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A METHOD FOR DETERMINING THE THERMAL RESISTANCES OF EXPERIMENTAL FLAT ROOF SYSTEMS USING HEAT FLOW METERS

by C.P. Hedlin, H.W. Orr and S.S. Tao

09776

Reprinted from
Thermal Insulation Performance
American Society for Testing and Materials
Special Technical Publication 718, 1980
p. 307 - 321

ANALYZED

DBR Paper No. 967
Division of Building Research

Price \$1.25

OTTAWA

NRCC 19274

SOMMAIRE

Les auteurs étudient in situ des systèmes de toits plats. Ils mesurent les vitesses d'écoulement thermique et les températures avec des fluxmètres thermiques et des thermocouples, enregistrant les données sur bandes magnétiques à intervalles fixes. Ils font la moyenne des résultats pour des périodes de 24 heures.

Les auteurs déterminent la résistance thermique des systèmes et des composants à l'aide des vitesses d'écoulement thermique nettes moyennes et des différences de température. Ils utilisent deux méthodes analytiques. La première, dans laquelle on calcule le rapport entre l'écoulement thermique et les différences de température, n'est pas fiable pour les vitesses d'écoulement thermique faibles à cause d'une erreur systématique dans les résultats. La deuxième fait appel à la courbe d'écoulement thermique en fonction de la différence de température.

Les auteurs comparent la résistance thermique de plusieurs éléments d'isolation, trouvée grâce à cette méthode, avec les résultats obtenus en laboratoire. Les différences varient entre 0.5 et 5% environ.

C. P. Hedlin,¹ H. W. Orr,¹ and S. S. Tao¹

A Method for Determining the Thermal Resistances of Experimental Flat Roof Systems Using Heat Flow Meters

REFERENCE: Hedlin, C. P., Orr, H. W., and Tao, S. S., "A Method for Determining the Thermal Resistances of Experimental Flat Roof Systems Using Heat Flow Meters," *Thermal Insulation Performance, ASTM STP 718*, D. L. McElroy and R. P. Tye, Eds., American Society for Testing and Materials, 1980, pp. 307-321.

ABSTRACT: Experimental flat roof systems were studied at an outdoor test facility. Heat flow rates and temperatures were measured with heat flow meters and thermocouples, and the values were recorded on magnetic tape at fixed intervals. The results were averaged over 24-h periods. Thermal resistances of systems and individual components were found using average net heat flow rates and temperature differences. Two analytical methods were used. In the first, the ratio of heat flow to temperature difference was calculated. This method was unreliable at low heat rates due to a bias in the results. In the second method, the slope of heat flow versus temperature difference was used as the basis for calculation. Thermal resistances of several pieces of insulation found by this method were compared with results obtained using laboratory equipment. The differences ranged from about 0.5 to 5 percent.

KEY WORDS: heat flow meters, thermal insulation, thermal resistance, flat roofs, buildings

As part of a study of flat roofs being carried out at Saskatoon, Saskatchewan, thermal resistances of roofing systems and their components are being determined *in situ* by measuring heat flow rates and temperature differences. This permits the thermal performance of the specimens to be studied while they are in a working environment. Experimental panels were constructed and mounted in the roof of a research building at the Prairie

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Regional Station, Division of Building Research, National Research Council of Canada (DBR/NRCC). The interior of the panel faces a room maintained at about 21°C; the exterior surface is exposed to the elements. Thus the heat flow rate varies almost continuously in response to weather changes.

This report describes the equipment used for the measurements, and the analytical procedure employed to compute thermal conductance. It also includes example test results and a discussion of errors in the method.

Heat flow meters have been used extensively to measure heat flow through building components in order to evaluate thermal performance [1-6].² Details of the measurement techniques and the possible sources and magnitudes of errors encountered, however, are not always described.

Equipment

Temperature Measurement

Temperatures were measured using 26-gage copper-constantan thermocouples. The reference junctions were sealed with epoxy and taped to an aluminum block that was thermally insulated from the surroundings. A single thermopile was used to measure the difference in temperature between the aluminum block and an automatic ice point. In this way, all the thermocouples were referenced to ice point temperature without having to contend with the serious stem conduction problem that would exist if all were placed directly in the ice (Fig. 1).

Thermocouples were checked against a platinum wire resistance thermometer calibrated at the Division of Applied Physics, National Research Council of Canada, Ottawa, and were found to be accurate within approximately 0.05 deg. C. As a further check on the reliability of the temperature measuring system, thermocouples were embedded together in insulation so that they would be at the same temperature. Their outputs were recorded and averaged for up to 24 h. The maximum difference was 0.03 deg. C.

Heat Flow Meters

Heat flow measurements were made with commercially available heat flow meters, 50 or 106 mm in diameter [7]. These consisted of a thermopile embedded in polyvinyl chloride which produced a voltage signal that was proportional to the rate of heat flow through the disk. The calibration values, used to calculate the heat flow rate, were about 15 and 3 W/m²mV for the smaller and larger meters, respectively. The electrical resistance was about 130 Ω for the smaller and 1100 Ω for the larger meters.

The manufacturer provided calibration values. In addition, the meters

²The italic numbers in brackets refer to the list of references appended to this paper.

FIG. 1—Wiring diagram for temperature and heat flow measurement and detailed view of intermediate temperature reference.

were recalibrated periodically by the Energy and Services Section of DBR/NRCC in Ottawa.

Mounting arrangements for heat flow meters were designed so that they could be moved easily from one site to another. Two methods were used:

1. A piece of bakelite, 150 by 150 by 6 mm, was machined to receive the meter and the combination was secured to the test surface so that the heat flow meter was in contact with it. The thermal resistance of the bakelite was nearly the same as that of the heat flow meter, thus minimizing the edge effect on the heat flow pattern. The bakelite holder may also be surrounded by a 6-mm-thick plywood mask (Fig. 2a) to reduce heat flow distortion.

2. The test specimen and heat flow meter were held between a pair of aluminum plates, 456 mm square and 6.34 mm thick. Here, also, the heat flow meter was mounted in a bakelite holder with a plywood mask (Fig. 2b).

Data Recording and Processing

The voltage outputs from the thermocouples and heat flow meters were recorded on 7-track magnetic tapes by a digital data acquisition system having a resolution of $1\mu\text{V}$ and a long-term accuracy of $2.5\mu\text{V}$. At predetermined intervals, this system scanned and recorded transducer outputs at a rate of about seven channels per second. The voltage of an internal reference cell and the zero of the system were also recorded, and adjustments were subsequently made to each of the readings to correct for any error in the voltmeter. The tape was processed at the Saskatchewan Computer Utility Corp. facility. The data were first converted into the appropriate quantities, for example, heat flow rate or temperature, and were placed on a 9-track magnetic tape that was kept for permanent storage and from which data could be withdrawn for analysis [8].

FIG. 2—Two arrangements for heat flow measurements: (a) meter is secured to the lower side of a roof panel; test of insulation and heat flowmeter mounted between aluminum plates.

Initially, analyses were based on 5-min scans; this was later changed to one every 20 min. There is evidence that this frequency could be further reduced without substantial effect on the precision of the method.

Calculation of Thermal Conductance

Fluctuations in outdoor temperature and solar radiation produce continual change in the temperature difference across the wall or roof of a structure. Because of the thermal mass of a building, the heat flow cycle lags behind that of the temperature (Fig. 3). Nominally the cycle is repeated, with temperature and heat flow returning to the values that existed 24-h before.

It has been demonstrated mathematically that thermal resistance for repetitive heat flow cycles could be computed using the ratio of the mean temperature difference $\Delta\theta$ to mean heat flow rate ΔQ for the cycle period. The authors considered the heat flow to be made up of periodic and steady-state components and showed that the first of these disappears in the analysis, leaving only the steady-state component [9]. On the same basis the thermal conductance would be

$$C_r = Q/\Delta\theta \quad (1)$$

Theoretically at least, the conductance as given in Eq 1 is in accord with thermal conductance as defined in the ASTM Test for Steady-State Thermal Transmission Properties by Means of Heat Flow Meter (C 518-76).

Daily heat flow cycles in buildings are not exactly repeated. Nevertheless, this pseudo steady-state relationship provides a basis for calculating conductance, which approximately nullifies the lag and storage effects.

FIG. 3—Plot of heat flow and temperature difference across a foam plastic insulation 51-mm-thick with a density of 32 kg/m^3 from midnight to midnight for an August day.

The net rate of heat flow, $Q(\text{W/m}^2)$, is found by taking the difference between the outgoing and incoming heat average over the 24-h period from midnight to midnight (or for multiples of this 24-h period). $\Delta\theta(^{\circ}\text{C})$ is the daily average temperature difference across the component under study [8]. Outward heat flow is arbitrarily designated as positive, and inward as negative flow. The conductance can be found using Eq 1.

The same values can be used in a second way to calculate thermal conductance. If the heat flow rate is found as a continuous function of temperature difference

$$Q = f(\Delta\theta) \quad (2)$$

a thermal conductance can be found by taking the slope of the relationship

$$C_s = \frac{dQ}{d(\Delta\theta)} \quad (3)$$

It should be noted that the conductances given by Eqs 1 and 3 are not the same. They are referred to here as "ratio" and "slope" values, respectively, to differentiate between them. An empirical relationship between them is given in the next section.

Results and Discussion

Heat Flow Measurements

In the study, measurements were made continuously for more than a year on a rigid glass fiber specimen (145 kg/m³, 49.5 mm thick, 0.41 m square) mounted between aluminum plates (Fig. 2b) and on a specimen of extruded polystyrene (32 kg/m³, 51 mm thick, 0.61 m square) mounted as in Fig. 2a. Least-squares analysis was used to find the relationship between heat flow and temperature difference. First- and second-order fits were made using values each representing approximately a two-week average.

Using the form

$$Q = a + b\Delta\theta + c(\Delta\theta)^2 \quad (4)$$

equations for glass fiber and extruded polystyrene were

$$Q_{gf} = -0.186 + 0.774\Delta\theta - 0.00223(\Delta\theta)^2 \quad (5)$$

$$Q_{ep} = 0.0006 + 0.561\Delta\theta - 0.000760(\Delta\theta)^2 \quad (6)$$

The indices of determination were 0.9999 and 0.9995, respectively. The standard errors of estimate were 0.055 and 0.126 W/m². It should be noted that the constants a and c in these equations are very sensitive to the data and may change by 20 or 30 percent (or more) with rather small changes in the input values.

The mean temperature of the insulation θ_m can be represented approximately as a function of the temperature difference $\Delta\theta$. For example, for these glass fiber data

$$\theta_m = 24.2 - 0.753\Delta\theta$$

Equation 6 passes near to the origin, but Eq 5 does not, the ordinate intercept being a negative value. In 15 other observations of this type, in nominally dry materials, the intercepts ranged from 0.20 to -0.45 W/m². The corresponding abscissa intercepts ranged from -0.30 to 1.21°C.

Errors in measurement can contribute to a finite intercept. Outputs from heat flow meters at zero heat flow and errors in temperature measurement which would indicate a temperature difference across the subject material even though none existed could cause it. The zero heat flow output for the

meter used to measure data given in Eq 3 was $+0.01 \text{ W/m}^2$.³ This is consistent with Eq 6 intercept. Zero heat flow output for the meter used with the glass fiber was -0.03 W/m^2 , however, and (even allowing for some uncertainty in the intercept value) appears to account only partially for the -0.186 W/m^2 intercept.⁴ Further, the glass fiber curve cuts the abscissa at 0.24°C , a value that is too large to be accounted for by temperature measurement error.

Tests have been made on a variety of wet thermal insulations using this equipment. When heat flow is plotted against temperature difference, ordinate intercepts of -1 W/m^2 or lower have been observed. Possibly moisture, even in nominally dry insulations, may contribute to this effect. Further, other unidentified cyclic heat flow effects or shortcomings in the analytical procedure may contribute to the finite intercept.

For large heat flow rates, the effect of the intercept quantity is small but increases as the heat flow rate decreases. For the glass fiber specimen, with an intercept of -0.186 W/m^2 , the error (real or apparent) in conductance, computed using Eq 1, would be 1 percent for $Q = 19 \text{ W/m}^2$, 10 percent for $Q = 1.9 \text{ W/m}^2$, and infinite when $Q = 0$ (Fig. 4).

Comparison of Ratio and Slope Methods

Thermal conductance can be calculated using either the ratio or the slope method. First, using the ratio method given by Eq 1

$$C_r = Q/\Delta\theta$$

If heat flow rate is expressed by a second-order relationship

$$C_r = \frac{Q}{\Delta\theta} = \frac{a}{\Delta\theta} + b + c\Delta\theta \quad (7)$$

Further, if the intercept value a is zero, or if subtracted from Q , a modified value (C_r') is obtained

$$C_r' = b + c\Delta\theta \quad (8)$$

In the second method, if a continuous Q versus $\Delta\theta$ relationship is known, conductance can be calculated from its slope

³The meters were always mounted with the same surface against the test panel. The sign corresponds to the convention used to designate heat flow direction; that is, when there was no heat flow, this meter would indicate an outward heat flow rate 0.01 W/m^2 .

⁴The voltage output of the meter at zero heat flow was found by embedding it in thick layers of thermal insulation and measuring its output periodically for several days. Care was taken to avoid preferential warming of one side of the assembly by radiation or convective air flow.

FIG. 4—Thermal conductance C_r —the ratio of heat flow rate and temperature difference—illustrates the systematic error that may occur at temperature differences near to zero. Based on a set of results with rigid glass fiber.

$$C_s = \frac{dQ}{d(\Delta\theta)} = b + 2c\Delta\theta \quad (9)$$

Usually the Q versus $\Delta\theta$ relationship is not known and the slope must be estimated from a few points as described later. Based on Eqs 8 and 9,

$$C_r' = C_s - c\Delta\theta \quad (10)$$

Fig. 5 is based on the glass fiber data represented by Eq 5. The curve in Fig. 4 is reproduced and the upper set of data points (open squares) was produced by adding 0.186 W/m^2 (the intercept value from Eq 5 to each measured heat flow value before calculating thermal conductances. Finally, the solid line was given by $0.774 - 0.00223\Delta\theta \text{ W/m}^2\cdot^\circ\text{C}$. A comparison of this line and the adjusted data points provides an illustration of the equivalence proposed in Eq 10.

The best-fit first-order relationship for all $|\Delta\theta| > 1^\circ\text{C}$ for the adjusted values is

$$C = 0.780 - 0.00250\Delta\theta$$

and for $|\Delta\theta| > 4^\circ\text{C}$ is

$$C = 0.772 - 0.00220\Delta\theta$$

These relationships, neither of which is shown in Fig. 5, differ from the slope-based conductance by less than 1 percent for $\Delta\theta$ in the range 0 to 30°C .

The intercept effect cannot be demonstrated so clearly in all cases. In some the intercept value is small; in others scatter of results masks the effect.

Precision of the Ratio Method

The precision of the ratio method, excluding the intercept effect, was estimated by comparing measured heat flow rates, Q_m , averaged over one, two, and three-day periods, against heat flow rates, Q_c , calculated using Eqs 5 and 6 for the same values of $\Delta\theta$.

Percentage deviations are given by

$$D = \left(\frac{Q_c - Q_m}{Q_c} \right) 100 \quad (11)$$

FIG. 5—Graph based on glass fiber results contains three sets of data: thermal conductance based on original values (dotted line), thermal conductance found by adding 0.186 W/m^2 to each heat flow value (open squares), and thermal conductance based on Eq 10 (solid line).

These were plotted without regard to sign against the corresponding values of $\Delta\theta$ in Fig. 6a, b, and c.

Values for $\Delta\theta$ less than 1°C are often unreliable. If the daily heat flow averages oscillate between positive and negative, their sum may be very small and, even after a week or more of measurements, the deviation may be large. For $\Delta\theta$ greater than 5°C , the deviations were less than 5 percent in nearly all cases. For $\Delta\theta$ greater than 10°C , the deviations appeared to be nearly independent of $\Delta\theta$. Standard deviations for greater than 10°C were 1.41, 1.04, and 0.94 percent for one, two, and three-day averages, respectively.⁵

Precision of the Slope Method

Thermal resistance calculations based on the ratio method can be unreliable at low values of $\Delta\theta$ and the slope method may be a suitable alternative in that region. Generally, the slope method is less precise than the ratio method, but is not affected by low values of $\Delta\theta$.

Estimation of conductance by slope requires at least two Q versus $\Delta\theta$ points

$$\begin{aligned}\Delta\theta_1 - \Delta\theta_2 &= \Delta(\Delta\theta) \\ C_s^1 &= \Delta Q / \Delta(\Delta\theta)\end{aligned}\quad (12)$$

The data used to find Eqs 5 and 6 were used also to estimate the precision of conductances based on slopes found using two, three, four, six, and twelve-day periods. Deviations are defined here as the fractional or percentage differences between these values and the slopes predicted by taking the first differential of Eqs 5 and 6, and using the average value of $\Delta\theta$

$$D = \frac{C_s - C_s^1}{C_s} \quad (13)$$

$\Delta(\Delta\theta)$ is the average of the differences between all possible pairs of $\Delta\theta$ values; that is, there would be three such pairs for three days, six for four days, etc.⁶

⁵If the frequency distribution of the deviations is a normal one, there would be a 68 percent chance that a value obtained by averaging over a one-day period would fall within 1.41 percent of the line of best fit. If it represented a two- or three-day average, there is the same chance that it would fall within 1.04 or 0.94 percent of the line of best fit, respectively. Further, there would be a 95 percent chance that it would be less than two standard deviations away from the line of best fit.

⁶ $\Delta(\Delta\theta) = \frac{(N-1)\Delta\theta_1 + (N-3)\Delta\theta_2 + (N-5)\Delta\theta_3 + \dots + |N-(2N-1)|\Delta\theta_N}{(N-1) \text{ arith}}$

where N is the number of days and $\Delta\theta_1, \Delta\theta_2$ are arranged according to size in descending (or ascending) order.

FIG. 6—Percent deviations in measured heat flow from values predicted by the second-order best-fit relationship: a, b, and c are for one, two, and three-day averages of heat flow and temperature.

These deviations from predicted slopes are large, particularly for two-day values and low values of $\Delta(\Delta\theta)$. (Note that the vertical scales of Fig. 7 are different than those of Fig. 6 to accommodate the larger deviations in the latter.)

These data were not subjected to statistical analysis. Inspection of Fig. 7, however, indicates that, for $\Delta(\Delta\theta)$ less than 2°C , measured values might deviate from the best-fit values by up to 100 percent. For $\Delta(\Delta\theta)$ in excess of 2°C the deviation was less than 20 percent. The agreement between measured and best-fit values improved with increased averaging periods.

Most of the deviations for the three- and four-day averages are less than 10 percent when $\Delta(\Delta\theta)$ exceeds 3°C . For six- and twelve-day averages (Fig.

FIG. 7—Deviations of observed slopes from slopes predicted by best-fit curves: a, b, c, d, and e are for two, three, five, six, and twelve-day periods, respectively.

7d,e) the deviations vary slightly with $\Delta(\Delta\theta)$. Deviations for $\Delta(\Delta\theta)$ greater than 1°C average 3.6 percent for the six-day periods and 2.1 percent for the twelve-day periods for glass fiber, and 5.7 and 3.8 percent for the extruded polystyrene for the same periods, respectively.

Comparison with Other Measurements

The values obtained with this method have not been rigorously compared with laboratory tests; however, measurements have been made on several pieces of insulation in both ways. (Method B, Fig. 2, was used in the outdoor test building measurements.) In the laboratory tests, guarded hot-plate and heat flow meter equipment was used. The perlite-fiber and 49.5-mm-thick glass fiber were tested at the Outdoor Test Building at Saskatoon and subsequently in the laboratory at Ottawa. Thermal resistances $\text{m}^2\text{C}/\text{W}$ are given in Table 1. Tests were run at the Outdoor Test Building on other glass fiber of different origin than the preceding, that is, the 38.1 and 60.3-mm-thick specimens. Subsequently specimens were cut from it for laboratory testing; in the latter case, the thickness was reduced to 25.4 mm. The laboratory (LAB) thermal resistances for 38.1- and 60.3-thick glass fiber were calculated from that result.

The LAB value for the perlite-fiber is based on a test at a single

TABLE 1—*Thermal resistances of insulations measured in the laboratory at Ottawa (LAB) and at the Saskatoon outdoor test building (OTB): $m^2 \cdot ^\circ C/W$. The perlite-fiber specimen was tested in the laboratory at a mean temperature (Θ_m) of $21.9^\circ C$ and the glass fiber specimens at two or more temperatures in the range from 17 to $50^\circ C$.*

Insulation	Thick- ness, mm	Density, kg/m ³	Thermal Resistance, $m^2 \cdot ^\circ C/W$	
			LAB	OTB
Perlite-fiber	53.3	161	0.963	1.011
Glass fiber	49.5	149	$1.468 - 0.00603\Theta_m$	$1.42 - 0.0054\Theta_m$
Glass fiber	38.1	145	$1.151 - 0.00319\Theta_m^a$	$1.20 - 0.0049\Theta_m$
Glass fiber	60.3	145	$1.822 - 0.00505\Theta_m^a$	$1.86 - 0.0063\Theta_m$

^aCalculated from laboratory tests on 25.4-mm-thick material cut from the specimens used in the OTB tests.

temperature (Θ_m) of $21.9^\circ C$ while the thermal resistance equations for the glass fiber specimens came from tests at two or more temperatures in the range from 17 to $50^\circ C$. (The 49.5-mm specimen was of a different origin than the other two.)

The mean insulation temperature in the Outdoor Test Building measurements ranged from about 5 to $25^\circ C$. Resistance values were computed using the reciprocal of Eq 10. The resistance equations were then calculated using these resistance values and corresponding values of Θ_m . Differences for the two methods ranged from about 0.5 to 5 percent depending on the specimen and temperature of comparison.

Summary and Conclusions

1. Calibrated heat flow meters, supported in bakelite holders and secured to the underside of roof panels, were used for studies of experimental systems.

2. Outputs from heat flow meters and thermocouples were recorded on magnetic tape and subsequently averaged over 24-h periods.

3. The relationship between heat flows (net value) and temperature differences were expressed by relationships of the form

$$Q = a + b\Delta\Theta + c(\Delta\Theta)^2$$

with a standard error of estimate that was typically 0.2 W/m^2 . Deviations in heat flow were generally less than 2 percent for $\Delta\Theta > 10^\circ C$, based on one-day averages. The values improved as the averaging period was increased.

4. Plots of heat flow versus temperature difference did not generally pass through the origin intersecting the ordinate at 0.20 to -0.45 W/m^2 .

5. Thermal conductances were calculated as the ratio $Q/\Delta\Theta$ and as the ratio $\Delta Q/\Delta(\Delta\Theta)$. In the case of the first, the ordinate intercept introduced

significant errors at low values of $\Delta\theta$. Conductances found from $Q/\Delta\theta$ were improved by adding the ordinate intercept to each heat flow value.

6. Thermal conductances estimated from $\Delta Q/\Delta(\Delta\theta)$ were not affected by the ordinate intercept. When two or three values were used the results were imprecise but improved as the number of points used to calculate the slope increased.

7. Based on a few tests, results obtained with this method differed by 0.5 to 5 percent from those obtained with laboratory equipment.

These results suggested that average net heat flows and temperature differences over 24-h periods provided a suitable basis for calculating thermal resistance of at least some types of building components subjected on the outside to daily weather changes. When conductance was calculated as the ratio of heat flow to temperature difference, the percentage error became large at low values of temperature difference and heat flow.

The recorder was accurate to about $2.5 \mu\text{V}$. Any increase in the error of the recording system would be reflected in an increased uncertainty in heat flow, temperature, and thermal conductance values.

In many kinds of measurement, one is principally concerned with differences in heat flow or conductance, and systematic error in the calibration coefficient may not be very important. The need for high absolute accuracy would require careful calibration and correlation between the calibration procedure and field measurements.

Acknowledgments

The authors wish to express appreciation to D. G. Cole, who carried out the measurements at the Saskatoon Outdoor Test Station, and to C. J. Shirliff and M. Bomberg, who made arrangements for the calibration of the heat flow meters for the laboratory measurements on the specimens used to compare laboratory and outdoor test results, and for their comments on the subject.

This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

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