Designation: E2684 – 09

Standard Test Method for Measuring Heat Flux Using Surface-Mounted One-Dimensional Flat Gages[1]

1. Scope

1.1 This test method describes the measurement of the net heat flux normal to a surface using flat gages mounted onto the surface. Conduction heat flux is not the focus of this standard. Conduction applications related to insulation materials are covered by Test Method C518 and Practices C1041 and C1046. The sensors covered by this test method all use a measurement of the temperature difference between two parallel planes normal to the surface to determine the heat that is exchanged to or from the surface in keeping with Fourier's Law. The gages operate by the same principles for heat transfer in either direction.

1.2 This test method is quite broad in its field of application, size and construction. Different sensor types are described in detail in later sections as examples of the general method for measuring heat flux from the temperature gradient normal to a surface (**1**).[2] Applications include both radiation and convection heat transfer. The gages have broad application from aerospace to biomedical engineering with measurements ranging form 0.01 to 50 kW/m^2. The gages are usually square or rectangular and vary in size from 1 mm to 10 cm or more on a side. The thicknesses range from 0.05 to 3 mm.

1.3 The values stated in SI units are to be regarded as the standard. The values stated in parentheses are provided for information only.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

C518 Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus

C1041 Practice for In-Situ Measurements of Heat Flux in Industrial Thermal Insulation Using Heat Flux Transducers

C1046 Practice for In-Situ Measurement of Heat Flux and Temperature on Building Envelope Components

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *heat flux*—the heat transfer per unit area, q, with units of W/m^2 (Btu/ft^2-s). *Heat transfer* (or alternatively heat-transfer rate) is the rate of thermal-energy movement across a system boundary with units of watts (Btu/s). This usage is consistent with most heat-transfer books.

3.1.2 *heat-transfer coefficient, (h)*—an important parameter in convective flows with units of W/m^2-K (Btu/ft^2-s-F). This is defined in terms of the heat flux q as:

$$h = \frac{q}{\Delta T} \tag{1}$$

where ΔT is a prescribed temperature difference between the surface and the fluid. The resulting value of h is intended to be only a function of the fluid flow and geometry, not the temperature difference. If the surface temperature is non-uniform or if there is more than a single fluid free stream temperature, the proper definition of ΔT may be difficult to specify (**2**). It is always important to clearly define ΔT when calculating the heat-transfer coefficient.

3.1.3 *surface emissivity, (ε)*— the ratio of the emitted thermal radiation from a surface to that of a blackbody at the same temperature. Surfaces are assumed to be gray bodies where the emissivity is equal to the absorptivity.

4. Summary of Test Method

4.1 A schematic of the sensing technique is illustrated in Fig. 1. Temperature is measured on either side of a thermal resistance layer of thickness, δ. This is the heat-flux sensing mechanism of this test method. The measured heat flux is in the same direction as the temperature difference and is proportional to the temperature gradient through the thermal-resistance layer (TRL). The resistance layer is characterized by its thickness, δ, thermal conductivity, k, and thermal diffusivity, α. The properties are generally a weak function of temperature.

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[1] This test method is under the jurisdiction of ASTM Committee E21 on Space Simulation and Applications of Space Technology and is the direct responsibility of Subcommittee E21.08 on Thermal Protection.

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[2] The boldface numbers in parentheses refer to the list of references at the end of this test method.

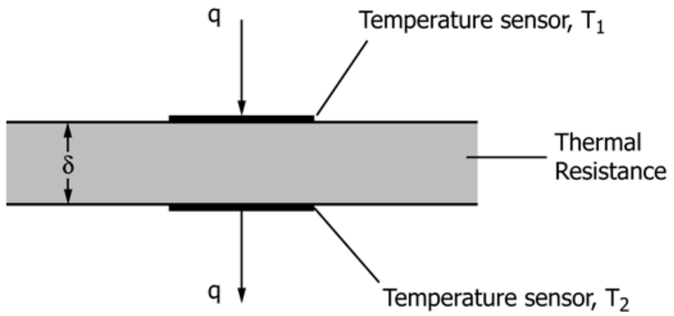

FIG. 1 Layered Heat-Flux Gage

$$q = \frac{k}{\delta}(T_1 - T_2) \quad (2)$$

From this point the different gages may vary substantially in how the temperature difference $T_1 - T_2$ is measured and the thickness of the thermal resistance layer used. These aspects of each different type of sensor are discussed along with the implications for measurements.

4.2 Heat-flux gages using this test method generally use either thermocouple elements or resistance-temperature elements to measure the required temperatures.

4.2.1 Resistance temperature detectors (RTDs) generally have greater sensitivity to temperature than thermocouples, but require separate temperature measurements on each side of the thermal-resistance layer. The temperature difference must then be calculated as the small difference between two relatively large values of temperature.

4.2.2 Thermocouples can be arranged in series across the thermal-resistance layer as differential thermocouple pairs that measure the temperature difference directly. The pairs can also be put in series to form a differential thermopile to increase the sensitivity to heat flux.

$$S = \frac{E}{q} = \frac{N\sigma_T\delta}{k} \quad (3)$$

Here N represents the number of thermocouple pairs forming the differential thermopile and σ_T is the effective temperature sensitivity (Seebeck coefficient) of the two thermocouple materials. Although the voltage output is directly proportional to the heat flux, the sensitivity may be a function of the gage temperature.

5. Significance and Use

5.1 This test method will provide guidance for the measurement of the net heat flux to or from a surface location. To determine the radiant energy component the emissivity or absorptivity of the gage surface coating is required and should be matched with the surrounding surface. The potential physical and thermal disruptions of the surface due to the presence of the gage should be minimized and characterized. For the case of convection and low source temperature radiation to or from the surface it is important to consider how the presence of the gage alters the surface heat flux. The desired quantity is usually the heat flux at the surface location without the presence of the gage.

5.1.1 Temperature limitations are determined by the gage material properties and the method of application to the surface. The range of heat flux that can be measured and the time response are limited by the gage design and construction details. Measurements from 10 W/m^2 to above 100 kW/m^2 are easily obtained with current sensors. Time constants as low as 10 ms are possible, while thicker sensors may have response times greater than 1 s. It is important to choose the sensor style and characteristics to match the range and time response of the required application.

5.2 The measured heat flux is based on one-dimensional analysis with a uniform heat flux over the surface of the gage surface. Because of the thermal disruption caused by the placement of the gage on the surface, this may not be true. Wesley (3) and Baba et al. (4) have analyzed the effect of the gage on the thermal field and heat transfer within the surface substrate and determined that the one-dimensional assumption is valid when:

$$\frac{\delta k}{R k_s} >> 1 \quad (4)$$

where:

k_s = the thermal conductivity of the substrate material,
R = the effective radius of the gage,
δ = the combined thickness, and
k = the effective thermal conductivity of the gage and adhesive layers.

5.3 Measurements of convective heat flux are particularly sensitive to disturbances of the temperature of the surface. Because the heat transfer coefficient is also affected by any non-uniformities of the surface temperature, the effect of a small temperature change with location is further amplified, as explained by Moffat et al. (2) and Diller (5). Moreover, the smaller the gage surface area, the larger is the effect on the heat-transfer coefficient of any surface temperature non-uniformity. Therefore, surface temperature disruptions caused by the gage should be kept much smaller than the surface to environment temperature difference causing the heat flux. This necessitates a good thermal path between the gage and the surface onto which it is mounted.

5.3.1 Fig. 2 shows a heat-flux gage mounted onto a plate with the surface temperature of the gage of T_s and the surface temperature of the surrounding plate of T_p. The goal is to keep

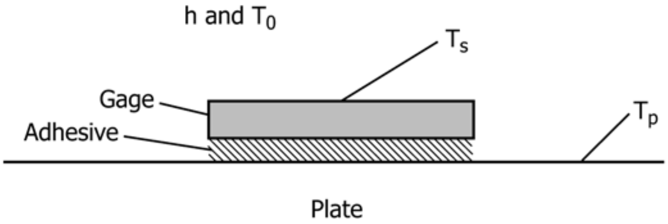

FIG. 2 Diagram of an Installed Surface-Mounted Heat-Flux Gage

the gage surface temperature as close as possbible to the plate temperature to minimize the thermal disruption of the gage. This requires the thermal resistance of the gage and adhesive to be minimized along the thermal pathway from T_s and T_p.

5.3.2 Another method to avoid the surface temperature disruption problem is to cover the entire surface with the heat-flux gage material. This effectively ensures that the thermal resistance through the gage is matched with that of the surrounding plate. It is important to have independent measures of the substrate surface temperature and the surface temperature of the gage. The gage surface temperature must be used for defining the value of the heat-transfer coefficient. When the gage material does not cover the entire surface, the temperature measurements are needed to ensure that the gage does indeed provide a small thermal disruption.

5.4 The time response of the heat-flux gage can be estimated analytically if the thermal properties of the thermal-resistance layer are well known. The time required for 98 % response to a step input (**6**) based on a one-dimensional analysis is:

$$t = \frac{1.5\,\delta^2}{\alpha} \tag{5}$$

where α is the thermal diffusivity of the TRL. Covering or encapsulation layers must also be included in the analysis. Uncertainties in the gage dimensions and properties require a direct experimental verification of the time response. If the gage is designed to absorb radiation, a pulsed laser or optically switched Bragg cell can be used to give rise times of less than 1 µs (**7**,**8**). However, a mechanical wheel with slits can be used with a light to give rise times on the order of 1 ms (**9**), which is generally sufficient.

5.4.1 Because the response of these sensors is close to an exponential rise, a measure of the time constant τ for the sensor can be obtained by matching the experimental response to step changes in heat flux with exponential curves.

$$q = q_{ss}\left(1 - e^{-t/\tau}\right) \tag{6}$$

The value of the step change in imposed heat flux is represented by q_{ss}. The resulting time constant characterizes the first-order sensor response.

6. Apparatus-Sensor Construction

6.1 Temperature sensors are mounted or deposited on either side of the thermal-resistance layer (TRL), which is usually a thin material which can be mounted on the test object. The method of construction and details of operation varies for each different type of gage. Although most of the gages place the temperature sensors directly over top of each other across the TRL, it is not a requirement for proper measurement. The bottom temperature sensors simply need to be at a uniform temperature and the top temperature sensors need to be at a temperature dictated by the heat flux perpendicular to the surface. This can be accomplished on a high-conductivity substrate by separate thermal-resistance pads for the top temperature measurements. Several examples are given of the thermopile and RTD based types of gages.

6.2 *Thermopile Gages*—Thermopile gages are based on thermocouples forming multiple junctions on either side of the TRL. If properly mounted and designed for the application, the operation of these heat-flux gages is simple. There is no activation current or energy required for the thermocouple sensor units. The output voltage is continuously generated by the gage in proportion to the number of thermocouple pairs wired in series. The output can be directly connected to an appropriate differential amplifier and voltage readout device.

6.2.1 An early report of the layered sensor (**6**) used a single thermocouple pair across the resistance layer. Ortolano and Hines (**10**) used a number of thermocouple pairs as described by Eq 3 to give a larger voltage output. The thermocouples are placed as foils around a Kapton thermal-resistance layer and butt welded on either side, as illustrated in Fig. 3. Kapton sheets are used around the gage for encasement and protection. The resulting Micro-Foil gage is 75 to 400 µm thick and flexible for easy attachment to surfaces, but the low conductivity (high thermal resistance) of the materials must be considered when used for convection measurements. The sensors are limited to temperatures below (250°C) and heat fluxes less than 100 kW/m^2. The time response can be as fast as 20 ms, but transient signals may be attenuated unless the frequency of the disturbance is less than a few hertz.

6.2.2 Terrell (**11**) describes a gage design (Episensor) made with screen printing techniques of conductive inks. A copper/nickel thermocouple pair is used with a dielectric ink for the thermal-resistance layer. The inks are printed onto anodized aluminum shim stock for the substrate. Although the entire package is 350 µm thick, the thermal resistance is low because of the high thermal conductivity of all of the materials. Because of the large number of thermocouple pairs (up to 10,000), sensitivities are sufficient to measure heat fluxes as low as 0.1 W/m^2. The thermal time constant is about 1 s and the upper temperature limit is approximately 150°C. The aluminum base allows some limited conformance to a surface.

6.2.3 The thermopile connections can also be made through small holes in the TRL. Plating of copper and nickel is used to create such a gage (BF Heat Flux Transducer) from 1 cm square to 32 cm square with a high density of junctions per area. The thickness is 200 µm which gives a time constant of

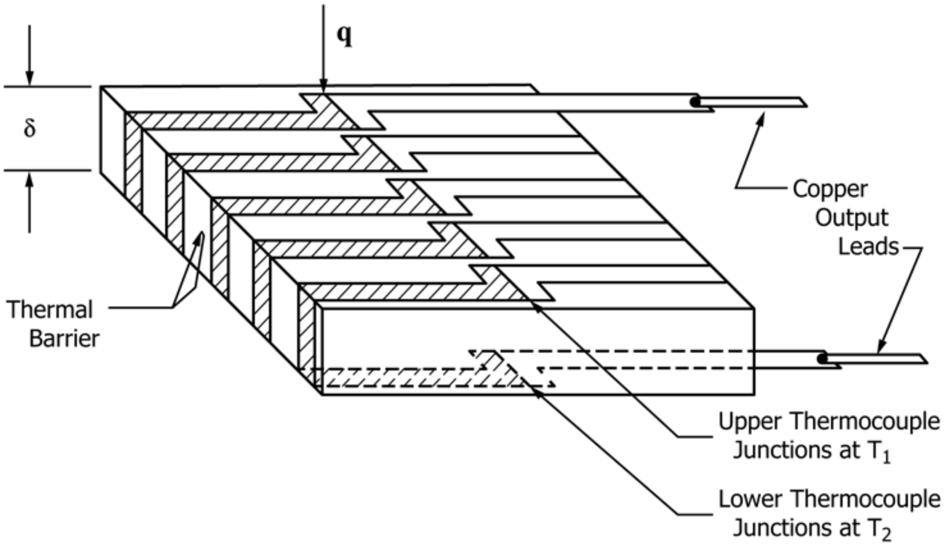

FIG. 3 Micro-Foil Heat-Flux Gage

approximately 1 s. It has limited flexibility and has a maximum operating temperature of 150°C.

6.2.4 Another design uses welded wire to form the thermopile across a TRL about 1 mm thick. This gives a higher sensitivity to heat flux, but also a larger thermal resistance. Time constants are greater than 1 s and the upper temperature limit is 300°C. These are manufactured in a range of sizes. Applications include heat transfer in buildings and physiology. Sensors with higher sensitivity are made with semi-conductor thermocouple materials for geothermal applications. Lower sensitivity sensors are made for operating temperatures up to 1250°C.

6.2.5 Another technique for measuring the temperature difference across the TRL is to wrap wire and then plate one side of it with a different metal. A common combination is constantan wire with copper plating. The resulting wire-wound sensor looks similar to the sensor shown in Fig. 3. The difference is that the constantan wire is continuous all around the sensor so it does not form discrete thermocouple junctions. A summary of the theory is given by Hauser (**12**) and a general review is given by van der Graaf (**13**). Because of the hundreds of windings around the 0.5 to 3 mm thick strips, the sensitivity to heat flux is high. The corresponding thermal resistance is also large and time constants are greater than 20 s. Temperatures are normally limited to about 150 to 200°C, but ceramic units are available for operation above 1000°C. Some of the units are flexible and can be wrapped around objects. The main use for these gages is to measure heat-flux levels less than 1 kW/m^2, so the applications are limited.

6.3 *RTD-Based Sensors*—These gages use RTDs and must be activated by a small current to provide an output voltage. They are generally used only for research applications and are not commercially available.

6.3.1 Hayashi et al. (**14**) produced thin film heat-flux gages using vacuum evaporation. A silicone monoxide layer is used for the thermal resistance with two layers of nickel, 0.2 mm wide and 3 mm long, deposited on either side. The nickel layers are used as RTDs to measure the temperature difference across the silicone monoxide. A bridge circuit is used with a one volt excitation across the two resistances to provide two output voltages which can be related to the heat flux. The frequency response of the gage, obtained from tests with a shuttered light source, was estimated to be 600 Hz. Gages were used in supersonic flow to measure shock passage.

6.3.2 Epstein et al. (**15**) use a 25 µm thick sheet of polyimide (Kapton) with nickel RTDs deposited on either side. The sensing area is 1.0 mm by 1.3 mm. The nickel resistance elements are immediately contacted to gold leads because of the much lower resistance of gold. This isolates the voltage drop of the measurement at the sensor location. The leads from the bottom element are brought through the polyimide sheet so that all four leads can be taken to the edge of the sheet together. To avoid the physical and thermal disruption caused by placement of the gage on the measurement surface, the entire surface is completely covered with a polyimide sheet to match the gage thickness. Up to frequencies of about 20 Hz the gage responds directly to the heat flux, as indicated in Eq 2. For frequencies above 1 kHz the polyimide resistance layer appears infinitely thick, and the top resistance element (T_1) responds like a transient heat flux gage. To cover the entire range from dc to 100 kHz a numerical data reduction technique is used to reconstruct the heat-flux signal. One advantage is that these gages can be wrapped onto curved surfaces, although the temperature calibrations change during this process, which necessitates *in situ* calibration.

6.3.3 The heat-flux gage developed by Piccini et al. (**16**) is also made with a thin plastic sheet. Platinum RTDs are sputtered onto one surface of a 50 µm thick sheet of Upilex. However, the matching temperature sensors are not placed on the other side of the sheet. Instead, a thermocouple is mounted into the metal substrate onto which the sheet is glued. The heat flux at steady state is calculated from the temperature difference between the RTD and the thermocouple as shown in Eq 2. The thickness and thermal properties of the Upilex and the glue layer are determined from direct calibration. Analytical solutions of the unsteady heat transfer equations are used to determine the unsteady heat flux up to frequencies of 100 kHz, similar to the method used by Epstein et al. (15).

7. Calibration

7.1 The steady-state sensitivity of heat-flux gages is best determined by comparison with a secondary standard certified by NIST. The simplest method is to create a repeatable heat flux measured by the standard and substitute the gage to be calibrated. Alternatively, both gages can measure simultaneously if the same heat flux can be created for both. If the gage temperature will be outside the normal room temperature range, the heat-flux sensitivity should be measured over the range of gage temperatures for the intended use because it may be somewhat temperature dependent.

7.2 Recent work by NIST (17,18) has established standards for radiation heat flux to 50 kW/m^2. An electrical substitution radiometer acts as the primary standard. The resulting calibration for the gage sensitivity S_{rad} is based on the incident radiation to the gage surface, q_{inc}.

$$S_{rad} = \frac{E}{q_{inc}} \tag{7}$$

The emissivity of the surface, ε, is required to calculate the absorbed radiation.

$$q_{abs} = \varepsilon q_{inc} \tag{8}$$

The gage surface is assumed to be gray with the absorptivity equal to the emissivity and both values constant with angle and wavelength for the conditions of use.

7.2.1 The gage can also be mounted onto a calorimeter disc that permits the heat flux to be calculated from the temperature rise of the disc during the application of an incident radiant heat source. The mass, specific heat and area of the copper disc are needed along with the assumption of negligible heat loss. The calibration is performed in a vacuum to eliminate convection effects.

7.3 Conduction calibrations are relatively easy, but time consuming for the thin flat gages because of the long time needed to establish steady-state conditions in the system. Guarded hot plate calibration systems are commercially available and can be traced to standards at NIST.

$$S_{cond} = \frac{E}{q_{cond}} \tag{9}$$

7.3.1 If a calibrated standard is available, conduction can be used for comparative calibrations which are much quicker than the absolute calibrations of a guarded hot plate. The thin, flat sensors can be stacked together with the standard to match the measured heat flux under a locally steady-state condition. The system must be designed to ensure the same heat flux through all of the sensors.

7.4 Convection calibrations are more difficult, but have been done to heat flux levels of about 5 kW/m^2 using electrical power measurement as the standard (19). An order of magnitude higher heat flux can be achieved with high velocity impinging jets and a secondary standard (20). The gage sensitivity is based directly on the convective heat flux, q_{conv}.

$$S_{conv} = \frac{E}{q_{conv}} \tag{10}$$

8. Procedure

8.1 Mount the gage so that there is good thermal contact between the sensor and the test surface. Make a concerted effort to prevent any air bubbles, dirt, or water from becoming trapped between the transducer and the test surface. Poor contact with the test surface may result in measurement errors, so mount the gage on a smooth, clean, dry surface. Best results are achieved when using an adhesive backing or a thermally conductive paste. Apply a thin, uniform layer of paste or adhesive to the sensor and then press the sensor firmly to the test surface. Use the smallest amount of paste or adhesive possible while achieving complete coverage. The surface for mounting the gage should be a good heat sink. Without a good heat sink, the energy impinging on the gage cannot flow through to the surface and will instead just heat it up, resulting in erroneous heat-flux measurements.

8.2 Following proper installation on the surface, attach the gage leads to an appropriate amplifier.

8.2.1 For the thermopile type sensors (type 6.2) take the voltage output generated by the sensor directly to a differential amplifier. Because of the relatively low signal levels, be sure to use good shielding and grounding procedures and use leads that are a twisted, shielded pair, with one end of the shield attached to the amplifier ground and the other end floating.

8.2.2 For the resistance temperature sensors (type 6.3) a constant current excitation is needed. Use an isolated supply with a sufficiently small current (typically < 1 mA) that self heating is a negligible portion of the heat flux. Because the power dissipation is

$$P = \frac{E^2}{R} \tag{11}$$

a higher electrical resistance (R) allows a larger output voltage (E) with the same power dissipation in the sensors. Four lead measurements of the resistance help to isolate the temperature effects to the sensors versus the lead wires. Use a good operational amplifier to read the voltages across the two resistance temperature sensors. Repeat the calibration of the temperature sensors often to check for drift of the resistance values. A small shift in one of the sensors can give a large fictitious heat flux. Use good shielding and grounding techniques.

8.3 Check the zero of the amplifier before and after testing.

8.4 Any device to record the voltages from the amplifier may be used. Often the output is run directly into a computer for storage.

8.5 If time-resolved signals are required, the sampling rates and filtering of the signals are important. Ensemble averaging of the signals helps isolate ordered structures in the signal.

9. Calculation of Heat Flux

9.1 If available, the temperature of the gage should be used to determine the proper heat-flux sensitivity. Because most measurements in air involve a combination of convection and radiation, corrections for one or the other are often necessary.

9.1.1 The convective heat flux is found directly from the measured voltage with a correction for the net radiation absorbed by the gage. The value of S_{conv} should be the same as for S_{cond}.

$$q_{conv} = \frac{E}{S_{conv}} - q_{abs} \tag{12}$$

9.1.2 If the gage was calibrated based on incident radiation and the same coating is kept on the gage, it will read incident radiation with a correction for the convective heat flux.

$$q_{inc} = \frac{E}{S_{rad}} - q_{conv} \tag{13}$$

10. Report

10.1 The report of heat-flux measurements made with surface-mounted heat-flux gages should include the following items:

10.1.1 The type of gage used, as identified in Section 6, including the recommended range of operation.

10.1.2 The source and details of gage calibration.

10.1.3 The amplifiers and data recording equipment used because of the challenge in reading the small voltage signals generated by the sensors.

10.1.4 The details of gage application to the surface.

10.1.5 Any temperature measurements taken of the fluid, gage and surrounding surfaces.

10.1.6 Note discrepancies between the gage temperature and the temperatures of the surrounding surface.

11. Measurement Uncertainty

11.1 An uncertainty analysis shall be performed according to the standard of NIST TN-1297 (**21**). Both Type A and Type B uncertainties shall be included in the analysis. The heat-transfer rate shall be reported with its total uncertainty at a stated confidence level. Values that went into the uncertainty analysis, including those derived from calibration reports and manufacturers' specifications, as well as any assumptions or estimates, shall be documented.

12. Keywords

12.1 heat-flux gage; temperature gradient; thermal transport

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