

Thomas E. Diller. "Heat Flux."

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Heat Flux

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Thermal management of materials and processes is becoming a sophisticated science in modern society. It has become accepted that living spaces should be heated and cooled for maximum comfort of the occupants. Many industrial manufacturing processes require tight temperature control of material throughout processing to establish the desired properties and quality control. Examples include control of thermal stresses in ceramics and thin films, plasma deposition, annealing of glass and metals, heat treatment of many materials, fiber spinning of plastics, film drying, growth of electronic films and crystals, and laser surface processing.

Temperature control of materials requires that energy be transferred to or from solids and fluids in a known and controlled manner. Consequently, the proper design of equipment such as dryers, heat exchangers, boilers, condensers, and heat pipes becomes crucial. The constant drive toward higher power densities in electronic, propulsion, and electric generation equipment continually pushes the limits of the associated cooling systems.

Although the measurement of temperature is common and well accepted, the measurement of heat flux is often given little consideration. Temperature is one of the fundamental properties of a substance. Moreover, because temperature can be determined by human senses, most people are familiar with its meaning. Conversely, heat flux is a derived quantity that is not easily sensed. It is not enough, however, to only measure the temperature in most thermal systems. How and where the thermal energy goes is often equally or more important than the temperature. For example, the temperature of human skin can indicate the comfort level of the person, but has little connection with the energy being dissipated to the surroundings, particularly if evaporation is occurring simultaneously. Wind chill factor is another common example of the importance of convection heat transfer in addition to air temperature.

Maximizing or minimizing the thermal energy transfer in many systems is crucial to their optimum performance. Consequently, sensors that can be used to directly sense heat flux can be extremely important. The subsequent material in this chapter is intended to help individuals understand and implement heat flux measurements that are best suited for the required applications.

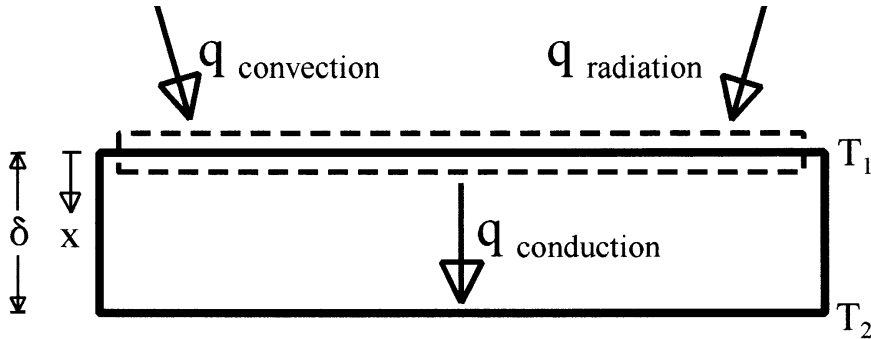


FIGURE 34.1 Illustration of energy balance.

34.1 Heat Transfer Fundamentals

The movement of thermal energy is known as “heat” and the rate of this transfer is commonly called “heat transfer.” It is given the symbol q and has the units of watts. The heat transfer per unit area is termed the “heat flux” and is given the symbol q'' with the units of $W\ m^{-2}$. Although in some cases only the overall heat transfer from a system is required, often the spatial and temporal variation of the heat flux is important to performance enhancement. Methods for measuring the spatial *or* temporal distribution of heat flux are identified and discussed in this chapter. Detailed simultaneous measurements of *both* spatial and temporal distributions of heat flux, however, are generally not feasible at this time.

One of the most important principles concerning heat transfer is the first law of thermodynamics, which states that the overall energy transfer to and from a system is conserved. It includes all types of energy transfer across the system boundary, including the three modes of heat transfer — conduction, convection, and radiation. For the simple example shown in Figure 34.1, the transient energy balance on the control volume marked can be expressed as:

$$mC \frac{\partial T}{\partial t} = q_{\text{convection}} + q_{\text{radiation}} - q_{\text{conduction}} \tag{34.1}$$

where m is the mass of the system and C is the corresponding specific heat. The effect of the thermal capacitance (mC) of the material causes a time lag in the temperature response of the material to a change in heat transfer. A short summary of important heat transfer principles follows, with many engineering textbooks available in the field that give additional details.

Conduction

Conduction encompasses heat transfer through stationary materials by electrons and phonons. It is related to the temperature distribution by Fourier’s law, which states that the heat flux vector is proportional to and in the opposite direction of the temperature gradient:

$$\vec{q}'' = -k \vec{\nabla} T \tag{34.2}$$

The constant k is the thermal conductivity of the material. Measuring this temperature gradient is one of the basic methods for determining heat flux.

For a homogeneous material in Cartesian coordinates Equation 34.1 becomes:

$$\frac{\partial T}{\partial t} = a \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \tag{34.3}$$

where a is the thermal diffusivity of the material with a density of ρ , $a = k/(\rho C)$. Measuring the temperature response of the system according to this equation is the second major method for determining the heat transfer. Because of the complexity of solutions to Equation 34.3, this method can be complicated if multidimensional effects are present.

If steady-state one-dimensional heat transfer can be assumed throughout the planar solid in Figure 34.1, the temperature distribution in the direction of heat flux q'' is linear. Equation 34.2 becomes simply:

$$q'' = k \frac{T_1 - T_2}{\delta} \quad (34.4)$$

where the temperatures are specified on either side of the material of thickness δ .

As illustrated in Figure 34.1, convection and radiation are the other modes of heat transfer typically present at the surface of a solid. These are usually the quantities of interest to measure with a heat flux sensor. Both are present at least to some extent in virtually all cases, although the effects of one or the other are often purposely minimized to isolate the effects of the other.

Convection

Although heat transfer by convection occurs by the same physical mechanisms as conduction, the fluid is free or forced to move relative to the surface. The fluid motion greatly complicates the analysis by coupling the heat transfer problem with the fluid mechanics. Particularly when the flow is turbulent, the fluid equations are generally impossible to solve exactly. Consequently, the heat transfer and fluid mechanics are commonly isolated by introduction of a heat transfer coefficient, which encompasses all of the fluid flow effects.

$$q'' = h_T (T_r - T_s) \quad (34.5)$$

The temperature of the fluid is represented by T_r , which for low-speed flows is simply the fluid temperature away from the surface. The recovery temperature is used for high-speed flows because it includes the effect of frictional heating in the fluid. The subscript T on the heat transfer coefficient, h_T , implies that the boundary condition on the surface is a constant temperature, T_s . Although other surface temperature conditions can be encountered, it is then important to carefully document the surface temperature distribution because it can have a profound effect on the values of h and q'' [1, 2].

Radiation

Heat transfer by radiation occurs by the electromagnetic emission and adsorption of photons. Because this does not rely on a medium for transmission of the energy, radiation is very different from conduction and convection. Radiation has a spectrum of wavelengths dependent on the temperature and characteristics of the emitting surface material. Moreover, the surface properties are often dependent on the wavelength and angular direction of the radiation. One classic example is material that looks black to the visible spectrum, but is transparent to the longer wavelengths of the infrared spectrum. Consequently, special coatings are sometimes applied to surfaces to control the absorption characteristics. For example, the surface of a radiation sensor is often coated with a high absorptivity paint or graphite.

Because the power emitted from a surface is proportional to the fourth power of the absolute temperature, radiation detectors are usually cooled sufficiently for the power emitted from the detector itself to be negligible. In this case, the temperature distribution of the sensor is not important. This is a big advantage over convection measurements where the temperature distribution on the surface has a big influence on the measurement.

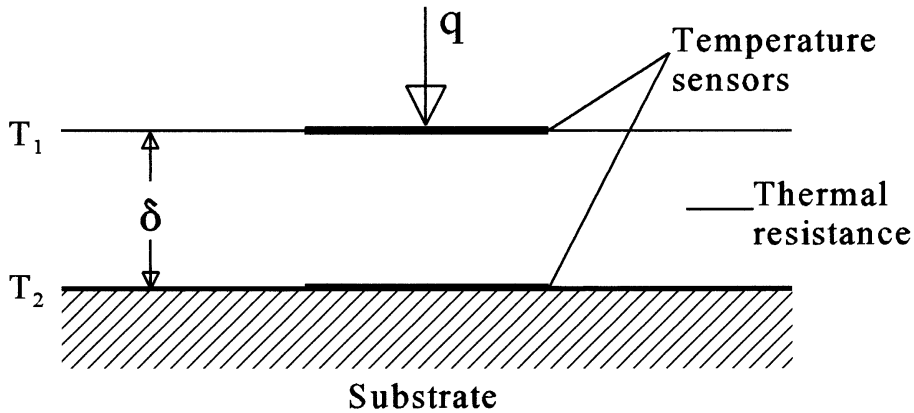


FIGURE 34.2 One-dimensional planar sensor concept.

34.2 Heat Flux Measurement

Most of the many methods for measuring heat flux are based on temperature measurements on the surface or close to the surface of a solid material. Usually this involves insertion of a device either onto or into the surface, which has the potential to cause both a physical disruption and a thermal disruption of the surface. As with any good sensor design, the goal for good measurements must be to minimize the disruption caused by the presence of the sensor. It is particularly important to understand the thermal disruption caused by the sensor because it cannot be readily visualized and because all heat flux sensors have a temperature change associated with the measurement. Consequently, wise selection of the sensor type and operating range is important for good heat flux measurements. The following sections emphasize important factors in using the currently available heat flux sensors, followed by short summaries of sensors used in research and possible future developments. They are grouped by the general type of sensor action.

34.3 Sensors Based on Spatial Temperature Gradient

The heat flux at the material surface can be found at a location if the temperature gradient can be determined at that position, as indicated in Equation 34.2. Because it is difficult to position temperature sensors with the requisite accuracy inside the material, sensors to measure heat flux are either applied on the surface or mounted in a hole in the material. In the following sections, the different types of commercially available sensors are discussed first and listed in a table by manufacturer. Shorter sections briefly describing sensors used in research labs or currently being developed follow.

One-Dimensional Planar Sensors

The simplest heat flux sensor in concept is illustrated in Figure 34.2. The one-dimensional heat flux perpendicular to the surface is found directly from Equation 34.4 for steady-state conditions:

$$q'' = \frac{k}{\delta}(T_1 - T_2) \quad (34.6)$$

The thickness of the sensor δ and thermal conductivity k are not known with sufficient accuracy for any particular sensor to preclude direct calibrations of each sensor. An adhesive layer may also be required between the sensor and surface to securely attach the sensor, which adds an additional thermal resistance

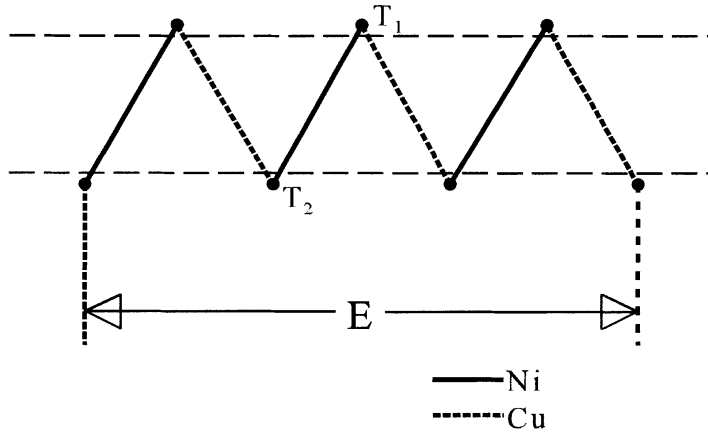


FIGURE 34.3 Thermopile for differential temperature measurement [2].

and increases the thermal disruption. Temperature measurements on the sensor and on the surrounding undisturbed material are recommended to quantify this disruption.

Although the temperature difference can be measured by any number of methods, the most commonly used are thermocouples. Thermocouples have the advantage that they generate their own voltage output corresponding to the temperature difference between two junctions. Consequently, they can be connected in series to form a thermopile that amplifies the output from a given temperature difference. An illustration of a thermopile for measuring a temperature difference is given in Figure 34.3. Most any pair of conductors (e.g., copper–constantan) can be used for the legs of the thermopile, but the output leads should be of the same material so that additional thermocouple junctions are not created. The voltage output, E , is simply:

$$E = NS_T(T_1 - T_2) \quad (34.7)$$

where N represents the number of thermocouple junction pairs, and S_T is the Seebeck coefficient or thermoelectric sensitivity of the materials, expressed in volts per degree Centigrade. The corresponding sensitivity of the heat flux sensor is:

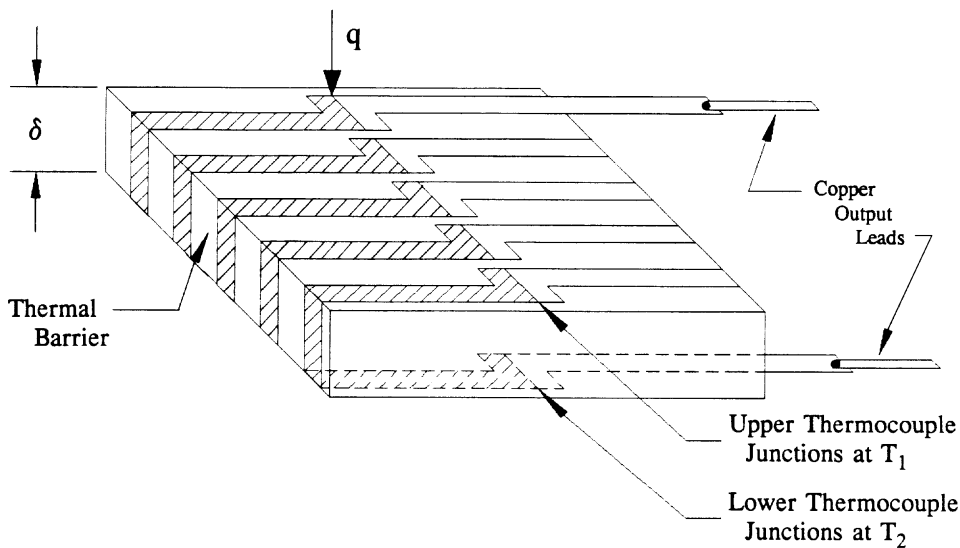
$$S = \frac{E}{q''} = \frac{NS_T \delta}{k} \quad (34.8)$$

Although the sensitivity is determined in practice from a direct calibration, the last part of the equation can be used to determine the effects of different parameters for design purposes.

One successful design using a thermopile was described by Ortolano and Hines [3] and is currently manufactured by RdF Corp., as listed in Table 34.1. Thin pieces of two types of metal foil are alternately wrapped around a thin plastic (Kapton) sheet and butt-welded on either side to form thermocouple junctions, as illustrated in Figure 34.4. A separate thermocouple is included to provide a measure of the sensor temperature. The flexible, micro-foil sensors are 75 μm to 400 μm thick and can be glued to a variety of surface shapes, but are limited to temperatures below (250°C) and heat fluxes less than 100 kW m^{-2} . This covers many general-purpose industrial and research applications. The time response can be as fast as 20 ms, but transient signals can be attenuated unless the frequency of the disturbance is less than a few hertz. First-order systems, such as these sensors, give 70% response to a sinusoidal input with a period six times the exponential time constant.

TABLE 34.1 Heat Flux Instrumentation

Manufacturer	Sensor	Description	Approximate price (U.S.\$)
RdF	Micro-foil	Foil thermopile	\$100
Vatell	HFM	Microsensor thermopile	\$900
Vatell	Episensor	Thermopile	\$100–250
Concept	Heat flow sensor	Wire-wound thermopile	\$100–300
Thermonetics	Heat flux transducer	Wire-wound thermopile	\$50–900
ITI	Thermal flux meter	Thermopile	\$150–350
Vatell	Gardon gage	Circular foil design	\$250–500
Medtherm	Gardon gage	Circular foil design	\$400–800
Medtherm	Schmidt-Boelter	Wire-wound thermopile	\$500–800
Medtherm	Coaxial thermocouple	Transient temperature	\$250–450
Medtherm	Null-point calorimeter	Transient temperature	\$650–800
Hallcrest	Liquid crystals	Temperature measurement kit	\$200
Image Therm Eng.	TempVIEW	Liquid crystal thermal system	\$30k–50k

**FIGURE 34.4** Thermopile heat flux sensor [3].

A similar design uses welded wire to form the thermopile across a sensor about 1 mm thick. This gives a higher sensitivity to heat flux, but also a larger thermal resistance. Time constants are on the order of 1 s and the upper temperature limit is 300°C. These are manufactured in a range of sizes by International Thermal Instrument Co., as listed in Table 34.1. Applications include heat transfer in buildings and physiology. Sensors with higher sensitivity are made with semiconductor thermocouple materials for geothermal applications. Lower sensitivity sensors are made for operating temperatures up to 1250°C.

A much thinner thermopile sensor called the Heat Flux Microsensor (HFM) was described by Hager et al. [4] and is manufactured by Vatell Corp., as listed in Table 34.1. Because it is made with thin-film sputtering techniques, the entire sensor is less than 2- μm thick. The thermal resistance layer of silicon monoxide is also sputtered directly onto the surface. The resulting physical and thermal disruption of the surface due to the presence of the sensor is extremely small. Use of high-temperature thermocouple materials allows sensor operating temperatures to exceed 800°C for the high-temperature models. They are best suited for heat flux values above 1 kW m⁻², with no practical upper limit. Because the sensor is so thin, the thermal response time is less than 10 μs [5], giving a good frequency response well above 1 kHz. A temperature measurement that is integrated into the sensor is very useful for checking the heat

flux calibration [6] and determining the heat transfer coefficient. The high temperature and fast time response capabilities are useful for aerodynamic applications, combusting flows in engines and propulsion systems, and capturing high-speed events such as shock passage.

Terrell [7] describes a similar sensor design made with screen printing techniques of conductive inks. A copper/nickel thermocouple pair was used with a dielectric ink for the thermal resistance layer. The inks were 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. These are currently offered commercially by Vatec Corp., as listed in Table 34.1. 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. Applications include the low heat fluxes typical of building structures, biomedicine, and fire detection.

Another technique for measuring the temperature difference across the thermal resistance layer 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 Figure 34.4. 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 [8] and a general review is given by van der Graaf [9]. Concept Engineering offers a range of these type of sensors at moderate cost. Because of the hundreds of windings on these sensors around 2-mm thick plastic strips, the sensitivity to heat flux is high. The corresponding thermal resistance is also large and time constants are around 1 s. Temperatures are limited to about 150°C. Thermonetics also makes a plated wire-wound heat flux sensor. Thicknesses range from 0.5 mm to 3 mm, with time constants greater than 20 s. Some of the units are flexible and can be wrapped around objects. The normal temperature limit is 200°C, but ceramic units are available for operation above 1000°C. The main use for these sensors is to measure heat flux levels less than 1 kW m^{-2} , with applications including building structures, insulation, geothermal, and medicine.

One popular version of plated wire sensors uses a small anodized piece of aluminum potted into a circular housing, commonly known as a Schmidt-Boelter gage. Kidd [10] has performed extensive analyses on these gages to determine the effect of the potting on the measured heat flux. Neumann [11] discusses applications in aerodynamic testing. The sensors are commercially available from Medtherm Corp. in sizes as small as 1.5-mm diameter. There is also some ability to contour the surface of the sensor to match a curved model surface for complex test article shapes.

Circular Foil Gages

The circular foil or Gardon gage consists of a hollow cylinder of one thermocouple material with a thin foil of a second thermocouple material attached to one end. A wire of the first material is attached to the center of the foil to complete a differential thermocouple pair between the center and edge of the foil as illustrated in Figure 34.5. The body and wire are commonly made of copper with the foil made of constantan. Heat flux to the gage causes a radial temperature distribution along the foil as illustrated in Figure 34.5. The circular foil gage was originated by Robert Gardon [12] to measure radiation heat transfer. For a uniform heat flux typical of incoming radiation the center to edge temperature difference is proportional to the heat flux (neglecting heat losses down the center wire):

$$T_o - T_s = \frac{q'' R^2}{4k\delta} \quad (34.9)$$

The thickness of the foil is δ and the active radius of the foil is R . The temperature difference produced from center to edge of the foil is measured by a single thermocouple pair, typically copper-constantan. The output voltage is proportional to the product of the temperature difference in Equation 34.9 and the thermoelectric sensitivity of the differential thermocouple.

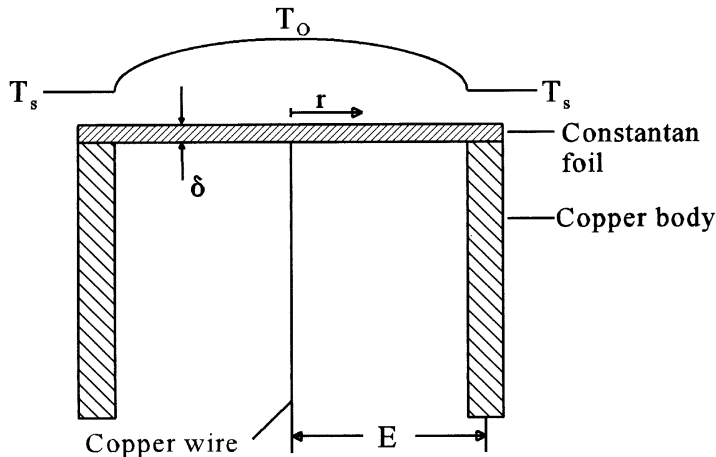


FIGURE 34.5 Circular foil heat flux gage.

These sensors are reasonably rugged and simple. They are manufactured by two companies at moderate cost (Medtherm and Vatel), and are often used as secondary standards for measurement of radiation. One important application is the measurement of the heat flux occurring during fire tests to check flammability of materials. The biggest problems with the circular foil gages arise when they are used with any type of convection heat transfer. It has been shown analytically and experimentally that the output is incorrect for convective heat transfer because of the distortion of the temperature profile in the foil from the assumed radially symmetric, parabolic profile of radiation [13]. Because the amount of error is a function of the gage geometry, the fluid flow, and the heat transfer coefficient, it is difficult to reliably correct. The errors become particularly large when the sensor is used in a flow that has a shear flow component [14], which encompasses most convection situations. Consequently, great care must be used to keep the temperature difference across the gage $T_o - T_s$ small if Gardon gages are used to measure convective heat transfer.

When the gages are used in high heat flux situations, such as combustors, water cooling is usually supplied through the body of the sensor to keep the temperature from exceeding material limits. Because of the resulting temperature mismatch of the gage and surrounding material in which it is mounted, a water-cooled gage is not recommended for convection heat transfer measurements. It is also important for a water-cooled gage to ensure that condensation does not occur on the sensor face.

Although most heat flux sensors are designed to measure the total heat flux, sensors have been developed to separate convection from radiation. The most common method is to put a transparent window over the sensor to eliminate convection to the sensor face. Because the resulting sensor only measures radiation, it is termed a radiometer. The field of view is limited, however, in these radiometers and must be included in the interpretation of results. In a dirty environment where the transmission of the window could be degraded, air is blown across the face of the window to keep the particles away from the sensor. Both manufacturers of the circular foil gages (Medtherm and Vatel) make these radiometer versions. Applications include use in high-ash boilers and gas turbine combustors.

Research Sensors

Although not commercially available, heat flux sensors using RTDs (resistance temperature devices) have been developed to measure the required temperature difference across a heat flux sensor. They are not as convenient for measuring small temperature differences as thermocouples, however, because RTDs require two individual temperature readings to be subtracted. Conversely, a thermocouple pair reads the temperature difference between the two junctions directly and allows the formation of thermopiles with many pairs of junctions to amplify the signal.

Researchers at MIT have developed a sensor like the Micro-Foil thermopile sensor using a nickel resistance element on each side of the plastic sheet [15]. One advantage of knowing the individual temperatures rather than the temperature difference is that the time response of the sensor can be analytically enhanced up to 100 kHz with appropriate modeling. Hayashi et al. [16] used vacuum deposition to create thin-film heat flux sensors like the HFM sputtered thermopile sensors except using a nickel RTD on either side of the silicon monoxide thermal resistance layer. The frequency response was estimated from shock-tunnel experiments to be 600 Hz.

Future Developments

The most exciting recent advances in the field of heat flux measurement have been provided by thin-film technology. Continued improvements in size, sensitivity, price, and time response are anticipated. As the size of sensors continues to decrease, the deposition of thin-film heat flux sensors directly on parts as they are manufactured should become a reality.

34.4 Sensors Based on Temperature Change with Time

Equations 34.1 to 34.3 give the form of the relationship between the unsteady response of temperature and surface heat transfer. If the thermal properties of the wall material are known along with sufficient detail about the temperature history and distribution, the heat transfer as a function of time can, in principle, be determined. Although temperature sensors are available from manufacturers, the necessary data manipulation must be done by the user to obtain heat flux. There are two types of solutions used to reduce the temperature history to heat flux. These are discussed separately as the semi-infinite solution and calorimeter methods. In addition, a variety of methods for measuring the required temperature history are discussed.

Semi-Infinite Surface Temperature Methods

An important technique for short-duration heat flux tests is to measure the surface temperature history on a test object with a fast-response temperature sensor. For short enough times and sufficiently thick material, it can be assumed that the transfer is one-dimensional and that the thermal effects do not reach the back surface of the material. Equation 34.3 reduces to a one-dimensional, semi-infinite solution, which is simple to implement for this case. For example, the surface temperature for a step change of heat flux at time zero is

$$T_s - T_i = \frac{2q_0''\sqrt{t}}{\sqrt{\pi k\rho C}} \quad (34.10)$$

The substrate properties are the thermal conductivity, density, and specific heat, represented by the product $k\rho C$. T_i is the uniform initial temperature of the substrate and T_s is the surface temperature as a function of time.

A good criteria for the time limit on the test is the time before 1% error occurs in the heat flux [17]:

$$t = 0.3 \frac{L^2}{a} \quad (34.11)$$

Here, a represents the thermal diffusivity of the substrate material and L is the substrate thickness. For a typical ceramic substrate (MACOR), the corresponding minimum thickness for 1 s of test time is 1.6 mm. High conductivity materials, such as metals, have much larger required thicknesses.

Data analysis of the measured temperature record can be performed by several methods. The simplest is to use the analytical solution with each sampled data point to recreate the heat flux signal. The most

popular equation for this conversion is that attributed to Cook and Felderman [18] for uniformly sampled data:

$$q''(t_n) = \frac{2\sqrt{k\rho C}}{\sqrt{\pi\Delta t}} \sum_{j=1}^n \frac{T_j - T_{j-1}}{\sqrt{n-j} + \sqrt{n+1-j}} \quad (34.12)$$

This can easily be implemented for digital data with a short computer program to perform the summation for the measured points. Modifications are also available to provide more solution stability [17]. More complex techniques include the use of parameter estimation techniques [19] and numerical solutions to account for changes in property values with the changing temperature [20]. Because of the noise amplification inherent in the conversion from temperature to heat flux, analog methods have been developed to convert the temperature signal electronically before digitizing the signal [21].

There are many methods for measuring surface temperature that can be used to determine heat flux. Two broad categories are point measurements using thermocouples or RTDs and optical methods that allow for simultaneous measurement of temperatures over the entire surface. They all require substantial effort from the user to initiate the test procedure and reduce the data to find heat flux. Places for additional information and a few sources for temperature sensors are given.

Point temperature measurements for determining convective heat flux are often made with thin-film RTDs. A metallic resistance layer is sputtered, painted and baked, or plated onto the surface. Because the resulting thickness of the sensor is less than 0.1 μm , the response time is a fraction of 1 μs and there should be no physical or thermal disruption of the measured temperature due to the sensor. Most researchers develop techniques for instrumenting models themselves. Transient flow facilities provide an easy method for quickly initiating the flow and heat transfer, as required by this transient method. However, the model can also be injected into the flow or the flow can be quickly diverted to provide the fast initiation of heat flux. The method is used for basic measurements applicable to gas turbine engines, rockets, internal combustion engines, and high-speed aerodynamics [2].

A special type of thermocouple is made for surface temperature measurement, called coaxial thermocouples [22]. It has one thermocouple wire inside the second thermocouple material with an insulating layer in between. One end is mounted into a metal sheath for press fitting into the surface material for testing. A thin thermocouple is formed by combining the two metals right at the end of the assembly. Response times are typically 1 ms or less, which although slower than the thin-film sensors is sufficient for most applications [11]. The cost per sensor is moderate and they are available from Medtherm Corp., as listed in Table 34.1.

A new approach to measure the transient surface temperature at a point is being developed using a fiber optic probe embedded in the surface [23]. A Fabry-Perot interferometer is the basis for the technique, which has the advantages of high spatial resolution and no electrical connections.

Null-point calorimeters [24] are a further extension of the semi-infinite surface temperature method. They are designed for measurement of extremely high levels of heat flux (over 1000 kW m^{-2}). To protect the thermocouple and wires, they are mounted in a cavity behind the surface. The geometry of the null-point calorimeter is designed, however, for the thermocouple to measure a temperature that would match the surface temperature of a semi-infinite material so that Equation 34.14 can be used for data reduction [24]. Medtherm is the current supplier of null-point calorimeters, as indicated in Table 34.1.

Optical methods give the opportunity to measure the entire temperature field over a section of the surface. Consequently, much data can be collected over each test, but interpretation to obtain quantitative heat flux values is more challenging than measurements with point sensors. The visual display of the temperature over the surface can be very qualitatively informative, however.

The most popular optical method for measuring temperature is to record the color change using liquid crystals. These are specially prepared molecules that reversibly change their color reflection through several distinct colors as a function of temperature, typically in the range of 25°C to 40°C. The best for transient measurements are the chiral-nematic form that have been microencapsulated to stabilize their properties. A variety of types can be obtained from Hallcrest (in Table 34.1), which can be used over the

temperature range from 5°C to 150°C. They can easily be spray-painted onto a blackened surface for testing. Setting the lighting for reproducible color, temperature calibration, image acquisition, and accurately establishing the starting temperature are crucial steps. Detailed procedures for accurate measurements have been established by several groups [25–28]. The basic materials are cheap, but the associated equipment is expensive. As listed in Table 34.1, Image Therm Engineering offers a complete system for temperature measurement, including a high-quality video camera, lighting system, calibration system, computer hardware and software for image processing, and a liquid crystal kit.

As previously discussed for radiation heat transfer, all surfaces emit radiation with an intensity and wavelength distribution that can be related to the surface temperature. The advent of high-speed infrared scanning radiometers has made it feasible to record the transient temperature field for determination of the heat flux distribution [29]. A coating is usually applied to establish a known, high absorptivity surface. To convert the measured radiation emission to surface temperature, the radiation field of the surroundings is also required. The camera and associated equipment are quite expensive.

Thermographic phosphors emit radiation in the visible spectrum when illuminated with ultraviolet light. The intensity of emission at specific wavelengths can be related to the temperature over a wide range of surface temperatures. The potential high-temperature applications are particularly appealing [30]. A CCD camera is required to record the transient optical images and calibration is challenging.

Calorimeter Methods

A *calorimeter* is a device for measuring the amount of absorbed thermal energy. The slug calorimeter [31] assumes that the temperature throughout the sensor is uniform while it changes with time. When exposed to a fluid at a temperature T_r and heat transfer coefficient h over an active area of A , the solution for the temperature change is simply an exponential:

$$\frac{T - T_r}{T_i - T_r} = e^{-t/\tau} \quad (34.13)$$

where T_i is the initial temperature and the time constant is:

$$\tau = \frac{mC}{hA} \quad (34.14)$$

with the active surface area represented by A . The thermal capacitance is the product of the mass of the sensor and the specific heat. The time constant can be found from the temperature response of the system, which can then be used in Equation 34.14 to quantify the heat transfer coefficient, h . Although these calorimeters are simple in principle, it is often difficult to obtain reliable results because of heat losses and nonuniform temperatures.

A more useful device, called the plug-type heat flux gage, was developed by Liebert [32] at NASA Lewis. An annulus is created on the backside of the surface by electrical discharge machining. Four thermocouples are attached along the remaining plug to estimate both the temperature gradient and the change in thermal energy content in the plug. This gives a better estimate of the heat flux than the slug calorimeter. An additional advantage is that the measurement surface is physically undisturbed.

Another calorimeter technique, called the *thin skin method*, uses the entire test article as the sensor. Models are constructed of thin metals and instrumented with thermocouples on the back surface. The temperature is assumed constant throughout the material at any location, but varies with time and position around the model. The main errors to be avoided are: (1) lateral conduction along the surface material, (2) heat loss by conduction down the thermocouple wires, and (3) heat loss from the back surface, which is usually considered adiabatic. Because of the recent advances in thin-film and optical surface temperature measurement, the thin-skin method is considered outdated for most modern aerodynamic testing [11].

34.5 Measurements Based on Surface Heating

For research on convective heat transfer, electric heating provides an easy method of controlling and measuring the heat flux to the surface. A combination of guard heaters and proper insulation allows control of the heat losses to give an accurate knowledge of the heat flux leaving the surface based on the total electrical power supplied once steady-state conditions have been established. The temperature of the surface and fluid are used in Equation 34.5 to give the heat transfer coefficient for the surface:

$$h = \frac{q''}{T_f - T_s} \quad (34.15)$$

As with the transient temperature methods, it requires considerable experimental design and expertise by the user to begin making measurements.

34.6 Calibration and Problems to Avoid

Calibration of heat flux is a complicated issue because some heat flux sensors respond to different modes and conditions of heat flux differently. For example, a sensor calibrated by radiation can have a substantially different response to the same amount of heat flux in convection.

For the low heat fluxes seen in building applications, the guarded hot-plate method has been well established [33]. The National Institute of Standards and Technology (NIST) maintains calibration devices for this range of conduction heat transfer. Calibrated insulation samples are readily available to check other guarded hot-plate calibrators. Calibration of sensors at elevated temperatures has demonstrated that there is a dependence of the heat flux sensitivity on sensor temperature [34].

There have been several important advances in heat flux calibration for more general industrial applications within the past few years. NIST is completing three heat flux calibration facilities. A black-body radiation facility operating to 100 kW m^{-2} , a laminar flow convection facility, and a helium conduction facility are currently being completed and tested [35–37]. This combination of facilities will allow comparison of sensor response under the different modes of heat transfer. In addition, Arnold Engineering Development Center (AEDC) has recently acquired a radiation calibration facility for elevated sensor temperatures (up to 800°C). The temperature dependence of the heat flux sensitivity is thought to be substantial for many sensors. Because in the past most all calibrations have only been performed with the sensors at room temperature, this is an important new facility.

As with many other measurements, the major problem with heat flux measurement is the error caused in the heat flux by the disruption of the sensor itself. For sensors based on the spatial temperature gradient methods, a larger signal implies a larger temperature difference and a larger temperature disruption. For the second type of sensors based on the transient temperature change, the surface temperature is changing while the measurement occurs. The larger the temperature change, the easier the determination of the sensor heat flux, but the larger the error from the sensor temperature disruption.

The error caused by the thermal disruption of the sensor can be estimated for conduction [38]. In convection, however, the effect of the surface temperature disruption on the developing thermal boundary layer is much more difficult to estimate and the effect on the heat flux can be much larger than the percentage change of the temperature [2]. Therefore, it is imperative in convection measurements to keep the thermal disruption of the sensor to a minimum.

34.7 Summary

There are a large number of off-the-shelf heat flux sensors available. Those commercially available have been listed in Table 34.1, and the information for contacting the manufacturers is given in Table 34.2.

TABLE 34.2 Companies That Make Sensors for Heat Flux Measurement

Concept Engineering 43 Ragged Rock Road Old Saybrook, CT 06475 (860) 388-5566	RdF Corporation P.O. Box 490 Hudson, NH 03051-9981 (603) 882-5195
Hallcrest Liquid Crystal Division 1820 Pickwick Lane Glenview, IL 60025 (312) 998-8580	Thermonetics Corp. Box 9112 San Diego, CA 92109 (619) 488-2242
International Thermal Instrument Co. P.O. Box 309 Del Mar, CA 92014 (619) 755-4436	Vatell Corporation P.O. Box 66 Christiansburg, VA 24073 (540) 961-3576
Medtherm Corporation P.O. Box 412 Huntsville, AL 35804 (205) 837-2000	Image Therm Eng., Inc. 159 Summer St. Waltham, MA 02154 (781) 893-7793

The differential temperature devices provide a direct readout of the heat flux over the surface of the sensor. With the proper choice of sensor for the application and care in measurement method, the results are easily interpreted and used. Alternatively, the transient temperature methods can provide more surface details, but the output is a surface temperature history that must be analyzed to obtain the corresponding heat flux. Although certain components of these systems are off-the-shelf, more work is required of the user to interpret the results. Issues of calibration and errors have been addressed briefly here. More detail on all aspects of heat flux measurement can be obtained from the manufacturers and the references listed.

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