Large-area, high-sensitivity heat-flow sensor

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A heat-flow sensor based on ac resistance thermometry and utilizing synchronous detection is described. The sensor design permits large-area sensors to be constructed economically. Calibration of an initial 0.09 m^2 prototype yielded a linear response with a sensitivity of (37.6 ± 0.01) mV$(W/m^2)^{-1}$. The minimum detectable heat flux is no larger than 0.08 W/m^2.

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INTRODUCTION

In studying the performance of building envelopes, either to improve their energy efficiency or to determine their behavior in passive solar applications, it is sometimes desirable to measure heat flows that are relatively small (≤ 6 W/m^2) and spatially nonuniform. While it is usually sufficient to determine the area-averaged heat flow, this must be measured with moderate accuracy over large areas. Existing commercial heat-flow sensors are generally too small (5–100 cm^2) to meet this measurement need and, in moderate sizes (~ 0.1 m^2), become very expensive.

In the process of building a room-sized calorimeter for testing windows,[1] we have developed a heat-flow sensor, based on ac resistance thermometry, that will accurately measure average heat flows over large areas. We have built several moderate-sized (0.09 m^2) prototypes, and are planning larger units (0.7 m^2). Here we present test results on one of the moderate-sized prototypes for heat flows between 1 and 100 W/m^2. Large-signal tests of the concept were reported earlier[2] but without a description of the method. An approach somewhat similar to ours, but designed to measure much larger heat flows and using a dc rather than an ac measurement technique, has been described by others.[3]

I. DESCRIPTION OF THE METHOD

A schematic description of the method we used is shown in Fig. 1. Fine resistance wires are laid on either side of a sheet of thermal insulator and connected to opposite sides of a Wheatstone bridge. If the wires and the thermal resistance are initially at some temperature, T, without heat flow, a thermal flux, J, across the thermal resistance will induce a temperature difference of $\Delta T = R_{th} J$ between the two layers of wires, where R_{th} (m^2 K/W) is the thermal resistance of the insulating material. This, in turn, will cause the electrical resistances of each of the two layers of wire to change by a magnitude of $\frac{1}{2}\alpha\Delta T$, with opposite signs, where α is the resistance temperature coefficient of the wire. Because the bridge output is proportional to the difference in resistance between the two sides, it will change by an amount proportional to $\Delta R_{el}/R_{el} = R_{th}\alpha J$. This difference in resistance is very ac-

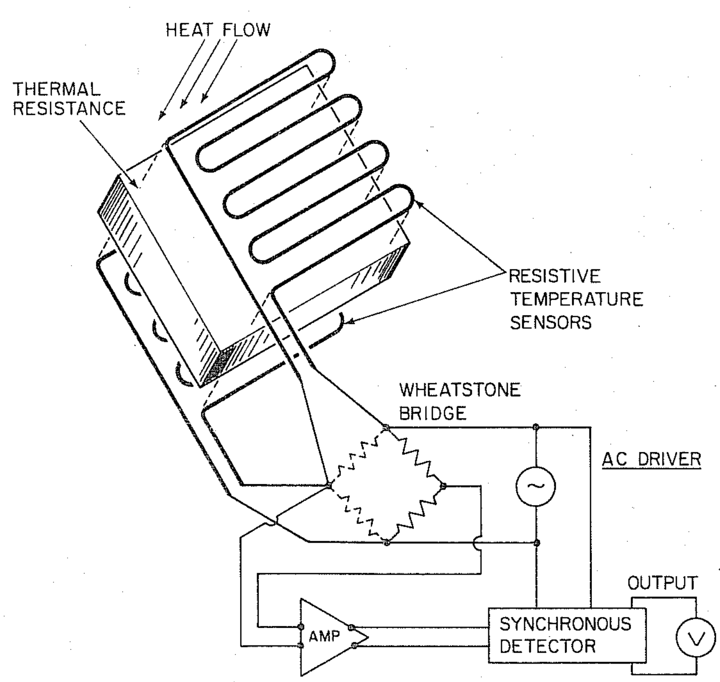

FIG. 1. Schematic description of the heat-flow meter.

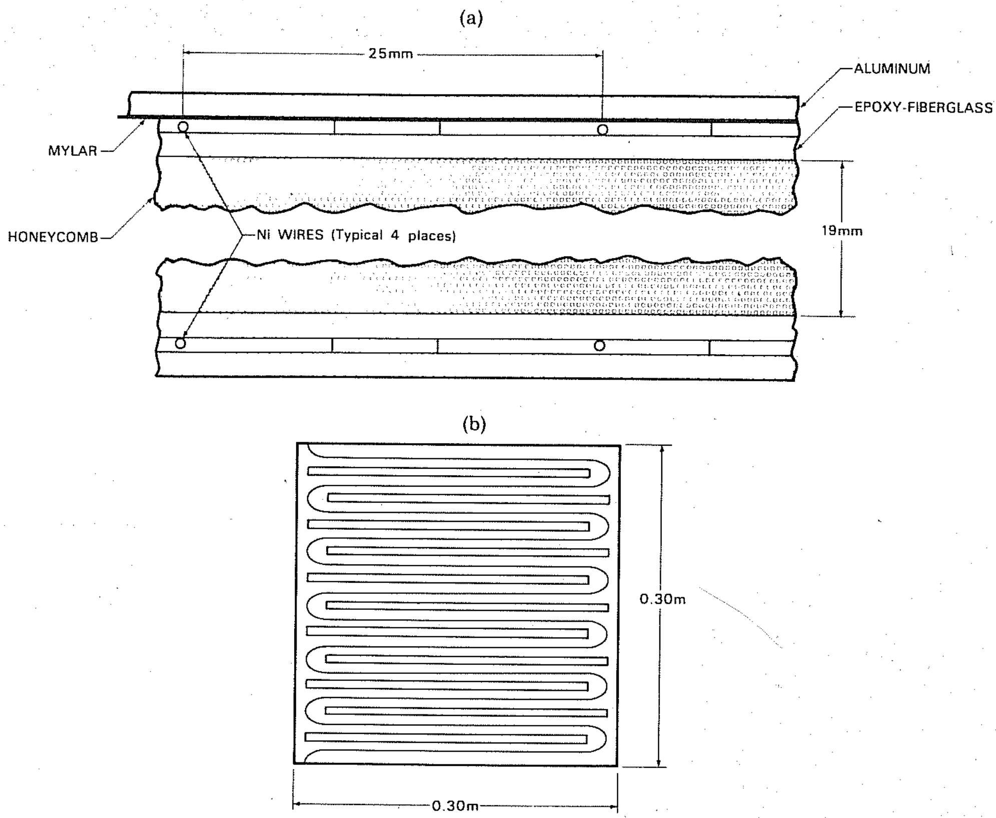

FIG. 2. Heat-flow sensor construction, (a) cross section of a "unit cell" of the heat-flow sensor. (b) Plan view of the sensor wires.

curately measured by driving the bridge with an ac signal and synchronously detecting the output after suitable amplification. We are able to measure electrical resistance changes of 10^{-6} Ω by this method. For the nickel wires that we use in the sensors, which have $\alpha \sim 5 \times 10^{-3}$ K^{-1}, resistance changes of this magnitude correspond to temperature differences across the thermal insulator in the mK range.

Compared with the usual method of measuring the temperature difference with a thermopile, this method has many advantages: economy, convenience of construction, noise immunity, and insensitivity to contact EMFs. We used a synchronous ac rather than a dc method of detecting resistance changes to suppress errors due to $1/f$ noise, thermal contact EMFs, and dc-level drifts in the amplifier.

The value of R_{th} should generally be matched to the application, since too large a value will disturb the heat flow being measured, while too small a value will reduce sensitivity unduly. For our intended application this effect is unimportant. We have, therefore, chosen a rather large value of R_{th} to simplify sensor construction and amplifier design.

II. SENSOR CONSTRUCTION

Construction details of the prototype are shown in Fig. 2. Approximately 0.37 m of alloy #270 0.1-mm-diam Ni wire was laid in a back-and-forth pattern on a sheet of epoxy-fiberglass laminate 0.3 × 0.3 m in size and 1.6 mm thick. The wire was fastened with epoxy. Laminate spacers 0.8 mm thick and 6 mm wide were fastened down between the wire strands. Copper lead wires were soldered to the ends of the Ni wires and secured with epoxy. A sheet of 0.1-mm Mylar insulation followed by a 1.6-mm aluminum plate, both 0.3 × 0.3 m, were then cemented to the spacers. Two identical units of this construction were fastened with contact cement to opposite sides of a 0.3 × 0.3-m × 19-mm piece of phenolic honeycomb having a 6-mm cell size filled with fiberglass batting.

The wire sensors are mounted on epoxy-fiberglass, which has about the same coefficient of thermal expansion as Ni, to avoid thermally induced strains on the wire over the temperature range of interest (0–40 °C). Strains on the wire induce resistance changes because of the sizable strain-gauge coefficient of Ni.[4] This effect was observed in the conceptual prototype tested in Ref. 2, in which the wires (in that case, Cu) were mounted on Plexiglas. Other aspects of the wire mounting were also designed to prevent strains. Honeycomb was chosen as a thermal insulator because it combined high-thermal resistance with strength and dimensional stability.

III. SENSOR PERFORMANCE AND CALIBRATION

The ideal performance of the heat-flow sensor is given by

$$V = \frac{V_0}{4} \alpha R_{\text{th}} J = \beta J, \tag{1}$$

where β is the effective calibration constant of the sensor, J is the heat flux flowing across the sensor, R_{th} is the effective thermal resistance of the honeycomb and the epoxy-fiberglass laminates, α is the resistance temperature

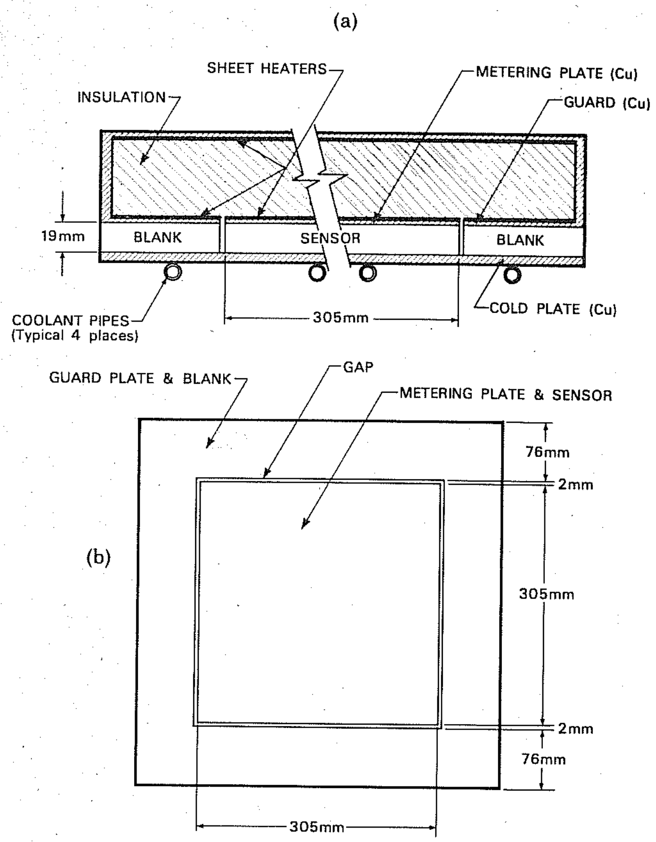

FIG. 3. Guarded hot plate calibration apparatus. (a) Cross section. (b) Plan view.

coefficient of the wire, and V_0 is the product of the amplifier gain, the efficiency of the synchronous detector, and the peak-to-peak voltage of the signal driving the Wheatstone bridge. This equation assumes that the two sides of the heat-flow sensor have equal resistance and that the bridge is balanced at some temperature, T_0, under conditions of no heat flow.

For the prototype, the thermal resistance of the honeycomb is 0.344 ± 0.008 m^2 K/W, the calibration of the bridge, amplifier, and synchronous detector system gave $V_0 = 82.4$ V, and α was measured to be $(5.38 \pm 0.12) \times 10^{-3}$ K^{-1} for the Ni wire. These yield a predicted value of 38.1 ± 1.2 mV (W/m^2)$^{-1}$ for β.

The actual performance of a heat-flow sensor may depart from the ideal because of nonlinearity of the output, dependence of β on the average sensor temperature, or dependence of the bridge balance point on the temperature, T_0, under no-heat-flow conditions. A mathematical analysis of the device shows that β should have a small intrinsic dependence on the mean sensor temperature, T_m, given by

$$\beta(T_m) = \beta\left[1 + \left(\frac{1}{R_{\rm th}}\frac{dR_{\rm th}}{dT} + \frac{1}{\alpha}\frac{d\alpha}{dT} - \alpha\right)(T_m - T_0)\right], \quad (2)$$

from which we estimate a temperature coefficient on the order of 1%/°C. The intrinsic nonlinearity is given by

$$\beta(J) = \beta\left(1 - \frac{1}{4}\frac{\delta R_{\rm el}}{R_{\rm el}}\alpha R_{\rm th} J\right), \quad (3)$$

where $\delta R_{\rm el}$ is the resistance mismatch between the two sensor windings. This implies a negligible nonlinear coefficient of approximately 2×10^{-6} m^2/W. A similar analysis indicates that the intrinsic temperature dependence of the balance point is also negligible. However, either of the latter two effects could arise from imperfections in construction of the sensor or the amplifier.

To measure the value of β, we constructed a guarded hot plate, shown schematically in Fig. 3. The sensor was placed between a copper plate, maintained at a fixed temperature by flowing coolant, and a heated metering plate of the same size as the sensor (0.305 m^2). The metering plate was surrounded by a heated thermal guard which was maintained at the same temperature as the metering plate. A thermal blank of the same construction as the sensor was placed between the guard and the cold plate. A 2-mm gap between the sensor and the thermal blank prevented transverse heat conduction. The amount of electric power necessary to maintain the metering plate at a constant temperature warmer than the cold plate yielded the rate at which heat flows through the sensor, after a small correction had been made for heat leaks to the guard and the surrounding room. A sample of fibrous glass board whose thermal conductivity had been measured at the National Bureau of Standards was used to calibrate the test apparatus.

Figure 4 shows the results of the sensor calibration. The output of the sensor and amplifier is linear with heat flux over two decades and has a β value of (37.6 ± 0.1) mV (W/m^2)$^{-1}$ at a mean sensor temperature of 25 °C. The sensor output has a temperature coefficient of -1.4%/°C. Agreement with the expected performance is excellent.

The minimum heat flux, about 3 W/m^2, measured in this calibration represents the practical lower limit of our calibration apparatus. The accuracy with which the sensor can measure smaller heat flows depends primarily on the accuracy and stability of its zero point. To establish the small-signal accuracy, we needed to verify that three conditions were satisfied: (1) The initial trimming of the Wheatstone bridge to give zero output was done under true conditions of zero heat flow; (2) the zero point did not depend on the average temperature of the sensor (such as could occur, for example, from a small mismatch of the temperature coefficients of the two windings or from differential strains induced by thermal expansion); (3) the zero point did not change with time (for example, due to strains in the sensor wires resulting from handling).

We insured a condition of zero heat flow by placing the heat-flow sensor in a copper cavity submerged in a thermostatically controlled, well-stirred water bath. This bath was then placed in a refrigerator to prevent variations in ambient room temperature from disturbing the measurement. The sensor was trimmed to give zero output at a bath temperature of 22 °C. When the bath temperature was varied between 12° and 30 °C to test the stability of the zero point with temperature, the output voltage was found to vary by less than 0.1 mV/K. A later repeat of this measurement after the sensor calibration showed a zero shift of 3 mV, independent of temperature.

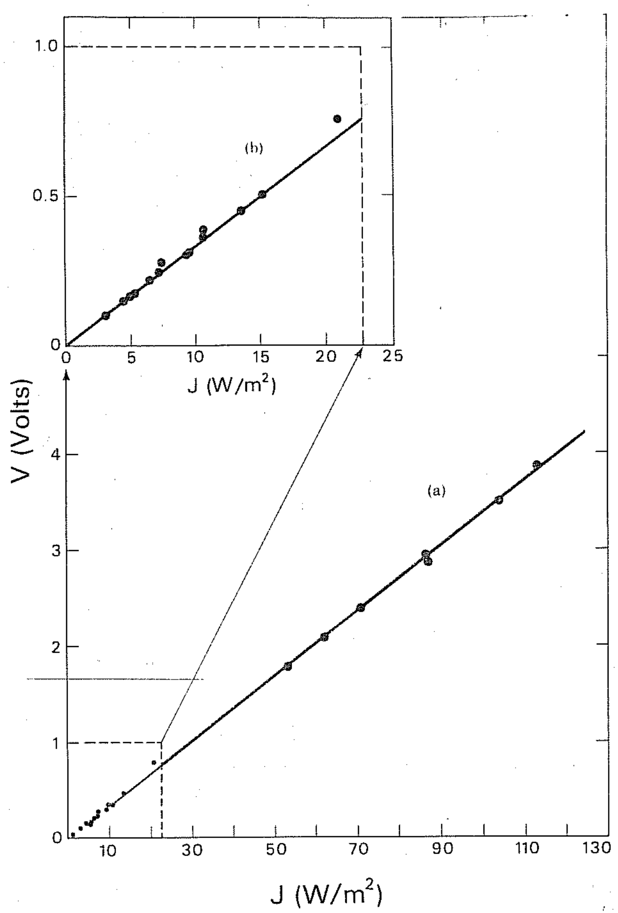

FIG. 4. Calibration of the heat-flow meter. (a) Complete calibration. (b) Expanded view of the small-signal region of the curve. Points are measurements made in the guarded hot plate and corrected to a 25 °C mean sensor temperature. The line is a least-squares fit to the data and has a slope of 37.6 mV $(W/m^2)^{-1}$.

If we take this value as the limiting uncertainty in heat-flow measurement, it would imply an uncertainty of 0.08 W/m^2, which is sufficiently small for our purposes. In fact, the shift was traced to small temperature-induced variations in the reference resistors and amplifier components during the test rather than to changes in the sensor properties. More careful electronic design could, therefore, lead to still greater accuracy.

Self-heating in this prototype amounts to 0.5 mW in each resistance winding and contributes an uncertainty of 0.01 W/m^2 to the heat flux measurement. This is insignificant for the measurements presented here. For our planned full-sized (0.7 m^2) sensor, this uncertainty would become 8×10^{-4} W/m^2 and could be made still smaller by increasing the resistance of the windings.

III. DISCUSSION

We have demonstrated that using a heat-flow meter based on ac resistance thermometry incorporating an economical synchronous detector permits measurement of average heat flows over an area of 0.09 m^2 with a limiting sensitivity of 0.08 W/m^2. It is clear that the same techniques can be used to construct larger heat-flow meters, and that average heat flows over large areas may be measured with comparable sensitivity by piecing together heat-flow meters of a convenient size. Our work has exposed no fundamental difficulty that would impede such a measurement scheme. We expect that the chief practical difficulties will be in protecting the wires in large units from strains and in developing a convenient method of calibration. A lower limiting sensitivity could be attained by improving the design of the amplifier.

ACKNOWLEDGMENTS

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