Designation: E2684 – 17

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

This standard is issued under the fixed designation E2684; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

## 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.*

1.5 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

## 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

C1130 Practice for Calibrating Thin Heat Flux Transducers

## 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:

$$h = \frac{q}{\Delta T} \quad (1)$$

where $\Delta T$ 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 $\Delta T$ may be difficult to specify (**2**). It is always important to clearly define $\Delta T$ 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

[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.

Current edition approved Sept. 1, 2017. Published October 2017. Originally approved in 2009. Last previous edition approved in 2009 as E2684–09. DOI: 10.1520/E2684-17.

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

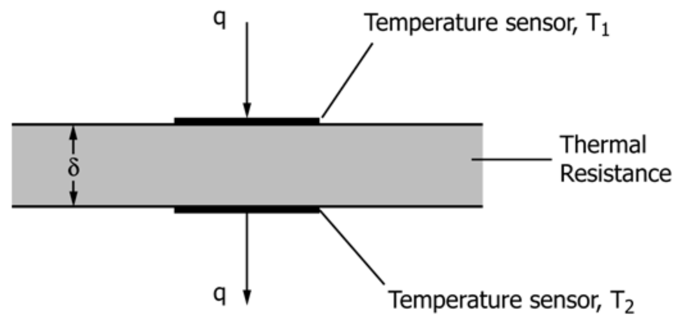


**FIG. 1 Layered Heat-Flux Gage**

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.

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

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.

$$S = \frac{E}{q} = \frac{N\sigma_T\delta}{k} \tag{3}$$

Here *N* represents the number of thermocouple pairs forming the differential thermopile and $\sigma_T$ 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:

$$\frac{\delta k}{R k_s} >> 1 \tag{4}$$

where:

$k_s$ = the thermal conductivity of the substrate material,
$R$ = the effective radius of the gage,
$\delta$ = 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 the gage surface temperature as close as possible 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 polyimide thermal-resistance layer and butt welded on either side, as illustrated in Fig. 3. Polyimide sheets are used around the gage for encasement and protection. The resulting Micro-Foil gage[3] 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 The gSKIN heat flux sensor by greenTEG[4] is a thermopile made by depositing bismuth telluride semiconductor materials. These thermocouples give a particularly high

[3] The sole source of supply of the apparatus known to the committee at this time is RdF Corporation. If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee,[1] which you may attend.

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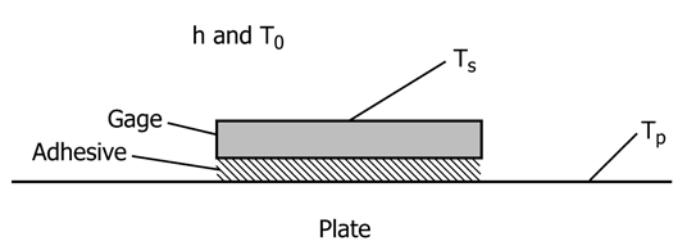


**FIG. 2 Diagram of an Installed Surface-Mounted Heat-Flux Gage**