices for sensing temperature change. Barium titanate ceramic polarized in direction normal to electrode surfaces.
(a) Disk is 1 mm thick and 1 cm^2 in cross section.
(b) Rod is about 1 cm long and about 0.1 cm^2 in cross section.

Fig. 2. Absolute value of pyroelectric coefficient p at zero applied stress as a function of temperature for barium titanate ceramic. (From Reference 5.)

Fig. 3. Equivalent temperature-change measuring circuit.

Fig. 4. (a) $(dE_f/dt)_0$ as a function of flashlight distance for pyroelectric device.
(b) $(dT/dt)_0$ as a function of flashlight distance for platinum resistance thermometer.

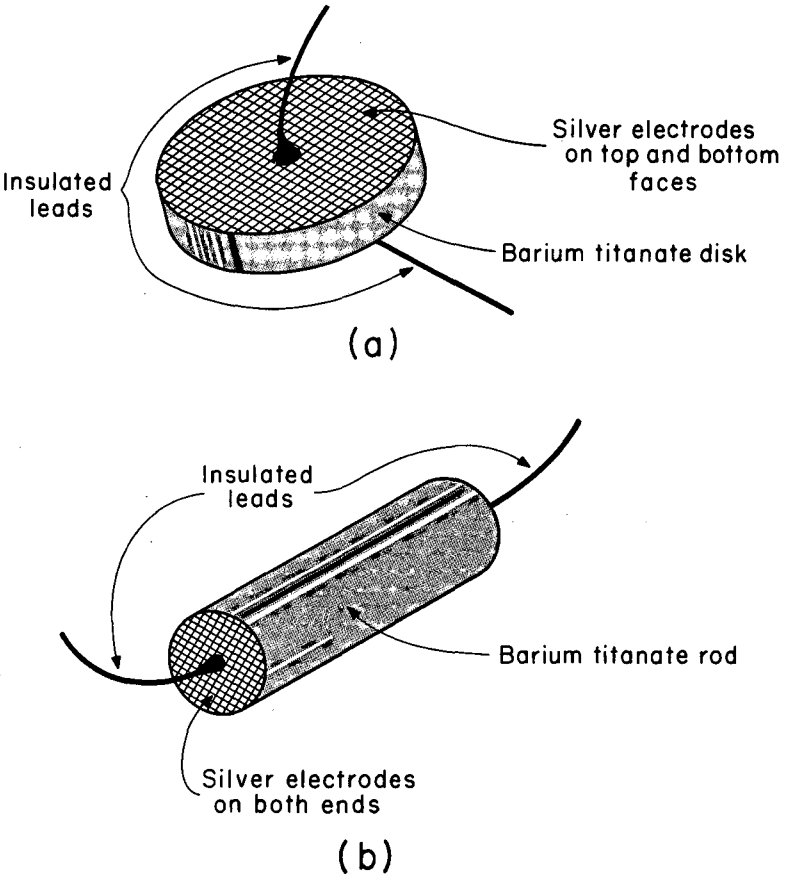
Insulated leads
Silver electrodes on top and bottom faces
Barium titanate disk
(a)
Insulated leads
Barium titanate rod
Silver electrodes on both ends
(b)
MU-21306

Fig. 1

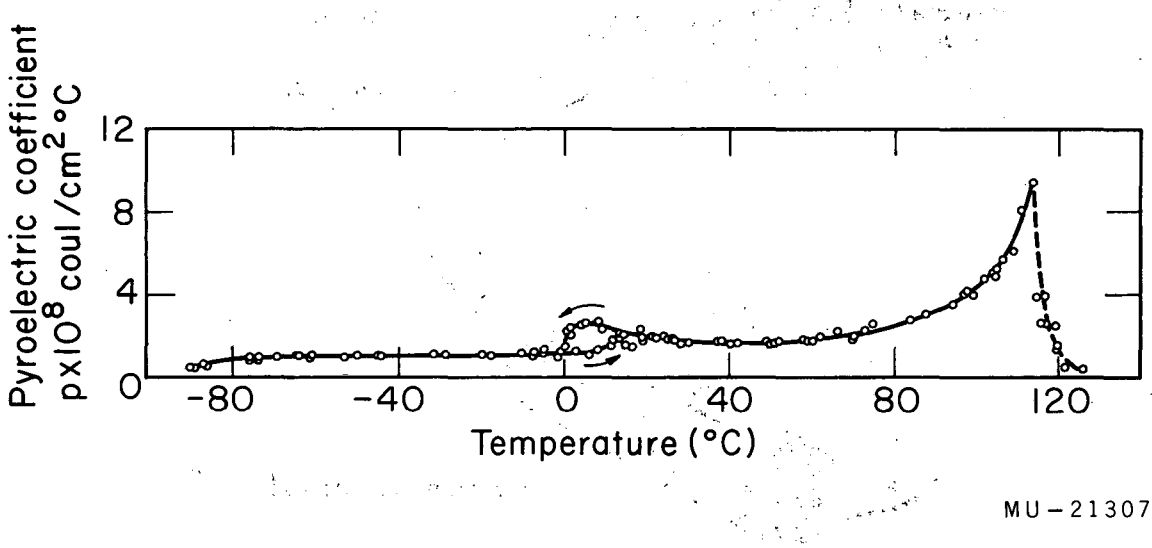
Pyroelectric coefficient
p x10^8 coul/cm^2 °C
12
8
4
0
-80
-40
0
40
80
120
Temperature (°C)
MU-21307

Fig. 2

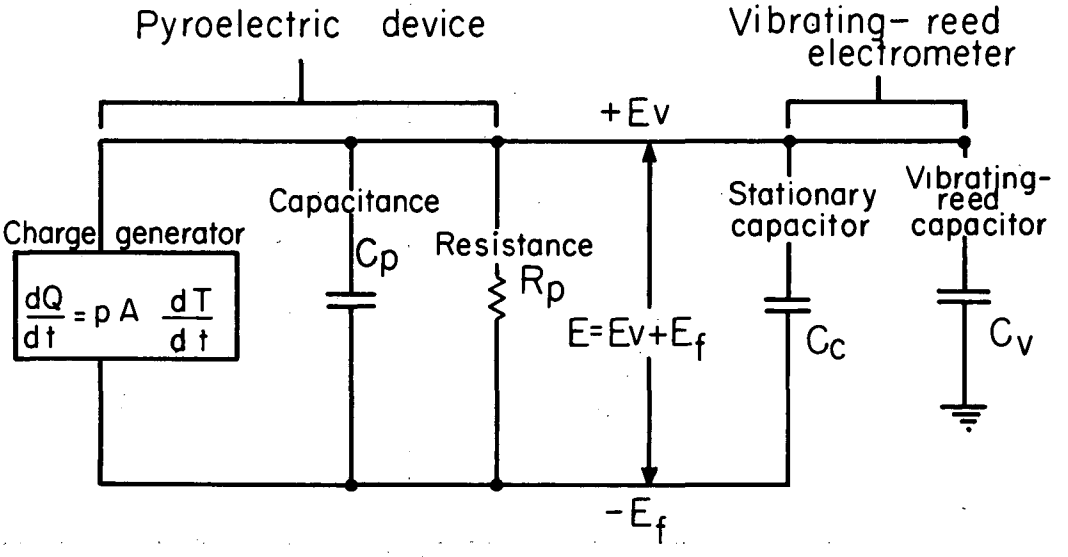
Pyroelectric device
Vibrating- reed electrometer
+Ev
Capacitance
Cp
Resistance
Rp
Charge generator
dQ/dt = p A dT/dt
E=Ev+Ef
Stationary capacitor
Cc
Vibrating-reed capacitor
Cv
-Ef
MU-22777

Fig. 3

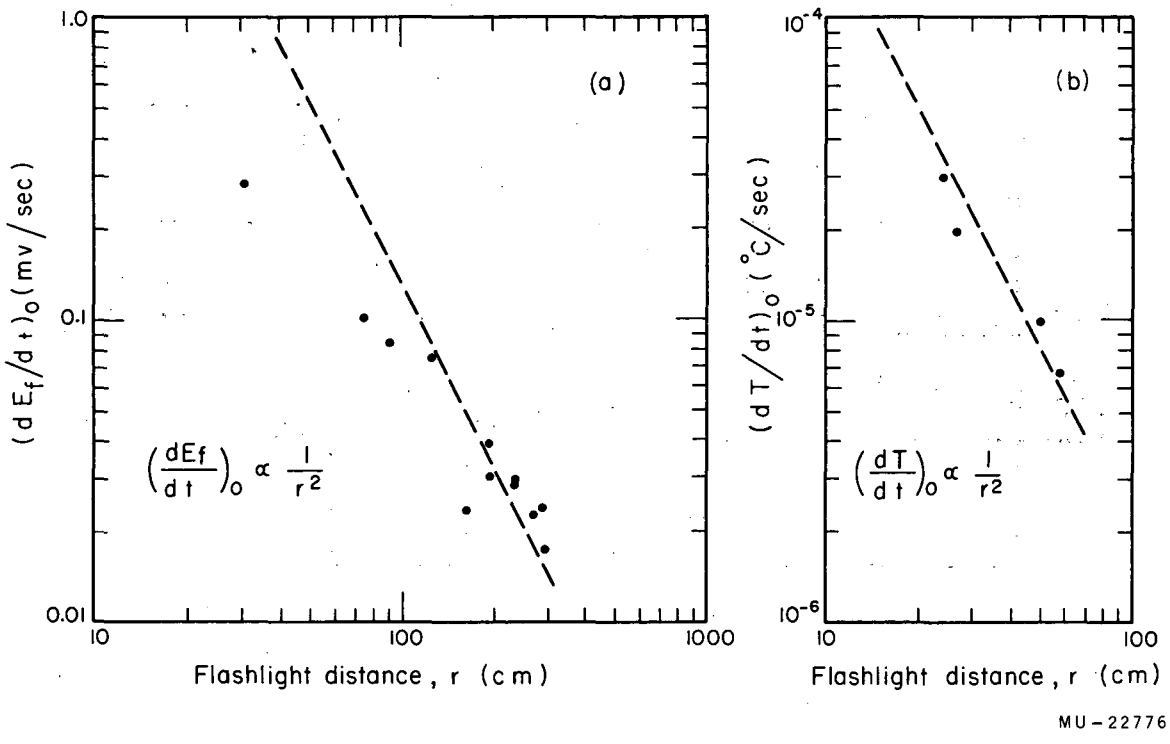
1.0
0.1
0.01
(a)
$\left(\frac{dEf}{dt}\right)_o \propto \frac{1}{r^2}$
$(dE_f/dt)_o$ (mv/sec)
10
100
1000
Flashlight distance, r (cm)
10^{-4}
10^{-5}
10^{-6}
(b)
$\left(\frac{dT}{dt}\right)_o \propto \frac{1}{r^2}$
$(dT/dt)_o$ (°C/sec)
10
100
Flashlight distance, r (cm)
MU-22776

Fig. 4