Sensors and Materials, Vol. 8, No. 5 (1996) 293–301
MYU Tokyo

S & M 0246

Peltier Effect for Measurement of Fluid Thermal Property —Application for Designing New Thermal Sensors—

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(Received October 14, 1994; accepted July 3, 1995)

Key words: thermoelectric effects, plated thermocouple, thermophysical properties

A new thermoelectric microsensor designed for identifying a gas based on its thermal properties is described. The measurement method involves the use of the Peltier effect to generate temperature differences between the numerous junctions of a microthermopile and the subsequent use of the Seebeck effect to measure the induced Peltier electromotive force [e.m.f.], using the same thermopile as the detector when the current is removed. Since the temperature differences occuring between the junctions are proportional to the thermal resistance between them, any change in thermal resistance between the junctions is directly converted into a change in the measured Peltier e.m.f. Since the thermal resistance is influenced by the heat transfer coefficient with the surrounding fluid, any change in the fluid thermal properties will be directly converted into a proportional change in output voltage. The main advantages of the proposed thermal microsensor are distributed measurement and slight warming up of the sensor which limits the thermal perturbations in the fluid.

1. Introduction

When carrying a current, a thermopile constituted by couples of thermojunctions, one of which is heated and the other cooled, temperature differences arise and thus an electromotive force [e.m.f.], called Peltier e.m.f., is induced in the circuit. This Peltier e.m.f. is in such a direction as to oppose the flow of current and is proportional to the current.

The ratio of this Peltier e.m.f. to current is a transduction impedance which is found to be proportional to the thermal impedance between the junctions. The purpose of this work is to describe new thermoelectric microsensors based on transduction impedance measurements. The sensor operation is based on measurement of the thermoelectric transduction resistance in a thermopile with a current flowing through it, under transient conditions. Specific applications for the sensors are in situations where a change in the heat transfer coefficient between the thermopile and its environment is to be measured.(1,2) For application, special attention has been devoted to a gas sensor giving the thermal conductivity of a fluid at rest from a calibration curve.

2. Thermopile Description

The basic thermoelectric sensor designed for measurements in a fluid medium is shown in Fig. 1. It comprises two interlaced identical planar thermopiles. Each planar thermopile consists of many identical plated thermocouples interconnected in series. It is basically a continuous metallic layer (of poor electrical conductivity) of constantan or chromel, for example, which is overlayed with patches or electrodes of high conductivity (*e.g.*, gold). Such planar thermopiles are easily miniaturized, as described in the literature.(3)

It is shown that for a sufficient thickness of the plated section, its physical properties are similar to those of the plating material, and that thermocouple junctions operating at the plating boundaries are then interconnected in series.

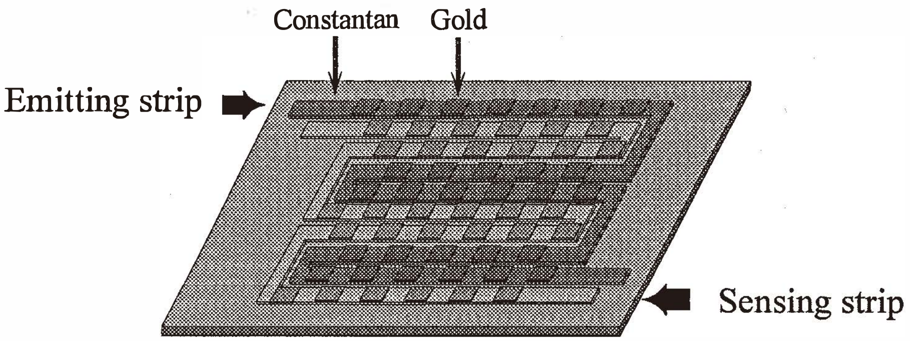
The simplest way of fabricating a prototype is to start with a thin constantan foil (thickness 5 μm) bonded on a kapton support (thickness 12 μm) and then to employ photolithography, plating and etching techniques to obtain gold patches and finally two interlaced planar thermopiles. Each planar thermopile consists of parallel rows of 100 μm width separated by etched spaces of 75 μm width.

Each planar thermopile, comprised of more than 100 plated thermocouples interconnected in series, will give, under open-circuit conditions, an output voltage proportional to the sum of the temperature differences occurring between the junctions. Thus, when such a device is immersed in a fluid at uniform temperature, the output voltage of each thermopile is zero since all the junctions are kept at the same temperature.

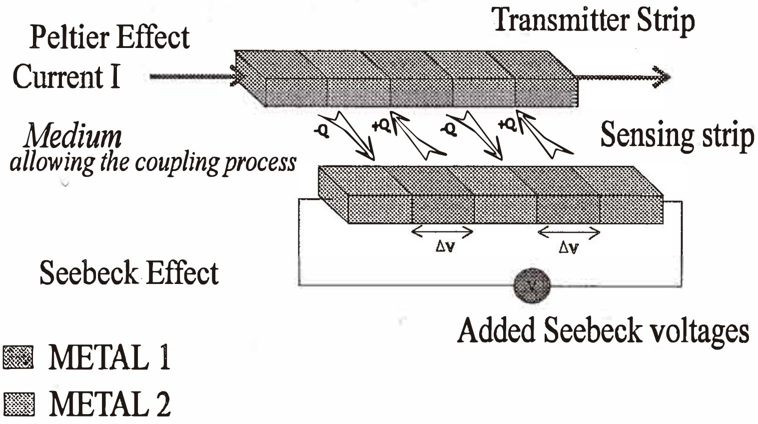
It is only in the case where an electrical current (as low as 4 mA, for example) has been flowing through one of the thermopiles (for a sufficiently long time to reach thermal equilibrium) that temperature differences will appear between the junctions of that thermopile, inducing temperature differences between the junctions of the other thermopile.

3. Operating Principle

The sensor described here makes use of two types of physical phenomena. Heat is, on the one hand, produced by the distributed joulean effect and dissipated in the surrounding medium, and on the other hand, generated by the Peltier effect localized at the junctions. In



Twin strip sensor configuration: two identical strips lying side by side on the same backing material.



Heat transmission through the surrounding medium.

Fig. 1. Basic thermoelectric sensor.

a previous article,(3) a plated thermopile was shown to behave as a classical bimetallic chainlike thermopile.

In order to describe the distributed effect, the energy conservation principle is applied to a one-dimensional metallic strip (Fig. 2(a)) carrying an electric current:

$$\frac{1}{r_t}\frac{\mathrm{d}^2\theta(x)}{\mathrm{d}x^2}+r_e I^2-h\theta(x)=0, \tag{1}$$

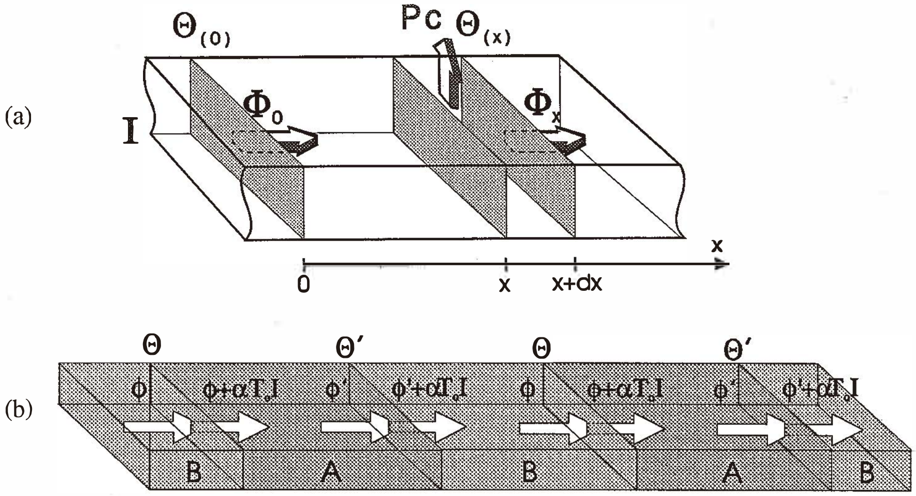


Fig. 2. (a) Energy conservation principle. (b) Classical bimetallic chainlike thermopile.

where $\theta(x) = T(x) - T_0$ is the difference between the temperature at a point x of the strip and the average temperature T_0 of the surrounding fluid, and r_t the lineic thermal resistance of the strip. The second term $r_e I^2$ of eq. (1) introduces the joulean heating power induced by the electric current I flowing through the strip, with r_e being the electric lineic resistance of the strip. Energy dissipation in the surrounding fluid is expressed by the third term where h is the heat transfer coefficient.

Integrating eq. (1), and introducing the thermal flow definition

$$\varphi(x) = -\frac{1}{r_t}\frac{\mathrm{d}\theta(x)}{\mathrm{d}x}, \tag{2}$$

we obtain

$$\begin{bmatrix}\theta(x)\\ \varphi(x)\end{bmatrix}=\begin{bmatrix} ch\gamma x & -R_c sh\gamma x\\ -\dfrac{sh\gamma x}{R_c} & ch\gamma x\end{bmatrix}\begin{bmatrix}\theta(0)\\ \varphi(0)\end{bmatrix}+r_e I^2\begin{bmatrix}-R_c(ch\gamma x-1)\\ \dfrac{sh\gamma x}{\gamma}\end{bmatrix} \tag{3}$$

with $\gamma^2 = hr_t$ and $R_c^2 = r_t/h$,

where the first classical thermal matrix represents the heat propagation along the strip and the second one introduces the distribution of joulean heating.

Consequently, if l is the length of a strip section limited by points P and Q, the temperature difference can be written as

$$\theta_p - \theta_q = R_c \frac{1 - ch\gamma l}{sh\gamma l}\left(\varphi_p + \varphi_q\right), \tag{4}$$

where the uniformly distributed joulean effect is screened out.

Let us now consider a thermopile composed of two types of metallic strips (A, B) interconnected in series (Fig.2(b)). In such a periodical thermopile, both temperature and heat flow exhibit periodical patterns and will be written θ, θ' and φ, φ'. If $\alpha = \alpha_A - \alpha_B$ is the thermopower of the thermopile materials, for an average temperature T_0 of the sensor, the Peltier power generated is equal to $+\alpha(T_0 + \theta)I$ at the hot junction and $-\alpha(T_0 + \theta')I$ at the cold junction.

Assuming that θ and θ' are small compared with the absolute temperature T_0 the Peltier power can be approximately expressed as $+\alpha T_0 I$ and $-\alpha T'_0 I$.

The temperature difference $\Delta T = \theta - \theta'$ between two successive junctions is obtained by applying eq. (4) on each kind of material (A and B) with thermal flow balance (Fig.2(b)) at each junction

$$\Delta V_p = (\alpha_2 - \alpha_1)\Delta T = \alpha^2 TIR_{th} \tag{5}$$

$$\text{with } R_A = R_{cA}\frac{1 - ch\gamma_A l_A}{sh\gamma_A l_A} \quad \text{and } R_B = R_{cB}\frac{1 - ch\gamma_B l_B}{sh\gamma_B l_B}$$

R_{th} comes up as the slope thermal resistance whose value largely depends on thermal characteristics of the sensor and the surrounding fluid.

Thus the Peltier e.m.f. can be determined from temperature rise,

$$\Delta V_p = \left(\alpha_2 - \alpha_1\right)\Delta T = \alpha^2 TIR_{th}, \tag{6}$$

which may be interpreted as due to a transduction resistance defined as

$$R_t = \frac{\Delta V_p}{I} = \alpha^2 T_0 R_{th}, \tag{7}$$

added to ohmic resistance R_e.

For a thermopile consisting of many junctions, the transduction resistance R_t is the sum of R_t of each thermocouple (as is the electrical resistance).

Since the transduction resistance and electrical resistance are compounded as if connected in series, the electrical power supplied to the thermopile is accounted for by energy dissipation through electrical conduction (joulean heat in R_e) and through thermal conduction in the transduction resistance R_t.

In fact, electric dissipation through electrical conduction is one or two orders of magnitude greater than energy dissipation through thermal conduction, i.e.,the voltage between the thermopile leads when a current flowing through the sensor is nearly equal to the ohmic drop

$$\Delta V = R_e I + \Delta V_p \approx R_e I . \tag{8}$$

In measurements based on the Peltier effect, practically all the energy required for the measurement is dissipated through electrical conduction. Fortunately, due to the low electrical resistance of the metallic circuit, the electrical input power necessary to pass current of electrical intensity on the order of 4 mA is extremely low (nearly 6 mW).

When operating a sensor at 6 mW/cm^2, the average temperature rise is less than 0.1°C, and even at a power density level of 50 mW/cm^2, the temperature rise is lower than 1°C. Since the ohmic drop across the thermopile terminals is much higher than the Peltier e.m.f. to be measured, the only way to detect it is to remove the current quickly, that is, to induce the constant heat-flow boundary condition at the junctions, and to measure, under an open-circuit condition, the original value of the output voltage. Since the output voltage produced by the thermopile is equal to the Peltier e.m.f. just before removal of the current, e.m.f. proportional to the temperature difference between the junctions of the thermopile is obtained.

4. Results

Since the Peltier e.m.f. generated by a thermopile is proportional to the thermal resistance between the junctions, any change in the heat transfer coefficient with the surrounding fluid will be directly converted into electrical voltage.(4) As shown in eq. (6), the sensitivity of the Peltier sensor, which is proportional to its absolute temperature, is not greatly influenced by the relative variation of the temperature of the surrounding fluid. Consequently, unlike conventional sensors based on temperature variation measurements, there is no need of gas temperature control for the Peltier sensor.

An electronic circuit has been developed to characterize the sensor. When a step of current is established in the first thermopile, Peltier e.m.f. can be recorded across both the thermopile with a current flowing through it and the thermopile used as a detector operating under an open-circuit condition (Fig. 1).

The experimental results clearly indicate that any change in the asymptotic values of the Peltier e.m.f. corresponds to a change in the fluid thermal conductivity which can be determined from a calibration curve (Fig. 3).

The asymptotic Peltier voltage to current density (transduction resistance) was found to be constant regardless of electric current intensity in the range of 0 –10 mA. The quantity from which the fluid thermal conductivity is determined is not affected by joulean heating, that is, the average temperature of the sensor.

Despite the low power requirement, the Peltier sensor has a wide measurement range. Measurements ranging from 0.016 W/mK to 0.15 W/mK could be obtained with an

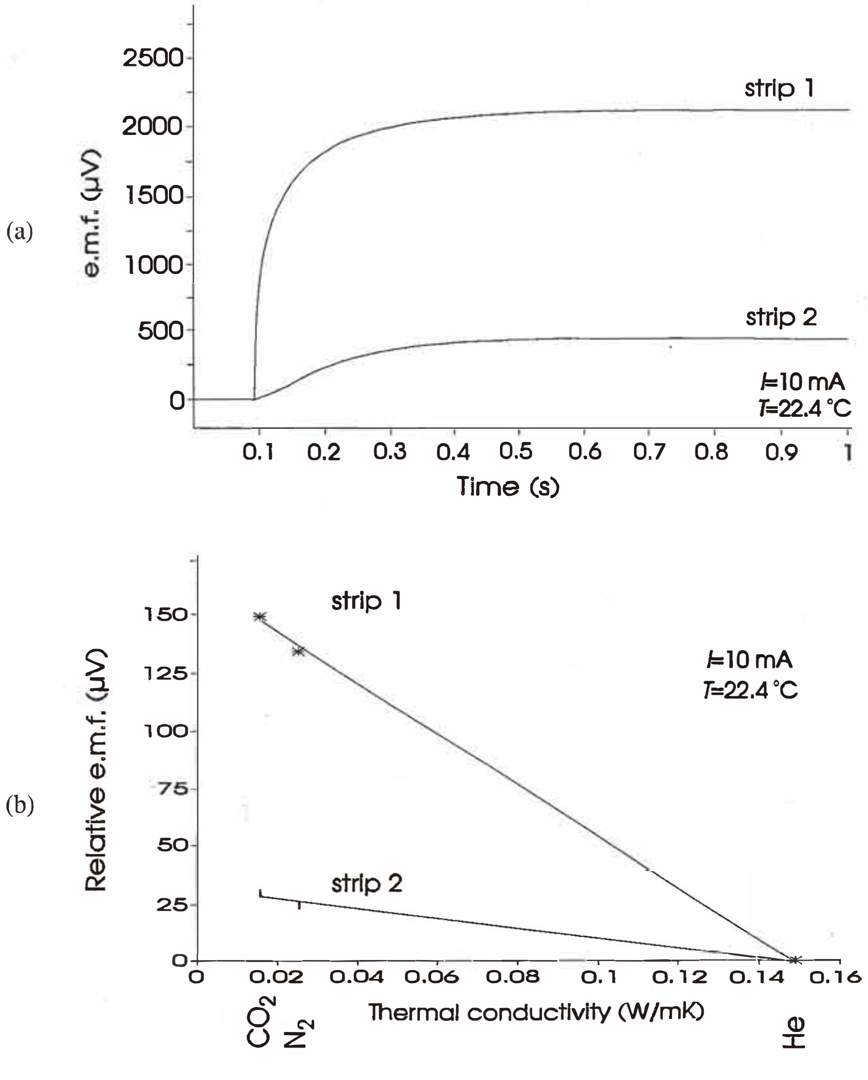
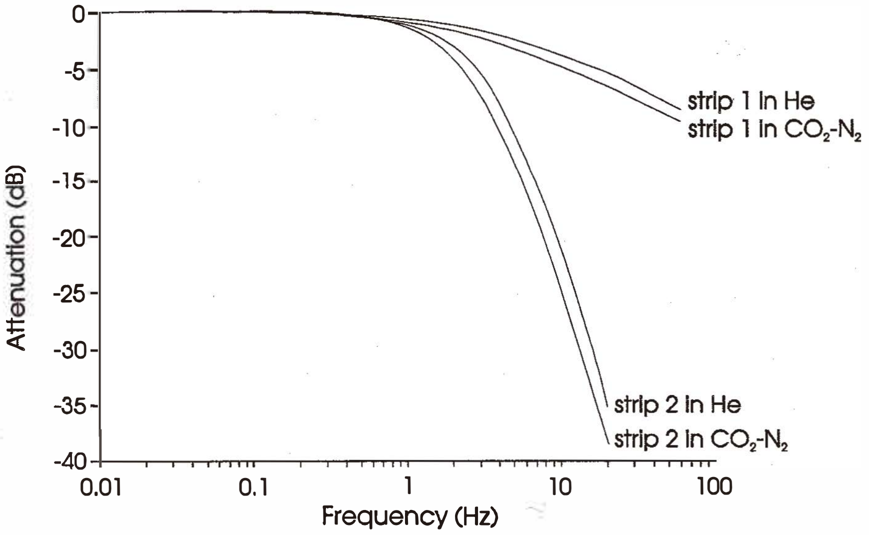


Fig. 3. (a) Step response for a sensor in carbon dioxide. (b) Relative e.m.f.'s for several gases.

accuracy better than 0.001 W/mK. The lower limit is governed by the reference gas (CO_2) and not by any intrinsic limit of the device.

Another measurable parameter which is influenced by the fluid conductivity is the response time of the Peltier e.m.f. (or the Fourier transform of this e.m.f.). The curves in Fig. 4 were obtained by operating the thermopile under the sinusoidal condition, and



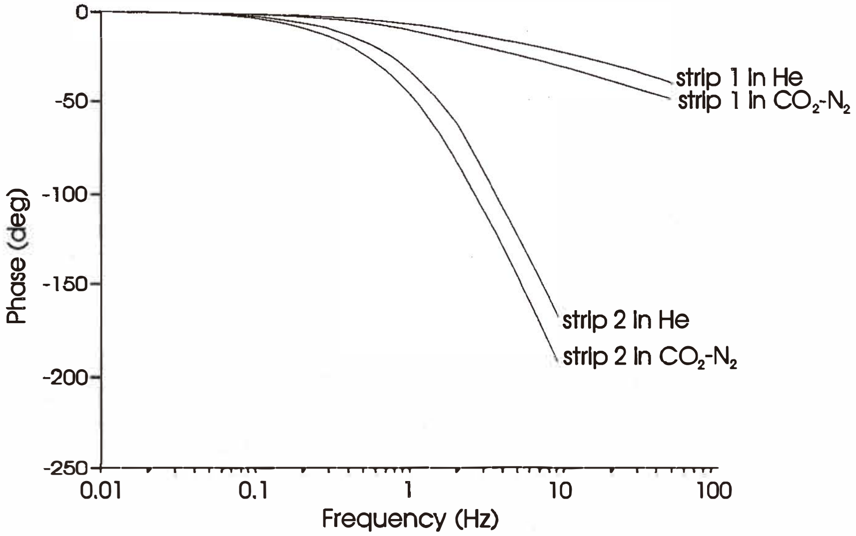


Fig. 4. Frequency response of the sensor.

clearly show that the frequency behavior of the response is influenced by the fluid thermal conductivity.

5. Conclusions

These experimental results demonstrate that a Peltier sensor is a very sensitive device which yields an output depending on the fluid thermal properties when immersed in a fluid at rest. Designing devices with smaller surface area (3 × 3 mm^2, for example) while maintaining constant dissipated electrical power per surface unit, is of interest to us due to the low noise related to the low offset of natural convection generated by the sensor in the fluid medium. Other experimental studies will be undertaken with the aim of matching the thermal resistance between the junctions of a microthermopile to that of the fluid in order to obtain optimal Peltier microsensors.

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