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Development of a Large Area Heat Flow Meter

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ABSTRACT: A large area heat flow meter (HFM) is required to measure heat flow from whole area of building walls. Therefore, the cost of the HFM must be as low as possible.

Under such background we developed a large area HFM by means of photoetching and electroplating techniques. The new large area HFM can be also used as a small area HFM by cutting it into small units. Further, we developed a new calibration method which enabled us to calibrate HFM, by both absolute and relative methods at the same time with a single apparatus due to capability of cross checking. The difference of the calibrated values by both methods was not greater than ±1%. For practical use of a large area HFM, calibration of several HFMs must be carried out at the same time; we also described the method in this paper.

KEY WORDS: heat flow meter, calibration, insulating materials

Recently, a large number of heat flow meters (HFMs) have been used to measure the thermal transmission properties of insulating materials and thermal behavior of whole building components under *in situ* field conditions. Since a large number commercial HFMs are only available in 10 by 10 cm sizes, they are unsuitable to measure accurately the previously mentioned properties without some modification [*1*].

The measurement of a limited small area does not usually indicate the overall properties of a whole building component, and also the placing of an HFM having a relatively small area on a surface leads naturally to some error due to thermal disturbance. Furthermore, if we attach the meters to the whole area, the cost might be considerably increased.

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As an example, a large area HFM will be required to evaluate the heat losses through the side walls of a guarded hot box. The walls themselves can be constructed using HFMs. A large area HFM which is thermally uniform in the area of 30 by 30 cm^2 is also required for a thermal conductivity measurement according to the HFM method [for example, ASTM Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter (C 518-76)].

Furthermore, if a temperature sensor and a plane heater are also included in an HFM, the total thermal measurement can be carried out more accurately.

Based upon these considerations, we have designed a new large area HFM by utilizing plating and photoetching techniques and then developing a calibration method that is capable of calibrating several HFM simultaneously. This paper describes the design of the HFM, its performance, and the method of calibration.

Structure and Performance

The detectors currently used in HFMs are generally thermopiles. The detector of our new HFMs is also a thermopile. Since most conventional thermopiles are prepared by winding metal wire, deposition, etc., its cost of construction is very high, and the preparation of large area HFMs is almost impossible. This is the main reason why we employed the techniques of both plating and the photoetching.

In applying these techniques, three problems arose; first, the combination of thermocouple materials was limited to pure metals such as plating materials. The combination of copper and nickel was selected. Although this combination has a relatively smaller electro magnetic force (emf) compared to other combinations such as copper and constantan, this disadvantage was overcome by using a large number of thermocouples arranged in a large area. The second problem was how to connect the cold and hot junctions in a series at opposite surfaces.

Fortunately the inner wall of the "through holes" formed in a substrate could be plated. Therefore, it was possible to connect electrically both surfaces of the substrate.

Last, it was necessary to construct the large area HFMs and to cut whole HFMs into the arbitrary sizes depending on particular measuring applications. The construction of the large area HFM is so designed that it can be used not only as a large area HFM but also as a small area HFM without any modification by cutting the former into small units. It is, therefore, possible to put them on a small area of a wall (such as corners) by cutting the large area HFM into small ones when the original one is too large to be installed.

As shown in Fig. 1*a*, a pattern design containing a canal solved this problem. In the example presented in Fig. 1*a*, the unit's pattern is 75 by 75 mm^2,

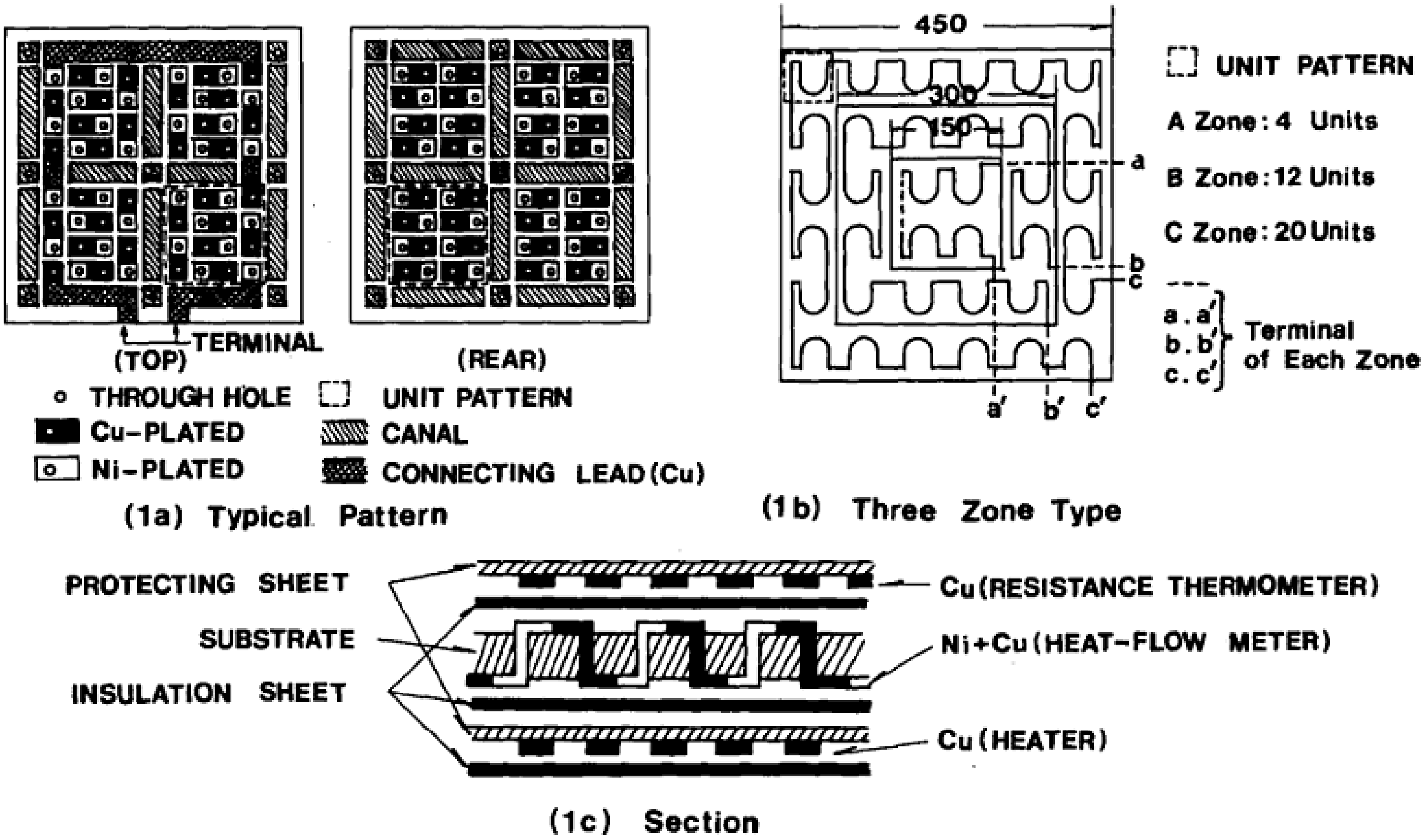

FIG. 1—*Structure of heat flow meter.*

and 16 (4 by 4) a unit pattern forms one 310 by 310 mm^2 HFM. The thermopile in each unit consists of 288 thermocouple junctions. As a result, the whole HFM contains 4608 junctions.

The temperature sensor and heater layer are also developed by utilizing similar techniques as shown in Fig. 1*c*. The three layers including the HFM can be also combined with each other by suitable processing.

An electrical insulation sheet is placed between them. The substrate which serves as a thermal barrier should be also electrically nonconductive, and it also must possess sufficient mechanical strength to serve as a support for the large number of thermopile junctions. For example, glass-fiber reinforced epoxy resin and the like can be used to form a plate having a thickness from about 0.4 mm to several millimetres depending on the required response of the HFM.

The number of junctions can be changed depending on the pattern design; therefore, both high- and low-thermal resistance HFMs are available, each having the same order of response because the response of the HFM is proportional to the number of junctions multiplied by thermal resistance.

A zone-type HFM, as illustrated in Fig. 1*b*, serves as a standard to calibrate other HFMs. Within its structure, the pattern is divided into three zones from center to edge. The output signals from the zones are independent.

Furthermore, when the heater and temperature sensor layer with the same zone type are combined, the operation is like a guarded hot plate. From another point of view, the lateral heat losses can be estimated in the special case of one dimensional heat transfer.

Calibration

The calibration was carried out in two steps: the first step was the establishment of a calibration constant for the standard HFM with three zones; and the second step was to calibrate several HFMs simultaneously. In the first step, two references are utilized during the calibration (it means that cross checking is possible): one is the electric power supplied to the heater layer that is bonded onto the HFM layer, and the other is the standard insulation sample that was cut out from a material whose thermal resistance was determined in accordance with the guarded hot plate method. The former is an absolute method; the latter is a relative one.

The general features of the calibration apparatus are illustrated in Fig. 2. It mainly consists of a hot plate (HP), two heater layers (PH), insulation material (IS), a heat flow meter to be calibrated (HM), a thermocouple sheet (SM), a standard insulation sample (RS), thermocouple sheet (SB), and a cold plate (CP).

A suitable mechanical clamping device (CL) is provided to assure that the various layers are in good contact with each other. A schematic drawing of the

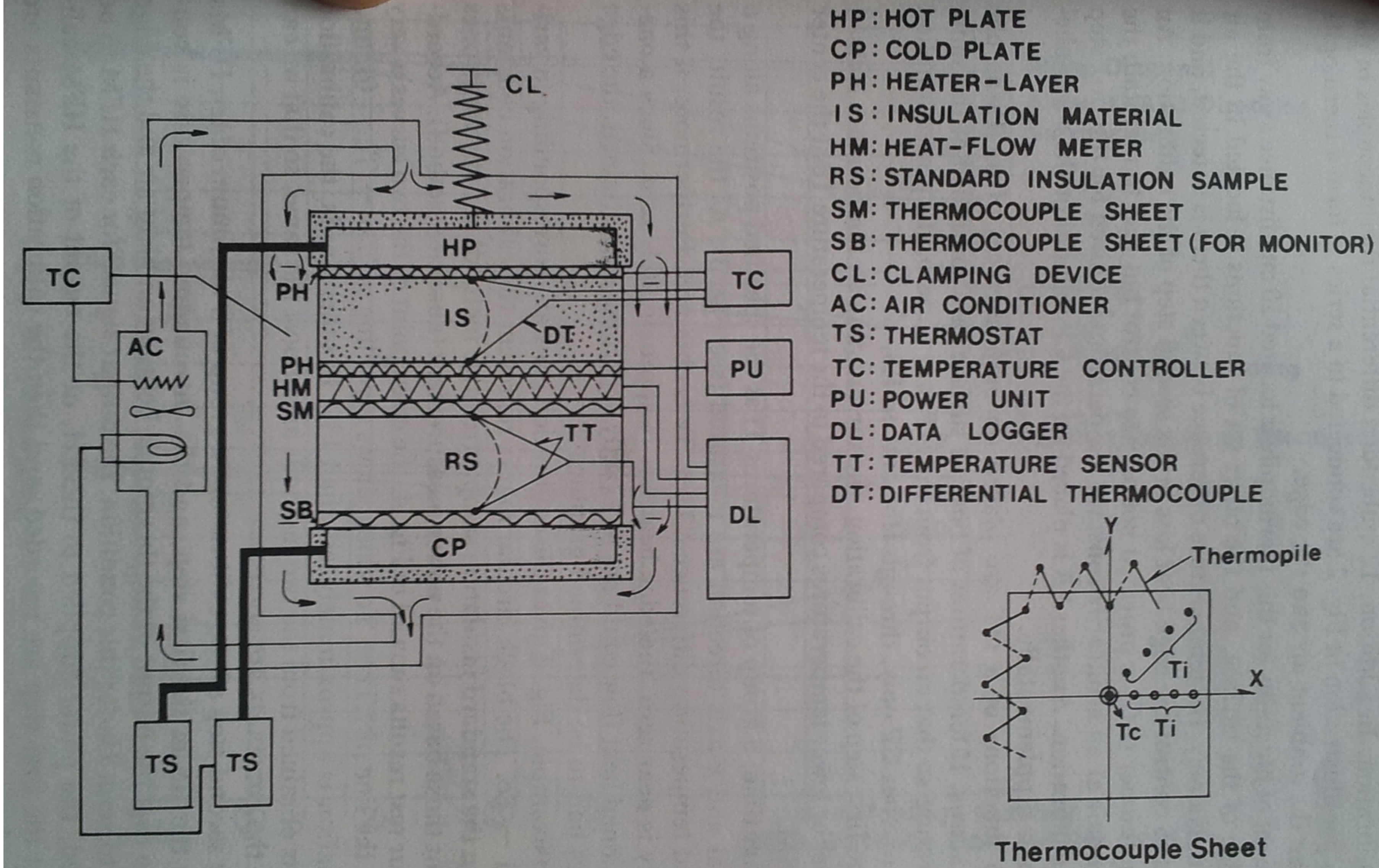

FIG. 2—*Schematic drawing of the calibration apparatus.*

SM is shown at the bottom of Fig. 2. It acts as the most important device on which 10 thermocouples are mounted along a diagonal and x-axis directions to measure the temperature distribution on the surface of the HFM during the calibration. In addition, 12 embedded differential thermocouples in the SM as per illustration in Fig. 2 are connected in a series to form a thermopile between the ambient air and the edge.

One set of junctions for this thermopile is located 10 cm distance away from the edge of the surface, and the other set of junctions is located in the air curtain. Namely, the temperature difference between them is detected, and it is used to control the edge heat loss in the second step of the calibration. An air conditioner (AC) is provided not only to control but also to maintain the ambient air at an arbitrarily constant temperature required for the first step of the calibration. Another SB is placed on the CP to monitor the same phenomenon supplementally.

Two junctions of a DT are placed on both surfaces of an IS as per Fig. 2 shows. If temperatures of both IS surfaces are controlled at the same temperature so that an output from the DT may be zero, the power supplied to PH reaches CP only, through HM and an RS.

In the first step of the calibration, the surrounding air temperature is fixed at higher or lower temperatures compared to the temperature Tc at the center of the SM.

At that time, a group of temperatures Ti at the specified positions along a diagonal and x-axis direction are measured (see Fig. 3). As the result, the summed temperature difference $\Sigma\mathrm{Ti} - \mathrm{Tc}$ is obtained. Furthermore, if this quantity is near zero, the edge heat loss is approximately zero. Since a one-dimensioned heat flow could not be exactly experimentally attained, the edge heat loss had to be determined graphically.

As an example, Fig. 4 gives the calibration constant corresponding to various $\Sigma\mathrm{Ti} - \mathrm{Tc}$. The black circular marks represent the calibration constants based on the standard insulation sample (relative method) and the white ones represent those based on the power measurement (absolute method). According to our test results showed in Fig. 4, the cross point of the two curves is very close to the line of $\Sigma\mathrm{Ti} - \mathrm{Tc}$ which shows zero (line of $\Sigma\mathrm{Ti} - \mathrm{Tc} = 0$), and the deviation is approximately less than 1%. In other words, the calibration constants obtained from the two methods are almost the same, so that we can see that the constants are correct.

In the second step of the calibration, a group of a maximum of ten HFMs replaces the RS in the first step, and the surrounding temperature is controlled so that the output of the thermopile between ambient air and the edge is equal to zero. Under this condition, the output signals for each HFM to be calibrated, the power supplied to the PH, or the output of the HFM calibrated at the first step are recorded, and then the calibration constants are determined.

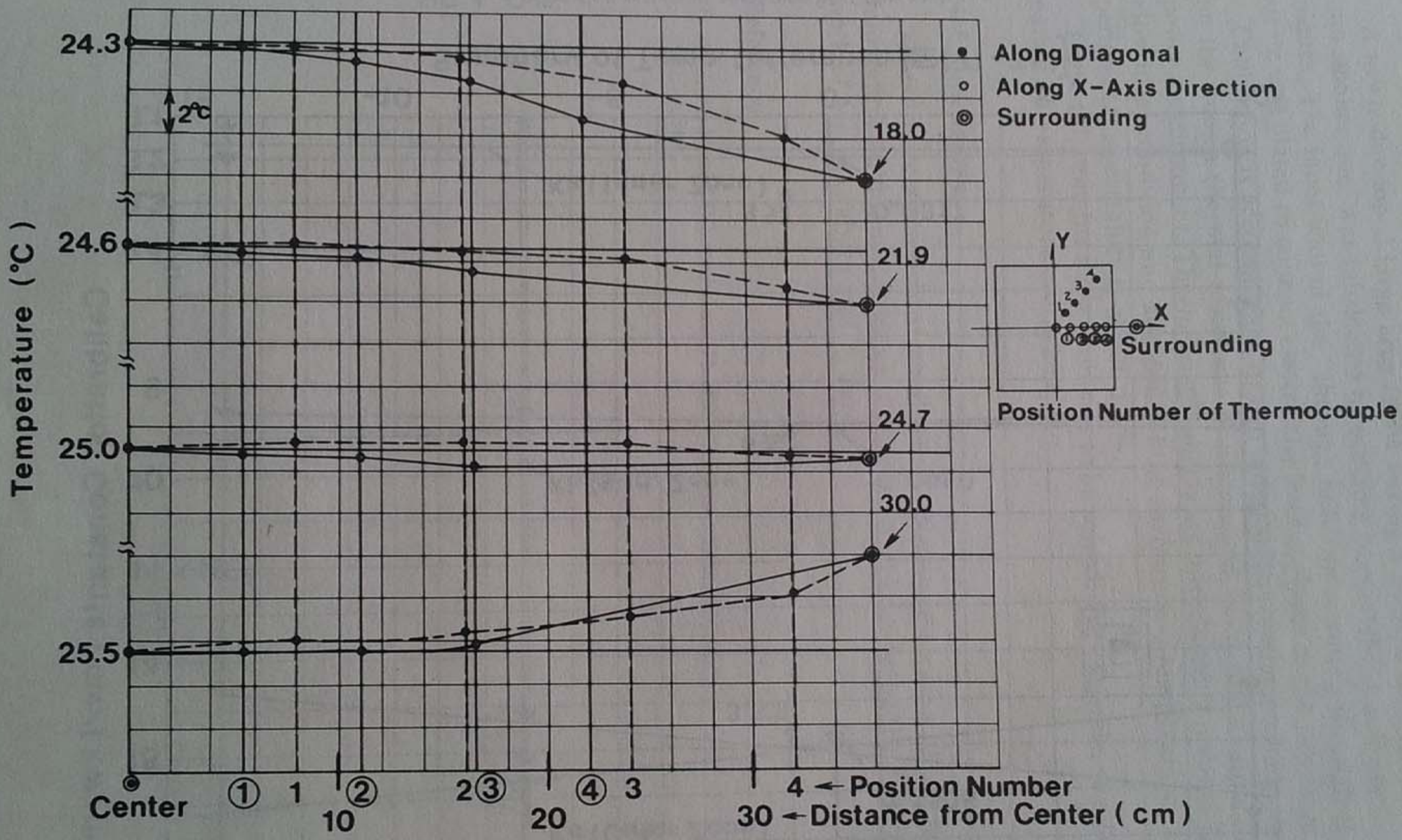

FIG. 3—*Surface temperature distribution.*

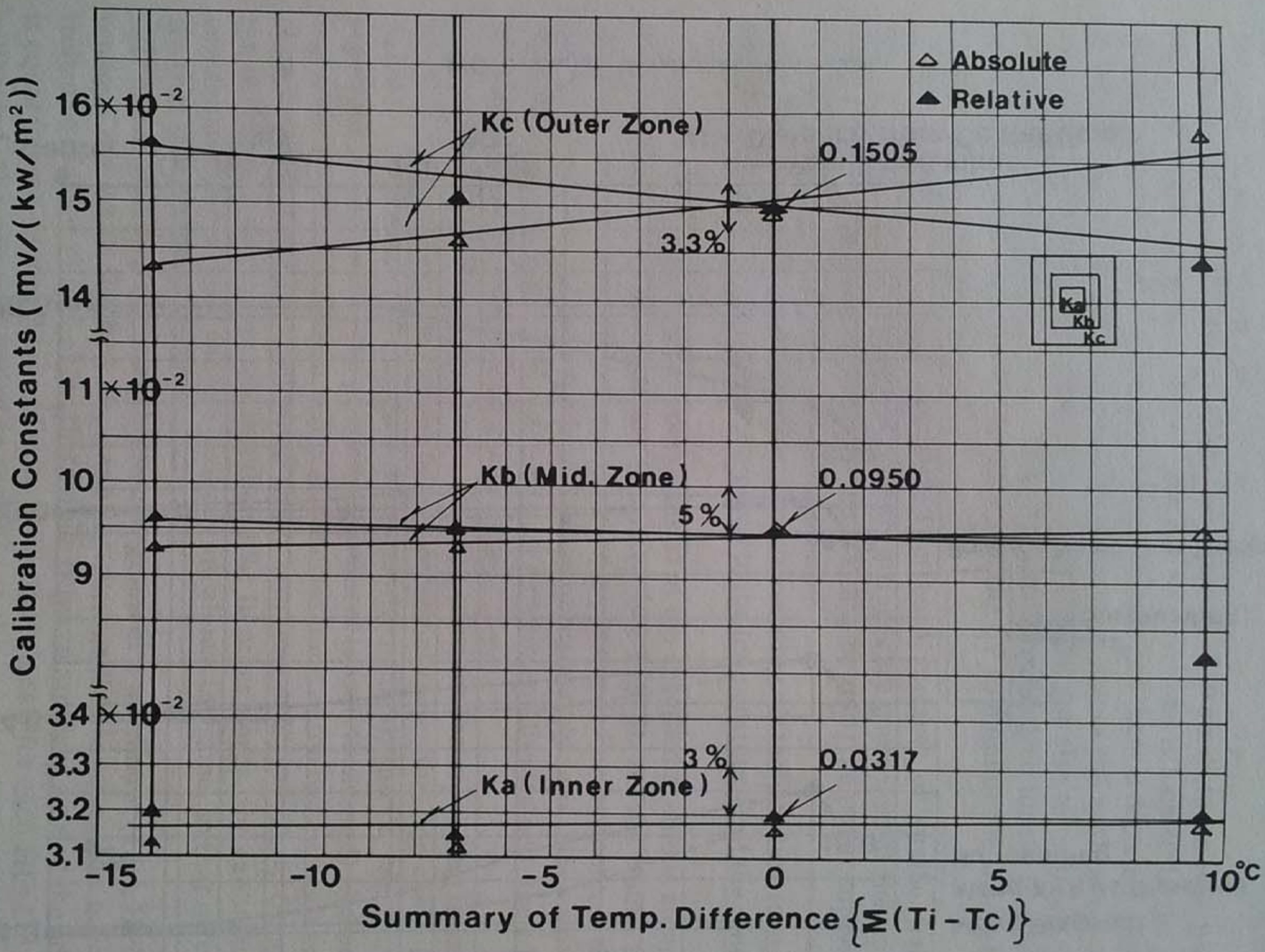

FIG. 4—*Calibration results of zone-type heat flow meter.*

Conclusion

A newly developed large area HFM having a pattern that can be divided into smaller ones was fabricated by utilizing photoetching and plating techniques. The inner wall of the "through hole" penetrating through the substrate was plated to connect electrically both surfaces of the substrate.

Calibration is accomplished by two independent methods which are based on the known thermal resistance of a standard insulating sample and the power measurement. Thermocouple sheets are introduced in order to find the most ideal condition and also control the surrounding temperature. The experimental uncertainty is about $\pm 1\%$.

There still remains a few problems to be solved. For example, the determination of temperature coefficient, etc.

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Reference

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