Use of the Vatell Heat Flux Microsensor with Thermocouple

The Vatell Heat Flux Microsensor with Thermocouple (HFM-8) will provide excellent heat flux measurement for a wide variety of applications, as long as it is used properly. This document will explain the use of the HFM-8 and important factors to take into consideration when making measurements. The temperature correction equations described for the HFM-8 and accompanying Vatell amplifier are all performed by the HFCOMP.EXE program on the diskette that is shipped with these products, but are reviewed here for user edification.

Output from the HFM-8

Two measurements are made with the HFM-8. The first is a temperature measurement obtained from a thin-film thermocouple (TC) deposited the sensor face. The second is a heat flux measurement obtained from a thermopile heat flux sensor (HFS) that occupies most of the surface area on the sensor face. The HFS signal should not be confused with the output from a thermocouple. The HFS acts like a differential voltage source, and so should not be grounded. Best results can be obtained by connecting it to a differential amplifier, such as the Vatell AMP-12 or similar amplifier. The thermocouple measurement is important to proper heat flux measurement, because the HFS is temperature dependent. The function describing the thermocouple output is linear, but because it is a thin-film device it does not necessarily conform to tabulated values of standard wire thermocouples. The function is characterized for each HFM at Vatell, and takes the form:

\[ T = a \cdot V^3 + b \cdot V^2 + c \cdot V + d \]  

where:
- \( T \) is the temperature (in Celsius).
- \( a, b, c, d \) are the coefficients of the polynomial, which are given on the Calibration Data Sheet supplied with the sensor.
- \( V \) is the output voltage of the TC (in mV).

Note that the thermocouple output is linear, so typically \( a \) and \( b \) are zero. The higher order polynomial numbers are only used for specific custom applications. Coefficient \( d \) is a default ambient temperature. If the system is zeroed at a known temperature, use the zeroing temperature in place of \( d \). The voltage output of the TC is related to the voltage output from the amplifier by:

\[ V = \frac{V_{TC}}{G_{TC}} \]  

where:
- \( V_{TC} \) is the voltage output of the TC amplifier channel (in volts), which may be positive or negative.
- \( G_{TC} \) is the amplifier gain for the TC channel. For the AMP-12 this value is given on the Gain Settings Label on the bottom of the amplifier.
The voltage value from equation (2) can then be entered into equation (1) to determine the temperature. Once the temperature, $T$, is known, the heat flux can be computed from:

$$q'' = \frac{V_{HFS}/G_{HFS}}{g \cdot T + h}$$

(3)

where:
- $q''$ is the heat flux (in W/cm$^2$).
- $V_{HFS}$ is the instantaneous amplified voltage signal from the HFS (in $\mu$V).
- $G_{HFS}$ is the amplifier gain for the HFS channel. For the AMP-12 this value given on the Gain Settings Label on the bottom of the amplifier.
- $g, h$ are coefficients for the relationship between sensitivity and temperature. These are given on the Calibration Data Sheet.

**Example Measurement:**
The following is an example on using the HFM-8 and the AMP-12 to measure heat flux. For our example, we want to measure the heat flux in a furnace that has a thermocouple to monitor its temperature during a slow temperature ramp. Note that if a Vatell amplifier is not available, some other differential amplifier should be used to read the HFS and TC voltage outputs in order to obtain the best signal.

1. The TC offset potentiometer is adjusted until the amplifier output for the TC channel measures close to zero volts. Be sure to allow the amplifier sufficient time to warm up; this takes approximately 8 minutes for Vatell amplifiers. This will prevent drift in measurements taken later.
2. Because our system is thermally static at the moment, there is no heat flux, so we can zero the HFS signal. This is done by adjusting the HFS offset potentiometer until the amplifier output for the HFS channel measures close to zero.
3. The ambient temperature is noted to be 27°C. This measurement will be used in place of the default zeroing temperature given by coefficient $d$.
4. When the furnace is turned on, the HFS begins to register a voltage, indicating that the sensor is measuring heat flux. Note that a positive voltage indicates heat flow into the sensor face and a negative voltage indicates heat flow out of the sensor face.
5. After 1 minute, we take a measurement. The HFS channel reads 0.290 V (290,000 $\mu$V) and the TC channel reads 1.03 V. The gain setting for the HFS and TC channels are 1000 and 500 respectively. From the Gain Settings Label on the bottom of the AMP-12, we find that these correspond to actual gains of $G_{HFS} = 980.6$ and $G_{TC} = 495.1$.
6. The TC voltage computed using equation (2). For our example

$$V = \frac{V_{TC}}{G_{TC}}$$

$$= \frac{1.03V}{495.1}$$

$$= 0.00208V = 2.08mV$$

7. The temperature can now be computed from equation (1). Note that for accurate determination of the heat flux, the temperature measurement should be at the face of the sensor. This is why the TC temperature value has to be used instead of some other
temperature reading, such as that of the furnace thermocouple. Although the thin-film TC does not measure the temperature right at the face of the sensor, the measurement is spatially very close to the surface. Actual surface temperature will differ from the TC measurement depending on the level and duration of the heat flux event. The coefficients, which can be found on the Calibration Data Sheet, are \( a = 0.0, b = 0.0, c = 14.12145, \) and \( d = 30.34. \) However, because we have an ambient temperature measurement, we will use that value in place of \( d. \) The temperature is then

\[
T = a \cdot R^3 + b \cdot R^2 + c \cdot R + d
= (0.0)(2.08)^3 + (0.0)(2.08)^2 + (14.12145)(2.08) + (27)
= 56.32 ^\circ C
\]

8. Finally the heat flux, \( q'' \), is computed from equation (4), using coefficient values from the Calibration Data Sheet of \( g = 0.026844 \mu V/W/cm^2/\circ C \) and \( h = 173.2807 \mu V/W/cm^2 : \)

\[
q'' = \frac{V_{HFS}}{G_{HFS}} g \cdot T + h
= \frac{290.000 \mu V}{980.6}
\]

\[
= \frac{(0.026844 \mu V/W/cm^2/\circ C)(56.32 ^\circ C)+173.2807 \mu V/W/cm^2}
= 1.692 W/cm^2
\]

Note that if we had used coefficient \( d \) in place of the ambient temperature measurement, the heat flux value would have been 1.691 W/cm², a 0.05% difference.

**Radiation Measurements and the Importance of Emissivity**

All heat flux transducers made by Vatell are calibrated using radiative heat sources, because they are the most consistently repeatable. However, the fraction of the radiation absorbed by the transducer is never 100%, and so the absorbed heat flux differs from the incident heat flux. The relation of incident and absorbed heat flux for a radiation source is given by

\[
q_{ab}'' = \varepsilon q_{in}''
\]

where

\( \varepsilon \) is the emissivity

All Vatell heat flux transducers are calibrated in terms of incident heat flux, so that for a radiative heat flux measurement, the heat flux is simply the output voltage divided by the sensitivity of the transducer. Vatell transducers are typically coated with a high temperature black paint, which has an emissivity of 0.86 and a fairly flat spectral response over most wavelengths of interest. The output voltage from the transducer is a function of the heat flux and the sensitivity, which can be expressed as:

\[
V_o = S_{in} q_{in}'' = S_{ab} q_{ab}''
\]
where
\( V_o \) is the output voltage of the transducer
\( S_{in} \) is the sensitivity of the transducer for incident radiative heat flux; this number is given on the calibration certificate
\( q_{in} \) is the incident heat flux
\( S_{ab} \) is the sensitivity of the transducer for absorbed heat flux
\( q_{ab} \) is the absorbed heat flux

The sensitivity to incident and absorbed heat flux is related by the emissivity as:

\[
S_{in} = \varepsilon S_{ab}
\]  

(6)

To find the incident heat flux from a radiation source, use the equation

\[
q_{in} = \frac{V_o}{S_{in}}
\]

(7)

If the standard coating is removed or replaced with some other coating of known emissivity, the new emissivity must be used to calculate incident heat flux. For example, if the transducer is coated with colloidal graphite that has an emissivity of 0.82, the radiative heat flux would be given by

\[
q_{in} = \frac{V_o}{S_{in}} \cdot \varepsilon_{Standard} / \varepsilon_{graphite}
\]

(8)

**Conduction Measurements**

When the heat flux is not from a radiation source, the sensitivity should be scaled by the emissivity because the emissivity only affects radiation measurements. For a conductive heat flux, the governing equation is

\[
q_{ab} = -k \frac{\delta T}{\delta n} = \frac{V_o}{S_{ab}} = \frac{V_o \varepsilon}{S_{in}}
\]

(9)

where
\( k \) is the thermal conductance
\( \frac{\delta T}{\delta n} \) is the thermal gradient with \( n \) as the unit vector normal to the surface across which the heat flux is being measured.

**Convection Measurements**

As with conduction measurements, when measuring convective heat flux the sensitivity must be scaled by the emissivity to determine the proper value. For convection, the heat flux equation is

\[
q_{ab} = h \Delta T = \frac{V_o}{S_{ab}} = \frac{V_o \varepsilon}{S_{in}}
\]

(10)
The heat transfer coefficient is a function of the thermal conductivity of the fluid, and the fluid flow characteristics. Unfortunately fluid flow is extremely complex and difficult to model; consequently the heat transfer coefficient is difficult to determine except in an empirical fashion. Heat flux transducers are commonly used in fact to determine the heat transfer coefficient. By using the heat flux measurement in conjunction with temperature measurements of the fluid and the transducer face to obtain a $\Delta T$, the heat transfer coefficient can be found. This procedure assumes that the heat transfer coefficient for the transducer and the surrounding system are the same, so that the incident and absorbed heat fluxes are equal. The accuracy of this assumption will vary with different system configurations and materials. In general, the less the transducer alters the system the better.

**Measurements with Mixed Modes of Heat Transfer**

All three modes of heat transfer can be measured as described above. Conductive and convective modes can be mixed without any loss of accuracy in the measurement, assuming the incident and absorbed convective heat fluxes are equal. When radiation is mixed with the other modes however, there is the question of what fraction of the heat flux needs to be corrected for emissivity, and what fraction does not. Ideally the different modes can be isolated so that the question does not occur; for example, using a radiometer to view only radiation sources. If the modes cannot be differentiated experimentally, some intelligent estimates of the relative fractions of the heat flux that each mode contributes must be made. In these cases the emissivity of the HFM-8 should be as high as possible to minimize error.

**Sensor Temperature versus Application Temperature**

The HFM-8 has a thermocouple (TC) to monitor the temperature of the substrate on which the thermopile has been deposited, in order to account for temperature variations in the HFS signal. The substrate temperature that the TC measures should not be taken as the transient temperature of the test surface or the heat flux source. This is because the thermal gradient through the test surface and the HFM-8 will not be the same unless the system is in thermal equilibrium. Consequently the TC will register a transient temperature somewhere between the test surface temperature and the ambient surface temperature, as depicted below.

\[
\begin{align*}
    T_2 &= T_1 + n(\Delta T) \\
    T_3 &= T_1 + m(\Delta T)
\end{align*}
\]

\(m \neq n\) for transient
The TC can be used to measure the test surface temperature once the system is in thermal equilibrium, provided that the test surface is at a uniform temperature. In such a case the temperature gradient through the HFM-8 and the test surface will be the same because of the high thermal conductivity of the HFM-8.

**Sensor Response Time versus Amplifier Gain**

The time constant of the uncoated HFM is 17 $\mu$s, which give it a 0-95% rise time ($R$) of 50 $\mu$s. For a coated HFM, those numbers are 300 $\mu$s and 900 $\mu$s respectively. The measured response may be slower than that however, because it is dependent on the bandwidth and gain of the amplifier being used. There is an inherent trade-off between bandwidth and gain. This is usually expressed in the Gain-Bandwidth product

$$F = GB$$  \hspace{1cm} (11)\

which is a constant for simple amplifiers. Consequently, higher gains result in lower bandwidth. To take full advantage of the speed of the HFM, the bandwidth of the amplifier should be

$$B = \frac{2}{R} = \frac{2}{50 \times 10^{-6} \text{ s}} = 40 \text{ kHz}$$

Knowing the minimum bandwidth required for an application, the maximum gain can be computed. For example, to fully utilize the time response of the HFM with an amplifier having a Gain-Bandwidth product of 1 MHz, the maximum gain would be

$$G = \frac{F}{B} = \frac{1 \text{ MHz}}{40 \text{ kHz}} = 25$$

For more sophisticated amplifiers, like the Vatell AMP-12, the Gain-Bandwidth product is not necessarily constant. Refer to the specification sheet to determine bandwidth at any given gain. To keep signal noise to a minimum, one should set the gain as high as possible while keeping the bandwidth large enough to achieve the needed time response.

**HFM Calibration**

Each HFM-8 is individually calibrated in a multi-step procedure. The TC is first characterized in a computer-controlled furnace that maps voltage values to corresponding temperature values. From these data points a curve fit is performed to acquire the coefficients for equation (1).

Then the HFS is calibrated by comparing its output voltage ($V_{HFM}$) against the output voltage of a standardized reference heat flux gage ($V_{ref}$) when each gage is exposed to the same radiation heat flux source ($q''$). Both the HFM-8 and the reference gage are coated with the same high-temperature black paint, which is a high emissivity coating (so that $\varepsilon_{HFM} = \varepsilon_{ref} = 0.86$). The sensitivity of the HFM-8 ($S_{HFM}$) is calculated from the sensitivity of the reference gage ($S_{ref}$) by
\[ q'' = (S_{\text{HFM}})(V_{\text{HFM}}) = (S_{\text{ref}})(V_{\text{ref}}) \] (12)

Because the HFM-8 is calibrated to incident heat flux, the emissivity is factored into the sensitivity automatically. Equation (8) is applied to a whole series of data points during the calibration, allowing a linear fit of the data so that the coefficients of equation (3) can be obtained.

**Glossary for heat transfer**

As in any technical discussion, keeping the terminology straight is important. Refer to this glossary if things start to get confusing.

- **Heat** is the amount of energy moved across a thermodynamic barrier, and is measured in Joules (J).
- **Heat transfer** is the rate at which energy moves across the thermodynamic barrier, measured in Watts (W), that is, Joules per second. Heat transfer occurs in three different modes, conduction, convection, and radiation.
- **Heat flux** is the rate of energy transfer per unit area, expressed in W/m², W/cm², or similar units. Heat flux can be positive or negative, depending on the direction of heat transfer.
- **Temperature** is a fundamental property that indicates the internal energy of matter. Any temperature scale (Celsius, Fahrenheit, etc.) may be used as long as the units are kept consistent.
- **Conduction** is a mode of heat transfer through a substance, either solid or fluid, on a molecular level as a result of a temperature gradient being present.
- **Convection** is a mode of heat transfer when there is fluid flow. As in conduction, a temperature gradient must be present, but convection is influenced by fluid flow, which alters the temperature gradient.
- **Radiation** is a mode of heat transfer that occurs via electromagnetic radiation, and does not require any transport medium or material.
- **Emissivity** is the ratio of the actual energy emitted by a real body to that emitted by a blackbody. Emissivity can be considered equal to absorptivity for a gray body; that is a body whose emissivity is independent of wavelength and which reflects radiation in a diffuse manner. Most objects can be reasonably approximated as gray bodies.
- **A thermocouple** is used to measure temperature. It consists of a pair of junctions between two different metals that will produce a voltage proportional to the temperature difference between the junctions of the wires due to the Seebeck effect. Commercially available thermocouples will appear to have only one junction; the second junction is essentially where the two leads are connected to a voltmeter or electronic thermometer. For a thermocouple to give an accurate reading the second junction must be at a reference temperature; frequently this is taken to be room temperature. For more accurate measurements, the second junction is lowered to a known temperature, such as the ice point.
- **A thermopile** is an array of thermocouples. By connecting many thermocouples in series, the temperature sensitivity is increased, because the thermocouple voltages add when linked in series. Like a thermocouple, the thermopile reads the temperature difference between two points. For a heat flux transducer, these two points are the top and bottom layers of the thermopile.