Hukseflux
Thermal Sensors

USER MANUAL **FHF03**

Economical foil heat flux sensor with thermal spreaders, flexible, 30 x 15 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.

Contents

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List of symbols

Quantities	Symbol	Unit
Heat flux	Φ	W/m²
Voltage output	U	V
Sensitivity	S	V/(W/m²)
Temperature	T	°C
Thermal resistance per unit area	$R_{thermal,A}$	K/(W/m²)

subscripts	
property of heatsink	heatsink
maximum value, specification limit	maximum

Introduction

FHF03 is an economical sensor for general-purpose heat flux measurement. It is small, thin and versatile. FHF03 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. FHF03 is often applied as part of a larger test- or measuring system.

FHF03 measures heat flux through the object in which it is incorporated or on which it is mounted, in W/m². The sensor in FHF03 is a thermopile. This thermopile measures the temperature difference across FHF03's flexible body. 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 FHF03 is independent of its environment. Many competing sensors do not have thermal spreaders. Equipped with well-protected wire connections and a sturdy, shielded cable, FHF03 is designed for robustness. Qualities like these are unmatched at this price level.

Figure 0.1 *FHF03 foil heat flux sensor with thermal spreaders: small, thin and versatile*

The economical FHF03 foil heat flux sensor has unique features and benefits:

- flexible (bending radius ≥ 25 x 10^{-3} m)
- low thermal resistance
- wide temperature range
- fast response time
- integrated type T thermocouple
- robust: well-protected wire connections and a sturdy, shielded cable
- IP protection class: IP67 (essential for outdoor application)
- thermal spreader included, low thermal conductivity dependence

Using FHF03 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 FHF03 output, a small voltage, by the sensitivity. The sensitivity is provided with FHF03 on its product certificate. For increased sensitivity, robustness and a larger sensing area, consider using model FHF02 and, in particular for building physics and soil heat flux, model HFP01, the world's most popular heat flux sensor.

FHF03 calibration is traceable to international standards. The factory calibration method follows the recommended practice of ASTM C1130-17. When used under conditions that differ from the calibration reference conditions, the FHF03 sensitivity to heat flux may be different than stated on its certificate. See Chapter 2 in this manual for suggested solutions.

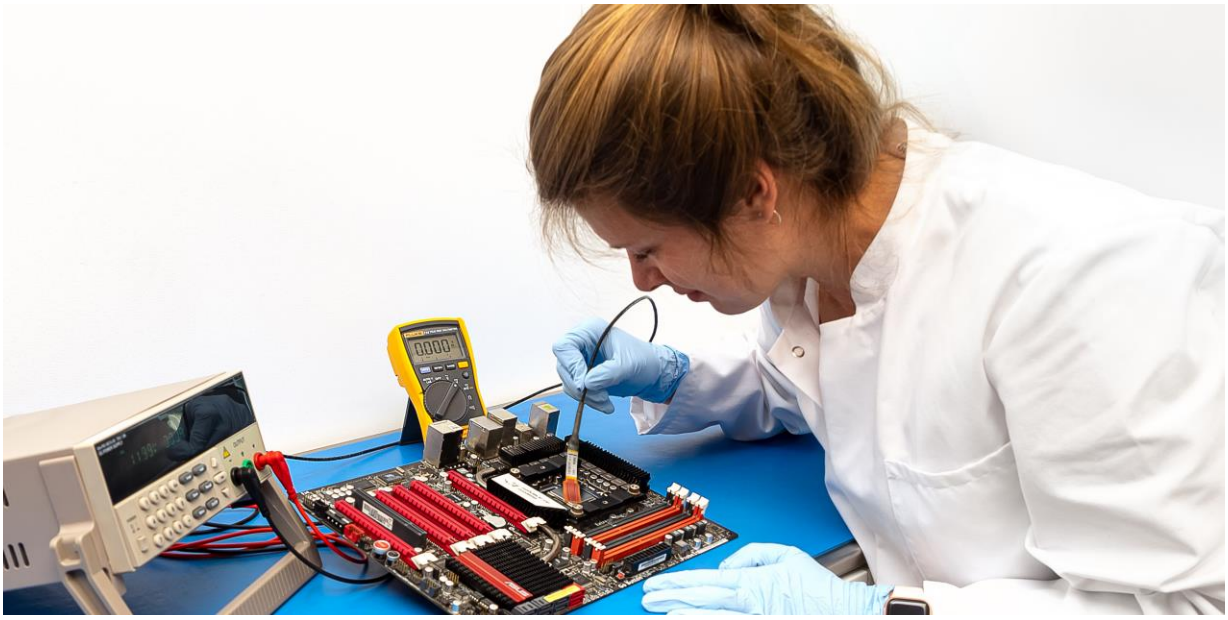

Figure 0.2 *FHF03 foil heat flux sensor being installed to measure heat flux on a computer processor*

See also:

- model FHF02 for increased sensing area and sensitivity
- model FHF02SC for a self-calibrating version of FHF02
- model HFP01 for increased sensitivity (also consider putting two or more FHF02's in series)
- Hukseflux offers a complete range of heat flux sensors with the highest quality for any budget

1 Ordering and checking at delivery

1.1 Ordering FHF03

The standard configuration of FHF03 is with 2 metres of cable.

Common options are:

- with 5 metres of cable
- with LI19 hand-held read-out unit / datalogger

1.2 Included items

Arriving at the customer, the delivery should include:

- heat flux sensor FHF03 with cable of the length as ordered
- product certificate matching the instrument serial number

Figure 1.2.1 *FHF03's serial number and sensitivity are visible on the sticker close to FHF03's strain relief. The sensor is delivered with bundled cable and wire ends.*

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 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. Measured resistance should be the nominal sensor resistance of 25 Ω plus 0.2 Ω/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 thermocouple resistance first with one polarity, then reverse the polarity. Take the average value. Measured resistance should be the nominal thermocouple resistance of 2.5 Ω plus 2.5 Ω/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

FHF03'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".

FHF03 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 FHF03 is a thermopile. This thermopile measures the temperature difference across the polyimide body of FHF03. 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 FHF03 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.

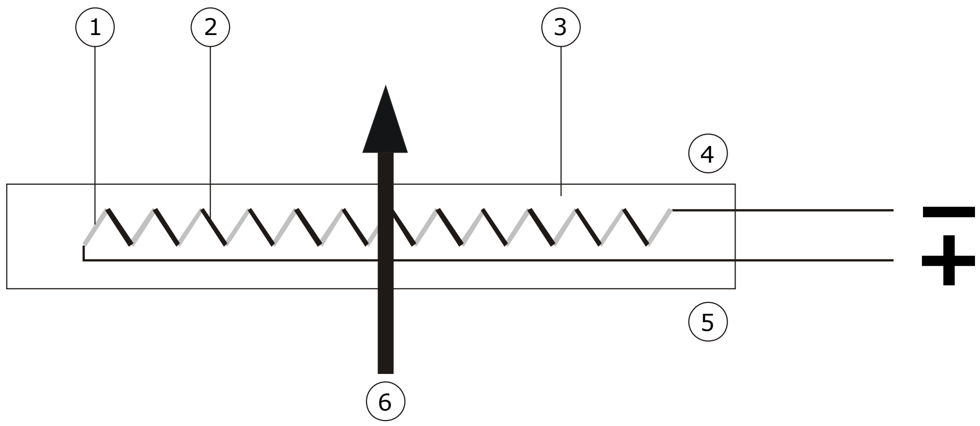

Figure 2.1 *The general working principle of a heat flux sensor. The sensor inside FHF03 is a thermopile. A thermopile consists of a number of thermocouples, each consisting of two metal alloys marked 1 and 2, electrically connected in series. A single thermocouple generates an output voltage that is 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.

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

FHF03 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.

Unique features of the economical FHF03 include flexibility (bending radius ≥ 25 x 10^{-3} m), low thermal resistance, a wide temperature range, a fast response time, cable with strain relief for robustness, IP67 protection class rating (essential for outdoor application), and the inclusion of thermal spreaders to reduce thermal conductivity dependence.

The FHF03 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

FHF03 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 FHF03 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 FHF03 operating temperature range is -40 to +150 °C. Prolonged exposure to temperatures near +150 °C can accelerate the aging process.

3 Specifications of FHF03

3.1 Specifications of FHF03

FHF03 measures the heat flux density through the surface of the sensor. This quantity, expressed in W/m², is called heat flux. Working completely passive, using a thermopile sensor, FHF03 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 FHF03 (continued on next page)*

FHF03 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/m²
Measurement range	(-10 to +10) x 10^3 W/m² at heat sink temperature 20 °C see appendix for detailed calculations
Sensitivity range	(1.5 to 2.5) x 10^{-6} V/(W/m²)
Sensitivity (nominal)	2 x 10^{-6} V/(W/m²)
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	(-25 to +25) x 10^{-3} 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 Ω
Optional readout	1 temperature channel
Rated load on cable	≤ 10 kg
Rated bending radius	≥ 25 x 10^{-3} m
Operating temperature range	-40 to +150 °C
Temperature dependence	< 0.3 %/°C
Non-linearity	< 5 % (0 to 10 x 10^3 W/m²)
Solar absorption coefficient	0.75 (indication only)
Thermal conductivity dependence	negligible
Sensor length and width	(31 x 14.5) x 10^{-3} m
Sensing area	2.5 x 10^{-4} m²
Sensing area length and width	(25 x 10) x 10^{-3} m
Passive guard area	2 x 10^{-4} m²
Guard width to thickness ratio	2.8 m/m
Sensor thickness	0.8 x 10^{-3} m
Sensor thermal resistance	28 x 10^{-4} K/(W/m²)
Sensor thermal conductivity	0.29 W/(m·K)
Response time (95 %)	15 s
Sensor resistance range	20 to 30 Ω
Required sensor power	zero (passive sensor)
Temperature sensor	type T thermocouple incorporated
Thermal spreaders	incorporated

Table 3.1 *Specifications of FHF03 (started on previous page)*

Standard cable length	2 m
Wiring	3 x copper and 1 x constantan wire, AWG 24, stranded
Cable diameter	3.6×10^{-3} m
Marking	1 x sticker, showing serial number and sensitivity
IP protection class	IP67
Rated operating relative humidity range	0 to 100 %
Use under water	FHF03 is not suitable for continuous use under water
Gross weight including 2 m wires	0.12 kg
Net weight including 2 m wires	0.05 kg
Packaging	box of 230 x 170 x 35 mm
INSTALLATION AND USE	
Typical conditions of use	in experiments, in measurements in laboratory and industrial environments. Exposed to heat fluxes for periods of several minutes to several years. Connected to user-supplied data acquisition equipment. Regular inspection of the sensor. Continuous monitoring of sensor temperature. No special requirements for immunity, emission, chemical resistance.
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 cable extension or order sensors with longer cable
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/m², 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 FHF03 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.

Table 3.1 *Specifications of FHF03 (started on previous page)*

VERSIONS / OPTIONS	
With 5 metres of cable	option code = cable length in metres
ACCESSORIES	
Hand-held read-out unit	LI19 handheld read-out unit / datalogger

3.2 Dimensions of FHF03

Figure 3.2.1 *FHF03 heat flux sensor; dimensions in x 10^{-3} m*

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

4 Standards and recommended practices for use

FHF03 should be used in accordance with recommended practices.

4.1 Heat flux measurement in industry

FHF03 sensors are often used to 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.

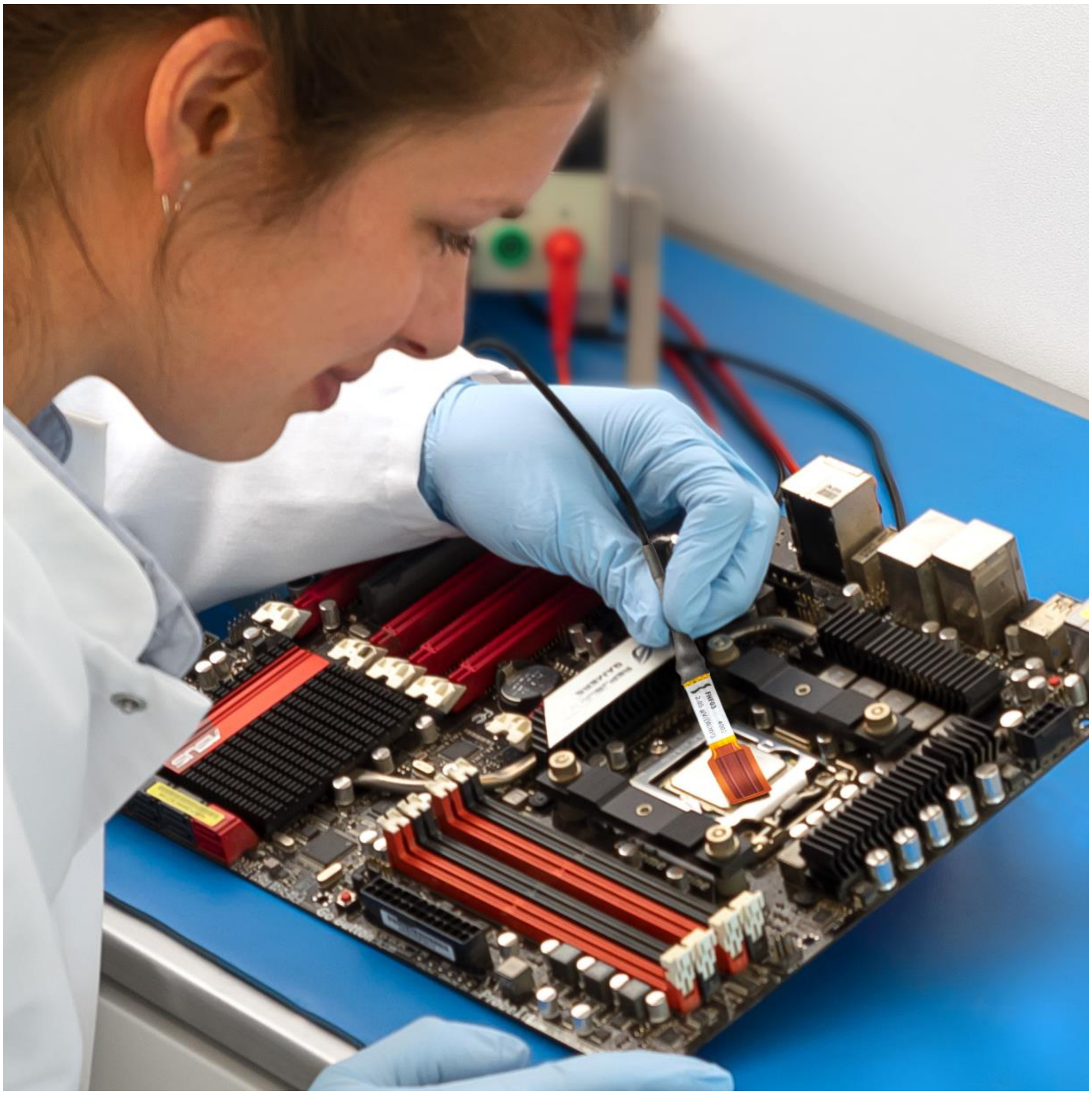

Figure 4.1.1 *Example of an FHF03 foil heat flux sensor being installed for measurement on a computer processor. The sensor is mounted on a well-prepared flat surface.*

5 Installation of FHF03

5.1 Site selection and installation

Table 5.1.1 *Recommendations for installation of FHF03 heat flux sensors*

Location	choose a location that is representative of the process that is analysed if possible, avoid exposure to sun, rain, etc. do not expose to drafts and lateral heat fluxes do not mount in the vicinity of thermal bridges, cracks, heating or cooling devices and fans
Performing a representative measurement / recommended number of sensors	we recommend using > 2 sensors per measurement location. This redundancy also improves the assessment of the measurement accuracy
Mounting	when mounting an FHF03, keep the directional sensitivity in mind heat flux from the back side to the front side (side with sticker, logo readable) generates a positive voltage output signal
Surface cleaning and levelling	create a clean and smooth surface of (31 x 14.5) x 10^{-3} m
Mechanical mounting: avoiding strain on the sensor to cable transition	the sensor-to-cable transition is vulnerable during installation as well as operation, the user should provide proper strain relief of the cable so that transition is not exposed to significant force first install the cable including strain relief and after that install the sensor
Short term installation	avoid any air gaps between sensor and surface. Air thermal conductivity is in the 0.02 W/(m·K) range, while a common glue has a thermal conductivity around 0.2 W/(m·K). A 0.1 x 10^{-3} m air gap increases the effective thermal resistance of the sensor by 200 % to avoid air gaps, we recommend thermal paste or glycerol for short term installation use tape to fixate the sensor on the surface. If possible, tape only over the passive guard area (surrounding the sensing area). See Figure 3.2.1 use tape to fixate the strain relief of the sensor usually the cables are provided with an additional strain relief, for example using a cable tie mount as in Figure 5.1.1
Permanent installation	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. we discourage the use of thermal paste for permanent installation because it tends to dry out. silicone glue is more stable and reliable
Signal amplification	see the paragraph on electrical connection

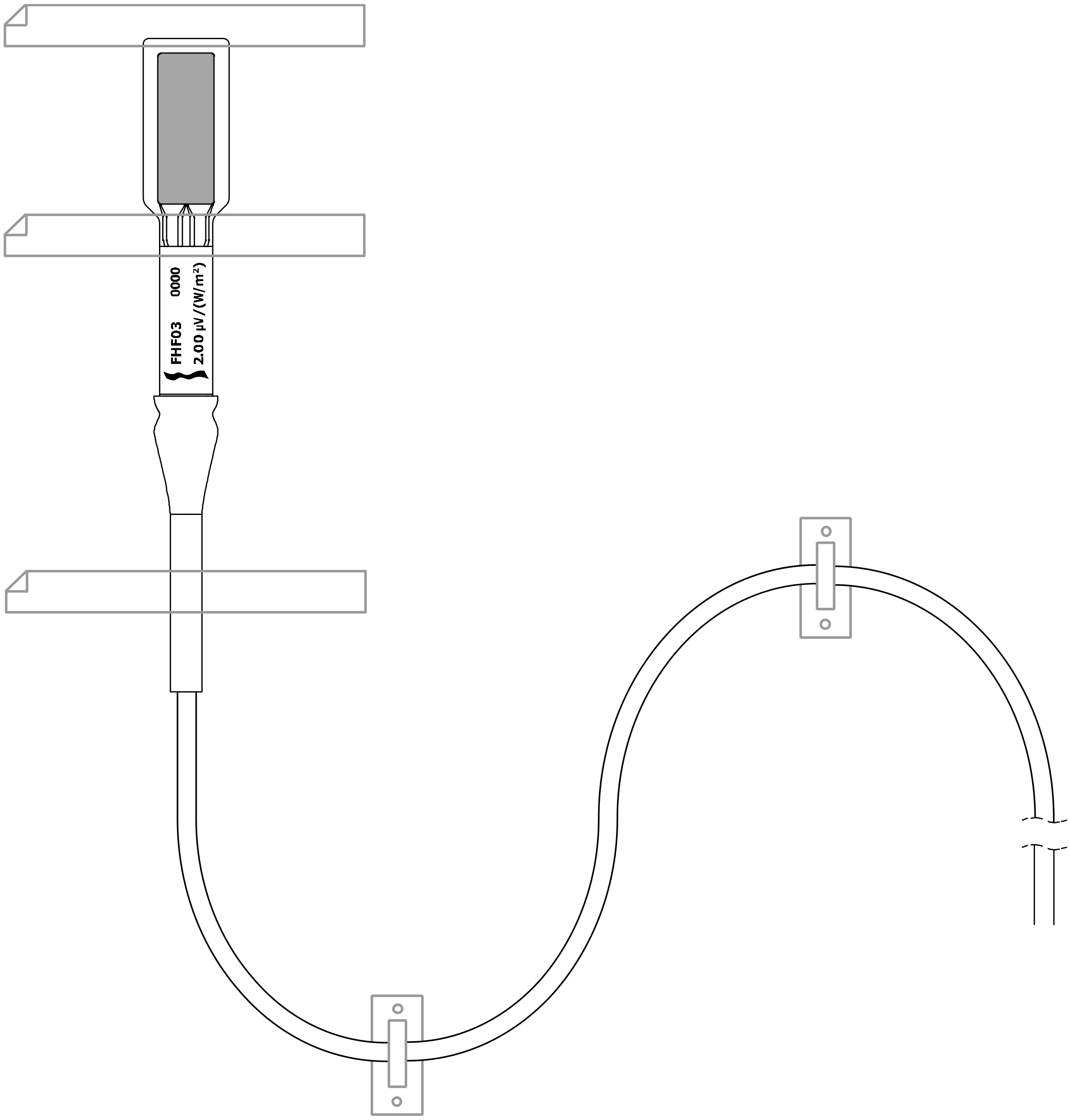

Figure 5.1.1 *Installation of FHF03 using tape to fixate the sensor and the strain relief. Extra strain relief of the cable is provided using cable tie mounts equipped with double sided tape as adhesive. As indicated in Table 5.1.1, tapes fixating the sensor are preferably taped over the passive guard area and not on the sensing area (the latter indicated by grey shading in Figure 5.1.1). 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 FHF03 makes it perfectly suitable to be installed on singly curved surfaces. Bend the sensor in the direction indicated in Figure 5.2.1.

Figure 5.2.1 *Bending of an FHF03 foil heat flux sensor, in this image on a pipe.*

FHF03 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. Use sufficient tape to make sure the sensor remains fixed and in good thermal contact with curved surface. Avoid air gaps. Tape can be used over the sensing area when necessary.

Table 5.2.1 *Extra recommendations for installation of FHF03 foil heat flux sensors on curved surfaces*

Bending	bend the sensor in the direction indicated in Figure 5.2.1
Rated bending radius	≥ 25 x 10^{-3} m
Effect on sensitivity	sensitivity increases slightly with decreasing bending radius, when bent in the recommended way

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. FHF03 is a passive sensor that does not need any power. Although FHF03 is provided with a shielded cable, cables 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 FHF03*

WIRE		MEASUREMENT SYSTEM
Red	heat flux signal [+]	voltage input [+]
Black	heat flux signal [−]	voltage input [−]
Brown	thermocouple type T [+]	thermocouple input [+]
White	thermocouple type T [−]	thermocouple input [−]
Grey	shield	ground

The shield is not connected to the sensor itself. Connect the shield to a local ground to protect from capacitive noise picked up by the cable.

The sensor serial number and sensitivity are shown on the FHF03 product certificate and on the sticker.

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.

$\Phi = U/(S_1 + S_2)$ (Formula 5.3.2.1)

and

$U = U_1 + U_2$ (Formula 5.3.2.2)

Table 5.3.2.1 *The electrical connection of two FHF03'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	Brown	thermocouple type T [+]	
1	White	thermocouple type T [−]	
1	Grey	shield	ground
2	Red	signal 2 [+]	connected to signal 1 [−]
2	Black	signal 2 [−]	voltage input [−] or ground
2	Brown	thermocouple type T [+]	
2	White	thermocouple type T [−]	
2	Grey	shield	ground

The serial number and sensitivity of the individual sensors are shown on the FHF03 product certificate and on the sticker.

5.3.3 Connection to read out half signals

See the figure on the left: FHF03 can be connected to read out only the heat flux through the left 50 % of the sensing area or the heat flux though the right 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 left – and right.

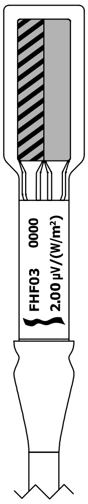

Figure 5.3.3.1 *Picture of FHF03 with left 50 % indicated by diagonal lines*

Table 5.3.3.1 *The electrical connection of FHF03 for 100 % signal*

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

Table 5.3.3.2 *The electrical connection of FHF03 for left 50 % signal*

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

Table 5.3.3.3 *The electrical connection of FHF03 for right 50 % signal*

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

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 FHF03 are available. In case a program for similar instruments is available, this can be used. FHF03 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 FHF03 in the standard configuration*

Capability to measure small voltage signals	preferably: < 5 x 10^{-6} V uncertainty minimum requirement: 20 x 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: < ± 3 °C uncertainty
Data acquisition input resistance	> 1 x 10^{6} Ω
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

FHF03 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 FHF03. 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 FHF03*

General	Inspect the sensor for any damage. Inspect the quality of mounting / installation. Inspect if the wires are properly attached to the data logger. Check the condition of the wires. Check the datalogger program in particular if the right sensitivity is entered. FHF03 sensitivity and serial number are shown on the product certificate and on the sticker. 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 25 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.
The sensor does not give any signal	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. Check the data acquisition by replacing the sensor with a spare unit.
The sensor signal is unrealistically high or low	Check the cable condition. 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. 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/m^2.
The sensor signal shows unexpected variations	Check the presence of strong sources of electromagnetic radiation (radar, radio). Check the condition of the sensor cable. Check if the cable is not moving during the measurement.

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/m^2
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 cable extension

FHF03 is equipped with one cable, and is available in cable lengths of 2 and 5 m.

Cables may act as a source of distortion by picking up capacitive noise. Keep the distance between data logger or amplifier and sensor as short as possible.

In an electrically “quiet” environment the FHF03 cable may be extended without problem. 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).

Cable and connection specifications are summarised below.

Table 7.1.1 *Preferred specifications for cable extension of FHF03*

Cable	4-wire, shielded, with 2 copper conductors and 2 type T thermocouple conductors
Extension sealing	make sure any connections are sealed against humidity ingress
Conductor resistance	< 0.1 Ω/m (copper wire)
Outer diameter	typically 3 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	either solder the new cable conductors and shield to those of the original sensor cable, and make a waterproof connection using heat-shrink tubing with hot-melt adhesive, or use gold plated waterproof connectors. Always connect the shield. when using connectors, use dedicated type T thermocouple connectors for extending the thermocouple wires

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 - 16.

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

FHF03 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 FHF03 depends on the temperature of the sensor. The temperature dependence of the FHF03 is specified as < 0.3 %/°C. Characterisation of FHF03s that we produced so far gives consistent values of +0.2 %/°C.

The calibration reference temperature is 20 °C.

Users that measure at temperatures that deviate much from 20 °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

$$\Phi = U/(S \cdot (1 + 0.002 \cdot (T - 20))) \quad \text{(Formula 7.4.1)}$$

with Φ the heat flux in W/m², U the FHF03 voltage output in V, S the sensitivity in V/(W/m²) at 20 °C and T the FHF03 temperature.

S is shown on the product certificate and on the sticker.

7.5 Appendix on measurement range for different temperatures

The measurement range of FHF03 is specified as (-10 to +10) x 10^3 W/m^2 at 20 °C heat sink temperature. This is a very conservative specification.

In reality, the maximum temperature of +150 °C is the limiting specification. The sensor temperature T in °C in a specific application depends on the heatsink temperature $T_{heatsink}$ in °C, the heat flux Φ in W/m² and the thermal resistance per unit area $R_{thermal,A}$ of the sensor in K/(W/m²).

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

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

$\Phi_{maximum} = (150 - T_{heatsink})/R_{thermal,A}$ (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 °C	46 x 10^3 W/m²
40 °C	39 x 10^3 W/m²
60 °C	32 x 10^3 W/m²
80 °C	25 x 10^3 W/m²
100 °C	18 x 10^3 W/m²

7.6 EU declaration of conformity

CE

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

in accordance with the requirements of the following directive:

2011/65/EU	The Restriction of Hazardous Substances Directive

hereby declare under our sole responsibility that:

Product model:	FHF03
Product type:	Foil heat flux sensor

has been designed to comply and is in conformity with the relevant sections and applicable requirements in the directive under typical conditions of use as defined in product specifications.

Eric HOEKSEMA
Director
Delft
April 27, 2020