Heat Flux Gauges

What They Are and What They Do

Heat flux sensors are used to measure the rate of heat flow in many applications. Examples include heat flow measurements through walls, human skin (diagnostics), clothing (insulation testing) and soils (water evaporation). Heat flux sensors can also measure the heat dissipation from electronic components, and are used in instruments to measure gas flow and the thermal conductivity of gases, liquids and solids [1].

A basic heat flux sensor is made of thermocouple junctions attached in series between the hot and cold sides of an object whose heat flow is being measured, as shown in Figure 1.

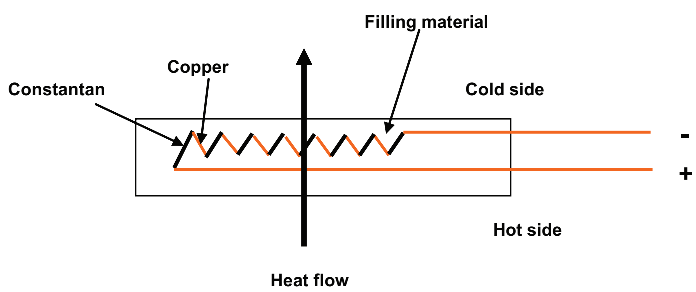

Figure 1. Thermopile Concept of a Heat Flux Sensor Based on Thermocouples in Series.

Most heat flux gauges are based on the thermopile concept in which a series of connected thermocouples are embedded in a filling material, typically a plastic such as Kapton. A single thermocouple generates a voltage that is proportional to the temperature difference between the joints (copper-constantan, constantan-copper) [1]. The voltage output of a series of thermocouples is proportional to the heat flow through the filling material.

Heat flux sensors can be used in different configurations. If conductive heat flux is measured as shown in Figure 2, the sensor actually measures the convection and conduction at the surface at equilibrium, which must be equal.

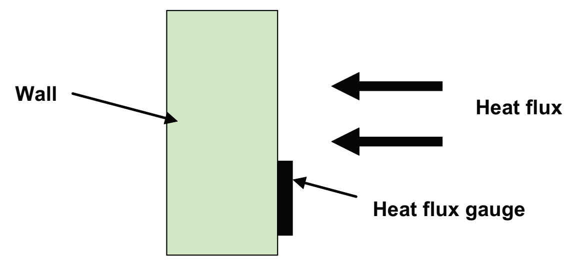

Figure 2. Heat Flux Gauge for Measuring Conductive Heat Flux

A heat flux gauge can also be used as a radiation sensor, as shown in Figure 3. The top of the gauge has a coating to absorb radiation, and its sides are attached to copper heat sinks. By this method, the heat absorbed by the gauge is laterally conducted to the heat sinks, and the voltage generated by the temperature difference between the hot and cold sides can be related to the heat flux. When a filter is placed between the gauge and the radiation source, the gauge can detect a spectral range from UV to the far infrared, thus covering a large, dynamic range from weak to strong radiation intensities. Applications for these gauges are found in laser power measurement, solar energy measurement, pyrometry and burglar alarms [1].

There are inherent errors in calibrating and measuring heat flux, and they must be overcome in order to account for accuracy. Figure 4 shows one of the methods of calibrating a heat flux gauge. In this setup, the gauge is sandwiched

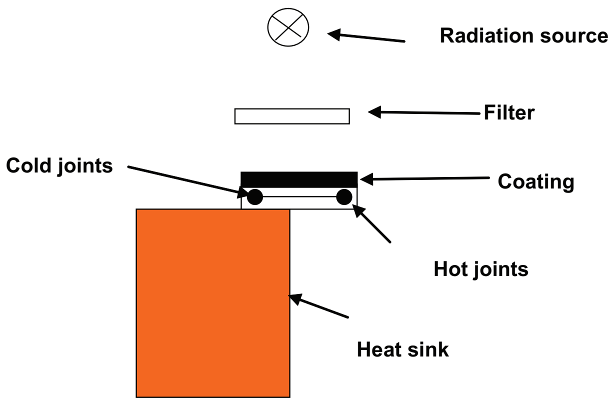

Figure 3. Radiation Sensor with Lateral Sensitivity [1].

between a hot and a cold plate and is embedded into a material with known thickness and conductivity. By measuring the temperatures of the cold and hot plate at equilibrium, and knowing the conductivity of the filling material, one can find the heat flux from the conduction equation,

$$q = \frac{T_{hot} - T_{cold}}{L/kA}$$

Where,

q = Heat flux

T_{hot} = Hot plate temperature

T_{cold} = Cold plate temperature

L = Thickness of the filling material

k = Conductivity of the filling material

A = Cross section area of the filling material

Errors associated with this technique typically occur when measuring temperatures, thickness, thermal conductivity and contact resistances. A more accurate way of calibrating is shown in Figure 5.

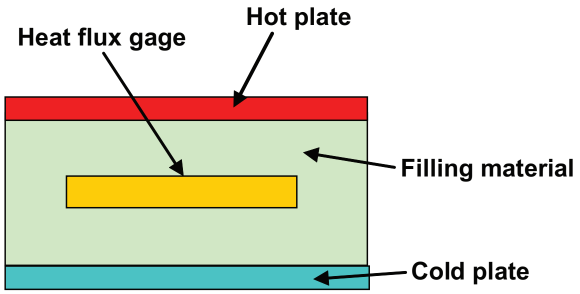

Figure 4. Calibration of a Heat Flux Gauge Using Hot and Cold Plates [1].

In Figure 5, heat flux gauges are mounted on the top and bottom of a heater, and the assembly is sandwiched between a hot plate and a cold plate. By adjusting the heater power, a zero voltage from the top heat flux gauge will indicate that all the heat is being dissipated to the bottom. Because the voltage and current of the heater can be very accurately measured, the heat or heat flux from the heater to the bottom gauge can be accurately measured.

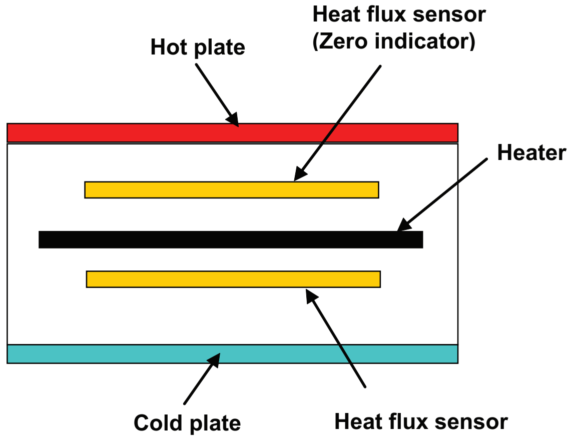

Figure 5. Calibration of a Heat Flux Gauge Using Hot and Cold Plates and a Heater [1].

A heat flux gauge used in an environment with convection can face more challenges compared to conduction measurement. An error analysis is conducted considering the Gardon gauge model [2] shown in figure 6.

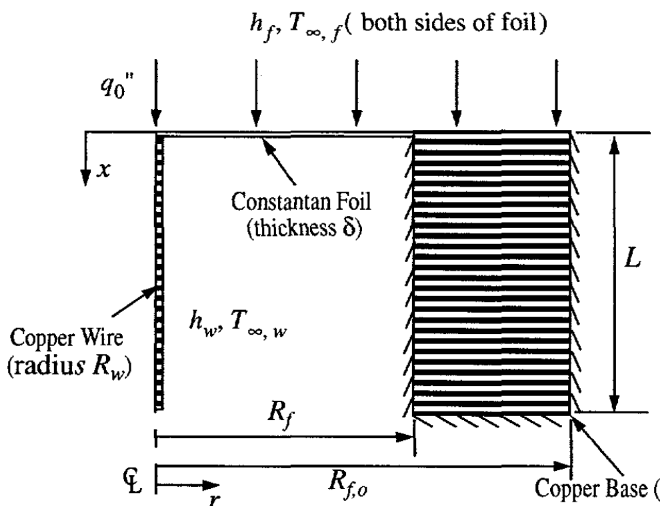

Figure 6. Model of a Gardon Gauge [3].

This sensor is designed to measure the intensity of radiation energy. It features a constantan foil with radius R_f. The center of the foil is attached to a copper wire with radius R_w and length L. The outer edge of the foil is attached to a copper base with height L and outer radius of $R_{f,o}$. The copper base is insulated. The heat transfer coefficient and air temperature on both sides of the foil are assumed to be h_f and $T_{\infty,f}$ respectively. The heat transfer coefficient and temperature on the copper wire are assumed to be h_w and $T_{\infty,w}$ respectively.

To analyze the problem, a simple model was proposed that neglects the conduction from the foil to the wire and convection from the foil [4]. It is also assumed the radiation flux is uniform, and the outer side of the copper base is maintained at a fixed temperature of T_B. Radiation from the bottom of the foil is neglected. The steady state temperature distribution is shown as:

$$T(r) - T_B = \frac{q_0''}{4 k_f \delta}\left(R_f^2 - r^2\right)$$

Where,

$T(r)$ = Radial temperature distribution in the foil (K)
r = Radial distance from the center of the foil (m)
q_0'' = Radiation heat flux (W/m²)
k_f = Thermal conductivity (W/m·K)
R_f = Radius of the foil gage (m)
T_B = Temperature of the foil outer edge (K)
δ = Thickness of Gardon gauge (m)

The temperature at the center of the base can simply be calculated at r = 0.

$$T_0 - T_B = \frac{q_0''}{4 k_f \delta} R_f^2$$

This equation shows that there is a linear relationship between the temperature difference and the heat flux.

A more detailed analysis of the Gardon gauge uses finite element analysis [4]. The input data used in this analysis are as follows:

$\delta = R_w = 0.0000127$ m
$R_f = 0.00311$ (m)
L = 0.00368 (m)

$R_{f,0}$ = 0.00411 (m)
K_f = 24.6 (W/m·K)
K_B = KW = 397 (W/m·K)
C_f = 3.63E06 (J/m^{3}K)
$C_B = C_W$ = 3.645E06 (J/m^{3}K)
q_0'' = 1.0 x 10^4 (W/m^2)

Where C_B and C_W are the heat capacitance of base and wire respectively.

Figure 7 shows the finite element analysis results of the Gardon gauge,in Figure 6 for different values of the heat transfer coefficient. It was assumed that the heat transfer coefficient was the same on the foil and the wire.

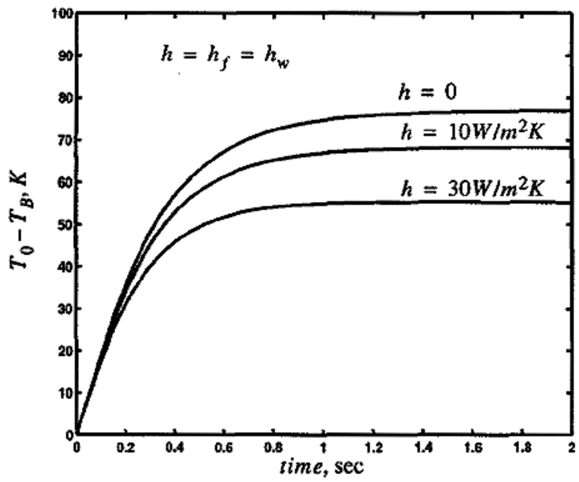

Figure 7. Gardon Gage Temperature Response [3].

The graph shows that if we neglect the convection heat transfer, the value of T_0-T_B is about 78 K. For h = 10 W/m^{2}K, this value drops to 68 K, or a 12% error, and at h = 30 W/m^{2}K, the temperature difference reduces to 55 K, or a 30% error. This implies that if the gauge had been calibrated by neglecting the convection, the predicted heat flux would have had the same errors.

Calibrating heat flux gages is of utmost importance to prevent large errors. Figure 8 shows a calculated calibration of a Gardon gauge. The graph shows the ideal response and the real response considering a convective loss with a heat transfer coefficient of 30 W/m^{2}K. The uncertainty bounds shown in the plot assume a 10% uncertainty in thermal properties, heat transfer coefficient and temperature. The discrepancy between the ideal calibration and the real case increases as the heat flux increases.

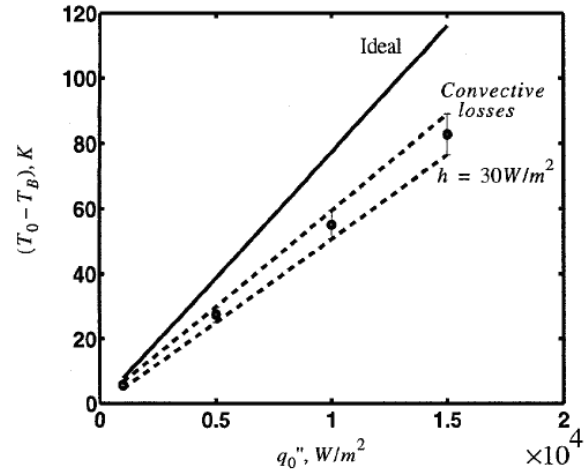

Figure 8. Gardon Gauge Calibration [3].

Even though an experimental calibration can reduce the effects of thermal properties, convective losses are not easily calculated. This requires a series of graphs that consider all the environmental effects, including ambient temperature and air flow. The user then must properly match the curve with the appropriate calibration curve to obtain reliable data. Using heat flux gauges is not a trivial task; the user has to be aware of all the variables that might affect the accuracy of results.

References:

1. Application and Specification of Heat Flux Sensors, Hukseflux Thermal Sensors, www.hukseflux.com.
2. Gardon, R., An Instrument for the Direct Measurement of Intense Thermal Radiation, Review of Scientific Instruments, Vol. 24, No. 5, 1953.
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