Use of a Large Thermocouple Junction to Locate Temperature Disturbances

PHILIP L. JACKSON
Acoustics and Seismics Laboratory, Institute of Science and Technology, The University of Michigan, Ann Arbor, Michigan

(Received November 6, 1959; and in final form, January 8, 1962)

A temperature disturbance within a large thermocouple junction produces a voltage which decreases with distance from the disturbance. Resulting voltage residues can be compared at two or more points on the junction to indicate positions, magnitudes, and sizes of temperature disturbances. Useful measurement applications result.

INTRODUCTION

A THERMOCOUPLE customarily requires a measuring junction small enough so that negligible temperature gradients occur over its surface. Great care in construction and placement is often taken to achieve this state. However, by deliberately constructing a large junction, the locations of temperature disturbances along the junction can be determined. A temperature disturbance at a point located on a large thermocouple junction will produce currents which fall off exponentially with distance from the disturbance. Residual potential differences between selected leads indicate the location of the disturbance.

The voltage residues so produced can be used advantageously for a number of measuring applications. Potential applications include measurement of the magnitude, position, and size of small heat sources, liquid level, fluid mixing, velocity gradients, turbulence, and of temperature equilibrium over a continuum.

Analysis of the voltage potentials in a large thermocouple junction and exploratory experiments are presented in this paper.

ANALYSIS

A long thermocouple junction is illustrated in Fig. 1. The junction may be constructed by twisting, soldering, or fusing two wires together. Five fixed leads are shown: two at each end and one along element A. As shown in the Appendix, the voltage between a and b of Fig. 1 due to a temperature disturbance along the junction is

$$E_{ab}=E_X \operatorname{sech}(RG)^{\frac{1}{2}}X, \qquad (1)$$

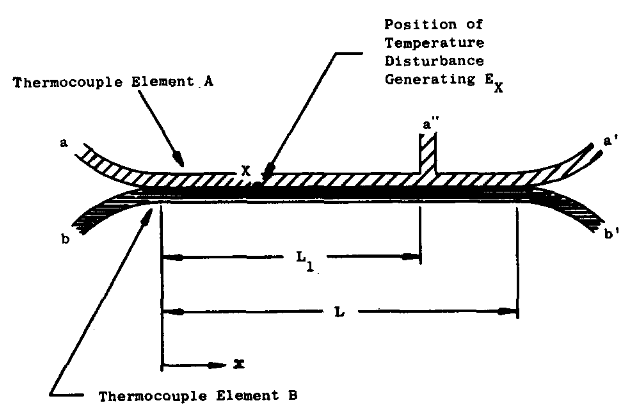

FIG. 1. Construction of long thermocouple.

where E_{ab} is voltage measured with a potentiometer circuit maintained at the same temperature as the junction between $x=0$ and $x=X$; E_X is voltage between elements developed at a point $x=X$ by external temperature disturbances, i.e., by disturbances located at points $x\geq X$; R is resistance of both elements per unit length; G is conductance between elements per unit length; and X is the distance along the junction; and when isothermal conditions exist between $x=0$ and $x=X$.

E_X is dependent upon the thermoelectrically generated voltage E_{gX} at position X, the extent ΔX of the disturbance producing E_{gX} and the resistances of the junction on both sides of X. When the two ends of the junction are terminated in the characteristic resistance $(R/G)^{\frac{1}{2}}$, and ΔX is small, we find

$$E_X\cong\tfrac{1}{2}KE_{gX}\Delta X, \qquad (2)$$

where $K=(RG)^{\frac{1}{2}}$. Also, when ΔX is small, we find the following for the open-ended junction:

$$F_X\cong KE_{gX}\Delta X/[\tanh KX+\tanh K(L-X)]. \qquad (3)$$

Note that Eq. (3) approaches Eq. (2) in value at large L and large X.

The bases for Eqs. (2) and (3) are shown in the Appendix, where it is also shown that

$$E=K\cosh K(L-x)\int_0^x E_{gX}\frac{\operatorname{sech}K(L-X)dX}{\tanh KX+\tanh K(L-X)}$$
$$+K\cosh Kx\int_x^L E_{gX}\frac{\operatorname{sech}KXdX}{\tanh KX+\tanh K(L-X)}, \qquad (4)$$

where E is the voltage between elements at an arbitrary location x, and E_{gX} is the generated voltage level at X. For the above, it is assumed that a voltage-measuring instrument draws no current.

Since elements A and B may have different values of resistance per unit length, a reference voltage is taken at a level $[R_b/(R_a+R_b)]E_X$ above the voltage level generated in element B. R_a is resistance per unit length of element A, and R_b of element B. Letting $R=R_a+R_b$, the voltages E_a, $E_{a'}$, $E_{a''}$, E_b, $E_{b'}$, at locations indicated in Fig. 1, follow. For simplicity we use E_X and consider it generated by E_{gX} for a small ΔX at position X.

$$E_a=(R_a/R)E_X \operatorname{sech}KX \qquad (5)$$

$$E_{a'}=(R_a/R)E_X\,\mathrm{sech}K(L-X) \quad (6)$$

$$E_{a''}=(R_a/R)E_X\,\mathrm{sech}K(L-X)\cosh K(L-L_1) \quad \text{for } X<L_1 \quad (7)$$

$$E_{a''}=(R_a/R)E_X\,\mathrm{sech}KX\cosh KL_1 \quad \text{for } X>L_1 \quad (7a)$$

$$E_b=-(R_b/R)E_X\,\mathrm{sech}KX \quad (8)$$

$$E_{b'}=-(R_b/R)E_X\,\mathrm{sech}K(L-X). \quad (9)$$

The voltage differences between leads are found by subtracting the value at one lead from the value at another lead. For example, the voltage difference between lead a and lead a' in Fig. 1 is

$$E_a-E_{a'}=(R_a/R)E_X[\mathrm{sech}KX-\mathrm{sech}K(L-X)]. \quad (10)$$

A voltage difference of zero occurs at $X=\frac{1}{2}L$ in this example.

In a junction consisting of two large surfaces an analogous voltage decrement extends radially from the position of a temperature disturbance. A radial voltage decrement along a surface enables measurement in two dimensions. However, this discussion is limited to a junction of negligible width.

EXPERIMENTS

Experiments were performed to confirm the basic idea of using a large junction for position measurement and to explore its measurement applications. The experiments were preliminary. Ultimate sensitivity, accuracy, and refinements for particular applications were not investigated.

Measurements were made with a Leeds and Northrup K potentiometer and a 2430-A galvanometer. Descriptions of three experiments follow.

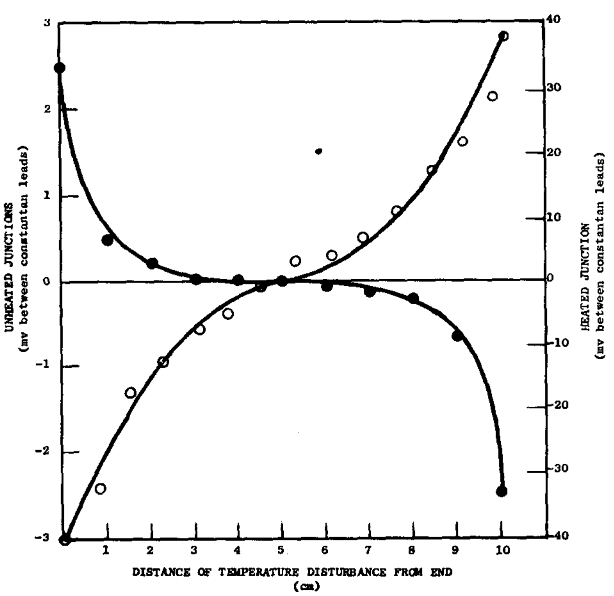

FIG. 2. Voltage between Constantan leads at each end of a long iron-Constantan junction. Heated by metal contact: ● 24 B & S gauge, soldered. Cooled by air jet: ○ 30 B & S gauge, soldered, heated by 1.25-amp, 1000-cps current.

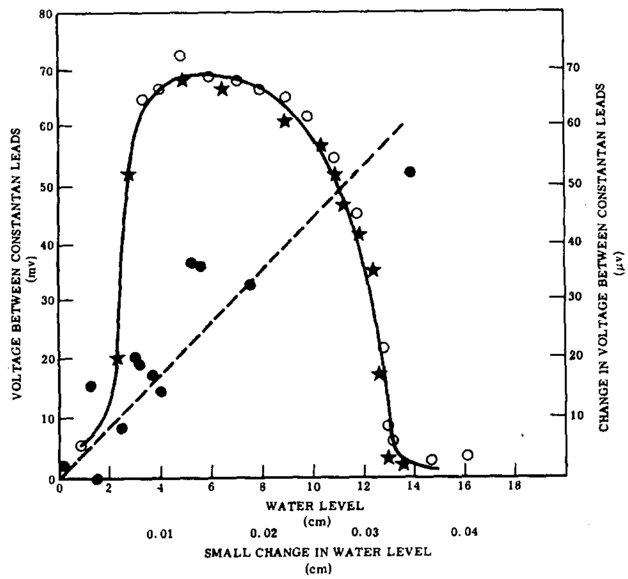

FIG. 3. Long iron constantan thermocouple water level indication.
——— ○ Water level increased, ★ Water level decreased,
– – – ● Small change in water level (μv changes).

1. Discrete Heat Source Applied to an Unheated Long Junction. A heat source consisting of a wire attached to a 60-w soldering iron was applied at various positions along junctions approximately 10 cm long. Voltage residue differences were then plotted against the positions of the heat source. These experiments were performed to determine the dependence of voltage outputs on heat position.

The voltage differences between the two Constantan end leads of a #24 B & S gauge iron-Constantan junction are plotted as a function of heat source position in Fig. 2. The 10-cm long junction was constructed by soft soldering two parallel wires together.

It is seen in Fig. 2 that the voltage between the two end leads from the same element is of opposite polarity when heat is applied at opposite ends of the junction and null when applied at the center. The shape of this curve corresponds to Eq. (10).

2. Small Cooling Jet Applied to a Heated Long Junction. A long junction was artificially heated to investigate the measurement in environments where no temperature disturbance normally exists. A small jet of air (0.5 cm diam, 650 cm/sec) was blown on the junction at various distances from the ends. The cooled spot from the jet resulted in thermoelectric voltages of opposite polarities from those found in Type 1 experiments. Joule law heating (1.25 amp at a frequency of 1000 cps) was applied to the thermocouple junction.

The output across the two Constantan end leads as a function of position is shown in Fig. 2. These results also correspond to Eq. (10).

3. Measurement of Liquid Level. A large thermocouple may be used to locate an interface between two substances of different heat conductivity coefficients. To illustrate, the water level in a container was measured by means of a heated long junction. Measurement was possible because the water-immersed portion of the junction cools faster than that remaining in air.

Again, Joule law heating (1.25 amp at a frequency of 1000 cps) was applied to the junction. The heated 30-gauge iron-Constantan junction (10 cm long) was supported vertically, and the water level was raised and lowered. Also, the results of small water-level changes were observed. The resolution was limited by air currents in the room. The results in Fig. 3 show that the voltage output is a function of water level.

DISCUSSION

These preliminary experiments introduce the basic kinds of measurements possible with the large thermocouple junction. However, they also expose limitations and difficulties.

The experiments indicate that accuracy depends upon the type of junction and the uniformity of heat conduction of the junction. For example, twisted and unbonded junctions produce more erratic data points than straight, soldered junctions. Also, the width of the heat source, conduction of heat along the junction, and the difficulty of maintaining constant temperature over the undisturbed portion of the junction provide obstacles to accuracy.

Although the voltage outputs depend upon both the position and the magnitude of the heat source in the experiments reported, it is seen that the outputs from leads at the opposite ends of one element form a ratio independent of the magnitude of the voltage generated. By comparing the output of one end lead with the output between the elements at the opposite end of the junction, position alone is indicated. A potentiometer may be used for this purpose.

The voltage decrement described here occurs in any junction and should be avoided in conventional thermocouple applications. For instance, in measuring the temperature of a surface the lead take-offs from the junction bead should be on the measured surface. If only the side of the bead opposite the leads contacts the surface, a voltage decrement may result.

APPENDIX

The long thermocouple junction consists of two conductors with current leakage between them. Such a junction is an electrical transmission line, and as such, the resistances and voltage decrements are described in transmission line theory. The following principles of transmission line theory are employed.

(1) If a line is terminated by its characteristic resistance $(R/G)^{\frac{1}{2}}$, it is considered an "infinitely" long line, and its voltage is $E_X e^{Kx} e^{-KX}$, where x is the position of measurement, X is the position of voltage generation, and $x \leq X$.

(2) If a line is terminated by an open circuit at $x=0$, the resistance of the line measured at X is $(R/G)^{\frac{1}{2}} \coth KX$, and the voltage at x is $E_X \cosh Kx \,\mathrm{sech} KX$.

(3) In the derivation of the transmission line equations the term $K^2E - d^2E/dx^2 = K^2E_{gX}$ is zero outside the interval in which voltage is generated; therefore, the superposition of solutions for different voltage-generating regions dX is valid.

Take first the case of a long junction terminated at each end by the characteristic resistance $(R/G)^{\frac{1}{2}}$. Consider a voltage E_{gX} generated at any position X and confined to a small ΔX along the junction. The "internal" resistance is then $1/G\Delta X$, and the junction resistance is $\frac{1}{2}(R/G)^{\frac{1}{2}}$. By means of resistance ratios we find that

$$E_X = E_{gX}\tfrac{1}{2}(R/G)^{\frac{1}{2}}/[1/G\Delta X + \tfrac{1}{2}(R/G)^{\frac{1}{2}}], \qquad (11)$$

and one obtains $E_X \cong \frac{1}{2}KE_{gX}\Delta X$, when ΔX is small. (12)

If a small ΔX is located at X and the voltage E is to be measured at location x, we find, employing principle No. 1 above, that

$$E = E_X e^{Kx} e^{-KX} = \tfrac{1}{2}E_{gX} e^{Kx} e^{-KX}\Delta X, \quad x \leq X. \qquad (13)$$

By principle No. 3 we may superpose solutions for many ΔX's, so one obtains

$$E = \tfrac{1}{2}Ke^{Kx}\int_x^L E_{gX}e^{-KX}dX, \quad X \geq x. \qquad (14)$$

It follows that for the opposite junction end we have

$$E = \tfrac{1}{2}Ke^{K(L-x)}\int_0^x E_{gX}e^{-K(L-X)}dX, \quad x \geq X. \qquad (15)$$

Again, by principle No. 3 we can superpose Eqs. (14) and (15). We find

$$E = \frac{K}{2}\left\{e^{Kx}\int_x^L E_{gX}e^{-KX}dX + e^{K(L-x)}\int_0^x E_{gX}e^{-K(L-X)}dX\right\}. \qquad (16)$$

The distribution of the potential between the two elements of the junction is derived from the condition that the currents in the two must match at every point, hence $E_a/R_a = E_b/R_b = E/R$.

The open-ended long junction is treated in the same manner as the above junction. By resistance ratio, and referring to principle No. 2, one obtains

$$E_X = E_{gX}\frac{(R/G)^{\frac{1}{2}}\coth KX\coth K(L-X)/[\coth KX+\coth K(L-X)]}{(1/G\Delta X)+(R/G)^{\frac{1}{2}}\coth KX\coth K(L-X)/[\coth KX+\coth K(L-X)]}, \tag{17}$$

and, when ΔX is small, we find

$$E_X \cong KE_{gX}\Delta X/[\tanh KX+\tanh K(L-X)]. \tag{3}$$

Substituting in principle 2 the value of E_X from Eq. (3), one obtains

$$E \cong KE_{gX}\Delta X\cosh Kx\,\mathrm{sech}\,KX/[\tanh KX+\tanh K(L-X)],\quad x\leq X. \tag{18}$$

Imitating the treatment of the "infinite" junction we superpose solutions, and Eq. (4) results.

ACKNOWLEDGMENTS

The author appreciates the help of W. C. Meecham and V. L. Larrowe for discussions and suggestions concerning this work.

This investigation was supported in part by Project MICHIGAN under Department of the Army Contract DA-36-039-SC-78801, administered by the U. S. Army Signal Corps.

THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 33, NUMBER 3 MARCH, 1962

New Large Area CdS Photoconductor

PAUL H. WENDLAND
Electro Radiation, Inc., Los Angeles 64, California

(Received November 30, 1961; and in final form, January 8, 1962)

A CdS photoconductive cell, combining the mechanical properties of powder-binder type layers with photoconductive properties exhibited by sintered layers, is described in this report. The preparation process requires a single air firing and subsequent pressure-temperature molding with an acrylic. Data presented on the characteristics of these cells includes: photocurrent as a function of illumination intensity and electrical field, speed of response, spectral response, and mechanical properties.

I. INTRODUCTION

TWO types of large area CdS photoconductors, sintered layers and powder-binder layers, were described by Thomsen and Bube[1] in 1955. These two types have since come into rather wide use in the photodevice field. The sintered layers have been incorporated into photocells with exceptional characteristics[2] and the powdered layers have been used successfully with electroluminescent powders in solid state light amplifiers,[3] to mention a few of the applications. A sintered pellet,[4] powder pressed into pellet shape and then fired to cause sintering, with characteristics similar to the sintered layers of reference 1, has been described. Various activators, besides the copper and chlorine of reference 1, have also been used to produce photoconductive CdS powders.[5,6]

The sintered layers have an ohmic dependence of photocurrent on applied voltage, a high photosensitivity, a millisecond response time, and near-linear dependence of photocurrent on illumination intensity. They have rather poor mechanical properties, cannot be machined, and require a hermetic seal. The powder-binder layers have exceptional mechanical properties, a good photosensitivity, and are naturally hermetically sealed. However, they have a very nonlinear dependence of photocurrent on both applied voltage and illumination, a response time of seconds, exhibit photocurrent lag phenomena which reduces ac response, and require a delicate three-step firing process for their activation. The poorer photoconductive properties of powder layers compared to sintered layers have been attributed to the many nonohmic interparticle contacts associated with the binder.[7] It is this binder, however, that gives the layer excellent mechanical characteristics and a machining capability with some binders.

A CdS photoconductor has been developed which combines the mechanical characteristic of the powder-binder

[1] S. M. Thomsen and R. H. Bube, Rev. Sci. Instr. **26**, 664 (1955).
[2] C. P. Hadley and E. Fischer, Proceedings of the National Electronics Conference, XV, 253 (1959).
[3] B. Kazan and F. H. Nicoll, J. Opt. Soc. Am. **47**, 887 (1957).
[4] S. Yoshimatsu, C. Kanzaki, S. Ibuki, and N. Maurai, J. Phys. Soc. Japan **10**, 493 (1955).
[5] R. H. Bube and A. B. Dreeben, Phys. Rev. **115**, 1578 (1958).
[6] W. van Gool, Phillips Research Repts. **13**, 157 (1958).
[7] R. H. Bube, J. Appl. Phys. **31**, 2239 (1960).