Applications of Heat Flux Transducers: A Select and Annotated Bibliography

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RÉSUMÉ

Ce document est une bibliographie sélective et annotée portant sur la construction des thermofluxmètres, leur étalonnage et le calcul de l'erreur, ainsi que sur les méthodes de détermination de la résistance thermique.
Applications of Heat Flux Transducers: A Select and Annotated Bibliography


ABSTRACT: This paper is a select and annotated bibliography dealing with the construction of heat flux transducers, their calibration and error verification, and the methods used for thermal resistance determination.

KEY WORDS: heat flux transducers, annotated bibliography

The use of heat flux transducers (HFTs) for full-scale testing of the thermal resistance of walls started in Germany at the Thermal Protection Laboratory in Munich and in the United States at the Research Laboratory of the American Society of Heating and Ventilating Engineers in Pittsburgh, Pennsylvania, around 1924. The HFT slowly gained popularity until it became an integral part of different measuring systems used to evaluate the thermal performance of buildings. The papers published in this volume, which were presented at the Workshop on Building Applications of Heat Flow Sensors, held in Philadelphia, Pennsylvania, in September 1983, cover the topic well. However, they relate to only a small fraction of the industrial and research applications of HFTs. The following annotated bibliography is offered as a commentary on the development of the heat flux transducer. The bibliography is divided into three subject areas:

1. Construction of HFTs.
2. HFT calibration and error verification.
3. Methods for field determination of thermal resistance.

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Bibliography

Construction of Heat Flux Transducers


A 2-mm-thick Plexiglas disk with coils of resistor wire on each surface was built. It was calibrated by measuring the output of a heater guarded by an isothermal plate having the same temperature, with the radiative heat flowing through a narrow air gap.


The paper discusses HFTs that integrate the rate of heat flow with respect to time, built and used for special applications where the cumulative rate of heat flow is of primary interest.


A theoretical analysis of the heat exchange between the metering and compensating (guarding) part of a zero-flow transducer is provided.


Another improvement in HFTs was effected in the manufacturing of thermopiles by photoetching techniques. This paper contains a description of the photoetched transducer developed by Degenne and its application. (See also the following entry.)


This HFT follows the principle introduced by Schmidt and Hencky (see Schmidt, E.) but the thermopiles are manufactured in a different man-
ner. Constantan spirals with diameters of 2.5 mm and a wire gage of 0.15 mm are placed in a galvanic bath and partly covered with copper. Other types of HFTs contain constantan wire wound in rectangular fashion and partly coppered or silvered.


This paper and those by Ravalitera et al, Thery et al, and Devisme et al, as well as the paper by Degenne and Klarsfeld published in this publication, deal with new types of thermopiles developed by integrating a large number of thermoelements created on a thin conductor sheet covered with an electrolytic deposit. These transducers are usually manufactured by using printed circuit technology. (See also the following reference.)


See Devisme, J.-M., above.


See Brown, G.


A transducer was made out of a thermopile wound on a glass microscope slide, sandwiched between two anodized aluminum sheets. Contact between the soil and the transducer appeared to be largest source of errors. Under different experimental conditions the error varied between 15 and 50%.


The use of an artificially anisotropic thermoelectric material for a core of a heat flux transducer, the method of selecting its components, and the optimization of the parameters are discussed.


A copper-constantan thermopile was wound on a Perspex core with about 80 turns per 5-cm width; in this way inexpensive and reasonably quickly responding transducers were built.


The principal feature of this construction is the use of thermocouple chains made from copper-constantan foil or ribbon. A bar of constantan was welded to a bar of copper and rolled into a thin ribbon. Then notches were cut in the ribbon and the thermocouple chains were woven over and under strips of the core material providing the thermal resistance. Because of its ability to integrate heat flow over the entire metering area and the ease with which different shapes and sizes can be constructed, this design is still used in some research laboratories. It is interesting to note that this development, as well as the research of Lustig and Cammerer on foil HFTs (*Gesundheits-Ingenieur*, Vol. 76, 1955, pp. 289 ff.), was directed towards measuring the rate of heat exchange between mammals and their environment.


The paper describes HFTs based on A-C resistance thermometry and built to integrate heat flows over a large area.

See Klems, J. H., above.


This heat flux transducer for local heat flux measurement contained a thermistor operated by a differential thermocouple and heated in such a way that the surface remained isothermal. (See also Tamura, T., et al.)


This heat flux transducer has a copper-constantan thermopile penetrating through a core material. The metering area is 38 by 38 cm and the total area is 60 by 60 cm.


See Nicholls, P., above.


See Divisme, J.-M. and Maréchal, J.-C.


In 1923 Schmidt introduced a new heat flow meter or heat flux transducer. In contrast to Hencky’s auxiliary wall (*Gesundheits-Ingenieur* 42, No. 43, October 1919, pp. 437-438), Schmidt’s transducer was expected to produce a negligible disturbance in the pattern of heat flow through the wall, because it had low thermal resistance. However, the fact that the thermal resistance of the transducer was considerably lower than the resistance of the wall was not sufficient to guarantee the uniformity and unidirectional pattern of heat flow within the transducer. The situation was improved by applying a guard around the transducer made of a material with identical thermal resistance. This technique has been used in the
Thermal Protection Laboratory’s transducers since 1923; they have a metering area of 0.5 by 0.5 m. but the guard extends the total area to 1 by 1 m or 1.5 by 1.5 m. (See also Schmidt. E., following.)

See Schmidt, E., above.


The paper describes a miniature transducer used to measure heat transfer by conduction, convection, and radiation in the range of 75 to 300 K. The temperature compensation of the transducer is achieved by matching the changing properties of the insulating material with the changing properties of the semiconductor over a given temperature range. A testing apparatus operating under a vacuum of $10^{-1}$ Pa or less is described, as well as the construction of sensors and the test results obtained on semiconductors and resins suitable for HFT cores.

See Kraabel, J. S., et al.

See Devisme, J.-M. and Maréchal, J.-C.


The sensor (often called a Gardon transducer) is built in the form of a disk of constantan foil, 0.05 mm thick, soldered into a cylindrical copper case with a 5-mm-diameter hole. A copper thermoelectrode, 0.05 mm in diameter, is welded to the center of the thin element. The interior of the case is filled with insulation and closed by a copper lug. A wire is connected to the case. Between this wire and the thermoelectrode in the center, a differential thermocouple is created.
Heat Flux Transducer Calibration and Error Verification


Thin-foil heat flux sensors were coated with camphor black soot and exposed to radiative heat fluxes. Errors were shown to be caused by changes in the physical properties of the coating under varied levels of vacuum and free convection between the window and the sensor.


A pair of novel circular foil heat flux sensors was tested against a Kendall radiometer. An error analysis performed on the data indicates that atmospheric conditions and limitations of the facility preclude accurate comparison of the heat flux sensors with the Kendall radiometer. Details about the data acquisition and error analysis, as well as considerations about the proper gage calibration, are included.


In order to estimate the optimum size of a transducer, the averaging error, $e(x)$, for one-dimensional heat flux distribution must be known. This paper presents $e(x)$ functions for a dimensionless distance in cases of heat flux distributions, such as polynomial exponential peaks and general formulas based on the Taylor expansion series.


A heat flux source capable of producing levels up to 1 MW/m² and a calibration technique were developed for use in the calibration of heat flux sensors.

The calibration of the HFT used in the apparatus for determination of thermal conductivity was performed with mineral fiber insulation of different densities and polystyrene. The calibration procedures gave different results, depending on the insulating materials. A difference was also observed between the heat flux measured by the guarded hot plate apparatus and that calculated from the transfer standards. By rebuilding the transducers, more constant results were obtained with different calibration procedures.


The transducer was mounted between two sections of a copper bar. The upper section was provided with a heater operated by a differential thermocouple, and the lower section contained a liquid coolant and was insulated. The whole assembly was placed in a chamber evacuated to $10^{-2}$ Pa.

The paper describes briefly some problems caused by the non-uniformity of the transducer, the effect of the clamping pressure, and the fact that the calibration obtained with a conductive calibrator may differ from that obtained with a radiative calibrator.


Assuming that the thermal inertia is usually determined experimentally by suddenly exposing the transducer to a constant heat flux, and, further, that the time required to achieve 63% of the change on the transducer is known as the thermal inertia parameter, $\eta$, the paper presents an analytical method for determining this parameter. It also gives the boundaries of applicability of the approximate relationship for calculating the non-steady-state heat fluxes.


The monograph presents basic information on the theory, design, and application of devices for measuring heat fluxes over a wide range of temperatures. The main chapters deal with methods of heat flow measurements, self-contained HFTs, banked HFTs, calibration of radiative fluxes at low and moderate temperatures, calibration of conductive fluxes up to 600°C, and other applications of HFTs.

The calibration is performed under vacuum on a setup consisting of transducers alternating with heaters. The balance of heat transfer involves two transducers and the power output of a heater.


Several short, heavy gage constantan wires bridging a narrow air gap between two parallel steel plates create an iron constantan thermopile. An insulating cord and ceramic seal are used to maintain the position of the plates and to enclose the air gap space.

The calibration was performed in the furnace with the calibrated transducer on top of the furnace transducer. The calibrated transducer acted as a small fin, which increased the heat flux and affected the calibration coefficient. To correct this, master curves were prepared for different temperatures and locations in the furnace.


The paper lists the sources of errors that can influence measurements in the field or laboratory testing, as well as the design criteria for the transducers and the basic elements of HFT calibration and application.


To determine the measurement error of HFTs under non-steady-state conditions, an equation for damping temperature waves in the multilayer construction was applied. Graphs are provided for maximum error as a function of the measured heat flux and the amplitude of 2-h oscillations, linear changes in temperature, and different thicknesses of damping layer applied to the metering section of the transducer.

Heat flow transducers were used in the evaluation of convective body heat losses in hyperbaric environments. Environmental conditions were varied to observe the HFT responses. When the appropriate temperature correction was made, the ambient pressure variations were found to have only little effect. However, a significant change in HFT response was observed when the environmental gas composition varied, probably because of a slight porosity of the material used in the core of the HFT.


The influence of the protective insulation coating on the dynamic characteristics of a thin-film impulse energy flux thermotransducer is investigated. Recommendations based on an analysis of amplitude-phase frequency characteristics are given for the development of an optimal fast-response film sensor. Results are reported for an experimental investigation of heat-impulse fluctuations in the combustion chamber of a diesel engine; they confirm the possibility of reproducing the high-frequency portion of the pulsation spectrum without distortion.


Assuming that the mean temperature gradient established between the sensing surfaces of the heat flow transducer may be equal, smaller, or larger than the one existing in the thermally undisturbed region of the surroundings, Schwerdtfeger defined the geometric parameter of the transducer, after analyzing the HFT temperature response and the heat flux response. The report also discusses the use of pairs of HFTs and different calibrating techniques such as the one making use of a novel radiation enclosure in which meters are temporarily tested as net radiometers. (See also Tuck, E. O.)


See Schwerdtfeger, P., above.

Methods for Field Determination of Thermal Resistance Based on Steady-State Approximation

The dependence of the thermal resistance of attic insulation on the air speed at its exposed upper surface has been measured in situ. This paper represents one of several field studies that illustrate applications of HFTs. (See also Becker, R.; Larson, D. C.; Roberts, C. C.; Reinke, K., Jr.; and Shuman, E. C.)


In this field study of the thermal resistance of a wood-frame wall, two methods were utilized: the portable wall calorimeter and embedded heat flux transducers. The study was designed to compare the measured thermal resistance with that which had been predicted and to determine the effect of factors such as the wall orientation, the duration of the measurement, the thermal lag, and the mean temperature.

By analyzing the heat flux delay versus the temperature difference across the south-facing wall, and by cross-correlating these data with those collected for walls having different orientations, a thermal lag was determined. The values of the thermal resistance were then calculated for a seven-day period, making use of two different procedures, with and without thermal lag. The results showed in each case a common R-value within a range of ±5%. The comparison over a 24-h period, starting at different times of the day, showed that the starting time for integration had less of an effect on the apparent R-value than the use of shorter integration periods (for example, 4 h).


The report discusses the measurement error resulting from a variety of changes (cyclical, step, and random change) in temperature for walls of different time constraints.

In view of this report, as well as research reported in the entries for Brown and Schuyler, Flanders and Marshall, Hedlin et al, Orlandi et al, Siviour and McIntyre, and Treado, S. J., it is generally agreed that a 24-h integration period should be used for the steady-state evaluation of the R-value under field conditions. If the thermal lag and the thermal resistance as a function of temperature are known, and, further, if the temperature difference across the wall is steadily between 15 and 20 K, at
least, one 24-h period can be sufficient for testing wood-frame or masonry walls. On the other hand, if the thermal lag is unknown or if the temperature difference is less than 10 to 15 K, a much longer measuring period will be required. This was the case in the survey performed in New Zealand (discussed by Trethowen in this publication), in which a 72-h period of testing was used. Finally, it should also be noted that, in cases where there are concrete walls and roofs or when a moisture movement occurs in the building construction, the field testing period will be prolonged for a total of seven to ten days.


The presence of a high temperature difference, $\Delta T$, is the most powerful factor assuring convergence on the thermal resistance measured, the $R$-value. The results of measurements at quadruple the average $\Delta T$ converged very closely with the ultimate value within 24 h, whereas measurements related to the average $\Delta T$ did not converge until a week had passed.

This investigation demonstrated that the technique employed is adequate to obtain precise measurements of thermal resistance with at least a 6-K average $\Delta T$, which was the lowest utilized.

The measurements were repeatable at a given location within a standard deviation of 10% of the mean. Two fully insulated areas, far removed from each other, were measured at different times of the year by different researchers, yet the differences were only 2%.


See Treado, S. J.


Heat flow rates and temperatures were measured with heat flow meters and thermocouples. The values were recorded and averaged over 24-h periods.

Thermal resistances of systems and individual components were found using two analytical methods. In the first, the ratio of the heat flow to the temperature difference was calculated. This method was unreliable at low heat flow rates. In the second method, the slope of the heat flow versus the
temperature difference was used. Hedlin et al reject data with temperature difference of less than 4 K but recommend a $\Delta T$ of not less than 10 K.

The 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%.


See Anderson, B. R. and Ward, T. I.


As the convection and radiation factors are specific to the particular environment in which measurements are carried out, in situ calibration precedes the use of HFTs to determine the thermal resistance of building envelope systems. During the calibration, the HFTs are attached to the substrate of the portable calibrator, which is built as a replica of the building envelope substrate. The calibration is performed with careful consideration of convective and radiative factors, as well as lateral heat flow in the substrate.


See Anderson, B. R. and Ward, T. I.


See Anderson, B. R. and Ward, T. I.


See Siviour, J. B. and McIntyre, D. A., below.

The thermal resistance established by field testing can differ from the mean value for a number of reasons, including the external temperature variation, sunshine, the internal temperature variation, the position of the transducer, the contact between the transducer and the wall surface, and the temperature difference across the wall. (See also Siviour, J. B., above.)


The objective of this report is to identify factors affecting thermal performance of existing built-up roof systems and to describe a technique for determination of thermal resistance which uses thermography heat flux transducers and thermocouples. A field validation of the measurement system was performed and reported. (See also Grot, R. A., et al.)


This paper discusses an experimental evaluation of the effect of the resistance of a thermal contact, which demonstrates a possibility of substantial errors in the heat flux measurement.

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