



HUKSEFLUX
THERMAL SENSORS

APPLICATION AND SPECIFICATION OF HEAT FLUX SENSORS

Version 9904

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Hukseflux Thermal Sensors
<http://www.hukseflux.com>
P.O. BOX 2816
NL 2601 CV Delft
The Netherlands
e-mail: info@hukseflux.com

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Using Hukseflux sensor type HFP01 please read: 1.1.1., 3.1, 3.2 and 3.3

Using Hukseflux sensor type UT03 please read: 1.1.1., 3.1, 3.2, 3.3 and 3.4

Using Hukseflux sensor type HFP01-SC please read: 1.1.1., 3.1, 3.2 and 3.5

Using Hukseflux calibration facility HFCAL please read: 4

List of symbols

Thermal resistance	R	K/W
Heat capacity	C	J/K
Response time	T	s
Thickness	d	m
Thermal conductivity	λ	W/mK
Surface area	A	m ²
Density	ρ	Kg/m ³
Specific heat capacity	C _p	J.m ² /K.Kg
Voltage output	U	V
Sensitivity	E	V.m ² /W
Time	t	s
Temperature	T	K
Heat Flux	λ	W/m ²
Dynamic temperature offset	D	W/m ²
Electrical resistance	R _e	Ω
<i>Subscripts</i>		
Property of Heat Flux Sensor	sen	
Condition during calibration	cal	
Property of the film heater for self test	self	
Property of the current sensing resistor	cur	

Introduction

In many physical phenomena heat is exchanged. Everyday examples are buildings cooling down by cold wind and solar radiation heating a solar collector. Knowing the heat flow, one can analyse insulation of buildings and the efficiency of solar collectors.

Heat Flux Sensors are meant for measuring heat flows.

As such they are used in studies of thermal phenomena like the ones mentioned above.

Alternatively Heat Flux Sensors can be incorporated in measurement equipment as a sensor, for example to measure radiation.

Figure 1 shows the general characteristics of a Heat Flux Sensor.

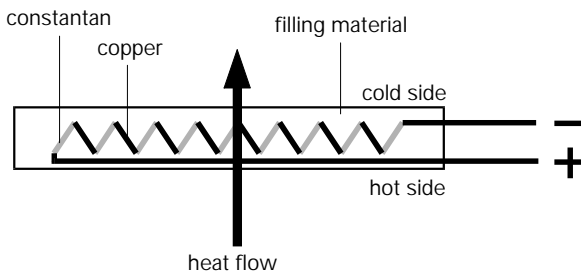


Figure 1 General characteristics of a Heat Flux Sensor. When heat is flowing through the sensor in the indicated direction, the filling material will act as a thermal resistance. Consequently the heat flow, ϕ , will go together with a temperature gradient across the sensor, flowing from the hot to the cold side. The majority of Heat Flux Sensors is based on a thermopile; a number of thermocouples connected in series. A single thermocouple will generate an output voltage that is proportional to the temperature difference between the joints (copper-constantan and constantan-copper). This temperature difference is, provided that errors are avoided, proportional to the heat flux, depending only on the thickness and the thermal conductivity of the sensor. Using more thermocouples in series, will enhance the output signal. In the picture the joints of a copper-constantan thermopile are alternatively placed on the hot- and the cold side of the sensor. The thermopile is embedded in a filling material, usually a plastic.

Each individual sensor will have its own sensitivity, E_{sen} , usually expressed in Volts output, V_{sen} , per Watt per square metre heat flux, ϕ . The flux is calculated $\phi = V_{sen} / E_{sen}$.

Heat Flux Sensors have been used since the fifties, and have proven to be very well applicable. There is a great diversity of fields of application; the scientific disciplines of building physics, agricultural meteorology and medicine are major users of Heat Flux Sensors.

Essentially, Heat Flux Sensors are very sensitive temperature difference sensors. Differences of less than 0.001 degree Celsius can easily be detected.

It has however to be acknowledged that the behaviour of Heat Flux Sensors is more complex than it seems. As a result measurement results are often misinterpreted.

Causes for this misinterpretation are error sources related to both the sensor and to the application.

This paper gives background information on Heat Flux Sensors and their application. It concentrates on the application for measurement of conductive heat fluxes in soil and in walls. As a conclusion it proposes a set of specifications that should be watched when choosing a sensor for a particular application.

Chapter 1 will give general theory, chapter 2 will treat sensor related properties and sensor related error sources.

In chapter 3 the physics and error sources of particular applications are addressed. Chapter 4 treats the subject of calibration. The quality assurance of the measurement is discussed in chapter 5 and the resulting conclusions are listed in chapter 6.

1 General theory

1.1 Frequent applications of Heat Flux Sensors

The two major applications of Heat Flux Sensors are measuring conductive heat flows and measuring radiation.

A few cases are known of Heat Flux Sensors being used for different purposes. Incorporated in measurement equipment they are used for determining mass flow of gasses, thermal conductivity of gasses, liquids and solids and hydration heat of materials.

1.1.1 Measuring conductive heat flow

Used as a sensor for measuring conductive heat flow, expressed in Watts per square metre, the sensor is simply mounted on or in the object of interest. (see figure 2). Mounted on top of an object, the sensor will also measure heat that is transferred by convection. At the sensor surface, the convective heat is transformed into conductive heat.

Frequent applications include the measurement of heat flows through walls in studies of building physics, heat flows through soils in climatological studies, and heat flows through human skin for medical studies and tests of insulation of clothing and suits. These three applications are treated below.

In the following paragraphs of this paper, under chapter 3, the same applications are again treated in more depth, specifically focusing on the role of the Heat Flux Sensor.

In building physics, a frequently occurring measurement is that of the U-value of walls. This factor contains information on the insulation of the wall. This result is obtained from long term monitoring of inside- and outside air temperature and of the heat flux.

Heat flux measurements are also used in building climate control. Knowing the heat flux through a wall, a temperature change in a room can be anticipated. This can make the control more efficient, saving energy.

In climatological studies, the measurement of heat flux through soils is used to determine evaporation of water. Besides the heat flux data,

the estimation of evaporation also requires data on solar radiation, wind speed and temperature. The estimation is used for scheduling irrigation in agriculture. This generally serves to give crops sufficient water, which is of major importance in areas where water is scarce.

In medical applications, heat exchange of human beings can be studied using Heat Flux Sensors. This information can be of use in diagnostics. Also insulation of clothing can be assessed. This is often done when designing clothing for arctic or desert environments or insulating suits for diving.

1.1.2 Measuring radiation

Apart from measuring conductive fluxes, which was done in the applications mentioned in 1.1.1, Heat Flux Sensors are often used for measuring radiation. This is not the main subject of this paper, and this application is only treated in this paragraph.

When using Heat Flux Sensors for radiation detection, one should be aware of the fact that a sensor that is mounted on the outside of an object is always, whether or not on purpose, detecting both convective and radiative fluxes.

The spectral properties are determined by the outer sensor surface.

In order to act as a radiation sensor only, the Heat Flux Sensor is provided with an absorbent coating, and is mounted on a heat sink. (see figure 3). The coating will transform radiation into a heat flux. The coating, possibly in combination with a filter, should have the right spectral properties for the specific radiation that one wants to detect.

In order to eliminate sensitivity to convective fluxes, construction should be such that convective losses are negligible. This can be achieved by creating an environment without convection, and by keeping the sensor as close as possible to ambient air temperature. Whenever the sensor temperature differs from ambient air temperature, this will cause thermal convection.

Advantages of using Heat Flux Sensors as radiation sensors are the possibilities of detecting within a broad spectral range, from UV to the Far Infra Red, and of having a large dynamic range, from weak to strong radiation intensities.

Applications are found in laser power measurement, solar energy measurement, pyrometry and burglar alarms.

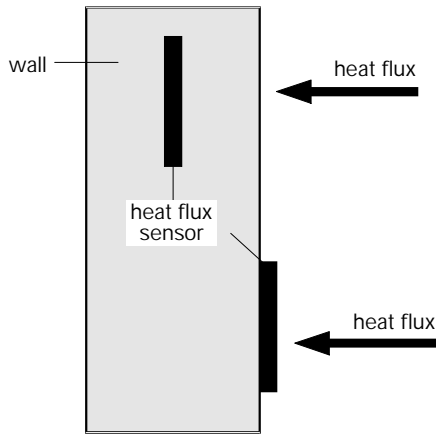


Figure 2 Estimation of conductive heat flux. The Heat Flux Sensor is simply mounted on or in the object of interest.

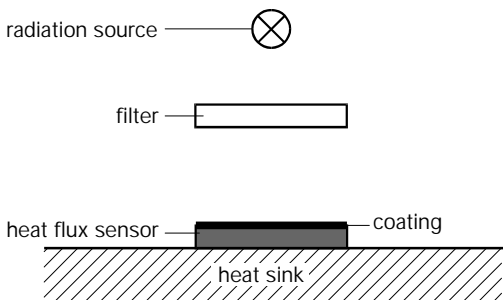


Figure 3 Heat Flux Sensor being used as a radiation sensor. The sensor is provided with a radiation absorbent coating and is mounted on a heat sink. Sometimes spectrally selective filters are used to get the total spectral properties right.

1.2 Special Heat Flux Sensor designs

In the application of measuring soil heat flux, conventional Heat Flux Sensors are not very reliable. This has to do with the fact that thermal parameters of soil are constantly changing by absorption and subsequent evaporation of water. In other applications, like building physics, the accuracy of conventional sensors is judged to be insufficient.

In some testing applications where one works with human beings, an on-line test of sensor performance is useful.

An alternative way of dealing with these problems is the use of so-called "self-calibrating heat flux plates". The working principle of this kind of sensor is described in figure 4. These sensors essentially will give an indication of the quality of

the measurement, and will show a deviation from the ideal behaviour if either the contact with the surrounding environment is lost or if the thermal properties of the sensor and the surrounding environment do not match any longer. An additional advantage is that a self test heat flux plate can easily be recalibrated by the user, only requirements are a metal block, a voltage source and a 2-channel Voltage measurement.

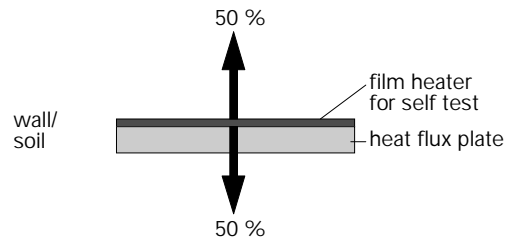


Figure 4 Self-calibrating heat flux plate. On top of a conventional heat flux sensor, a film resistor is mounted. In the ideal case, the heat that is generated by the film resistor will be equally divided between the up- and down- direction. The artificially generated heat flux is known, and the heat flux sensor output should indicate 50% of this. If the output deviates from the predicted value, either the thermal contact is disturbed, or the thermal properties of the sensor and the surrounding medium do not sufficiently match. Main applications of self-calibrating heat flux plates are the measurement of soil heat flux, testing of clothing and suits, and heat flux in walls.

For constructing radiation sensors sometimes laterally sensitive Heat Flux Sensors are used. These have the advantage that the mass can be made very low, so that sensors with rapid response times can be constructed.

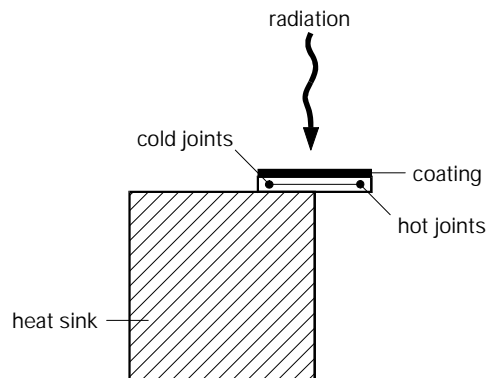


Figure 5 Radiation sensor. The sensor consists of a Heat Flux Sensor with lateral sensitivity, that is mounted on a heat sink.

2 The Heat Flux Sensor

In paragraph 2.1 the sensor properties are treated. These are roughly determined by the dimensions, the material properties of the filling material and by the electrical characteristics of the thermocouples.

Apart from these "ideal" specifications there are various error sources that are specifically caused by sensor shortcomings. Two major sources are the sensor "mass", resulting in dynamic errors, and the sensor layout, possibly resulting in sensitivity to lateral fluxes. The topic of sensor related error sources is addressed in paragraph 2.2.

Error sources that are related to the application are treated in chapter 3.

2.1 Heat Flux Sensor properties

A Heat Flux Sensor should measure the local heat flux in one direction. The result is expressed in Watts per square metre. The calculation is done according to formula 1.

$$\varphi = V_{\text{sen}} / E_{\text{sen}} \quad (1)$$

As shown before in figure 1, Heat Flux Sensors generally have the shape of a flat plate and a sensitivity in the direction perpendicular to the sensor surface.

Usually thermopiles are used. General advantages of thermopiles are their stability, low ohmic value (which implies little pickup of electromagnetic disturbances), good signal-noise ratio and the fact that zero input gives zero output. Disadvantageous is the low sensitivity.

For better understanding of Heat Flux Sensor behaviour, it can be modeled as a simple electrical circuit consisting of a resistance, R, and a capacitor, C.

In this way it can be seen that one can attribute a thermal resistance R_{sen} , a thermal capacity C_{sen} and also a response time T_{sen} to the sensor. Usually, the thermal resistance and the thermal capacity of the entire Heat Flux Sensor are equal to those of the filling material.

$$T_{\text{sen}} = R_{\text{sen}} \cdot C_{\text{sen}} = d^2 \cdot \rho \cdot C_p / \lambda \quad (2)$$

In which d is the sensor thickness, ρ the density, C_p the specific heat capacity and λ the thermal conductivity.

From 2 one can conclude that material properties of the filling material and dimensions are determining the response time.

As a rule of thumb, the response time is proportional to the thickness to the power of two.

Other parameters that are determining sensor properties are the electrical characteristics of the thermocouple.

The temperature dependence of the thermocouple causes the temperature dependence and the non-linearity of the Heat Flux Sensor. The non linearity at a certain temperature is in fact the derivative of the temperature dependence at that temperature.

However, a well designed sensor may have a lower temperature dependence and better linearity than expected. There are two ways of achieving this:

As a first possibility, the thermal dependence of conductivity of the filling material and of the thermocouple material can be used to counterbalance the temperature dependence of the voltage that is generated by the thermopile. Another possibility to minimise the temperature dependence of a Heat Flux Sensor, is to use a resistance network with an incorporated thermistor. The temperature dependence of the thermistor will balance the temperature dependence of the thermopile.

Another factor that determines Heat Flux sensor behaviour, is the construction of the sensor. In particular some designs have a strongly non-uniform sensitivity. Others even exhibit a sensitivity to lateral fluxes. The sensor in figure 1 would for example also be sensitive to heat flows from left to right.

This type of behaviour will not cause problems as long as fluxes are uniform and in one direction only.

To promote uniformity of sensitivity, a so-called sandwich construction as shown in figure 6 can be used. The purpose of the plates, which have a high conductivity, is to promote the transport of heat across the whole sensitive surface.

It is difficult to quantify non-uniformity and sensitivity to lateral fluxes. Some sensors are equipped with an extra electrical lead, splitting the sensor into two parts. If during application, there is non-uniform behaviour of the sensor or the flux, this will result in different outputs of the two parts.

Finally there is the question of stability. Material properties of the filling material and the thermopile will largely determine this. Generally, stability will have to be proven empirically, by doing repeated calibrations.

Summarising: The intrinsic specifications that can be attributed to Heat Flux Sensors are thermal conductivity, total thermal resistance, heat capacity, response time, non linearity, stability, temperature dependence of sensitivity, uniformity of sensitivity and sensitivity to lateral fluxes. For the latter two specifications, a good method for quantification is not known.

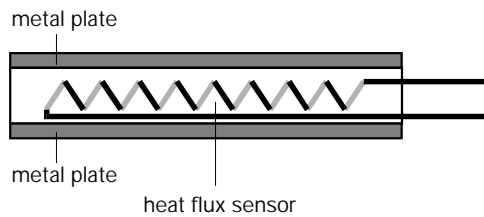


Figure 6 Sandwich construction. In order to promote uniformity of sensitivity and to minimise sensitivity to lateral fluxes, some Heat Flux Sensors are placed in a sandwich between two plates of high thermal conductivity.

2.2 Sensor related error sources

The interpretation of measurement results of Heat Flux Sensors is often done assuming that the phenomenon that is studied, is quasi-static and taking place in a direction transversal to the sensor surface. Dynamic effects and lateral fluxes are possible error sources.

2.2.1 Dynamic effects

The assumption that conditions are quasi-static should be related to the response time of the detector.

The case that the Heat Flux Sensor is used as a radiation detector (see figure 3) will serve to illustrate the effect of changing fluxes. Assuming that the cold joints of the sensor are at a constant temperature, and an energy flows from $t > 0$, the sensor response is

$$U = E \cdot (1 - e^{-t/T_{sen}}) \quad (3)$$

This shows that one should expect a false reading during a period that equals several response times, T_{sen} . Generally Heat Flux Sensors are quite

slow, and will need several minutes to reach 95% response. This is the reason why one prefers to work with values that are integrated over a long period; during this period the sensor signal will go up and down. The assumption is that errors due to long response times will cancel. The upgoing signal will give an error, the downgoing signal will produce an equally large error with a different sign. It is obvious that this will only be valid if periods with stable heat flow prevail.

In order to avoid errors caused by long response times, one should use sensors with low value of $R_{sen} \cdot C_{sen}$ (see formula 2). In other words: sensors with low mass or small thickness.

Equation 3 holds as long as the cold joints are at a constant temperature. An unexpected result shows when the temperature of the sensor changes.

Assuming that the sensor temperature starts changing at the cold joints, at a rate of $\delta T/\delta t$, starting at $t=0$, T_{sen} is the sensor response time, the reaction to this is:

$$U = E \cdot \{ \delta T/\delta t \cdot t - \delta T/\delta t \cdot T_{sen} \cdot (1 - e^{-t/T_{sen}}) \} \quad (4)$$

The term $-\delta T/\delta t \cdot T_{sen}$ can be considered to be an offset. It has to do with the fact that the sensor itself takes up energy when its temperature rises.

$$D = \delta T/\delta t \cdot R \cdot C \quad (5)$$

In the output signal the dynamic temperature offset, D , is not easily detected because it stabilises at a constant level if $\delta T/\delta t$ is constant.

The offset will be at worst when the sensor changes temperature quickly and with sensors with high resistance and high heat capacity. These dynamic temperature offsets can be avoided by using low mass Heat Flux Sensors, or stable heat sinks. Another possibility, seen in radiation sensors, is to use a compensation sensor that is exposed to the same temperature changes, but not to radiation. This compensation sensor is electrically connected in anti-series. In other measurement equipment, like thermal flow sensors, the same effect is achieved by using a symmetrical buildup. In case of a temperature change, energy will flow to both sides of the sensor at the same rate, resulting in a negligible offset.

Whether or not dynamic temperature offsets are significant in a certain application, can be estimated by comparing D of formula 5 with the occurring fluxes.

Although the case that is presented here is a single one (the sensor is mounted as in figure 3),

the point is that in all applications of Heat Flux Sensors, errors will occur due to slow response times and dynamic temperature offsets. The analysis of both the step response and the reaction to temperature changes show that, when this is possible, sensors with low mass are to be preferred.

2.2.2 Sensitivity to lateral heat flux

Using Heat Flux Sensors, it is silently assumed that heat flux is uniform and flowing perpendicular to the surface of the sensor. An exception to the rule is mentioned in paragraph 1.2. It follows that errors are made when sensors are sensitive to lateral heat fluxes or when heat is flowing in another direction. The problem of the sensor's sensitivity to lateral fluxes has been addressed in chapter 2.1. Lateral heat flux should be avoided as much as possible by choosing the right experimental setup.

3 The application of Heat Flux Sensors

Choosing a sensor for a particular application, first of all one has to consider practical things such as size, operating temperature and sensitivity. A second consideration is that the measurement should be correct. Apart from the sensor, which is treated in chapter 2, the measurement-setup or application also contains possible error sources. Assuming that the Heat Flux Sensor is applied for measuring conductive fluxes, errors can be caused by the fact that the sensor either is not calibrated under the right conditions or significantly influences the undisturbed thermal phenomenon. A third error source is the data acquisition. The paragraphs under 3.1 will treat these application related error sources. Paragraph 3.2 will focus on application for measuring soil heat flux, 3.2 will treat measurement of heat flux in walls, paragraph 3.3 will deal with measuring heat exchange of human beings.

3.1 Application related error sources

3.1.1 Traceability; application versus specification

With any sensor one can distinguish between sensor specifications and application related specifications. The overall measurement accuracy is affected by both.

As an example: A sensor has been calibrated at 20 °C, resulting in a sensitivity of 10 $\mu\text{Vm}^2/\text{W}$. Working at 120°C it will have a different sensitivity. When the sensor specification of temperature dependence of sensitivity is 0.1 %/°C, the sensitivity will be 11 $\mu\text{Vm}^2/\text{W}$. The conclusion is that the sensitivity has to be corrected under conditions that differ from the circumstances during calibration.

Calibration spec	Sensor spec.	Application	Calibration correction
T= 20°C	Temp. Dep: 0.1%/°C	120°C	+ 10%
$\phi = 500 \text{ W/m}^2$	Non linearity: 0.05 %m ² /W	800 W/m ²	+ 15%
...			

Table 1 Traceability
The schedule shows how calibration can be corrected in a certain application. One needs information on the calibration, on the sensor and on the application.

3.1.2 Distortion of the original thermal phenomenon

It is obvious that there is a possibility that the sensor significantly disturbs the phenomenon that it is supposed to measure; by adding a sensor to the material under observation, one adds some extra and sometimes differing thermal resistance's, contact resistance's and spectral properties. These error sources will be treated in the following text.

Knowing that the heat flux is likely to be disturbed by the Heat Flux Sensor, the sensor should have a large surface; a small surface would show a proportionally large dependency on local conditions and of local irregularities.

As a rule, a surface area of at least $4 \cdot 10^{-4} \text{m}^2$ is suggested.

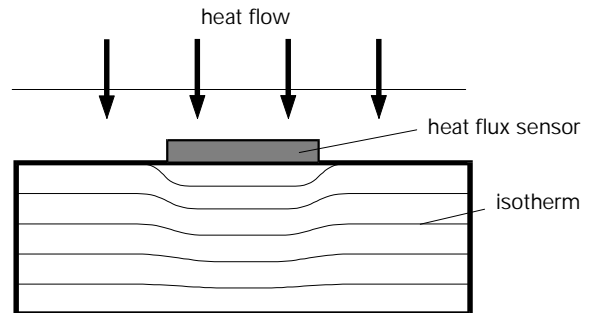
It has been shown by Van der Graaf [1] that resistance effects can be separated into two classes: a resistance error and a deflection error. (see figures 8 and 9). Both errors add.

The resistance error represents the case in which a sensor is mounted on or in an existing material. The total heat resistance changes, and therefore the heat flux is not representative any more. This error is relevant when mounting sensors on walls and on human skin. A typical value for a 10 cm insulating wall is 5%. This error can easily be calculated and corrected for. The resistance error can also be minimised by using a thin sensor.

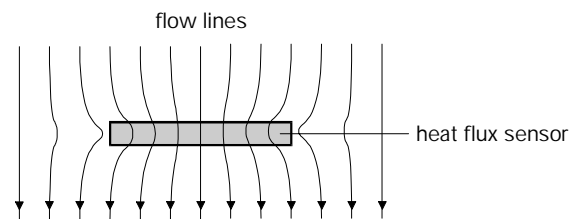
The deflection error represents the effect that as a result of differing resistance's the flow pattern will change, especially at the edges of the Heat Flux Sensor. An order of magnitude of this error for strongly different thermal conductivity's between sensor and its environment (0.6 for a typical sensor and 0.03 for an insulating wall) is 40%.

The deflection error can be minimised by using a guard, which is a non-sensitive part consisting of the same filling material, around the sensitive area. The flow pattern may be irregular at the guard. This however will not influence the measurement. At the sensitive area, the flow pattern will be improved.

In some applications, the deflection error is the largest error source. In particular this is true for measurements in soils, where the thermal properties of the medium (and with it the deflection error) are constantly changing.



*Figure 7 Resistance error
Added or less resistance will cause that less or more heat will flow through the part of the material where the sensor is mounted.*



*Figure 8 Deflection error
The heat flux is deflected at the edges of the sensor. As a result, the heat flow at the edges is not representative.*

Apart from the sensor thermal resistance, contact resistance's between sensor and surrounding material are demanding special attention. In all cases the contact between sensor and surrounding material should be as well and as stable as possible, so that it is not influencing the measurement. It should be noted that the conductivity of air is approximately 0.02 W/m.K , ten times smaller than that of the Heat Flux Sensor [3]. It follows that air gaps form major contact resistance's. Usually air gaps are filled using glues or pastes.

The aspects of differing thermal properties between sensor and its environment and contact resistance can also be dealt with during the

measurement using a "self-calibrating Heat Flux Sensor" (see 1.2 and 3.2).

Finally spectral properties of the Heat Flux Sensor can influence the measurement.

When measuring radiant heat transfer, the sensor surface should have the same absorption and reflection properties as the surface under observation. This is especially recommendable when solar radiation is involved; spectral differences of different materials are typically large in the solar range of the spectrum. Solar radiation intensities are typically large, ranging from 0 to 1300 W/m².

If no solar-, but only Far Infra Red radiation is involved, most materials and paints behave like black bodies, metals excepted. Intensities are proportional to the temperature difference between sensor surface and the object within the field of view, typically 5 W/m² per degree temperature difference. In this case the spectral properties of the sensor surface are less significant.

3.1.3 Data acquisition

Because of the low sensitivity of Heat Flux Sensors, the readout of the sensor signal is critical. Outputs of Heat Flux Sensors are generally in the 0 to 50 millivolt range.

When choosing the data acquisition equipment, one should watch the following specifications:

- Sensor output range (equals expected heat flux range multiplied by sensitivity)
- Sensor impedance
- Wiring impedance
- Readout range
- Readout temperature dependence of sensitivity
- Readout zero offset (output at short circuited input, 0 Volt)
- Readout temperature dependence of zero offset
- Readout input impedance
- Readout resolution of analog to digital conversion

The sensor output range should match the readout input range.

If one has a certain accuracy demand, this implies that readout zero offset and resolution should be an order of magnitude better than this, at all relevant temperatures.

As a rule sensor impedance should be as low as possible, to avoid pickup of electromagnetic disturbances. In most surroundings with electrical noise, one should preferably use sensors with an impedance below 500 ohms.

To avoid sensitivity loss, the input impedance of the readout equipment should be larger than the combined resistance of sensor and wiring. It is advised to use a readout device with an input impedance that is at least 1000 times higher. In this case the sensitivity will be affected less than 0.1%. A typical cable resistance is 0.1 Ω/ m.

3.2 Measuring soil heat flux

Soil heat flux is a most important parameter in agro-meteorological studies. Typically two or three sensors are buried in the ground around a meteorological station at a depth of around 4 cm below the surface. In many aspects this measurement is comparable to the measurement of heat flux in walls. (see 3.3).

The problems that are encountered in soil are threefold: First is the fact that the thermal properties of the soil are constantly changing by absorption and subsequent evaporation of water. Secondly the flow of water through the soil also represents a flow of energy, going together with a "thermal shock", which often is misinterpreted by conventional sensors. The third aspect of soil is that by the constant process of wetting and drying and by the animals living in the soil, the quality of the contact between sensor and soil is not known. The result of all this is the quality of the data in soil heat flux measurement is not under control; the measurement of soil heat flux is considered to be extremely difficult.

3.2.1 Conventional methods

Conventional methods of measuring soil heat flux simply consist of burying a conventional heat flux sensor. Apart from the defects that are described above, most conventional heat flux sensors do not have a thermal resistance that is matched to that of the soil, which causes large errors.

3.2.2 Using temperature difference sensors

A way of getting around several of the shortcomings of conventional sensors, is to do a number of temperature measurements at different levels in the soil. The advantages are evident, the disadvantages are that one needs an estimation of the thermal conductivity of the soil

at all times, an accurate positioning of the temperature sensors, and an accurate differential temperature measurement.

3.2.3 Using self-calibrating heat flux plates

A new, and probably the best solution for measuring soil heat flux with a well known level of accuracy, is to use a self-calibrating heat flux plate. This method is developed at Hukseflux.

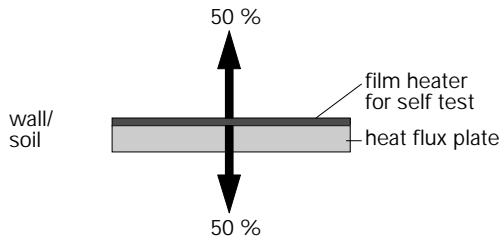


Figure 9 In the self-calibrating heat flux plate, a heater is incorporated. The reaction to a pulse in heating represents the currently valid calibration constant. This principle is valid in all environments, and eliminates errors due to the changing thermal conductivity of the environment (soil moisture), which causes the deflection error and temperature. (In reality, the heat fluxes will deviate from 50%. For calculation purposes however, the 50% -50% division remains valid. Actually, in the ideal situation 50% of the generated flux ϕ would pass through the plate (typically 150 W/m^2). In case of non matching thermal conductivities, a deviation (X) will occur. The essence of this approach is that the flow is divided in an upward flow through undisturbed medium ($1+X$) and a downward flow through the heat flux sensor (a disturbance) plus underlying medium. The difference in signal level still represents the same 0.5ϕ , automatically correcting for disturbances of the flow, and sensor instability.

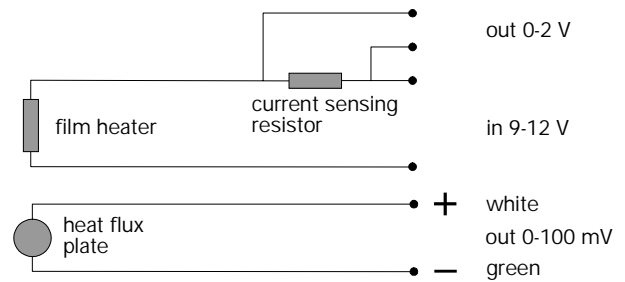


Figure 10 The electrical connection of a self-calibrating heat flux plate. The film heater for self test is attached to the heat flux sensor in order to generate a well known heat flux when this is judged to be necessary. This is done by closing a relay. The resistance of the film heater for self test, R_{self} , is known, also the sensor surface, A_{sen} , is known. R_{self} typically is 100Ω , A_{sen} typically is $40.71 \cdot 10^{-4} \text{ m}^2$. The current through R_{self} is measured by doing a voltage measurement across a current sensing resistor, with a known R_{cur} . This setup is chosen to avoid errors due to variations in the supply voltage and errors by a varying length of the lead wires.

The self-calibrating possibility generally is switched on every two hours. The total self test takes about 8 minutes. During these 8 minutes, a current is lead through the film resistor for self test, in order to generate a well known heat flux. The difference in voltage output of the sensor when heating and not heating, V_{sen} , during the experiment multiplied by 2 (because only half of the flux passes the sensor) divided by the heat flux, ϕ_{sen} , is the valid sensor sensitivity, E_{sen} . Typically measurements are done at 0 and 190 seconds.

$$\phi_{sen} = (V_{cur}^2 \cdot R_{self}) / (R_{cur}^2 \cdot A_{self}) \quad (6)$$

$$V_{sen} = V_{sen}(0) - V_{sen}(190) \quad (7)$$

$$E_{sen} = 2 \cdot V_{sen} / \phi_{sen} \quad (8)$$

Concluding:

$$E_{sen} = 2 \cdot [V_{sen}(0) - V_{sen}(190)] \cdot (R_{cur}^2 \cdot A_{self}) / (V_{cur}^2 \cdot R_{self}) \quad (9)$$

For type HFP-01 SC a A_{self} of ($d=72 \text{ mm}$), a R_{cur} of 10Ω and a R_{self} of 100Ω , $\phi_{sen} = 246 \cdot V_{cur}^2$. Please mind that V_{cur} in this case is about 0.1 times the voltage that is applied across the total circuit. At a 12 Volt power supply, V_{cur} would be 1.09 Volt, the heat flux would be 292 W/m^2 , half of which would pass the Heat Flux Sensor. Power would be around 1.3 Watt, of which about 0.12 Watt would be consumed in the sensing resistor.

For type HFP-01SC:

$$E_{\text{sen}} = [V_{\text{sen}}(0) - V_{\text{sen}}(190)] / 123 * V_{\text{cur}}^2(0) \quad (5)$$

In normal soils, corrections of up to 20% relative to the normal calibration coefficient can be expected.

If *self-calibrating* heat flux sensors are used, there are additional requirements for data acquisition and control:

- a programmable or otherwise controllable relay
- 9-15 VDC 1.5 Watt power supply
- Voltage readout

The timing of the self-calibrating could be as follows.

Time	Film resistor for self test	Readout of V_{sen}	Readout of V_{cur}
Repetition every two hours or event controlled			
0	off	$V_{\text{sen}}(0)$	$V_{\text{cur}}(0)$
10	off	$V_{\text{sen}}(10)$	$V_{\text{cur}}(10)$
20	on	$V_{\text{sen}}(20)$	$V_{\text{cur}}(20)$
180	on	$V_{\text{sen}}(180)$	$V_{\text{cur}}(180)$
190	on	$V_{\text{sen}}(190)$	$V_{\text{cur}}(190)$
200	off	$V_{\text{sen}}(200)$	$V_{\text{cur}}(200)$

3.3 Measuring heat flux in walls

The measurement of heat flux in walls is comparable to that in soil in many respects. Two major differences however are the fact that the thermal properties of a wall generally do not change and that it is not always possible to insert the Heat Flux Sensor in the wall, so that it has to be mounted on top of the wall.

When the Heat Flux Sensor has to be mounted on top of the wall, one has to take care that the added thermal resistance is not too large. Also the spectral properties should be matching those of the wall as closely as possible. If the sensor is exposed to solar radiation, this is especially important. In this case one should consider to paint the sensor in the same color as the wall. Also in walls the use of *self-calibrating* heat flux sensors should be considered.

3.4 Measuring heat exchange of human beings

The measurement of the heat exchange of human beings is of importance for medical studies, and when designing clothing, immersion suits and sleeping bags.

A difficulty during this measurement is that the human skin is not particularly suitable for mounting of heat flux sensors. Also the sensor has to be thin; the skin essentially is a constant temperature heat sink, so added thermal resistance has to be avoided. Another problem is that test persons might be moving. The contact between the test person and the sensor can be lost. For this reason, whenever a high level of quality assurance of the measurement is required, it can be recommended to use a self-calibrating sensor.

4 The calibration of Heat Flux Sensors

The sensitivity E of a Heat Flux Sensor is defined as the output V for each Watt per square metre heat flowing through it, in a stationary transversal heat flow, see equation 1.

In a relatively well known method for calibration of Heat Flux Sensors, two plates of different temperatures are used. (see figure 11).

A well known heat flux is created by putting a plate of known thickness and thermal conductivity between the plates. In this heat flux a Heat Flux Sensor is placed for calibration.

A drawback of this method is that the accuracy of the relevant parameters (temperature measurements, the thickness, the conductivity and unknown contact resistance's) are large possible error sources.

A more sophisticated method [1] uses an additional Heat Flux Sensor and a heating element (see figure 12). In this way the only parameters are the heater power consumption and the heater area. These parameters can be determined with a high accuracy, resulting in a calibration with a higher reliability.

During calibration a stable signal should not be mistaken for a stationary flow. An additional temperature measurement should be done in order to check for dynamic temperature offsets as mentioned in paragraph 2.2.1.

Once a Heat Flux Sensor has been calibrated in an absolute way, as described above, it is possible to calibrate similar types using the calibrated sensor as a reference. These

comparative methods are generally simpler to perform and are more efficient in production.

With each calibration, at least information should be given on the sensor temperature and heat flux at which the calibration has been performed. This will serve for correction of the sensitivity in case of significant non-linearity and temperature dependence.

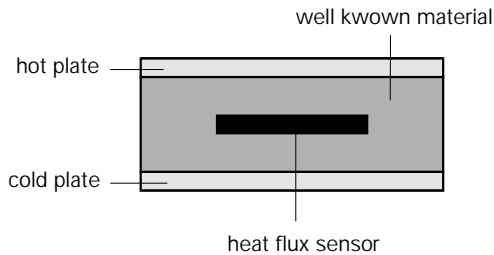


Figure 11 Measuring setup to determine the calibration factor of a Heat Flux Sensor. Hot and cold plates are temperature stabilised. The material between the plates is of known conductivity and thickness.

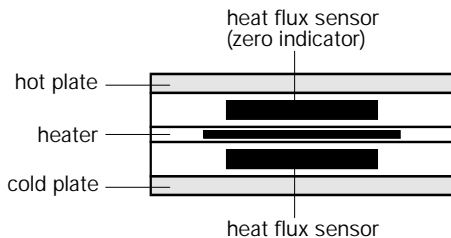


Figure 12 Measuring setup to determine the calibration factor of a Heat Flux Sensor. The heater is controlled in such a way that the zero-indicator (a Heat Flux Sensor) reads zero all the time. The heat flux equals the heater power consumption divided by the heater area.

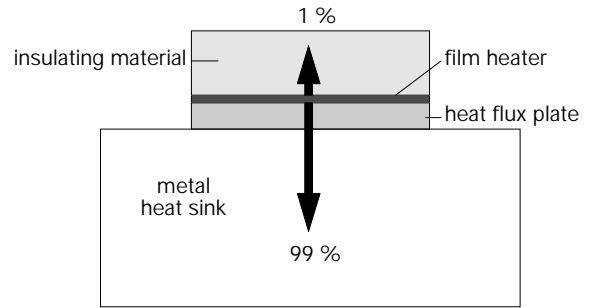


Figure 13 A modification of the method of figure 12: a self-calibrating Heat Flux Sensor is calibrated by mounting it on a metal heat sink with a constant temperature. When the thermal conductivity of the sensor is 0.8 W/m.K , at a heat flux of 300 W/m^2 , and a sensor thickness is 5mm , the temperature raise at the heater is 2 degrees. For an un-insulated sensor, this would result in an error of about 20 W/m^2 because of radiative and convective losses. For this reason the heater is again insulated, using foam insulating material. Now 99% of the heat flux passes through the sensor. As a result the accuracy is about 1%. As a result, a self-calibrating Heat Flux Sensor can easily be recalibrated by the user, only requiring a block of metal, insulating material, a voltage source and 2-channel Voltage data acquisition.

5 Quality assurance of the heat flux measurement

A problem with the measurement of heat flux is that in many applications the accuracy of the measurement is not known.

There are several methods to improve the reliability of the data; by data analysis using software, by doing additional temperature measurements and by using self-calibrating heat flux plates.

Software can be used to analyse unlikely events, like a heat flux that changes too quickly, that gets too high or that gets too low.

As an example, for soil heat flux, fluxes during daytime are generally positive and lower than 1000 W/m^2 . During night-time they are negative but not smaller than -200 W/m^2 . At a characteristic depth of 4 cm , changes quicker than $0.2 \text{ W/m}^2/\text{s}$ are unlikely to occur.

Additional temperature measurement is useful to detect the danger of dynamic temperature offsets (see 2.2.1).

Finally in demanding applications in which the Heat Flux Sensor is built-in, a *self-calibrating* heat flux plate can be used. Using this type of sensor, and the additional evaluation by software (see 3.2.3) is a very powerful tool in quality assurance of the data.

6 Conclusions

When choosing Heat Flux Sensors for a particular application, one will have to compromise between different sensor specifications. The choice will depend on the application.

The checklist below can be used as a first guideline.

Whenever this is possible, sensors of the lowest mass and largest area are to be preferred.

Designing an experiment, errors can be avoided by choosing the right setup. Please mind the following:

Application specifications

1. Maximum rate of temperature change
2. Occurrence of lateral fluxes
3. Data acquisition
4. Calibration conditions versus application conditions
5. Change of thermal parameters of the medium (eliminated using the self-calibration technique)
6. Allowable size
7. Heat flux time constants
8. Temperature dependence medium (eliminated using the self-calibration technique)

If used in an application measuring soil heat flux, heat flux in walls, tests with living test persons or applications in which quality control of the data and recalibration is particularly important, the use of *self-calibrating* heat flux plates could be considered.

Based upon the previous chapters, the checklist below can be suggested.

All specifications are supposed to be relative to calibration conditions.

Part of the terminology is taken from the ISO specification of radiation sensors [3].

Sensor specifications

1. Sensitivity
2. Response time (95% of end value, theoretical value based on sensor properties)
3. Non-linearity (output at twice the input during calibration, minus two times the output during calibration, divided by two times the output during calibration)
4. Sensitive area
5. Thermal conductivity
6. Thermal Resistance
7. Heat capacity
8. Guard area
9. Non stability (maximum % change of sensitivity per year under calibration conditions, empirical value)
10. Operating temperature

Electrical specifications

1. Impedance
2. Specifications of incorporated temperature sensor (if applicable)

Optical specifications

1. Spectral properties of the sensor surface

Calibration specifications

2. Temperature
3. Heat flux

Data quality assurance

1. Film resistor for self test
2. Software
3. Additional temperature measurement

7 References

- [1] Van der Graaf, F., Sensors: Heat Flux Sensors, Gopel, W., Hesse, J., Zemel, J.N., (eds); VCH Verlagsgesellschaft mbH.
- [2] Ortolano, D.J., Hines, F.F., A simplified Approach to Heat Flow Measurement, Advances in Instrumentation Volume 38, part 2. Proceedings of the International Conference and Exhibit, Houston Texas October 10-13, 1983. Instrument Society of America, 1983.
- [3] Holman, J.P., Heat Transfer; McGraw-Hill, 1990.
- [4] International Standard 9060, First edition 1990-11-01, Solar Energy-Specification and classification of instruments for measuring hemispherical solar and direct solar radiation, ISO 1990