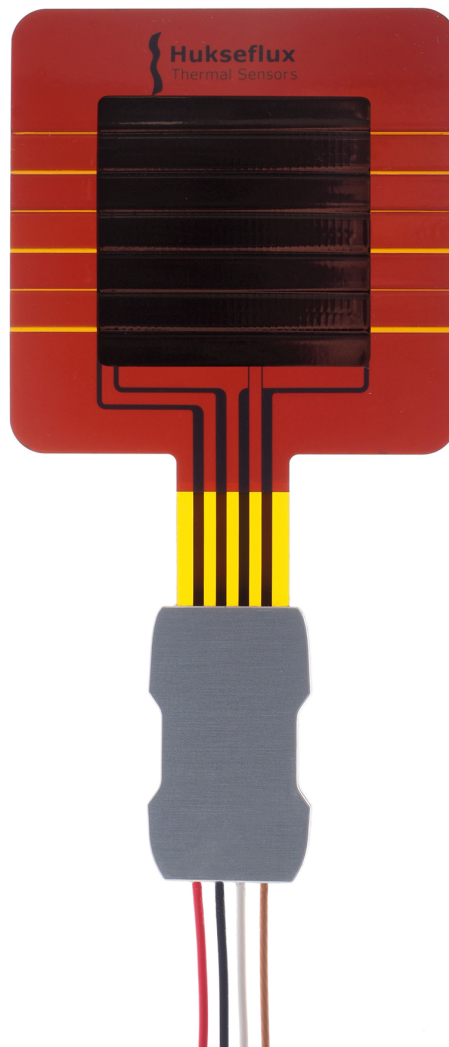


USER MANUAL **FHF02**

Foil heat flux sensor with thermal spreaders,
flexible, 50 x 50 mm, with temperature sensor



Warning statements



Putting more than 12 Volt across the sensor wiring can lead to permanent damage to the sensor.



Do not use "open circuit detection" when measuring the sensor output.

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List of symbols

Quantities

Heat flux
Voltage output
Sensitivity
Temperature
Thermal resistance per unit area

Symbol

Φ
U
S
T
 $R_{\text{thermal,A}}$

Unit

W/m²
V
V/(W/m²)
°C
K/(W/m²)

subscripts

property of heatsink
maximum value, specification limit

heatsink
maximum

Introduction

FHF02 is our standard model for general-purpose heat flux measurement. FHF02 is very versatile: it has an integrated temperature sensor and thermal spreaders to reduce thermal conductivity dependence. It is applicable over a temperature range from -40 to $+150$ °C. FHF02 measures heat flux from conduction, radiation and convection. It is often applied as part of a larger test- or measuring system.

FHF02 measures heat flux through the object in which it is incorporated or on which it is mounted, in W/m^2 . The sensor in FHF02 is a thermopile. This thermopile measures the temperature difference across the flexible body of FHF02. A type T thermocouple is integrated as well. The thermopile and thermocouple are passive sensors; they do not require power.

A thermal spreader, which is a conductive layer covering the sensor, helps reduce the thermal conductivity dependence of the measurement. With its incorporated spreaders, the sensitivity of FHF02 is independent of its environment. Many competing sensors do not have thermal spreaders. The passive guard area around the sensor reduces edge effects and is used for mounting.

Using FHF02 is easy. It can be connected directly to commonly used data logging systems. The heat flux in W/m^2 is calculated by dividing the FHF02 output, a small voltage, by the sensitivity. The sensitivity is provided with FHF02 on its product certificate.

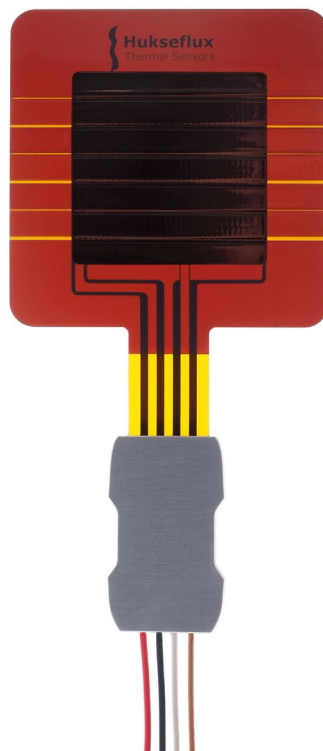


Figure 0.1 FHF02 foil heat flux sensor with thermal spreaders: thin, flexible and versatile

FHF02 foil heat flux sensor has unique features and benefits:

- flexible (bending radius $\geq 50 \times 10^{-3}$ m)
- low thermal resistance
- wide temperature range
- fast response time
- large guard area
- integrated type T thermocouple
- robustness, including wiring with strain relief block
- IP protection class: IP67 (essential for outdoor application)
- thermal spreader included, low thermal conductivity dependence

Equipped with wires with strain relief, protective covers on both sides and potted so that moisture does not penetrate the connection block, FHF02 has proven to be very robust and stable.

FHF02 calibration is traceable to international standards. The factory calibration method follows the recommended practice of ASTM C1130.

FHF02 has been calibrated using a well-conducting metal heat sink, representing a typical industrial application, at 20 °C and exposing it to a conductive heat flux. When used under conditions that differ from the calibration reference conditions, for example at extremely high or low temperatures, or exposed to radiative flux, the FHF02 sensitivity to heat flux may be different than stated on the certificate. In such cases, the user may choose:

- not to use the sensitivity and only perform relative measurements / monitor changes
- reproduce the calibration conditions by mounting the sensor on or between metal foils
- design a dedicated calibration experiment, for example using a foil heater which generates a known heat flux
- paint the sensor surface (black) to absorb radiation

If the sensitivity of a single sensor is too low, two or more sensors can be put in series electrically, creating an amplified single output signal. The user should analyse his own experiment and make his own uncertainty evaluation.

See also:

- model [FHF01](#) for increased flexibility
- model [FHF02SC](#) self-calibrating foil heat flux sensor with heater
- model [FHF03](#), our most economical foil heat flux sensor
- model [HFP01](#) for increased sensitivity (also consider putting two or more FHF02's in series)
- model [LI19](#) hand-held read-out unit / datalogger
- view our complete [range of heat flux sensors](#)

1 Ordering and checking at delivery

1.1 Ordering FHF02

The standard configuration of FHF02 is with 2 metres of wire.

Common options are:

- with longer wire length, specify desired wire length in m
- with **LI19** hand-held read-out unit / datalogger

1.2 Included items

Arriving at the customer, the delivery should include:

- heat flux sensor FHF02 with wires of the length as ordered
- product certificate matching the instrument serial number



Figure 1.2.1 FHF02's serial number and sensitivity are visible on the strain relief block. FHF02 is delivered with bundled wiring.

1.3 Quick instrument check

A quick test of the instrument can be done by connecting it to a multimeter.

1. Check the sensor serial number and sensitivity on the sticker on the strain relief block against the product certificate provided with the sensor.
2. Inspect the instrument for any damage.
3. Check the electrical resistance of the sensor between the red [+] and black [-] wires. Use a multimeter at the 100 Ω range. Measure the sensor resistance first with one polarity, then reverse the polarity. Take the average value. The typical resistance of the wiring is 0.1 Ω /m. Typical resistance should be the nominal sensor resistance of 80 Ω plus 0.2 Ω for the total resistance of two wires (back and forth) for each m. Infinite resistance indicates a broken circuit; zero or a lower than 1 Ω resistance indicates a short circuit.
4. Check the electrical resistance of the thermocouple between the brown [+] and white [-] wires. Use a multimeter at the 100 Ω range. Measure the sensor resistance first with one polarity, then reverse the polarity. Take the average value. The typical resistance of the wiring is 0.1 Ω /m. Typical resistance should be the nominal thermocouple resistance of 5 Ω plus 0.2 Ω for the total resistance of two wires (back and forth) of each m. Infinite resistance indicates a broken circuit; zero or a lower than 1 Ω resistance indicates a short circuit.
5. Check if the sensor reacts to heat: put the multimeter at its most sensitive range of DC voltage measurement, typically the 100 x 10⁻³ VDC range or lower. Expose the sensor to heat. Exposing the back side to heat should generate a positive signal between the red [+] and black [-] wires. Doing the same at the front side, reverses the sign of the output.

2 Instrument principle and theory

FHF02's scientific name is heat flux sensor. A heat flux sensor measures the heat flux density through the sensor itself. This quantity, expressed in W/m^2 , is usually called "heat flux".

FHF02 users typically assume that the measured heat flux is representative of the undisturbed heat flux at the location of the sensor. Users may also apply corrections based on scientific judgement.

The sensor in FHF02 is a thermopile. This thermopile measures the temperature difference across the polyimide body of FHF02. Working completely passive, the thermopile generates a small voltage that is a linear function of this temperature difference. The heat flux is proportional to the same temperature difference divided by the effective thermal conductivity of the heat flux sensor body.

Using FHF02 is easy. For readout the user only needs an accurate voltmeter that works in the millivolt range. To convert the measured voltage, U , to a heat flux Φ , the voltage must be divided by the sensitivity S , a constant that is supplied with each individual sensor.

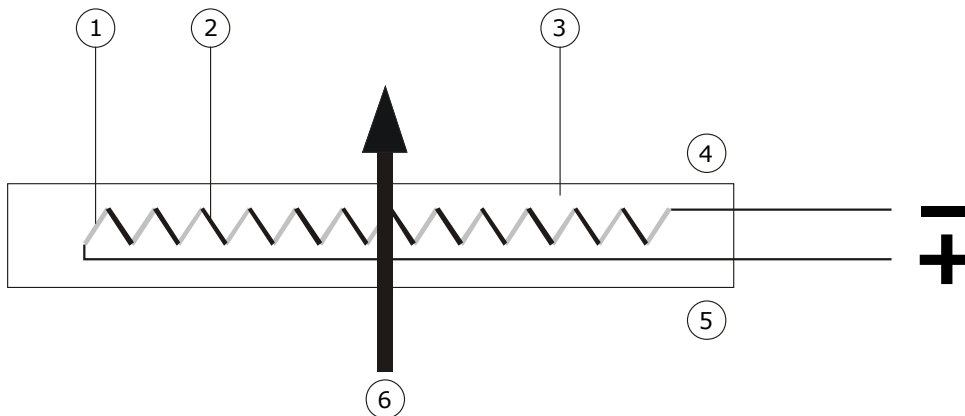


Figure 2.1 The general working principle of a heat flux sensor. The sensor inside FHF02 is a thermopile. A thermopile consists of a number of thermocouples, each consisting of two metal alloys marked 1 and 2, electrically connected in series. A single thermocouple generates an output voltage that is proportional to the temperature difference between its hot- and cold joints. Putting thermocouples in series amplifies the signal. In a heat flux sensor, the hot- and cold joints are located at the opposite sensor surfaces 4 and 5. In steady state, the heat flux 6 is a linear function of the temperature difference across the sensor and the average thermal conductivity of the sensor body, 3. The thermopile generates a voltage output proportional to the heat flux through the sensor. The exact sensitivity of the sensor is determined at the manufacturer by calibration, and can be found on the product certificate that is supplied with each sensor.

FHF02 is designed such that heat flux from the back side to the front side (side with sticker, logo readable) generates a positive voltage output signal.



Figure 2.2 Heat flux from the back side to the front side (side with sticker, logo readable) generates a positive voltage output signal

Unique features of FHF02 include flexibility (bending radius $\geq 50 \times 10^{-3}$ m), low thermal resistance, a wide temperature range, a fast response time, wiring with strain relief block for robustness, IP67 protection class rating (essential for outdoor application), and the inclusion of thermal spreaders to reduce thermal conductivity dependence.

The FHF02 is calibrated under the following reference conditions:

- conductive heat flux (as opposed to radiative or convective heat flux)
- homogeneous heat flux across the sensor and guard surface
- room temperature
- heat flux in the order of 600 W/m^2
- mounted on aluminium heat sink

FHF02 has been calibrated using a well-conducting metal heat sink, representing a typical industrial application, at $20 \text{ }^\circ\text{C}$ and exposing it to a conductive heat flux. When used under conditions that differ from the calibration reference conditions, for example at extremely high or low temperatures, or exposed to radiative flux, the FHF02 sensitivity to heat flux may be different than stated on the certificate. In such cases, the user may choose:

- not to use the sensitivity and only perform relative measurements / monitor changes
- reproduce the calibration conditions by mounting the sensor on or between metal foils
- design a dedicated calibration experiment, for example using a foil heater which generates a known heat flux
- paint the sensor surface (black) to absorb radiation

The user should analyse his own experiment and make his own uncertainty evaluation. The FHF02 operating temperature range is -40 to $+150 \text{ }^\circ\text{C}$. Prolonged exposure to temperatures near $+150 \text{ }^\circ\text{C}$ can accelerate the aging process.

3 Specifications of FHF02

3.1 Specifications of FHF02

FHF02 measures the heat flux density through the surface of the sensor. This quantity, expressed in W/m^2 , is called heat flux. Working completely passive, using a thermopile sensor, FHF02 generates a small output voltage proportional to this flux. It can only be used in combination with a suitable measurement system.

Table 3.1 Specifications of FHF02 (continued on next page)

FHF02 SPECIFICATIONS	
Sensor type	foil heat flux sensor
Sensor type according to ASTM	heat flow sensor or heat flux transducer
Measurand	heat flux
Measurand in SI units	heat flux density in W/m^2
Measurement range	$(-10 \text{ to } +10) \times 10^3 \text{ W/m}^2$ at heat sink temperature $20 \text{ }^\circ\text{C}$ see appendix for detailed calculations
Sensitivity range	$(4 \text{ to } 8) \times 10^{-6} \text{ V/(W/m}^2)$
Sensitivity (nominal)	$5.5 \times 10^{-6} \text{ V/(W/m}^2)$
Directional sensitivity	heat flux from the back side to the front side (side with sticker, logo readable) generates a positive voltage output signal
Increased sensitivity	multiple sensors may be put electrically in series. The resulting sensitivity is the sum of the sensitivities of the individual sensors
Expected voltage output	$(-80 \text{ to } +80) \times 10^{-3} \text{ V}$ turning the sensor over from one side to the other will lead to a reversal of the sensor voltage output
Measurement function / required programming	$\Phi = U/S$
Required readout	1 differential voltage channel or 1 single ended voltage channel, input resistance $> 10^6 \text{ } \Omega$
Optional readout	1 temperature channel
Rated load on a single wire	$\leq 1.6 \text{ kg}$
Rated bending radius	$\geq 50 \times 10^{-3} \text{ m}$
Operating temperature range	$-40 \text{ to } +150 \text{ }^\circ\text{C}$
Temperature dependence	$< 0.3 \text{ } \%/^\circ\text{C}$
Non-linearity	$< \pm 2 \text{ } \%$ ($0 \text{ to } 3.5 \times 10^3 \text{ W/m}^2$)
Solar absorption coefficient	0.75 (indication only)
Thermal conductivity dependence	negligible
Sensor length and width	$(50 \times 50) \times 10^{-3} \text{ m}$
Sensing area	$9 \times 10^{-4} \text{ m}^2$
Sensing area length and width	$(30 \times 30) \times 10^{-3} \text{ m}$
Passive guard area	$16 \times 10^{-4} \text{ m}^2$
Guard width to thickness ratio	22 m/m
Sensor thickness	$0.9 \times 10^{-3} \text{ m}$
Sensor thermal resistance	$30 \times 10^{-4} \text{ K/(W/m}^2)$
Sensor thermal conductivity	$0.29 \text{ W/(m}\cdot\text{K)}$
Response time (95 %)	10 s
Sensor resistance range	50 to $100 \text{ } \Omega$
Required sensor power	zero (passive sensor)
Temperature sensor	type T thermocouple incorporated
Thermal spreaders	incorporated

Table 3.1 Specifications of FHF02 (started on previous page)

Standards governing use of the instrument	ASTM C1041 - 10 Standard Practice for In-Situ Measurements of Heat Flux in Industrial Thermal Insulation Using Heat Flux Transducers
Standard wire length	2 m
Wiring	3 x copper and 1 x constantan wire, AWG 24, stranded
Wire diameter	1 x 10 ⁻³ m
Marking	1 x sticker on strain relief block, showing serial number and sensitivity
IP protection class	IP67
Rated operating relative humidity range	0 to 100 %
Gross weight including 2 m wires	approx. 0.5 kg
Net weight including 2 m wires	approx. 0.5 kg
INSTALLATION AND USE	
Recommended number of sensors	2 per measurement location
Installation	see recommendations in this user manual
Bending	see chapter on installation on curved surfaces
Wire extension	see chapter on wire extension or order sensors with longer wires
CALIBRATION	
Calibration traceability	to SI units
Product certificate	included (showing calibration result and traceability)
Calibration method	method FHFC, according to ASTM C1130 - 17
Calibration hierarchy	from SI through international standards and through an internal mathematical procedure
Calibration uncertainty	< ± 5 % (k = 2)
Recommended recalibration interval	2 years
Calibration reference conditions	20 °C, heat flux of 600 W/m ² , mounted on aluminium heat sink, thermal conductivity of the surrounding environment 0.0 W/(m·K)
Validity of calibration	based on experience the instrument sensitivity will not change during storage. During use the instrument "non-stability" specification is applicable. When used under conditions that differ from the calibration reference conditions, the FHF02 sensitivity to heat flux may be different than stated on its certificate. See the chapter on instrument principle and theory for suggested solutions
Field calibration	is possible by comparison to a calibration reference sensor. Usually mounted side by side, alternative on top of the field sensor. Preferably reference and field sensor of the same model and brand. Typical duration of test > 24 h
MEASUREMENT ACCURACY	
Uncertainty of the measurement	statements about the overall measurement uncertainty can only be made on an individual basis.
VERSIONS / OPTIONS	
With longer wire length	option code = wire length in metres
ACCESSORIES	
Hand-held read-out unit	LI19 handheld read-out unit / datalogger

3.2 Dimensions of FHF02

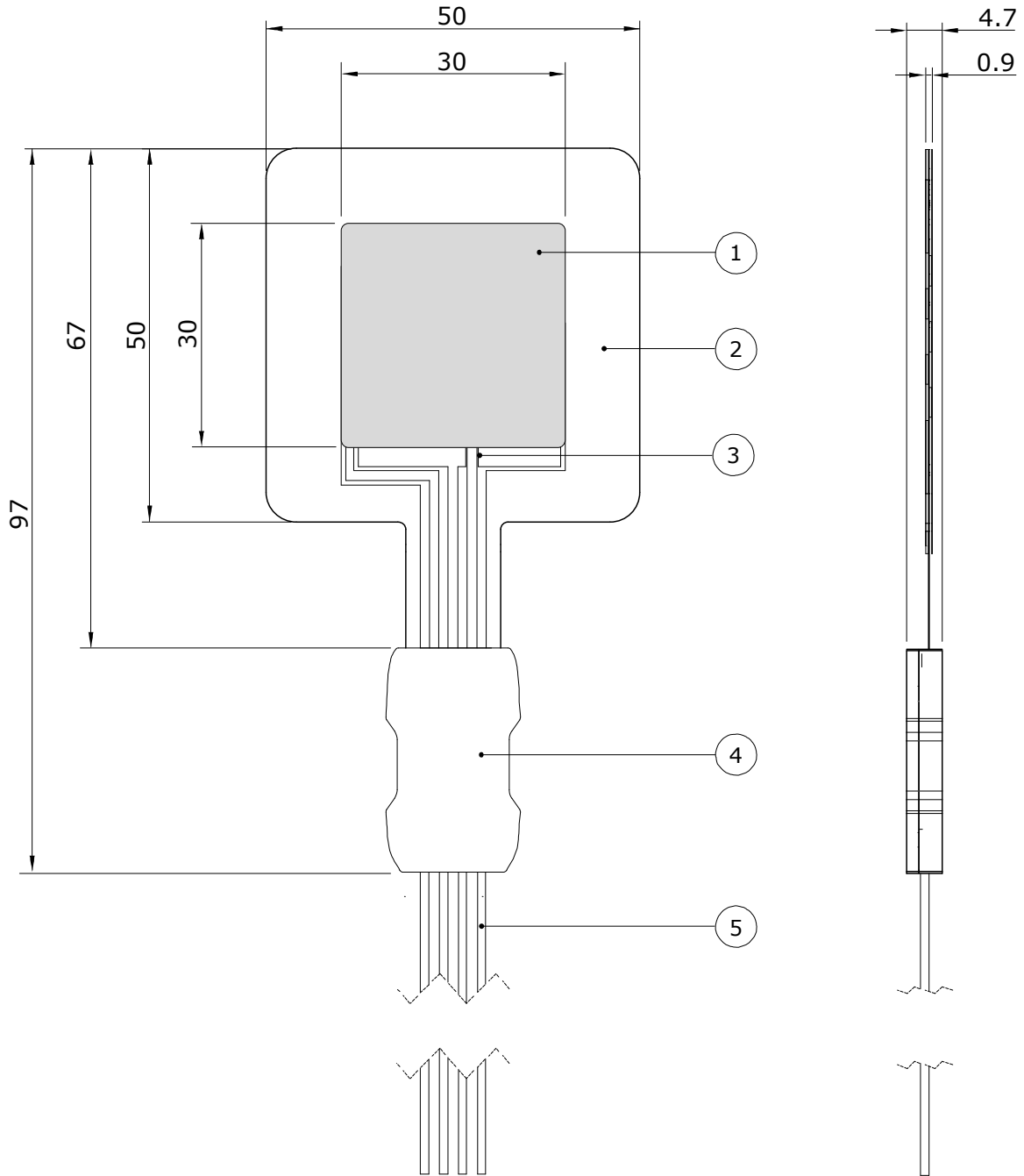


Figure 3.2.1 FHF02 heat flux sensor; dimensions in $\times 10^{-3}$ m

- (1) sensing area with thermal spreader
- (2) passive guard
- (3) type T thermocouple
- (4) strain relief block, showing serial number and sensitivity
- (5) wires, standard length 2 m

4 Standards and recommended practices for use

FHF02 should be used in accordance with the recommended practices of ASTM.

4.1 Heat flux measurement in industry

Many FHF02 sensors measure on industrial walls and metal surfaces, estimating the installation's energy balance and the thermal transmission of walls. Typically the total measuring system consists of multiple heat flux- and temperature sensors. In many cases heat flux sensors are used for trend-monitoring. In such cases reproducibility is more important than absolute measurement accuracy.



Figure 4.1.1 Example of a flexible foil heat flux sensor being installed on a pipe. The sensor is mounted on a well prepared flat surface. Wiring must be provided with strain relief.

Table 4.1.1 contains a listing of applicable standards. We recommend users to purchase the latest version of the standard.

4.1.1 Applicable standards

Table 4.1.1 *Standards with recommendations for instrument use in industry*

STANDARDS FOR INSTRUMENT USE FOR BUILDING ENVELOPE THERMAL RESISTANCE MEASUREMENT	
ASTM STANDARD	EQUIVALENT ISO STANDARD
ASTM C1041 - 10 Standard Practice for In-Situ Measurements of Heat Flux in Industrial Thermal Insulation Using Heat Flux Transducers	Not available

5 Installation of FHF02

5.1 Site selection and installation

Table 5.1.1 Recommendations for installation of FHF02 heat flux sensors

Location	<p>choose a location that is representative of the process that is analysed if possible, avoid exposure to sun, rain, etc.</p> <p>do not expose to drafts and lateral heat fluxes</p> <p>do not mount in the vicinity of thermal bridges, cracks, heating or cooling devices and fans</p>
Performing a representative measurement / recommended number of sensors	<p>we recommend using > 2 sensors per measurement location. This redundancy also improves the assessment of the measurement accuracy</p>
Mounting	<p>when mounting a FHF02, keep the directional sensitivity in mind</p> <p>heat flux from the back side to the front side (side with sticker, logo readable) generates a positive voltage output signal</p>
Surface cleaning and levelling	<p>create a clean and smooth surface of $(50 \times 50) \times 10^{-3}$ m</p>
Mechanical mounting: avoiding strain on the sensor to wire transition	<p>the sensor-to-wire transition is vulnerable during installation as well as operation, the user should provide proper strain relief of the wires so that transition is not exposed to significant force</p> <p>first install the wires including strain relief and after that install the sensor</p>
Short term installation	<p>avoid any air gaps between sensor and surface. Air thermal conductivity is in the $0.02 \text{ W}/(\text{m}\cdot\text{K})$ range, while a common glue has a thermal conductivity around $0.2 \text{ W}/(\text{m}\cdot\text{K})$. A 0.1×10^{-3} m air gap increases the effective thermal resistance of the sensor by 200 %</p> <p>to avoid air gaps, we recommend thermal paste or glycerol for short term installation</p> <p>use tape to fixate the sensor on the surface. If possible, tape only over the passive guard area (the area without thermopile traces)</p> <p>use tape to fixate the strain relief block of the sensor</p> <p>usually the cables are provided with an additional strain relief, for example using a cable tie mount as in Figure 5.1.1</p>
Permanent installation	<p>for long-term installation fill up the space between sensor and object with silicone construction sealant, silicone glue or silicone adhesive, that can be bought in construction depots.</p> <p>we discourage the use of thermal paste for permanent installation because it tends to dry out. silicone glue is more stable and reliable</p>
Signal amplification	<p>see the paragraph on electrical connection</p>

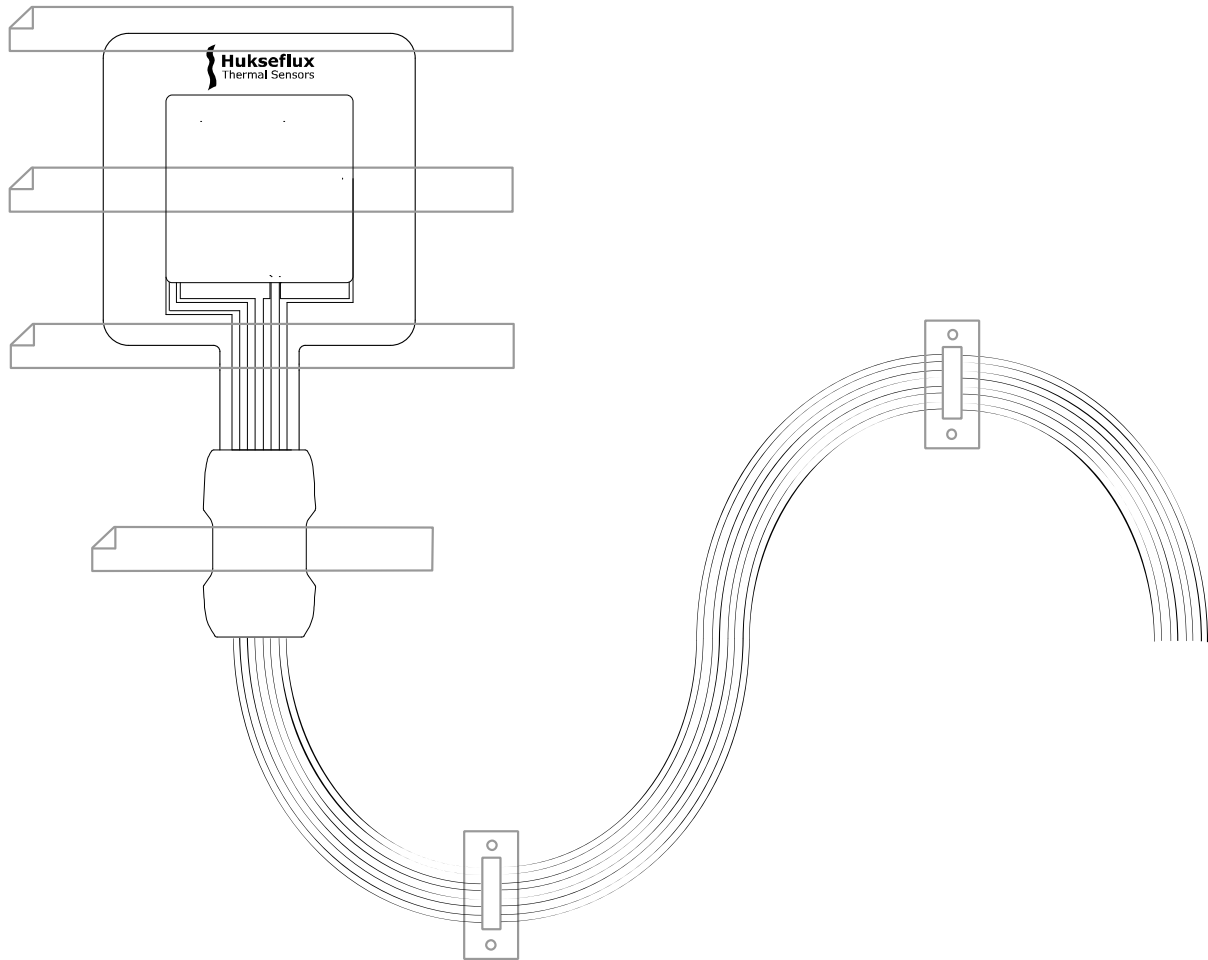


Figure 5.1.1 *Installation of FHF02 using tape to fixate the sensor and the strain relief block. Extra strain relief of the wire is provided using cable tie mounts equipped with double sided tape as adhesive. As indicated in Table 5.1.1, tapes fixating the sensor are preferably taped over the passive guard area. In this case a third tape (in the middle) is added for extra support. Please note the Hukseflux logo is readable in this image; this indicates that we are viewing the front side and that the other side, the back side, is attached on the object on which the sensor is mounted, as explained in Chapter 2.*

5.2 Installation on curved surfaces

The flexibility of the FHF02 makes it perfectly suitable to be installed on singly curved surfaces. Make sure to bend the sensor in the direction indicated in Figure 5.2.1.



Figure 5.2.1 *Bending direction of a foil heat flux sensor similar to FHF02. Bending the FHF02 in this direction minimizes the strain on the sensor and improves the measurement result*

FHF02 is not suited for dynamic bending.

The recommendations of the previous chapter apply. For installation on curved surfaces, it is usually not achievable to tape only over the passive guard area.

Table 5.2.1 *Extra recommendations for installation of FHF02 foil heat flux sensors on curved surfaces*

Bending	bend the sensor in the direction indicated in Figure 5.2.1 bending the FHF02 in this direction minimizes the strain on the sensor
Rated bending radius	$\geq 50 \times 10^{-3}$ m (for applications where a smaller bending radius is required, consider model FHF01)
Effect on sensitivity	sensitivity increases slightly with decreasing bending radius

5.3 Electrical connection

5.3.1 Normal connection

A heat flux sensor should be connected to a measurement system, typically a so-called datalogger. FHF02 is a passive sensor that does not need any power. Wires may act as a source of distortion, by picking up capacitive noise. We recommend keeping the distance between a datalogger or amplifier and the sensor as short as possible. For wire extension, see the appendix on this subject.

Table 5.3.1.1 *The electrical connection of FHF02*

WIRE	
Red	heat flux signal [+]
Black	heat flux signal [-]
White	thermocouple type T [-]
Brown	thermocouple type T [+]

The sensor serial number and sensitivity are shown on the FHF02 product certificate and on the sticker on the strain relief block.

5.3.2 Increasing sensitivity, connecting multiple sensors in series

Multiple sensors may be electrically connected in series. The resulting sensitivity is the sum of the sensitivity of the individual sensors. Below the equations in case two sensors are used. If needed, more than two sensors may be put in series, again increasing the sensitivity.

$$\Phi = U / (S_1 + S_2) \quad \text{(Formula 5.3.2.1)}$$

and

$$U = U_1 + U_2 \quad \text{(Formula 5.3.2.2)}$$

Table 5.3.2.1 *The electrical connection of two FHF02's, 1 and 2, in series. In such case the sensitivity is the sum of the two sensitivities of the individual sensors. More sensors may be added in a similar manner*

SENSOR	WIRE		MEASUREMENT SYSTEM
1	Red	signal 1 [+]	voltage input [+]
1	Black	signal 1 [-]	connected to signal 2 [+]
1	White	thermocouple type T [-]	
1	Brown	thermocouple type T [+]	
2	Red	signal 2 [+]	connected to signal 1 [-]
2	Black	signal 2 [-]	voltage input [-] or ground
2	White	thermocouple type T [-]	
2	Brown	thermocouple type T [+]	

The serial number and sensitivity of the individual sensors are shown on the FHF02 product certificate and on the sticker on the strain relief block.

5.3.3 Connection to read out half signals

See the figure below: FHF02 can be connected to read out only the heat flux through the top 50 % of the sensing area or the heat flux through the bottom 50 % of the sensing area. This feature may be used for quality assurance purposes; if the sensor is correctly installed we expect a constant percentage of the signal to be generated by the top – and bottom.

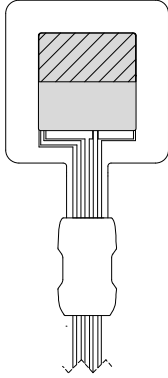


Figure 5.3.3.1 Picture of FHF02 with top 50 % highlighted (total sensing area is shaded grey; top 50 % is accentuated by diagonal lines in this image)

Table 5.3.3.1 The electrical connection of FHF02 for 100 % signal

WIRE	MEASUREMENT SYSTEM	
Red	heat flux signal [+]	voltage input [+]
Black	heat flux signal [-]	voltage input [-] or ground
White	thermocouple type T [-]	
Brown	thermocouple type T [+]	

Table 5.3.3.2 The electrical connection of FHF02 for top 50 % signal

WIRE	MEASUREMENT SYSTEM	
Red	heat flux signal [+]	voltage input [+]
Black	heat flux signal [-]	
White	thermocouple type T [-]	
Brown	thermocouple type T [+]	voltage input [-] or ground

Table 5.3.3.3 The electrical connection of FHF02 for bottom 50 % signal

WIRE	MEASUREMENT SYSTEM	
Red	heat flux signal [+]	
Black	heat flux signal [-]	voltage input [-] or ground
White	thermocouple type T [-]	
Brown	thermocouple type T [+]	voltage input [+]

5.4 Requirements for data acquisition / amplification

The selection and programming of dataloggers is the responsibility of the user. Please contact the supplier of the data acquisition and amplification equipment to see if directions for use with the FHF02 are available. In case a program for similar instruments is available, this can be used. FHF02 can be treated in the same way as other heat flux sensors and thermopile pyranometers.

Table 5.4.1 *Requirements for data acquisition and amplification equipment for FHF02 in the standard configuration*

Capability to measure small voltage signals	preferably: $< 5 \times 10^{-6}$ V uncertainty minimum requirement: 20×10^{-6} V uncertainty (valid for the entire expected temperature range of the acquisition / amplification equipment)
Capability for the data logger or the software	to store data, and to perform division by the sensitivity to calculate the heat flux. $\Phi = U/S$
Capability to measure thermocouple type T	preferably: $< \pm 3$ °C uncertainty
Data acquisition input resistance	$> 1 \times 10^6 \Omega$
Open circuit detection (WARNING)	open-circuit detection should not be used, unless this is done separately from the normal measurement by more than 5 times the sensor response time and with a small current only. Thermopile sensors are sensitive to the current that is used during open circuit detection. The current will generate heat, which is measured and will appear as a temporary offset.

6 Maintenance and trouble shooting

6.1 Recommended maintenance and quality assurance

FHF02 measures reliably at a low level of maintenance. Unreliable measurement results are detected by scientific judgement, for example by looking for unreasonably large or small measured values. The preferred way to obtain a reliable measurement is a regular critical review of the measured data, preferably checking against other measurements.

Table 6.1.1 *Recommended maintenance of FHF02. If possible the data analysis is done on a daily basis*

MINIMUM RECOMMENDED HEAT FLUX SENSOR MAINTENANCE			
	INTERVAL	SUBJECT	ACTION
1	1 week	data analysis	compare measured data to the maximum possible or maximum expected heat flux and to other measurements for example from redundant instruments. Look for any patterns and events that deviate from what is normal or expected. Compare to acceptance intervals.
2	6 months	inspection	inspect wire quality, inspect mounting, inspect location of installation
3	2 years	recalibration	recalibration by comparison to a calibration standard instrument in the field, see following paragraphs. recalibration by the sensor manufacturer
4		lifetime assessment	judge if the instrument will be reliable for another 2 years, or if it should be replaced

6.2 Trouble shooting

Table 6.2.1 *Trouble shooting for FHF02*

General	<p>Inspect the sensor for any damage. Inspect the quality of mounting / installation. Inspect if the wires are properly attached to the data logger.</p> <p>Check the condition of the wires.</p> <p>Check the datalogger program in particular if the right sensitivity is entered. FHF02 sensitivity and serial number are shown on the product certificate and on the sticker on the strain relief block.</p> <p>Check the electrical resistance of the sensor between the black [-] and red [+] wires. Use a multimeter at the 100 Ω range. Measure the sensor resistance first with one polarity, then reverse the polarity. Take the average value. The typical resistance of the wiring is 0.1 Ω/m. Typical resistance should be the nominal sensor resistance of 80 Ω plus 0.2 Ω for the total resistance of two wires (back and forth) of each m. Infinite resistance indicates a broken circuit; zero or a lower than 1 Ω resistance indicates a short circuit.</p>
The sensor does not give any signal	<p>Check if the sensor reacts to heat: put the multimeter at its most sensitive range of DC voltage measurement, typically the 100 x 10⁻³ VDC range or lower. Expose the sensor heat.</p> <p>Check if the sensor reacts to heat: put the multimeter at its most sensitive range of DC voltage measurement, typically the 100 x 10⁻³ VDC range or lower. Expose the sensor to heat. Exposing the back side to heat should generate a positive signal between the red [+] and black [-] wires, doing the same at the front side, the sign of the output reverses.</p> <p>Check the data acquisition by replacing the sensor with a spare unit.</p>
The sensor signal is unrealistically high or low	<p>Check the wire condition looking for wire breaks.</p> <p>Check the data acquisition by applying a 1 x 10⁻⁶ V source to it in the 1 x 10⁻⁶ V range. Look at the measurement result. Check if it is as expected.</p> <p>Check the data acquisition by short circuiting the data acquisition input with a 10 Ω resistor. Look at the output. Check if the output is close to 0 W/m².</p>
The sensor signal shows unexpected variations	<p>Check the presence of strong sources of electromagnetic radiation (radar, radio).</p> <p>Check the condition of the sensor wires.</p> <p>Check if the wires are not moving during the measurement.</p>

6.3 Calibration and checks in the field

The recommended calibration interval of heat flux sensors is 2 years.
Recalibration of field heat flux sensors is ideally done by the sensor manufacturer.

On-site field calibration is possible by comparison to a calibration reference sensor.
Usually mounted side by side, alternatively mounted on top of the field sensor.

Hukseflux main recommendations for field calibrations are:

- 1) to compare to a calibration reference of the same brand and type as the field sensor
- 2) to connect both to the same electronics, so that electronics errors (also offsets) are eliminated
- 3) to mount all sensors on the same platform, so that they have the same body temperature
- 4) typical duration of test: > 24 h
- 5) typical heat fluxes used for comparison: > 200 W/m²
- 6) to correct deviations of more than ± 20 %. Lower deviations should be interpreted as acceptable and should not lead to a revised sensitivity

Users may also design their own calibration experiment, for example using a well characterised foil heater.

7 Appendices

7.1 Appendix on wire extension

FHF02 is equipped with four wires. Keep the distance between data logger or amplifier and sensor as short as possible. Wires may act as a source of distortion by picking up capacitive noise. In an electrically “quiet” environment the FHF02 cable may be extended without problem to 100 metres. If done properly, the sensor signal, although small, will not significantly degrade because the sensor resistance is very low (which results in good immunity to external sources) and because there is no current flowing (so no resistive losses). Wire and connection specifications are summarised below.

Standard wire length is 2 m. It is possible to order FHF02 with longer wire lengths.

Table 7.1.1 Preferred specifications for wire extension of FHF02

Wire	3 x copper and 1 x constantan wire, AWG 24, stranded
Extension sealing	make sure any connections are sealed against humidity ingress
Conductor resistance	< 0.1 Ω /m (copper wire)
Outer diameter	1 x 10 ⁻³ m
Length	cables should be kept as short as possible, in any case the total cable length should be less than 100 m
Connection	<p>either use gold plated waterproof connectors, or solder the new wire conductors and shield to those of the original sensor wire, and make a waterproof connection using heat-shrink tubing with hot-melt adhesive</p> <p>when using connectors, use dedicated type T thermocouple connectors for extending the thermocouple wires</p>

7.2 Appendix on standards for calibration

The standard ASTM C1130 - 17 Standard Practice for Calibrating Thin Heat Flux Transducers specifies in chapter 6 that a guarded hot plate, a heat flowmeter, a hot box or a thin heater apparatus are all allowed. Hukseflux employs a thin heater apparatus, uses a linear function according to X1.1 and uses a nominal temperature of 20 °C, in accordance with X2.2.

The Hukseflux FHFC method relies on a thin heater apparatus according to principles as described in paragraph 4 of ASTM C1114 - 06, used in the single sided mode of operation described in paragraph 8.2 and in ASTM C1044 - 12.

ISO does not have a dedicated standard practice for heat flux sensor calibration. We follow the recommended practice of ASTM C1130 - 17.

Table 7.2.1 *heat flux sensor calibration according to ISO and ASTM.*

STANDARDS ON INSTRUMENT CLASSIFICATION AND CALIBRATION	
ISO STANDARD	EQUIVALENT ASTM STANDARD
no dedicated heat flux calibration standard available.	ASTM C1130 - 17 Standard Practice for Calibrating Thin Heat Flux Transducers ASTM C 1114 - 06 Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Thin-Heater Apparatus ASTM C1044 - 16 Standard Practice for Using a Guarded-Hot-Plate Apparatus or Thin-Heater Apparatus in the Single-Sided Mode

7.3 Appendix on calibration hierarchy

FHF02 factory calibration is traceable from SI through international standards and through an internal mathematical procedure that corrects for known errors. The formal traceability of the generated heat flux is through voltage and current to electrical power and electric power and through length to surface area.

The Hukseflux FHFC method follows the recommended practice of ASTM C1130 - 17. It relies on a thin heater apparatus according to principles as described in paragraph 4 of ASTM C1114 - 06, in the single sided mode of operation described in paragraph 8.2 and in ASTM C1044 - 16. The method has been validated in a first-party conformity assessment, by comparison to calibrations in a guarded hot plate.

7.4 Appendix on correction for temperature dependence

The sensitivity of a FHF02 depends on the temperature of the sensor. The temperature dependence of the FHF02 is specified as $< 0.3 \text{ \%/}^\circ\text{C}$. Characterisation of FHF02s that we produced so far gives consistent values of $+0.25 \text{ \%/}^\circ\text{C}$.

The calibration reference temperature is $20 \text{ }^\circ\text{C}$.

Users that measure at temperatures that deviate much from $20 \text{ }^\circ\text{C}$, or users that measure over a wide range of temperatures, may wish to correct for this temperature dependence.

To correct for the temperature dependence of the sensitivity, use the measurement function

$$\Phi = U/(S \cdot (1 + 0.0025 \cdot (T - 20))) \quad (\text{Formula 7.4.1})$$

with Φ the heat flux in W/m^2 , U the FHF02 voltage output in V , S the sensitivity in $\text{V}/(\text{W/m}^2)$ at $20 \text{ }^\circ\text{C}$ and T the FHF02 temperature.

S is shown on the product certificate and on the sticker on the strain relief block.

7.5 Appendix on measurement range for different temperatures

The measurement range of FHF02 is specified as $(-10 \text{ to } +10) \times 10^3 \text{ W/m}^2$ at $20 \text{ }^\circ\text{C}$ heat sink temperature. This is a very conservative specification.

In reality, the maximum temperature of $+150 \text{ }^\circ\text{C}$ is the limiting specification. The sensor temperature T in $^\circ\text{C}$ in a specific application depends on the heatsink temperature T_{heatsink} in $^\circ\text{C}$, the heat flux Φ in W/m^2 and the thermal resistance per unit area $R_{\text{thermal,A}}$ of the sensor in $\text{K}/(\text{W/m}^2)$.

$$T = T_{\text{heatsink}} + \Phi \cdot R_{\text{thermal,A}} \quad (\text{Formula 7.5.1})$$

This means the measurement range is lower for higher heat sink temperatures.

$$\Phi_{\text{maximum}} = (150 - T_{\text{heatsink}}) / R_{\text{thermal,A}} \quad (\text{Formula 7.5.2})$$

Table 7.5.1 shows measurement ranges for different heat sink temperatures. For applications where the sensor is not mounted on a heatsink, use the ambient temperature instead of heatsink temperature.

Table 7.5.1 measurement range for different heat sink temperatures

HEATSINK TEMPERATURE	MEASUREMENT RANGE
20 $^\circ\text{C}$	$43 \times 10^3 \text{ W/m}^2$
40 $^\circ\text{C}$	$37 \times 10^3 \text{ W/m}^2$
60 $^\circ\text{C}$	$30 \times 10^3 \text{ W/m}^2$
80 $^\circ\text{C}$	$23 \times 10^3 \text{ W/m}^2$
100 $^\circ\text{C}$	$17 \times 10^3 \text{ W/m}^2$

7.6 EU declaration of conformity



We, Hukseflux Thermal Sensors B.V.
Delftechpark 31
2628 XJ Delft
The Netherlands

in accordance with the requirements of the following directive:

2014/30/EU The Electromagnetic Compatibility Directive

hereby declare under our sole responsibility that:

Product model: FHF02
Product type: Foil heat flux sensor

has been designed to comply and is in conformity with the relevant sections and applicable requirements of the following standards:

Emission: EN 61326-1 (2006)
Immunity: EN 61326-1 (2006)
Emission: EN 61000-3-2 (2006)
Emission: EN 61000-3-3 (1995) + A1 (2001) + A2 (2005)
Report: 08C01340RPT01, 06 January 2009

A handwritten signature in blue ink, appearing to be 'Eric Hoeksema'.

Eric HOEKSEMA
Director
Delft
December 20, 2017

