Overview

The papers published in this volume were presented at a workshop on Building Applications of Heat Flow Sensors, which was sponsored by ASTM Committee C-16 on Thermal Insulation. The workshop was held with 64 in attendance at ASTM Headquarters on 22 and 23 Sept. 1983, following the regular fall semiannual meeting of Committee C-16. The need for a workshop sprang from attempts by ASTM Subcommittee C16.30 on Thermal Measurement to write a standard practice for using heat flow and temperature sensors for *in situ* building measurements and for monitoring the performance of industrial thermal insulation. As the several drafts of each document were developed it became apparent that there were several poorly understood issues and that it would be difficult to write statements on precision and accuracy. The workshop format was viewed as a way to develop recommendations for research and further action by Subcommittee C16.30. The workshop planning was carried out by an organizing committee, which represented a broad range of interests within the field of heat flux transducers.

The objective of the workshop was to create a situation in which researchers and serious users of heat flux transducers (HFTs) could freely join together to discuss their experiences, concerns, and frustrations and perhaps collectively generate new insights. To achieve this objective the workshop was a mixture of prepared presentations, small discussion panels, and instrument demonstrations. This volume contains the formal papers and summaries of the topical panels, which are included at the end of this volume as an appendix.

The last paper is an annotated bibliography on applications of heat flux transducers, prepared by Mark Bomberg, one of the editors of this volume, for the workshop. This partial bibliography contains useful material on field measurements and specific types of heat flux transducers.

Among the areas discussed at the workshop and important to the field are the following:

Field Testing

Field testing is an important part of engineering practice. Models on which decisions are based cannot exactly portray the variations in environmental conditions, materials, and construction practices encountered in the field. Only by testing is the user assured of the validity of these models. This is especially true for thermal performance modeling. Anomalous heat flows in buildings, such as thermal bridges or convective loops, are typically approximated in analysis, as are the effects of infiltration and moisture. Ample field evidence exists that these approximations can lead to serious errors. It is important that reliable techniques be made available to broaden this base of field evidence so that it can, in turn, be used to improve the way buildings are modeled. The heat flux transducer, a conceptually simple, direct measurement device can be instrumental in establishing this data base.

Heat Flux Transducers

Assuming that heat flows one-dimensionally through the layers of a building wall in a series fashion, each layer can be considered a resistor to heat flow. Under stable conditions, the heat that flows through one resistor is the same for any other or any combination of resistors (layers). The resistance or R-value of any layer or combination of layers is defined as the ratio of the temperature difference to the heat flow for that layer or combination. If there is a resistor of known value in a wall, one could measure its temperature difference, and the temperature difference across any unknown resistor in the same wall, and calculate the unknown R-value. The heat flux transducer provides this known resistance.

The physical heat flux transducer (HFT) is typically a thin wafer of a material with a known, stable thermal resistance. The temperature difference across the wafer is measured with a set of thermocouples in a series—a thermopile. The thermopile is used to multiply the small electrical signal produced by a single thermocouple across a thin, low-thermal-resistance wafer. Such a device can be affixed to a wall and connected to an appropriate readout device to measure heat flow.

The use of an HFT is complicated by several factors. For example, adding the transducer to a wall changes the local resistance and causes the local heat flow to differ from that for the undisturbed wall. In addition, since the resistance of the transducer generally differs from that of its immediate surroundings, the heat flow in this region is not one-dimensional, which changes the calibration of the device. Also, since temperature differences across walls are rarely, if ever, steady, the fundamental assumption of a uniform, steady heat flow is rarely, if ever, valid. A more general list of issues associated with the application of HFTs is shown in Table 1. A major portion of the workshop time was spent addressing the significance of these complications and the techniques available or needed to minimize their effects.

The issues and problems associated with HFT application can generally be grouped into three categories: calibration, applications, and analysis. These categories are also applicable to the use of other measurement sensors concerned with quantifying heat transfer, such as thermocouples. The difference is that the calibration, application, and analysis of thermocouples are well understood and accepted standard practices exist for this type of sensor.

TABLE 1—*Heat flux transducer applications—issues and problems.*

Varying conditions
Wall heat capacity (the time constant, thermal lag)
Varying external conditions
Temperature (air and surface)
Solar gain
Surface air motion (speed and direction)
Rain
Diurnal cycle
Radiation from surroundings
Varying internal conditions
Temperature (thermostat)
Radiation from surroundings
Surface air motion
Measurement factors
Added thermal resistance
Disturbed heat flow patterns
HFT surface conditions, emittance (indoor and outdoor)
Disturbed airflow patterns
Wall temperature measurement
Sensor temperature difference
Thermocouple, thermopile
Mounting pattern and technique
Output signal temperature dependence (change in emf, material changes)
Contact thermal resistance
Electrical noise on thermopile signal
Signal with no heat flux

Calibration

Among ASTM members there is a fundamental issue concerning the approach to writing standard practices for HFTs. One approach is to develop stand-alone standardized calibration procedures for HFTs and leave the interpretation of measurements to the user. The other is to identify generic types of applications and write application standards that cover calibration as a part of application. The latter approach is currently written into ASTM draft standards with the argument given that calibration and application cannot be unambiguously separated. Proponents of independent calibration suggest that there are too many different application schemes to write standards for each, and that the level of understanding of HFTs is now such that, in many applications, results from a precalibrated HFT are readily and reliably interpretable. There was agreement at the workshop that separate calibration and application standard practices should be written. It was, therefore, recommended that ASTM Subcommittee C16.30 immediately begin development of a standard practice for calibration of flat sensors using the ASTM

Test for Steady-State Thermal Transmission Properties by Means of the Guarded Hot Plate (C 177-76), taking care to ensure that the heat flow is one-dimensional and that the sensors are calibrated over a range of mean temperatures and heat fluxes.

Applications

The application issues that must be considered when using the HFT to measure heat flow and to determine thermal resistance can generally be categorized as calibration effects, surface effects, and multidimensional effects. The list in Table 1 is more specific. As discussed in the previous section, if the HFT characteristics are well known it is then up to the user to develop models to account for the *in situ* environmental conditions and to derive corrected terms or techniques from the models. Workshop attendees recommended that Subcommittee C16.30 develop standard practices for frequent applications (for example, the use of an HFT embedded in the section being measured). These standards should assume the HFT is calibrated and they should use the best available information for stating the accuracy and precision of the standard. It is clear that careless users can obtain unrealistic results by not being aware of the several application problems. On the other hand, experienced users often anticipate problems and have developed *ad hoc* compensations to improve accuracy. Unfortunately, no systematic examination of the magnitude and relative importance of errors has been done to date. Those who have had considerable experience with HFTs feel that accuracy is attainable within a 5% error in laboratory applications and within the range of 5 to 20% for *in situ* application for the careful user. Field use errors of the order of 100% are not unusual if attention is not paid to proper technique.

Surface-mounted transducers are subject to all the vagaries of the environment. Air temperature changes, radiative coupling to surroundings, and changing air currents all can influence the heat transfer across the HFT causing it to be different from that across the section being measured. Many times the HFT is embedded in the envelope section. This eliminates the surface effects but is expensive, as the HFT is usually not reusable.

Multidimensional effects include factors that cause the heat flow across an envelope section to vary, material differences, irregular voids, inconsistent workmanship, and thermal bridges. The point is that if the intent of the measurement is to determine the wall thermal resistance, then consideration must be given to where on the surface the measurements should be made. Usually some indication of the condition of the wall is sought, frequently with infrared equipment.

Analysis

The HFT itself is a thin, low-mass device, so that heat flow through it is nearly equal to the instantaneous ratio of the temperature differences to the internal resistance (time constants are of the order of 10 s). The same is not, however, true for building envelope sections in general. Thus, when calculating thermal resistance from the measured heat flow and the temperature differences for whole building sections, it is usually incorrect to use the simple ratio because of the variations in inside and outside temperatures and in the heat capacity of the wall.

Generally, an expression of the following form is used for the thermal resistance, R

$$R = \frac{\int \Delta T dt}{\int Q dt}$$

where ΔT is the temperature difference between the hot and cold sides, and Q is the heat flow per unit of area per unit of time. The integration is made over a sufficiently long period of time, t, in comparison with an estimated time lag dependent on thermal storage. The time lag is that time between the maximum temperature difference and the peak heat flow rate. The list in Table 2 was offered by R. Grot as a guideline.

Workshop Conclusions

The workshop participants were unanimous in agreeing that direct measurement of heat flows through building envelope sections in the laboratory and in the field under steady and dynamic conditions are important. It was also clear from papers and from discussions that there are many problems with calibration, application, and analysis of these devices. In addition, the participants generally felt that these problems are fairly well understood by users, especially at research laboratories, and that the immediate objective ought to be the development of standard calibration practices for stand-alone devices and standard-use practices for common and predictable application, such as HFTs embedded in uniform envelope systems. These two actions will contribute significantly to improving the understanding of building envelope thermal performance and they will provide heat flux transducer manufacturers with a clear signal as to what characterization information is most relevant to the building industry.

TABLE 2—*Typical phase lags for various wall and roof constructions.*

Construction	Phase Lag, h	Required Measurement Time, days
Built-up roof, concrete deck	12	6
Built-up roof, steel deck	1	0.5
Wood frame cavity wall	2	1.0
Masonry walls	2.5 to 9.6	1 to 5
Metal curtain walls	0.2	0.5

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