Design and construction of precision heat fluxmeters

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In this paper we discuss the design and construction of thermopiles for use as heat flux measurers. Compact structure, mechanical consistency, and a wide range of dimensions and sensitivities are possible. We can thus reach thermocouple densities up to 100 cm^{-2} and sensitivities of approximately 1 V W^{-1}.

Heat flux is traditionally measured, in a steady flow situation, with the heat passing through a medium of known thermal conductivity which has temperature sensors built in at determined distances. An alternative method consists of making the heat flow between the ends of a thermopile and measuring the resulting emf.

The first method has the disadvantage that it is necessary to know the thermal conductivity of the medium and its temperature dependence. Further difficulties include those specific to local temperature measurement; the sensors create errors due to their finite size and due to heat leaks through their terminals. In the second method, the difficulty lies in the fact that each thermocouple junction must be electrically isolated, which tends to produce a thermal isolation, and there is no guarantee of the homogeneity of the thermal conditions of each thermocouple. Delicate mechanical structure and lack of functionality are other typical defects in thermopiles to date. In order to achieve mechanical strength, substances of generally poor thermal conductivity are used as supports, even in more compact thermopiles made of semiconductors.[1]

We shall now discuss our technique for the design and construction of thermopiles for heat flux measurement in a stationary regime for a one-dimensional temperature gradient. Our method intends to achieve the following conditions: adequate sensitivity and linear electrical responses, absence of heat leaks, easy and accurate calibration, compact structure and mechanical strength, absence of poor thermal conductors, temperature homogeneity of the surfaces at the ends of the thermopiles, where the thermojunctions are located, and good thermal contact with the medium between which they are sandwiched.

Our thermopiles (see Fig. 1) consist of N thermocouples arranged electrically in series and thermally in parallel between a heat reservoir H (isothermal metallic block) and a metal plate B which has a built-in electrical resistance R. Each thermocouple is made up of a pair of metals or alloys a-b in wires of equal length, l, and section s. The electrical terminals come out of the end which is thermally anchored to the heat reservoir. The thermojunctions form two flat parallel surfaces and are adhesive bonded to two thin metal plates F_1 and F_2 which act as a thermal bridge with H and B. Vacuum isolation is normally used.

When a heat power is dissipated in the setup BR, or in an attached sample (see Fig. 1), a heat flux q passes through the thermopile and a temperature difference ΔT is established between its ends, giving rise to an emf E in the thermopile. If ΔT is small enough to admit linear approximation, we can write

$$q = E/Nr(\overline{T})S_{ab}(\overline{T}), \quad (1)$$

where r is the thermal resistance of the thermopile, and $\overline{T}$ is average temperature (approximately equal to that of the thermal reservoir). As the thermocouples are thermally in parallel, we have: $r = r_{ab}/N$, where r_{ab} is the thermal resistance of each thermocouple. Substituting in Eq.(1), we obtain the sensitivity of the thermopile:

$$E/q = r_{ab}S_{ab}(\overline{T}), \quad (2)$$

where $r_{ab} = l/(\lambda_a + \lambda_b)s$, and λ_a, λ_b are the thermal conductivities of metals a and b respectively.

In order to convert our thermopiles to measurers of heat flux "fluxmeters" it is necessary to calibrate them; establishing the factor proportionality $k = q/E$, as a function of T in the working range. This operation is carried out by measuring, at different temperatures, the electrical responses corresponding to known heat fluxes, and establishing the pertinent fitting. To avoid errors due to nonlinearity, we try to make the heat fluxes used in calibration of the same order as those we wish to measure. To produce known fluxes, we dissipate Joule heat in the electrical resistance R, which is built into B.

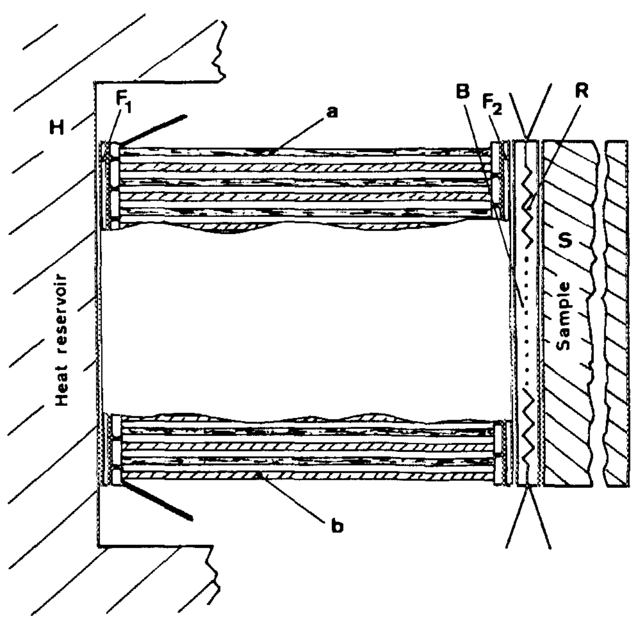

FIG. 1. Schematic of a heat fluxmeter.

We chose the couple a-b under the following considerations: their thermal conductivities must be approximately equal (so as not to create thermal inhomogeneity at the ends), they must be easy to manipulate, their relative Seebeck coefficient S_{ab} must be high, varying only slightly with temperature in the working range, to achieve linear responses. We use a Chromel-Constantan thermocouple most often.

The choice of the values l and s of the wires depends on the required sensitivity, which, according to Eq.(2), only depends on the quotient l/s (we use up the degree of freedom left in the limitations of the mechanical construction).

Obviously the sensitivity is independent of the number of thermocouples, and we can raise N with the advantage that r diminishes as does the temperature difference between the ends of the thermopile for the same heat flux. This promotes the linearity of the response, allows the generation of heat in the sample to be made in a quasi-isothermal way, and makes the heat leaks through radiation, as well as through conduction (when there is no vacuum) insignificant. Besides, a high density of thermocouples gives the thermopile mechanical strength and increases thermal homogeneity at each of its ends.

For its construction, we need two metal plates of high thermal conductivity (normally silver, copper, or copper-silver alloys), with the same shaped surface we require at the ends of the thermopile (circular or rectangular shapes are the ones we usually use). With the aid of an X-Y coordinate table we drill a set of $2N$ holes with the same distribution in each plate. The diameter and distances between these holes depends on the design adopted, and we try to make the x and y interdistances the same, thus forming a square pattern of holes. When this operation is finished, the plates are placed in spacers of anodized aluminum which keep them parallel to the distance chosen as the length of the thermopile. Then the wires (cut a little longer) are introduced through the confronted holes, alternating the a- and b-type wires (the diagonals of the pattern of holes are always occupied by wires of the same type). They are soldered to the plates and the exterior surfaces are faced by plain milling.

To convert the metal unit thus formed into a thermopile, it is necessary to cut the metal plates in the directions of X and Y so that each of the resulting little plates contains an a-b junction, and all the junctions of both surfaces are electrically in series. In order to maintain the stability of the structure during this stage, we must temporarily inject a soluble substance among the wires.

The cutting process can begin with either one of the two ends. The cuts are made with a milling saw or a friction saw. The width of these cuts must be minimal so as not to lose thermal contact surface of the junctions. (For microtype thermopiles, a diamond saw with 0.1-mm-thickness is used for this operation.) Figure 2 shows the cut end of a macrotype thermopile that faces the heat reservoir.

After making the cuts on the first end, we proceed to fill them by bonding the little metal plates with an adhesive of high thermal conductivity. The external surface is faced again to remove rough edges and excess adhesive. Then another thin metal plate of high thermal conductivity is adhesive bonded on top of the junctions. (See Fig. 1.) In the adhesive layer, we try to achieve a thin uniform film. (This operation is facilitated if the metal plate is made of anodized aluminum.) The new external surface is faced by surface grinding. An alternative method is to superimpose a thin ceramic layer over the junctions, followed by a thin metal layer over the ceramic one. These layers are applied by jet-spraying micropulverized alloys. All of this strengthens the end of the thermopile, electrically isolates the thermojunctions, and increases thermal homogeneity.

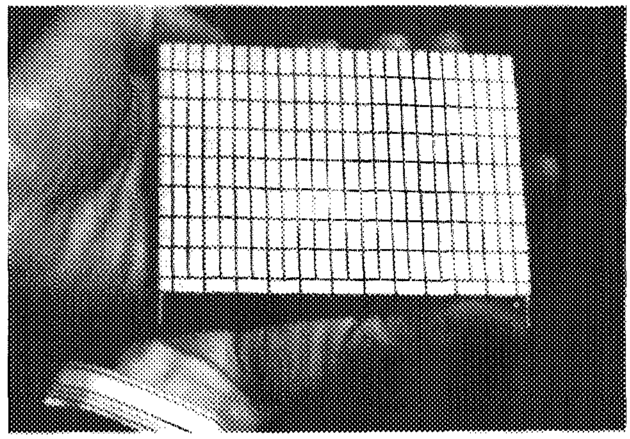

FIG. 2. View of the thermojunctions at one end of a macrotype thermopile.

All the operations we have just described are now repeated at the other end of the thermopile, taking care to ensure that both ends are exactly parallel. When the second end is finished, the soluble substance which had been injected among the wires is removed.

Maximum limits of 100 thermocouples to the cm^2 with wires of about 20 mm in length and a minimum diameter of 0.2 mm are possible with this method. This means that these thermopiles will have electrical responses to heat flux similar to those obtained with thermopiles made of semiconductors (10-nW resolution is possible). The absence of poor thermal conductors, the greater electrical stability, and the better linearity of response all constitute a great advantage. Their compact and resistant structure, and the ease with which a precise geometry can be achieved allows them to serve simultaneously as measurers, as well as physical supports. Their symmetry also ensures one-dimensional temperature gradient in the thermopile. For axial symmetry in the temperature gradient, it is possible, by means of a variant of the method described, to build thermopiles with the same characteristics, but with their ends forming concentric cylindrical surfaces.[2]

It is necessary to impose conditions on the setup B-R so that B-R does not create thermal inhomogeneities at the end of the thermopile where it is attached, nor errors caused by heat leaks through its electrical terminals.

With this purpose, B is made of a thin aluminum plate (its thickness ranging from about 0.5 mm to a little over 1 mm) with surface dimensions equal to those of the end of the thermopile. On both sides of B we engrave thin channels of about 0.1 mm in depth and width, we anodize it to a thickness of about 5 μm, and finally, with the aid of a high thermal conductivity adhesive, we insert a platinum wire of 0.05 mm in diameter into the channels; see Fig. 3. This arrangement has the advantage that most of the heat generated in the platinum wire flows towards the thermopile and the sample through the nonengraved surfaces of B (which constitute the largest part of its surfaces). Therefore, thermal inhomogeneity is not produced by this setup, and besides, a good thermal bridge is established between the thermopile and the sample.

Two copper or platinum wires come out of each end of R to carry electrical current and measure voltage. These four electrical terminals must be thermally anchored at B and H. This way, the thermal conditions at the ends of the thermopile are always the same as those of the ends of the terminals during the calibration phase as well as the measuring phase. Thus, the thermopile's electrical response in $k = q/E$ corresponds to the sum of the heat fluxes through the thermopile and the terminals. (The thermopile, in conjunction with the setup B-R, make up what we call a heat fluxmeter.) The length of these wires between their thermal anchorings is chosen so that the thermal resistance of each wire is approximately equal to any of the wires of the thermopile. This precaution is adopted so as not to create thermal inhomogeneities in B. Greater lengths should be avoided, because it takes longer to establish steady states, and also because at the calibration stage, the terminals carrying electrical current act as heaters, and half of the heat there generated is transferred towards B. So as not to cause these errors, we calculate the heat power in the following way: on each thermal anchor at H of the current terminals, we solder another auxiliary terminal. We can thus compute the heat flux transferred to B by means of the voltage between the new terminals. Therefore, according to the diagram shown in Fig. 4, the heat power to be considered during calibration will be $(V + V')V_s/2R_s$, where V is the voltage between the ends of R, V' is the voltage between the thermal anchors of the terminals carrying electrical current, and V_s is the voltage across the standard resistance R_s inserted in the network. Relative errors in the obtained calibration parameter are about 10^{-4} with this method.[3]

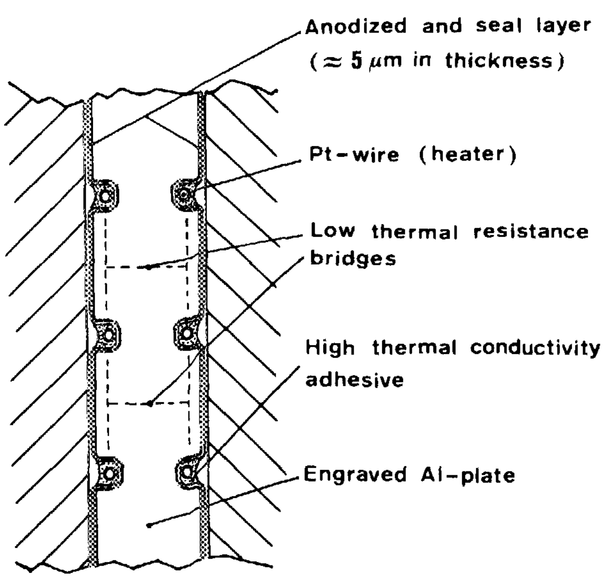

FIG. 3. Cross-section part of the setup B-R.

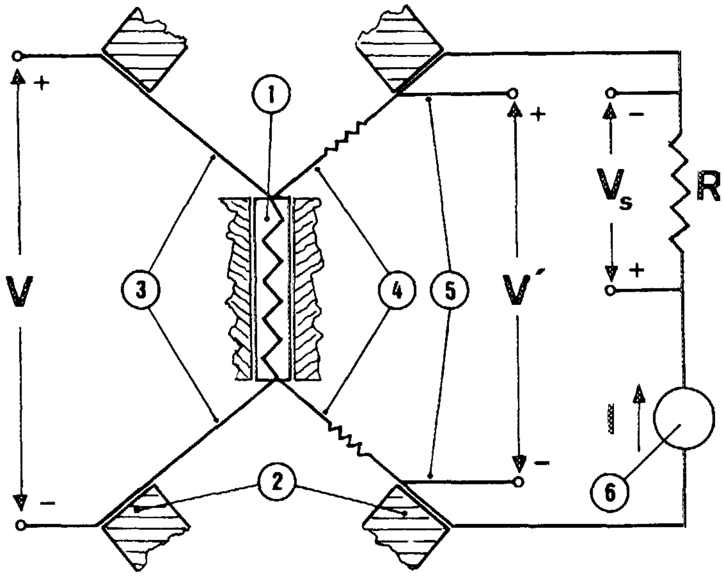

FIG. 4. Schematic diagram for heat power measurement during the calibration stage. (1) Setup B-R. (2) Thermal anchors. (3) Voltage terminals. (4) Current terminals. (5) Auxiliary terminals. (6) Current source.

The characteristics of the setup B-R allow it, when not in the calibration stage, to act as a thermometer,[4] measuring the local temperature at the end of the sample attached to it. Figure 5 shows a setup B-R to fit a microtype thermopile with circular ends of 12 mm in diameter.

Although the fluxmeter we have described is perfectly applicable to many problems,[5] we would like to point out a fluxmeter combination for thermal conductivity measurement that we have used successfully.[6] This combination consists of two fluxmeters with the sample sandwiched between them, but with only one heat reservoir; see Fig. 6. One of the fluxmeters can, via the Peltier effect, generate a one-dimensional temperature gradient in the sample, while the other measures the corresponding heat flux. At the same time, the setups B-R measure the temperature difference between the ends of the sample. We note the great stability of the temperature difference in the sample achieved with this method. Besides, the symmetry of the device makes it independent of slow temperature variations in the heat reservoir. The cali-

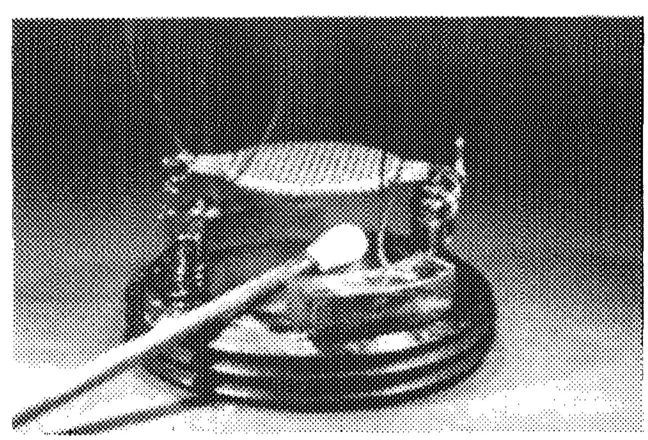

FIG. 5. View of a setup B-R for a microtype thermopile with circular end.

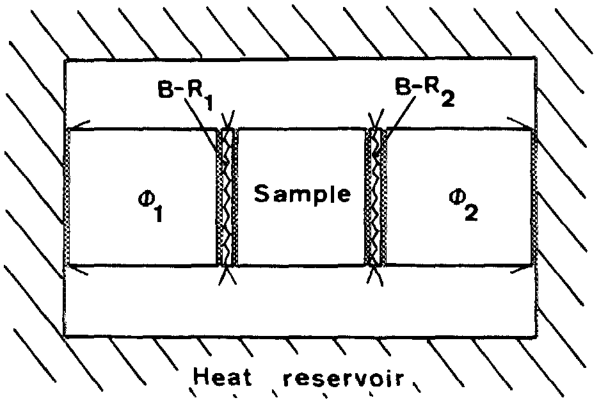

FIG. 6. Schematic of arrangement for thermal conductivity measurement. ϕ_1, ϕ_2: heat fluxmeters or generators of one-dimensional temperature gradients. B-R_1, B-R_2: thermometers or heaters.

bration of the fluxmeters here must be performed when the sample has been placed between them. (Thermal contact resistances are not repetitive.) This is done by dissipating Joule heat in either one of the setups *B-R* and measuring the emf's created in the thermopiles, and then repeating this procedure with the other setup.[4]

[1]E. H. Schulte and R. F. Kohl, *Low Temperature High Sensitivity Heat-Flux Transducer* (IEEE Sensor Symposiums, Minnesota, 1968).
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[5]J. Moreno, J. Jiménez, A. Córdoba, E. Rojas, and M. Zamora, Rev. Sci. Instrum. **51**, 82 (1980).
[6]J. Jiménez (unpublished).