A CALORIMETER FOR MEASURING HEAT FLOW THROUGH WALLS

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INTRODUCTION

Studies on residential energy use have indicated a need for field measurement of heat loss from houses. One of the prime areas of loss is transmission heat loss through the building envelope. Field measurement of heat loss through the basement walls and floor, the above-grade walls and the ceiling is useful in establishing the energy balance in a house. The field measurement of heat loss from these areas is also useful in comparing in-situ heat loss with heat loss predicted from steady-state thermal properties and field climatic conditions.

The measurement of heat flow in the field requires a calorimeter that does not affect the heat flow it is meant to measure; that is, it must not alter the surface temperature of the specimen. For field measurement the calorimeter should be simple to operate yet reasonably accurate, and it must be portable. The calorimeter must meter a large area to permit determination of a representative heat loss value, because of the inhomogeneous nature of building elements and the temperature variation over their surfaces.

This paper describes the construction, accuracy check and use of a portable calorimeter developed primarily for a study on energy conservation in four experimental houses (1), undertaken by the Division of Building Research, National Research Council of Canada.

FIELD CALORIMETRY

The calorimeter was designed to satisfy the following requirements:

(1) no heat gains to the calorimeter (no cooling provided),
(2) minimum disturbance of heat flow through the metered surface,
(3) capability to meter a large, representative area,
(4) capability to accommodate substantial surface temperature variations,
(5) no air exchange between the calorimeter and the surrounding environment,
(6) moderate accuracy,
(7) portability.

The calorimeter consists of a five-sided insulated box, the open side of which is sealed against the specimen to be measured (Fig. 1). The area of the test specimen covered by the calorimeter is the metered area; the area of the specimen surrounding this is the guard area. The room in which the calorimeter is located is the guard room. The calorimeter contains an electric heater which is controlled so that the temperature inside the calorimeter approximates that in the guard room. Extraneous heat flows to and from the calorimeter are minimized to ensure that the measured energy input to the heater equals the heat flow through the metered area.

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The heat balance for the calorimeter is given by,

$$Q_T = Q_M + Q_C + Q_L \tag{1}$$

where,

Q_T = measured energy input to the heater,

Q_M = heat flow through the metered area,

Q_C = heat flow through the calorimeter walls,

Q_L = lateral heat flow between the metered and guard areas.

Eq. 1 shows that the heater input (Q_T) will equal the heat flow through the metered area (Q_M) if the extraneous heat flows Q_C and Q_L are reduced to zero.

A good approximation of the heat flow through the calorimeter walls (Q_C) is given by,

$$Q_C = \frac{A\Delta T}{R} \tag{2}$$

where,

A = total surface area of the calorimeter walls,

ΔT = average temperature difference across the walls,

R = thermal resistance of the walls.

Because the calorimeter must be large enough to meter a representative area of the test surface, the area (A) cannot be reduced to minimize Q_C. The thermal resistance (R) is limited by space considerations. The major factor in reducing Q_C, therefore, is a reduction of the average temperature difference across the walls (ΔT). This reduction can be achieved by maintaining the temperature on the inside of the walls equal to that on the outside of the walls. A multi-junction thermopile can be used to measure ΔT and provide an input to the heater controller.

Because the guard room affects the temperature on the outside of the calorimeter walls, the dynamic thermal response of the calorimeter must be suited to the anticipated rate of temperature variation in the guard room. The response time of the calorimeter must be sufficiently short to enable the controller and heater to maintain the temperature difference across the calorimeter wall within acceptable limits. In most field tests, the temperature of the guard room will be sufficiently stable to eliminate problems associated with dynamic response.

A good approximation of the lateral heat flow between the metered area (Q_L) and the guard area is given by,

$$Q_L = \frac{d}{wr} \oint^{P} \Delta T(x)\,dx \tag{3}$$

where,

d = effective thickness of the surface material,

w = width of the calorimeter contact with the test surface,

r = resistivity of the metered surface material,

P = perimeter of metered area,

$\Delta T(x)$ = temperature difference between metered area and guard area at x,

x = position on the perimeter of the metered area.

The effective thickness (d) and the resistivity (r) of the surface material cannot be altered in field measurements. The contact width (w) could be increased, but this would cause the temperature at the edge of the metered area to differ significantly from that experienced under normal operating conditions without the calorimeter. The only method available for reducing Q_L, therefore, is to match the surface temperature at the edge of the metered area with that of the adjacent guard area.

It has already been stated that a major consideration in field measurement is that the calorimeter not disturb the surface temperature of the element being measured. This must be checked in the field and corrected if necessary. For example, if it is found that the test wall surface below the calorimeter is cooler than normal because of a stagnant air pocket, a small fan may be required to restore the temperature to normal.

Once it has been established that the surface temperature of the specimen has not been altered by the calorimeter, the surface temperature difference between the edge of the metered area and the adjacent guard area should be checked under test conditions and modified, if necessary. The surface temperature difference can be minimized by altering the radiative and convective heat transfer coefficients of the outside and inside surfaces of the calorimeter walls. The use of a low emissivity surface on the outside of the calorimeter will decrease the radiation exchange between the calorimeter and the surrounding guard room, and should bring the calorimeter surface temperature closer to the air temperature of the guard room. Within the calorimeter itself, the relationship between the surface temperature of the calorimeter wall and the surface temperature of the metered area can be altered by judicious selection of calorimeter wall surface emissivity, convective baffling arrangement, internal dimensions of the calorimeter, and by the design and location of the heater element.

The foregoing discussion considered ways of ensuring accurate measurement of heat flow through a portion of a building enclosure element, without the calorimeter itself affecting the measured heat flow. A consideration of equal importance in field calorimetry is that the measurement be made over a representative portion of the enclosure element. For example, consider a wood-frame wall containing an air space subject to convective heat exchange, measured with a calorimeter half as high as the wall. Because the heat flow paths through the wall will be distorted by the convective air space, the heat flow measured over the top, bottom or middle portion of the wall will be quite different. Care must be taken, therefore, in estimating the heat flow through the entire wall from the heat flux density measured by field calorimetry.

DBR/NRCC CALORIMETER

Several field calorimeters with a metering area of 1.2 m x 2.1 m were fabricated. The walls were constructed of two layers of 72 kg/m^3 foil-backed glass-fiber insulation board (0.6 m x 1.2 m x 50 mm thick) glued together. The combined thermal resistance of this assembly was 2.8 m$^2 \cdot$ K/W. The two layers of insulation were glued together with the foil backing exposed as facings for the walls. All joints were staggered and taped so that a continuous vapour-proof membrane was provided over the entire surface of the calorimeter. A 6 mm plywood frame was attached to the sides of the calorimeter to provide stiffness. Fig. 2 shows details of the finished calorimeter.

A 150 W electrical heating cable was fastened to wire supports which were attached to the plywood frame. When the calorimeter was used on a vertical surface, the heater cable spacing was adjusted to provide more heat near the bottom of the calorimeter and thereby counteract the temperature gradient resulting from convection within the unit. This gradient, unmodified, would have been much greater than the normal gradient occurring in a room because of the confined space and absence of forced-air movement inside the calorimeter.

An eighteen-junction thermopile measured the temperature difference across the back wall of the calorimeter. It was not considered necessary to place junctions on the sides since the area of the sides is a small percentage of the total surface area of the calorimeter. The thermopile output was used to control the heater to maintain the temperature difference near zero. A thermostat was connected in series with the heater to act as a high-temperature or safety cut-out. The energy input to the heater was measured with a standard household kilowatt-hour meter. The wiring schematic is shown in Fig. 3.

The accuracy of the calorimeter was checked in the guarded hot box facility of the Thermal Properties Laboratory (DBR/NRCC). For the purpose of the accuracy check, a test wall with dimensions 2.4 m x 2.4 m was constructed. It consisted of a 75 mm layer of polystyrene as the core with a 6 mm layer of plywood on one face and a 12 mm layer of gypsum board on the other face. The thermal resistance of this test wall was measured with a warm-side air temperature of 20.5°C and a cold-side air temperature of 4.2°C. The thermal resistance value of the wall was 2.70 m$^2 \cdot$ K/W.

The field calorimeter was installed against the test wall in place of the laboratory calorimeter with the temperature conditions on both sides of the test wall maintained identical to those prevailing during the thermal resistance test. The energy accumulated during a 21-hour test period as measured by the field calorimeter was 286 W·h. The accumulated energy during the same period as estimated using the wall resistance value and the measured surface temperature difference was 299 W·h. The difference was less that 5%.

Fig. 4 shows the temperature variation over the warm-side face of the test wall during the test. It was concluded from these temperature measurements that an adequate matching of surface conditions had been achieved between the metered and guard areas.

An example of the use of the calorimeters in the field is the measurement of heat loss below grade in one of the houses in the DBR/NRCC energy study (1). Three calorimeters were located in the basement as shown in Fig. 5. Calorimeters 1 and 2 were located against the north and west walls respectively. The walls were insulated with foam plastic insulation (resistance 1.3 $m^2 \cdot K/W$) applied against the outer face of the walls and over the full wall height. Calorimeter 3 was located on the floor of the same basement.

Variable radiation sources such as the sun and interior lighting affected the control stability of the calorimeters. Plywood radiation shields were located around the boxes to reduce this effect. The results of the heat loss measurements for the period between January 1979 and May 1979 are given in Fig. 6.

The heat flow through a section of an above-grade exterior wall was measured with another calorimeter to demonstrate that the calorimeter could properly measure the thermal behavior of such a wall. This calorimeter was located in the same house as the basement calorimeters. Calorimeter readings of wall heat flow integrated and averaged over time periods of 0.5, 1 and 2 hours are shown in Fig. 7 as running average heat flow rates. The large fluctuation in the 0.5-hour heat flow rates is due to the inability of the calorimeter, with its 150 W heater and its on-off controller, to follow closely the relatively small heat flow through the wall. The 2-hour running average heat flow rate eliminates the fluctuations due to the calorimeter controls and, as shown in Fig. 8, provides a reasonable representation of the wall heat flow when the indoor-outdoor air temperature difference does not change rapidly.

CONCLUSION

The calorimeters built for the DBR/NRCC energy study have proven successful in the application for which they were designed. It was determined that rapid and large fluctuations of room temperature must be avoided or eliminated to minimize measurement errors. When the room temperature is reasonably constant, as would be the case in a typical thermostatically-controlled room, the error in measurement of heat loss should be less that 5%. Although some care must be exercised in selecting appropriate test sections and care must be taken to shield the calorimeter from radiation sources and heating ducts, this calorimeter appears to be a reasonable tool for studying heat loss through sections of real buildings.

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REFERENCE

1. Quirouette, R.L., "The Mark XI Energy Research Project - Design and Construction," National Research Council of Canada, Division of Building Research, Building Research Note 131, October 1978.

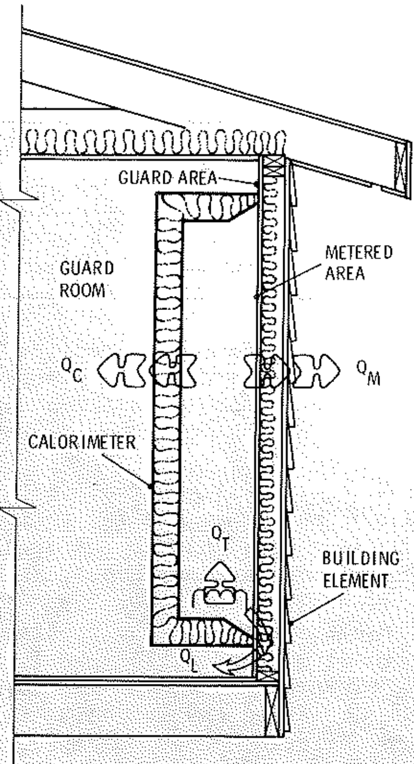

Fig. 1 Schematic of field calorimeter

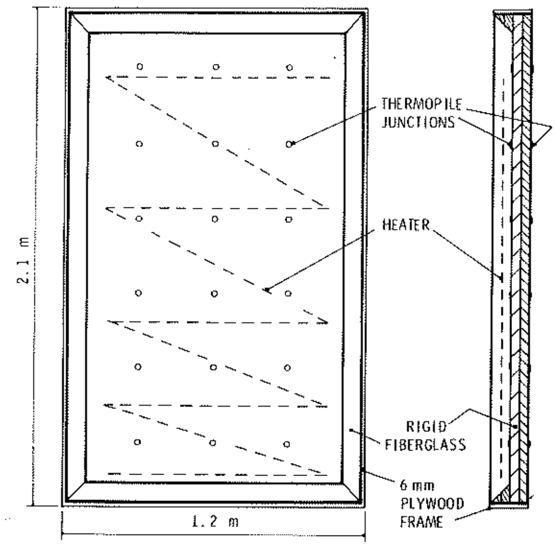

Fig. 2 DBR/NRCC field calorimeter

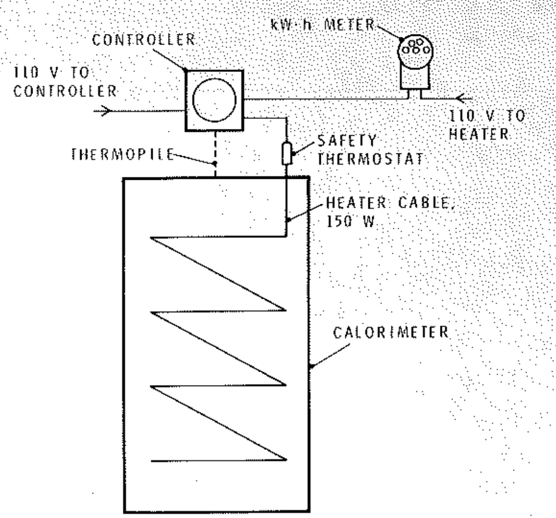

Fig. 3 Wiring schematic for DBR/NRCC field calorimeter

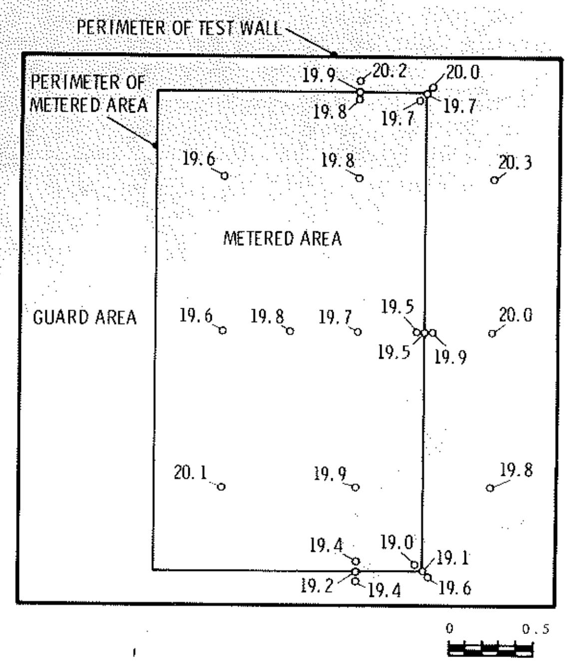

Fig. 4 Temperatures measured on the warm-side surface of the test wall

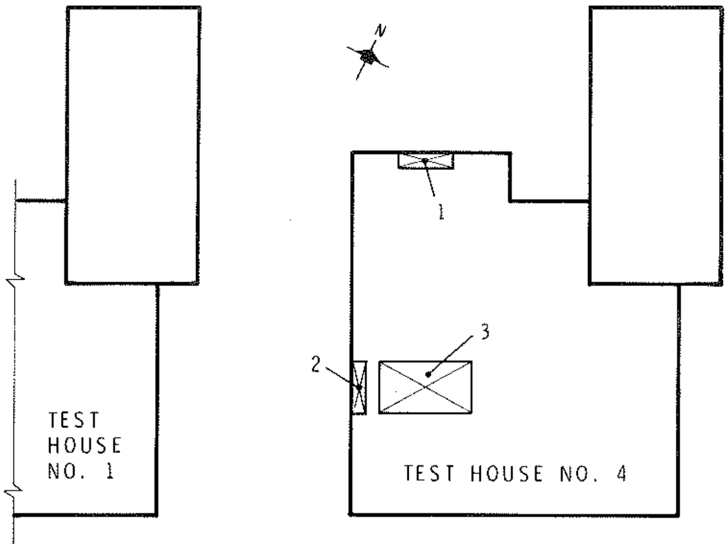

Fig. 5 Location of field calorimeters in basement of test house

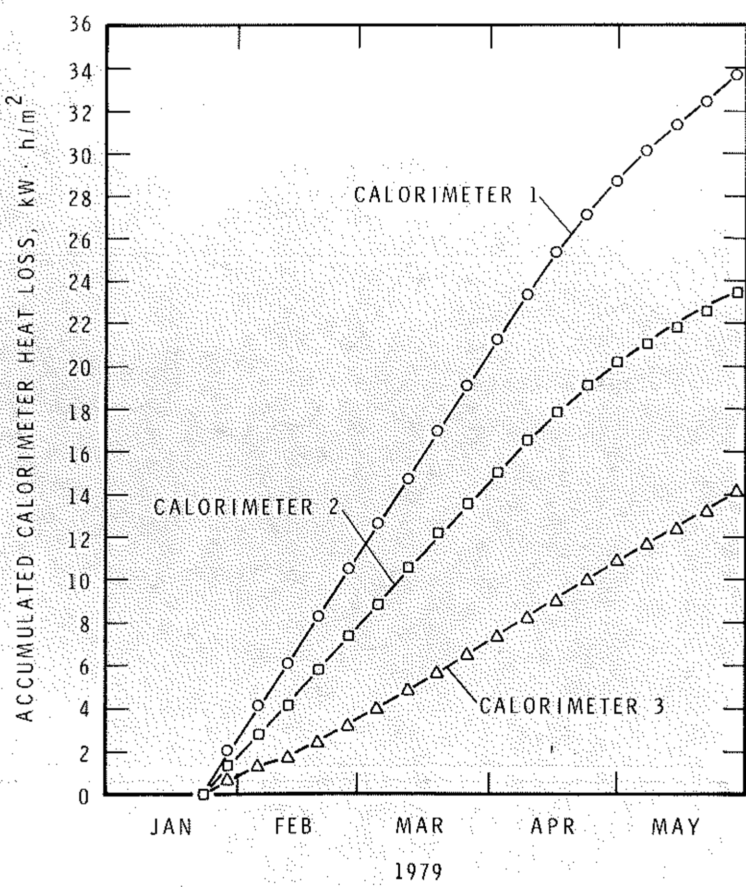

Fig. 6 Heat loss measured by field calorimeters

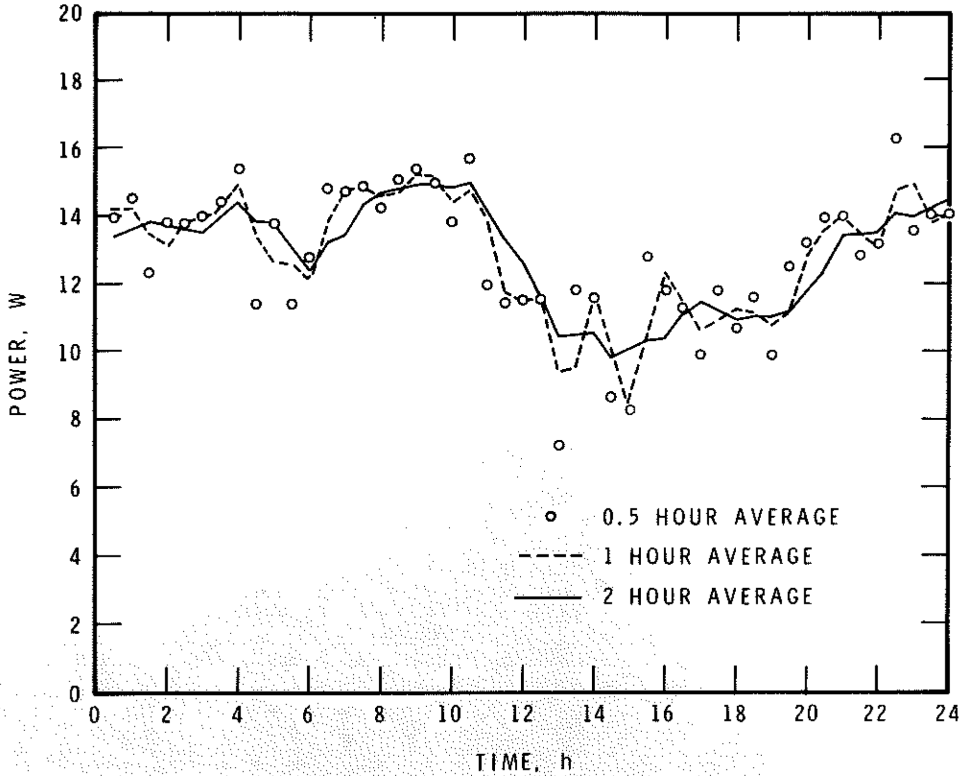

Fig. 7 Comparison of average calorimeter readings for different time periods

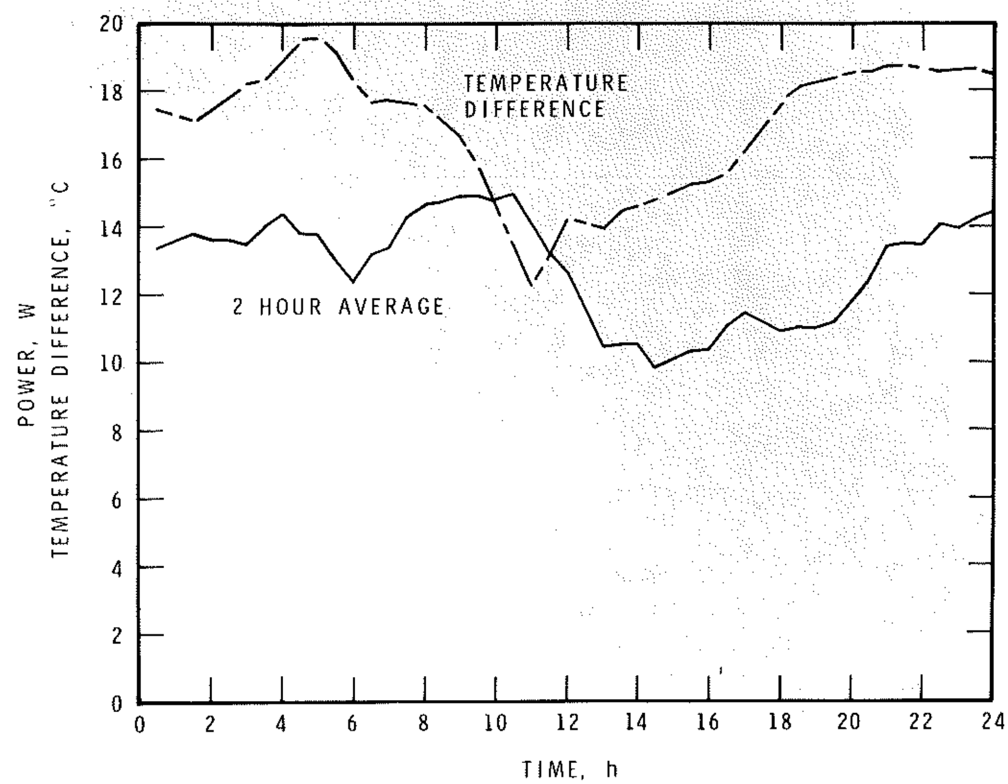

Fig. 8 Comparison of 2-hr average and temperature difference