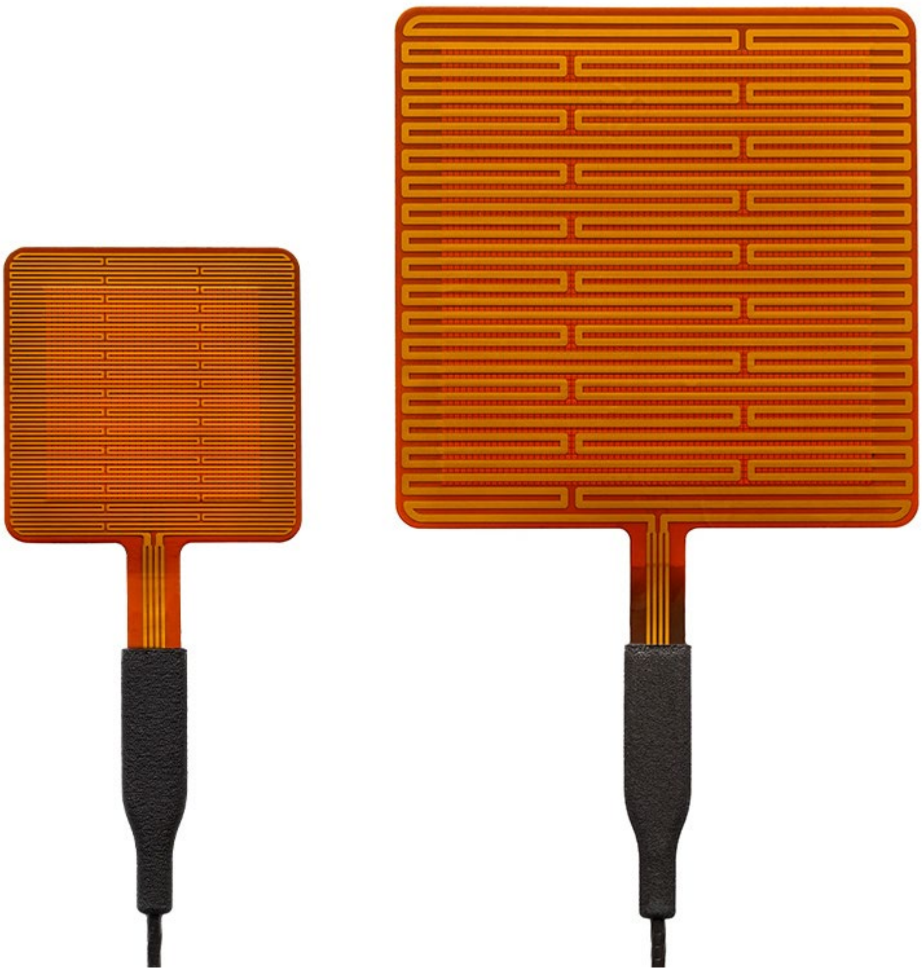
Hukseflux
Thermal Sensors

USER MANUAL

FHF05SC series

Self-calibrating foil heat flux sensors with thermal spreaders and heater



Cautionary statements

Cautionary statements are subdivided into four categories: danger, warning, caution and notice according to the severity of the risk.

⚠ DANGER
Failure to comply with a danger statement will lead to death or serious physical injuries.

⚠ WARNING
Failure to comply with a warning statement may lead to risk of death or serious physical injuries.

⚠ CAUTION
Failure to comply with a caution statement may lead to risk of minor or moderate physical injuries.

NOTICE
Failure to comply with a notice may lead to damage to equipment or may compromise reliable operation of the instrument.

Contents

List of symbols

Quantities	Symbol	Unit
Heat flux	Φ	W/m^2
Voltage output	U	V
Sensitivity	S	$V/(W/m^2)$
Temperature	T	°C
Thermal resistance per unit area	$R_{thermal,A}$	$K/(W/m^2)$
Area	A	m^2
Electrical resistance	R	Ω
Electrical power	P	W

subscripts

property of heatsink	heatsink
property of heater	heater
property of sensor	sensor
maximum value, specification limit	maximum

Introduction

FHF05SC series is a combination of the standard model FHF05 heat flux sensor and a heater. The heater allows the user to perform self-tests, verifying sensor functionality and stability during use, without having to remove the sensor. FHF05SC sensors are ideal for high-accuracy and long-term heat flux measurement, construction of calorimeters, (zero heat flux) core temperature measurement and thermal conductivity test equipment. Available in two models: size 50X50 mm and a larger and more sensitive size of 85X85 mm.

This manual offers information on the sensor, the working principle and all you need to know to successfully use it.

The heat flux sensor in FHF05SC measures heat flux through the object in which it is incorporated or on which it is mounted, in W/m^2. The heat flux sensor in FHF05SC is a thermopile. This thermopile measures the temperature difference across FHF05SC’s flexible body. A type T thermocouple is integrated as well to provide a temperature measurement. The thermopile and thermocouple do not require power.

Multiple small thermal spreaders, which form a conductive layer covering the sensor, help reduce the thermal conductivity dependence of the measurement. With its incorporated spreaders, the sensitivity of FHF05SC sensors is independent of their environment. Many competing sensors do not have thermal spreaders, so their sensitivity cannot be relied upon; it depends on the material on which they are mounted. The passive guard area around the FHF05SC sensor reduces edge effects and is also used for mounting.

The unique feature of the FHF05SC sensors is an incorporated heater. This heater may be used for self-testing purposes. When activated, the heater does require power.

Looking only for heat flux and temperature measurement without a heater? See our FHF05 series heat flux sensors.

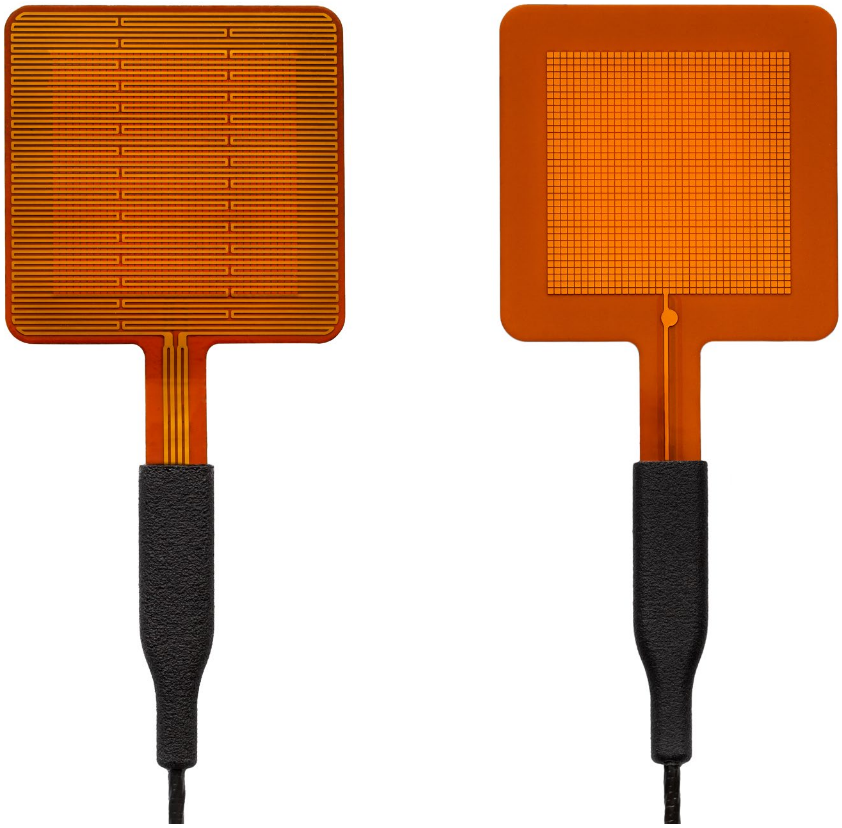


Figure 0.1 *Model FHF05SC-50X50 self-calibrating foil heat flux sensor with thermal spreaders and heater, showing its back- and frontside.*

Measuring heat flux, users may wish to regularly check their sensor performance. During use, the film heater can be activated to perform a self-test. The heat flux sensor response to the self-test, results in a verification of sensor performance. Implicitly also wire connection, data acquisition, thermal connection of the sensor to its environment and data processing are tested. Heat flux sensors are often kept installed for as long as possible. Using self-testing, the user no longer needs to take sensors to the laboratory to verify their stable performance. The heater has a well-characterised and traceable surface area and electrical resistance.

Figure 0.2 *Application example: FHF05SC-50X50 is being installed to measure heat flux on a pipe. The sensor is mounted on a well-prepared curved surface.*

The FHF05SC self-calibrating foil heat flux sensors have unique features and benefits:

- heater for self-test
- flexible (bending radius ≥ 15 x 10^{-3} m)
- low thermal resistance
- wide temperature range
- fast response time
- integrated type T thermocouple
- robustness, including cable and potted cable connection block which may be used as strain relief
- IP protection class: IP67 (essential for outdoor application and in humid environments)
- integrated thermal spreaders for low thermal conductivity dependence

FHF05SC series suggested use:

- high-accuracy scientific measurement of heat flux, with a high level of data quality assurance
- study of convective heat transfer mechanisms
- calorimeter prototyping
- (zero heat flux) non-invasive core temperature measurement
- thermal conductivity test equipment

Using an FHF05SC sensor 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 sensor output, a small voltage, by the sensitivity. The sensitivity is provided with the sensor on its product certificate.

Equipped with a potted cable connection block that prevents moisture from penetrating and may also serve as strain relief, FHF05SC has proven to be very robust and stable.

FHF05SC's calibration is traceable to international standards. The factory calibration method follows the recommended practice of ASTM C1130 - 21. When used under conditions that differ from the calibration reference conditions, the FHF05SC's sensitivity to heat flux may be different than stated on its certificate. See Chapter 2 in this manual for suggested solutions.

Optionally FHF05SC sensors can be provided with radiation-absorbing black BLK and radiation-reflecting gold GLD stickers. You can then measure convective + radiative flux with one, and convective flux only with the other. Subtract the 2 measurements and you have radiative flux. BLK – GLD stickers can be applied by the user to the sensor. There are stickers for every sensor dimension. Optionally, they can be ordered pre-applied; see the BLK – GLD sticker series user manual and installation video for instructions.

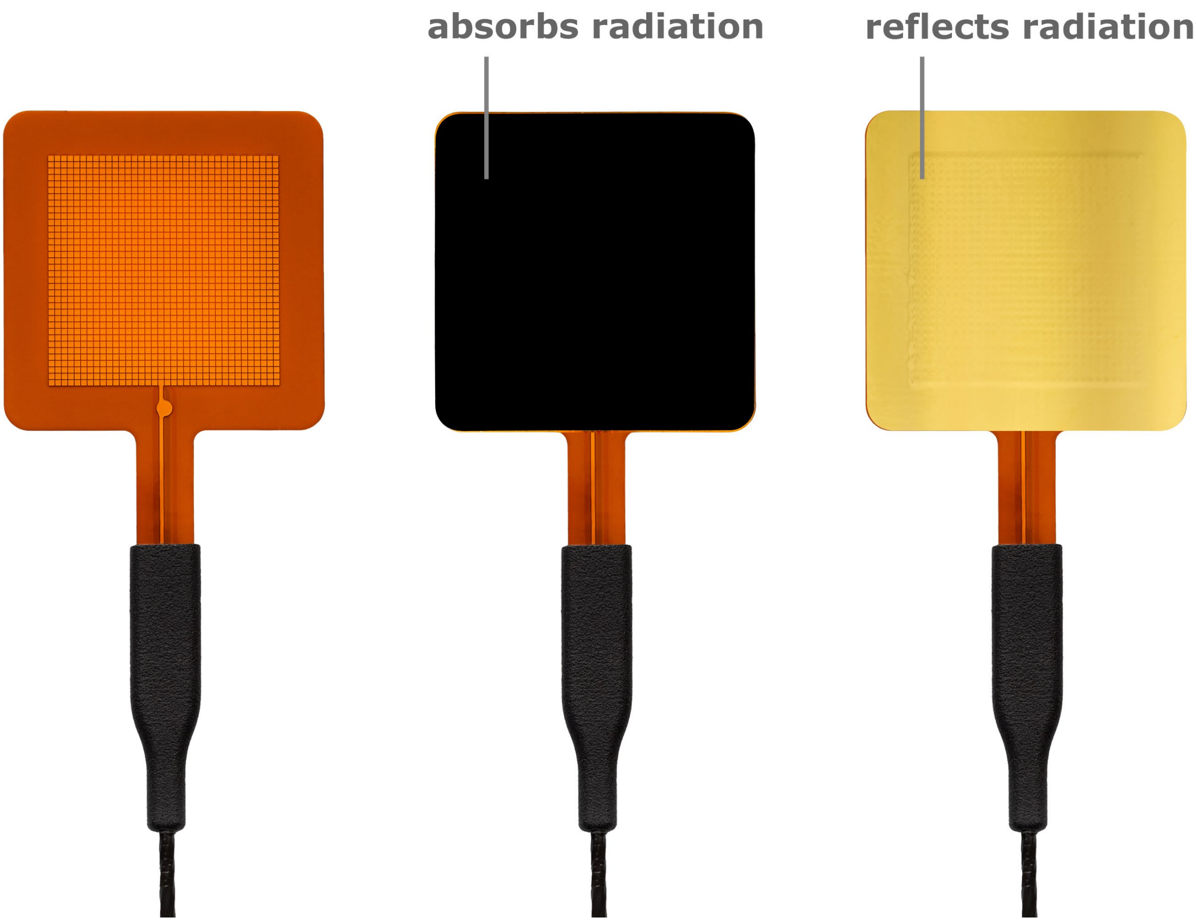


Figure 0.3 *FHF05SC-50X50 heat flux sensor: with BLK-5050 and GLD-5050 stickers.*

See also:

- FHF05 series, our standard sensor models for general-purpose heat flux measurement
- model HFP01 (used on walls and in soils as lower cost alternative to FHF05 85X85)
- HTR02 series heater, for verification of performance of FHF-type sensors.
- BLK – GLD sticker series to separate radiative and convective heat fluxes
- Hukseflux offers a complete product range of heat flux sensors with the highest quality for any budget

1 Ordering and checking at delivery

1.1 Ordering FHF05SC series

The standard configuration of FHF05SC series is FHF05SC-50X50-02, model 50X50 with 2 metres of cable. Common options are:

- model FHF05SC-85X85
- change -02 to -05 or -10 metres cable length
- with a separate cable of 2, 5 or 10 metres cable length
- with LI19 hand-held read-out unit / data logger; NOTE: LI19 does not measure temperature, only heat flux and does not support self-test functionality
- with a BLK black sticker (to measure radiative as well as convective heat flux)
- with a GLD gold sticker (to measure convective heat flux only)
- BLK – GLD sticker series can also be ordered pre-applied at the factory for every sensor dimension

1.2 Included items

Arriving at the customer, the delivery should include:

- heat flux sensor FHF05SC with cable of the length as ordered
- product certificate matching the instrument serial number

Figure 1.2.1 *Model FHF05SC-50X50 with serial number and sensitivity shown at the end of the cable.*

1.3 Quick instrument check

⚠ CAUTION
Do not put a voltage of more than 0.1 V over 2 wires that connect to the same side of the heater: the yellow and purple wire on one side of the heater, or the pink and green wire on the other side of the heater. **The traces on the heater foil may overheat and get damaged beyond repair.**

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 potted connection 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 1k 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 0.3 Ω/m. Typical resistance should be the nominal sensor resistance mentioned in Table 3.1.1 (specifications) plus 0.6 Ω for the total resistance of two wires for each metre (back and forth). 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. The typical resistance of the copper wiring is 0.3 Ω/m, for the constantan wiring this is 6.5 Ω/m. Typical resistance should be the nominal thermocouple resistance of 2.5 Ω plus 6.8 Ω for the total resistance of the two wires of each metre (back and forth). 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 100×10^{-3} VDC range or lower. Expose the sensor to heat. Exposing the backside (the side with the heater) to heat should generate a positive signal between the red [+] and black [-] wires. Doing the same at the frontside (the side with the dot), reverses the sign of the output.
6. Check the electrical resistance of the heater between purple or yellow wire and pink or green wire. Use a multimeter at the 1 kΩ range. Typical resistance should be around 120 Ω for model -50X50 and around 40 Ω for model -85X85. Infinite resistance indicates a broken circuit; zero or a lower than 1 Ω resistance indicates a short circuit.
7. Check the electrical resistance between the purple and yellow wires. These resistances should be in the 0.1 Ω/m range, so 0.2 Ω in case of the standard 2 m wire length. Higher resistances indicate a broken circuit. Repeat this measurement for the pink and green wire.

2 Instrument principle and theory

2.1 What a heat flux sensor is and how it works

FHF05SC sensor's scientific name is heat flux transducer. We use the expression heat flux sensor, because this is more common. 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".

FHF05SC sensor users typically assume that the measured heat flux is representative of the undisturbed heat flux at the sensor's location. Users may also apply corrections based on scientific judgement.

The sensing element that generates a signal in FHF05SCs is a thermopile, which formally is a sensor. This thermopile measures the temperature difference across the sensor's polyimide - a plastic body. Working completely passively, 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 an FHF05SC heat flux sensor 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 supplied with each individual sensor.

$$\Phi = U/S \qquad \text{(Formula 2.1)}$$

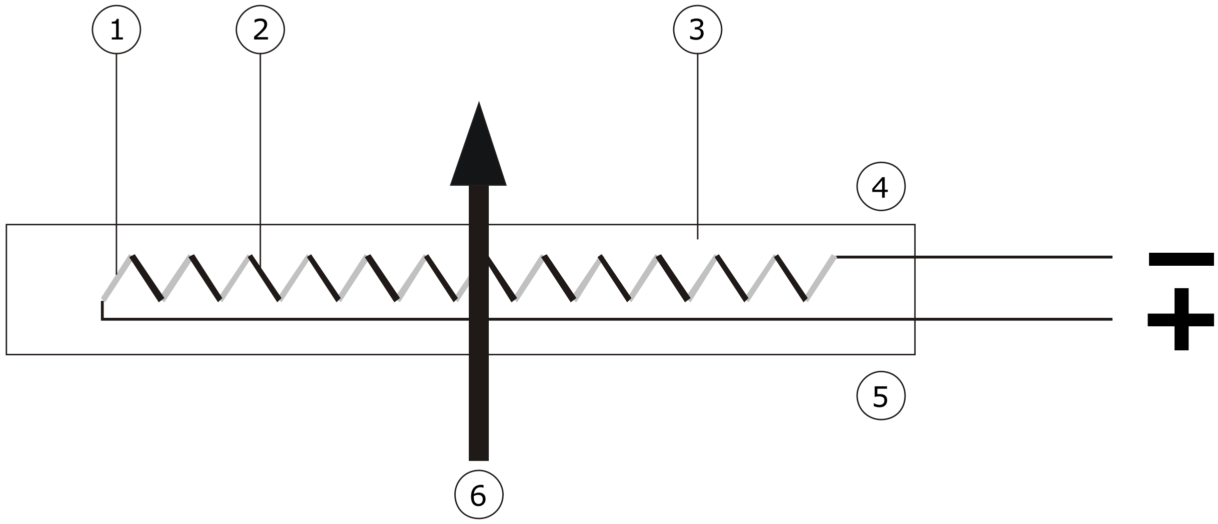


Figure 2.1.1 *The general working principle of a heat flux sensor. The sensor inside FHF05SC series is a thermopile. A thermopile consists of a number of thermocouples, each consisting of two metal alloys (marked 1 and 2), electrically connected in series. A single thermocouple generates an output voltage 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 a 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 2.1.2 *Heat flux from the backside to the frontside generates a positive voltage output signal. The dot on the foil indicates the frontside. The backside of the FHF05SC has a heater.*

All FHF05SC's are designed such that heat flux from the backside to the frontside generates a positive voltage output signal. The dot on the foil indicates the frontside.

Unique features of the FHF05SC sensors include flexibility (bending radius ≥ 7.5×10^{-3} m), low thermal resistance, a wide temperature range, a fast response time, IP67 protection class rating (essential for outdoor application and use under humid conditions), and thermal spreaders to reduce thermal conductivity dependence.

All FHF05SC's are 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 300 or 600 W/m^2
- mounted on aluminium heat sink

FHF05SC series 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 FHF05 series 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 (included in FHF05SC)
- correct the sensitivity for the temperature dependence. See the appendix on correction of temperature dependence for more information
- apply our BLK black sticker to the sensor surface to absorb radiation
- apply our GLD gold sticker to the sensor surface to reflect radiation

The user should analyse his own experiment and make his own uncertainty evaluation. The FHF05SC series rated temperature range for continuous use is -70 to +120 °C, for short intervals, peak temperatures -160 to +150 °C are allowed. Please contact Hukseflux when measuring at -160 °C, see also the appendix on use at low temperatures. Prolonged exposure to temperatures near +150 °C will accelerate the ageing process.

You may consider a single heat flux sensor as a sensor composed of several smaller heat flux sensors. In case users want to enlarge sensor surface area or sensitivity, consider putting multiple sensors electrically in series. See the chapter on electrical connection 5.3.

2.2 The self-test

A self-test is started by switching on FHF05SC's heater, while recording the sensor output signal and the heater power. It is finalised by switching the heater off. During the heating interval a current I_{heater} is fed through the foill heater, which generates a known heat flux proportional to the heater power. To calculate this heat flux, the heater power P_{heater} must be measured accurately. This power can be measured in several different ways;

- heater voltage and current, $P_{heater} = U_{heater} \cdot I_{heater}$ (Formula 2.2.1)

- heater voltage and known heater resistance, $P_{heater} = U_{heater}^2/R_{heater}$ (Formula 2.2.2)

- heater current and known heater resistance, $P_{heater} = I_{heater}^2 \cdot R_{heater}$ (Formula 2.2.3)

The user must interrupt the normal measurement of the heat flux during the self-test.

If performed in a four-wire configuration, the first method of formula 2.2.1 is preferred, because it is generally more accurate than the latter two methods. However, it requires both a voltmeter and an ammeter instead of just one of the two. This is why the method of formula 2.2.2 is more commonly applied.

Analysis of the heat flux sensor response to the heating (the self-test) serves several purposes:

- first, the amplitude and response time under comparable conditions are indicators of the sensor stability. See Sections 2.4 and 2.5 for application examples.
- second, the functionality of the complete measuring system is verified. For example: a broken cable is immediately detected.
- third, under the right conditions, after taking the sensor out of its normal environment, the self-test may be used as validation. See Section 2.3 for more details.

2.3 Validation

FHF05SC series calibration is traceable to international standards. The factory calibration method follows the recommended practice of ASTM C1130 - 21. When used under conditions that differ from the calibration reference conditions, the FHF05SC series sensitivity to heat flux may be different than stated on its certificate.

In a typical validation setup as shown in the next figure, the FHF05SC series is positioned between an insulating material and a heatsink with the FHF05SC series heater on the side of the insulating material. In such a setup, the heat losses through the insulation may be ignored. In this case, all heat generated by the heater flows through the heat flux sensor to the heat sink. Measuring the heater power P_{heater}, and dividing by the surface area A_{heater}, gives the applied heat flux:

$\Phi = P_{heater}/A_{heater}$ (Formula 2.3.1)

The heat flux sensor sensitivity *S* is the voltage output U_{sensor} divided by the applied heat flux Φ:

$S = U_{sensor}/\Phi$ (Formula 2.3.2)

The reproducibility of this test is much improved when using contact material (such as glycerol or a thermal paste) between sensor and heat sink.

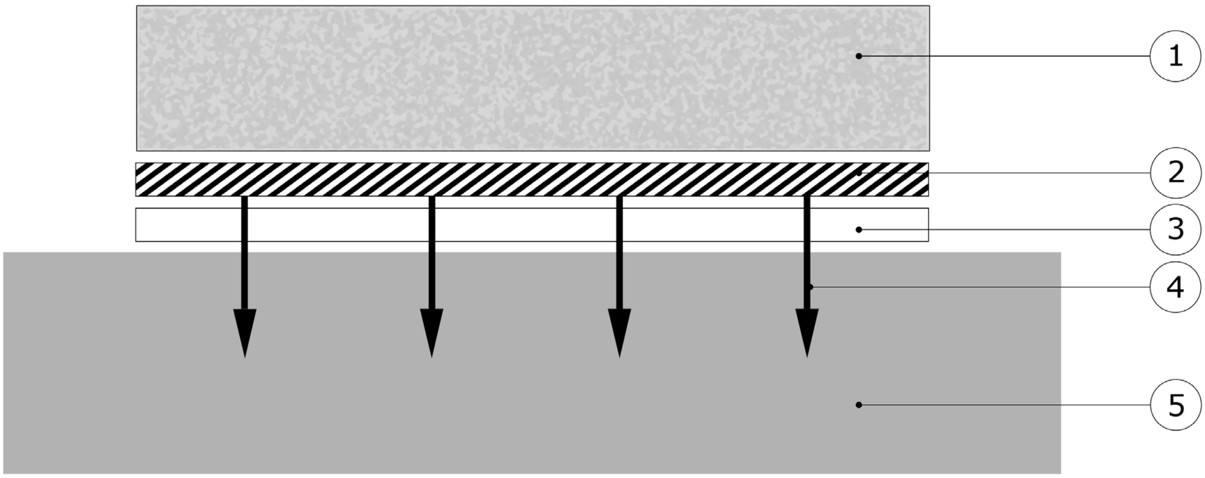


Figure 2.3.1 *Validation of FHF05SC sensors; a typical stack used for calibration consists of a block of metal (mass > 1 kg), for example aluminium (5), the heat flux sensor (3), with heater (2) and an insulation foam (1). Under these conditions, heat losses through the insulation are negligible. Heat flux (4) flows from hot to cold.*

2.4 Application example: stable performance check

FHF05SC's heater can be used to check for stable performance of the sensor at regular intervals without the need to uninstall the sensor from its application.

A typical stability check is performed based on the step response of the measured heat flux and sensor temperature to a heat flux applied by the heater. Upon installing the sensor, a reference measurement should be made. A time trace of the heater power, the measured heat flux and the measured sensor temperature should be stored as reference data. Stable operation of the sensor can then be confirmed at any time by comparing to the reference measurement. The test protocol consists of the following steps:

1. Make sure that the absolute temperature is similar to that during the reference measurement.
2. Check the heater resistance stability. This can be done accurately by using the four heater wires to conduct a four-point resistance measurement.
3. Record a time trace of the heater power, the measured heat flux and the sensor temperature; the same parameters as in the reference data. Normalise the data by the heater power. Under normal circumstances (if the heater is stable) this process scales with U_{heater}^2.
4. Compare patterns of heat flux and temperature rise and fall. In both cases, relative to the values just before heating. When the signal patterns match, amplitude differences, after correction for heater power, point towards sensor instability. In this case, recalibration of the sensor may be required (Figure 2.4.1). Non-matching patterns point towards changes in sensor environment. This can, for example, be the result of a loss of thermal contact between sensor and object (Figure 2.4.2) or the presence of convective heat losses (Figure 2.4.3).

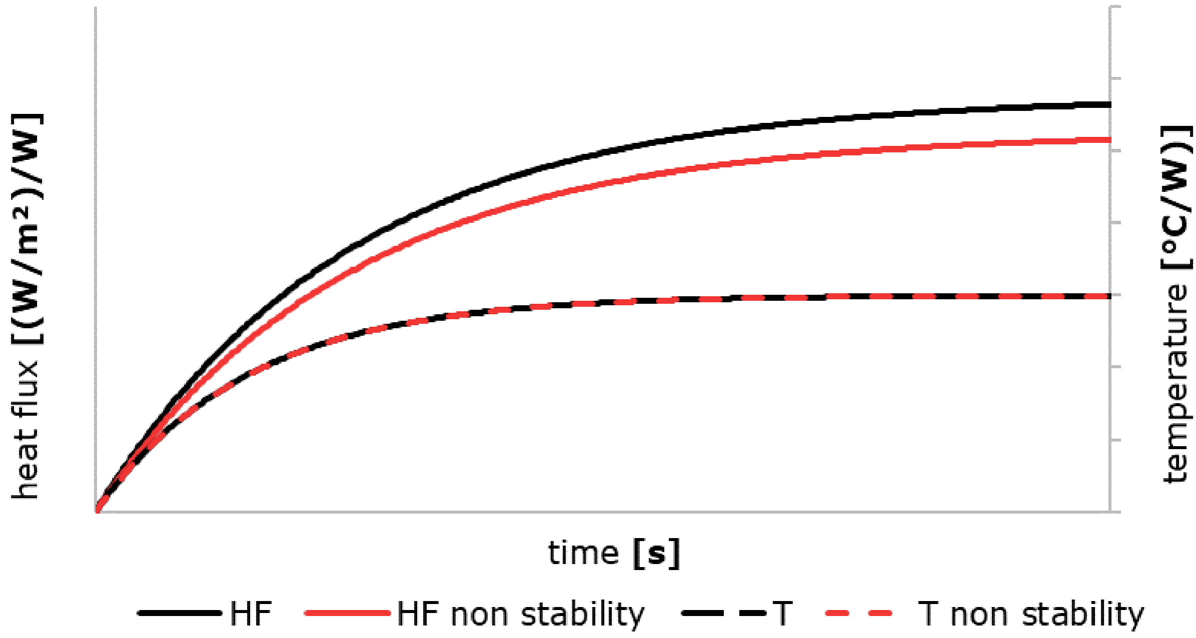


Figure 2.4.1 *In-situ sensor stability check. Comparison of responses to stepwise heating relative to reference curves. Normalised to heater power (P) and relative to the heat flux and the temperature just before heating. Solid graphs show heat flux, dotted graphs show temperature. The black HF and T signals are the reference curves at installation. The sensor shows non-stability, loses sensitivity over time, which results in the red responses: equal response times, lower heat flux and equal temperature rise.*

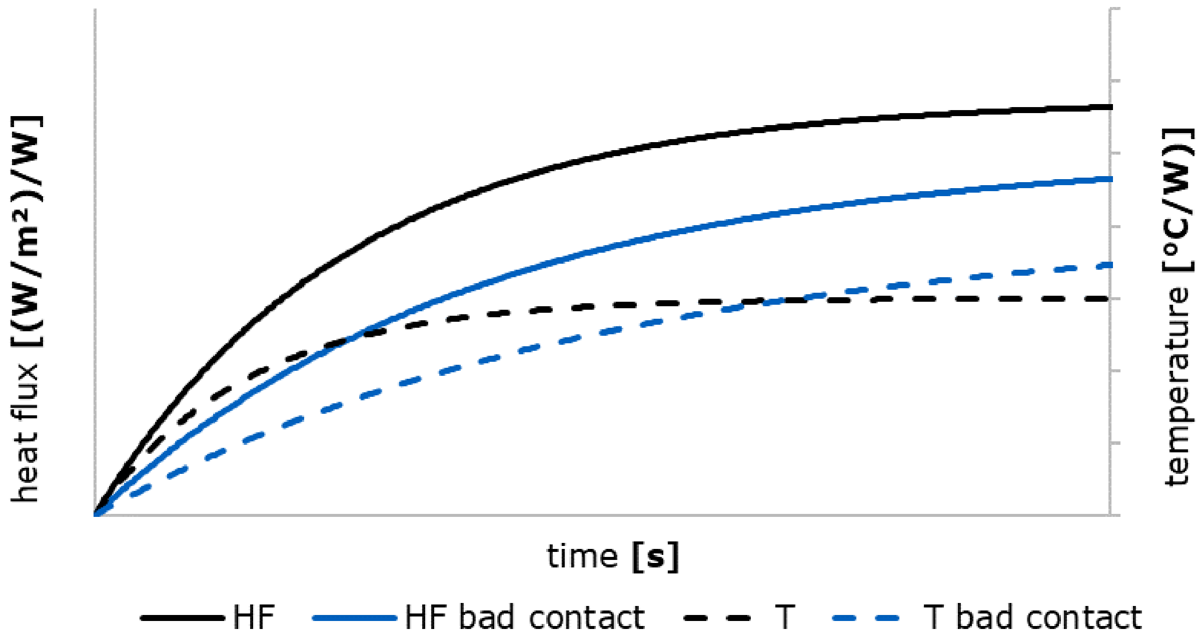


Figure 2.4.2 *In situ sensor stability check. Comparison of responses to stepwise heating relative to reference curves. Normalised to heater power (P) and relative to the heat flux and the temperature just before heating. Solid graphs show heat flux, dotted graphs show temperature. The black HF and T signals are the reference curves at good thermal contact. The sensor loses thermal contact, which results in the blue responses: slower response times, lower heat flux and higher temperature rise.*

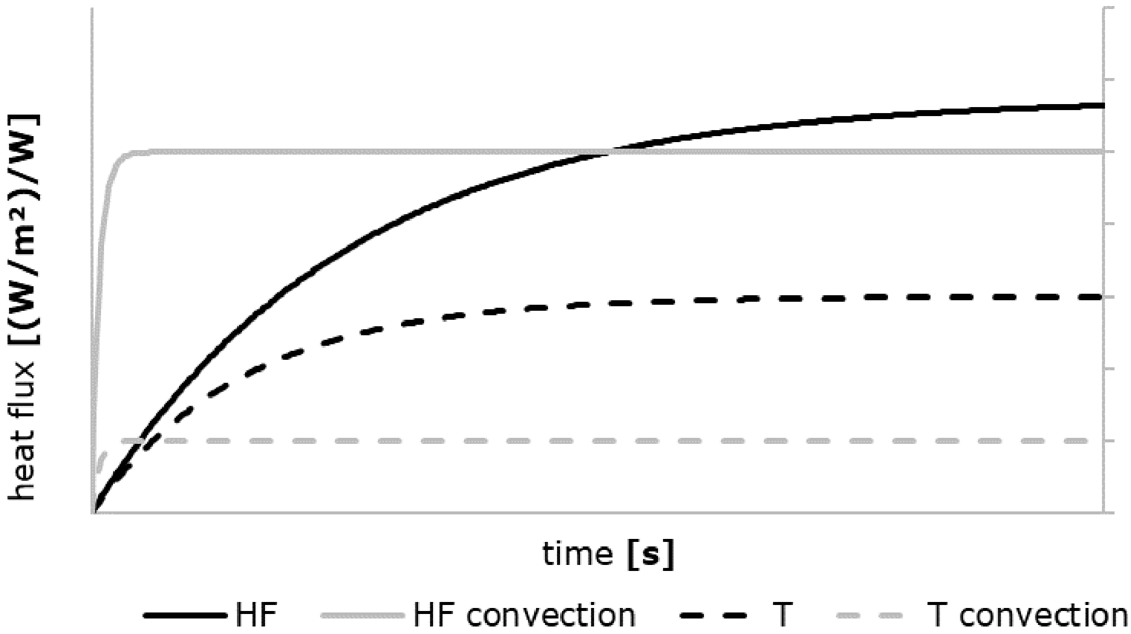


Figure 2.4.3 *In-situ sensor stability check. Comparison of responses to stepwise heating relative to reference curves. Normalised to heater power (P) and relative to the heat flux and the temperature just before heating. Solid graphs show heat flux, dotted graphs show temperature. The black HF and T signals are the reference curves at zero wind speed. The sensor is exposed to convection, which results in the grey responses: faster response times at lower heat flux and lower temperature rise.*

2.5 Application example: non-invasive core temperature measurement

FHF05SC sensors may be used for non-invasively measuring the core temperature of objects, for example of human beings.

The measurement is done by securely fixating the sensor on the object under test. The side of the heater should be surrounded with insulation material. All the heat is forced through the sensor. To determine the core temperature, the heater power should be adjusted such that the heat flux equals zero. When zero heat flux is attained, the temperature gradient equals zero and the measured temperature equals the core temperature.

To perform such a measurement, a PID controller can be used to regulate the heating power. The setpoint of the PID controller should be set to zero heat flux. The PID controller can regulate the heater power through a 0 – 12 V programmable power supply.

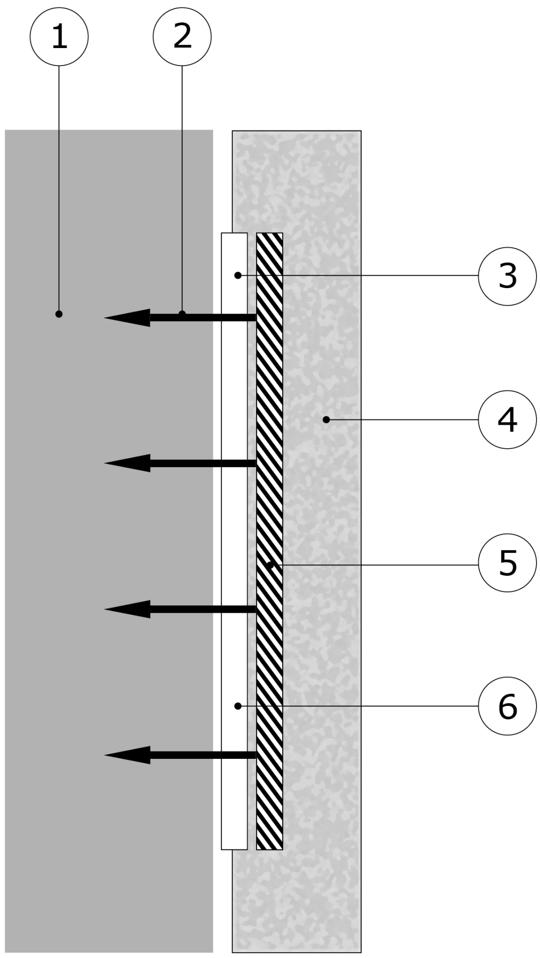


Figure 2.5.1 *FHF05SC sensor in a non-invasive core-temperature measurement. For measurement of the core temperature (1), the heater (5) is controlled to a setpoint of zero heat flux (2) measured by the heat flux sensor (3). At zero heat flux, the temperature of the core (1) and the temperature sensor (6) are equal. Insulation material (4) is attached to work at stable boundary conditions.*

2.6 Measuring radiation and convection

At a surface, heat will often be transferred by a combination of radiation and convection. To accurately measure the convective part, the thermal resistance of the sensor should be as low as possible. For the radiative part, the optical surface properties of the sensor should be representative of the surrounding area.

Some points to keep in mind:

- radiation is not only transmitted in the spectral range that humans can see (visible radiation) but also as non-visible far infra-red
- blank metal is reflective in the visible as well as in the far infra-red
- paints and plastic coatings, wood and stone absorb in different ranges, depending on their colour in the visible range. These materials typically all behave as "black" in the far infra-red

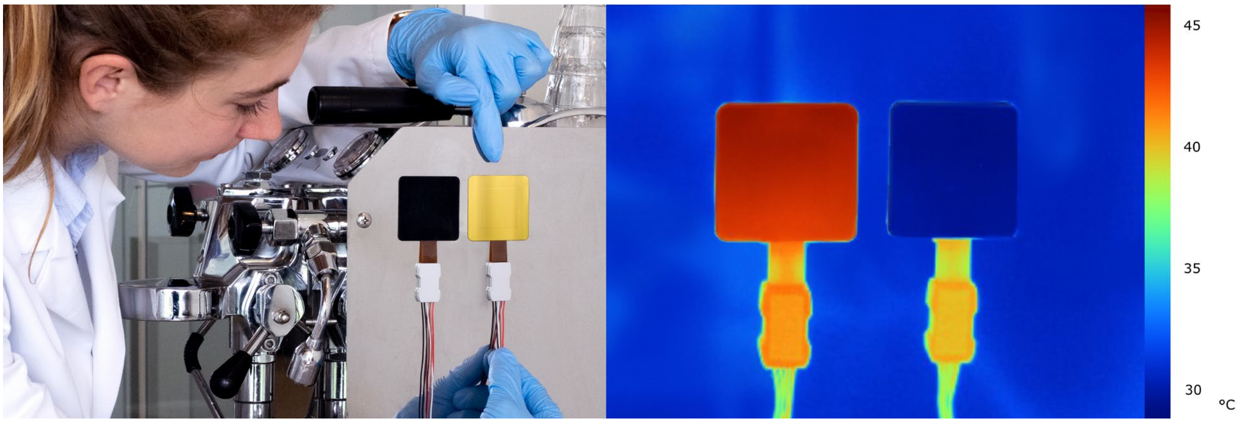


Figure 2.6.1 *Application of a BLK black sticker and a GLD gold sticker on FHF models for measuring radiative and convective heat flux on an espresso machine. The machine has a polished metal surface of about 45 °C. The IR image on the right shows that the black sticker on the left, as well as the sensor wires and connector blocks, emit radiation. They appear in red on the image. The gold sticker and the metal surface have lower emission and appear as "bluish" in the image. Mounted on the same surface, the BLK and GLD stickers have the same temperature. The measurement with the sensor with the GLD sticker is most representative of the heat flux at the polished metal surface, while the sensor with the BLK sticker overestimates the heat flux.*

3 Specifications of FHF05SC sensors

3.1 Specifications of sensors of the FHF05SC series

Sensors of the FHF05SC series measure the heat flux density through the surface of the sensor. This quantity, expressed in W/m^2, is called heat flux. Using a thermopile sensor, an FHF05SC generates a small output voltage proportional to this flux. A Type T thermocouple is included for temperature measurement. No power is required for the sensors. A heater can be activated to perform a self-test. This heater requires a switched or controlled power supply. FHF05SC sensors can only be used in combination with a suitable measurement and control system.

Table 3.1.1 *Specifications of sensors of the FHF05SC series (continued on next pages).*

FHF05SC SERIES SPECIFICATIONS	
Sensor type	self-calibrating 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 to +10) x 10^3 W/m^2 at heat sink temperature 20 °C see the appendix for detailed calculations
Sensitivity range (nominal)	
FHF05SC-50X50	13 x 10^{-6} V/(W/m^2)
FHF05SC-85X85	50 x 10^{-6} V/(W/m^2)
Directional sensitivity	heat flux from the backside (side with the heater) to the frontside (side with the dot) generates a positive voltage output signal
Increased sensitivity and spatial coverage	multiple sensors may be put electrically in series. The resulting sensitivity is the sum of the sensitivities of the individual sensors. The resulting measurement is representative for the heat flux over the area covered by the sensors and may also be representative for the area between the sensors.
Expected voltage output	(-100 to +100) x 10^{-3} V turning the sensor over from one side to the other will lead to a reversal of the sensor voltage output
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	≤ 1.6 kg
Rated bending radius	≥ 15 x 10^{-3} m
Rated operating temperature range, continuous use	-70 to +120 °C for use to -200 °C, see appendix
Rated operating temperature range, short interval	120 to +150 °C
Temperature dependence	< 0.2 %/°C (see also the chapter on correction for temperature dependence)

Table 3.1.1 *Specifications of FHF05SC series (started on previous page, continued on next pages).*

Non-linearity	< 5 % (0 to 10 x 10^3 W/m²)
Solar absorption coefficient	0.75 (indication only)
Thermal conductivity dependence	negligible, < 3 %/(W/m·K) for environments from 270 to 0.3 W/m·K
Sensor length and width	
FHF05SC-50X50	(50 x 50) x 10^{-3} m
FHF05SC-85X85	(85 x 85) x 10^{-3} m
Sensor sensing area	
FHF05SC-50X50	12.96 x 10^{-4} m^2
FHF05SC-85X85	47.70 x 10^{-3} m²
Sensing area length and width	
FHF05SC-50X50	(36 x 36) x 10^{-3} m
FHF05SC-85X85	(70 x 71) x 10^{-3} m
Sensor passive guard area	
FHF05SC-50X50	12.04 x 10^{-4} m^2
FHF05SC-85X85	22.55 x 10^{-4} m^2
Guard width to thickness ratio	
FHF05SC-50X50	17.5
FHF05SC-85X85	18.25
Sensor thickness	0.7 x 10^{-3} m
Sensor thermal resistance	24 x 10^{-4} K/(W/m^2)
Sensor thermal conductivity	0.29 W/(m·K)
Response time (95 %)	6 s
Sensor resistance range per dimension	
FHF05SC-50X50	200 – 300 Ω
FHF05SC-85X85	800 – 1300 Ω
Required sensor power	zero (passive sensor)
Temperature sensor	type T thermocouple
Temperature sensor accuracy	standard grade type T according to ASTM E230 (IEC 60584 Class 2) ± 1.0 °C or 0.0075 × | T | (whichever is greater) If the temperatures of the sensor foil and cable connection block are the same. See the appendix for other conditions.
Standard cable length	2 m
Optional cable length	0, 5 or 10 m
Wiring	7 x copper and 1 x constantan wire, AWG 28, solid core, bundled with a PFA sheath
Cable diameter	2.7 x 10^{-3} m
Marking	dot on foil indicating the frontside of the heat flux sensor; 1 x label at the end of FHF05SC's cable, showing serial number and sensitivity
IP protection class	IP67
Rated operating relative humidity range	0 to 100 %
Long-term exposure to water	see the appendix on long-term use under condensing, wet and underwater conditions
Rated operating pressure range	sensor foil only: 8 bar uniform pressure see the appendix on use under pressure Sensor foil only: may be used in vacuum see the appendix on use under vacuum

Table 3.1.1 *Specifications of FHF05SC series (started on previous pages, continued on next page).*

Gross weight including 2 m wires	approx. 0.5 kg
Net weight including 2 m wires	approx. 0.5 kg
HEATER	
Heater length and width per dimension	
FHF05SC-50X50	(48 x 47.6) x 10^{-3} m
FHF05SC-85X85	(83 x 82.6) x 10^{-3} m
Heater area	
FHF05SC-50X50	2381 x 10^{-6} m^2
FHF05SC-85X85	7022 x 10^{-6} m^2
Passive guard area	
FHF05SC-50X50	2152 x 10^{-4} m^2
FHF05SC-85X85	3692 x 10^{-4} m^2
Heater resistance (nominal) per dimension (measured value supplied with each sensor in the production report)	
FHF05SC-50X50	120 Ω
FHF05SC-85X85	40 Ω
Heater rated power supply	24 VDC
Heater power supply	12 VDC (nominal)
Suggested current sensing resistor	10 Ω ± 0.1 %, 0.25 W, < 15 ppm/°C
SELF-TEST	
Power consumption during heating interval (nominal)	
FHF05SC-50X50	1.20 W (@ 12 VDC)
FHF05SC-85X85	3.60 W (@ 12 VDC)
Nominal heat flux at 12 VDC per dimension	
FHF05SC-50X50	500 W/m²
FHF05SC-85X85	500 W/m²
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 or more per measurement location
Installation	see the recommendations in this user manual
Bending	see the chapter on installation on curved surfaces
Cable extension	see the chapter on cable extension or order sensors with longer cable length
Sensor foil installation	see the appendix on installation of FHF05SC foils

Table 3.1.1 *Specifications of sensors of the FHF05SC series (started on previous pages).*

CALIBRATION	
Calibration traceability	to SI units
Product certificate	included (showing calibration result and traceability)
Calibration method	method HFPC, according to ASTM C1130 - 21
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 300 (model -50X50) or 600 (model -85X85) 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 FHF05SC sensitivity to heat flux may be different than stated on its certificate. See the chapter on instrument principle and theory for suggested solutions
Field validation	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 see the paragraph on validation and calibration
MEASUREMENT ACCURACY	
Uncertainty of the measurement	statements about the overall measurement uncertainty can only be made on an individual basis.
VERSIONS / OPTIONS	
With longer cable length	option code = cable length in metres
With black sticker applied	BLK sticker applied to the sensor at the factory to absorb radiation
With gold sticker applied	GLD sticker applied to the sensor at the factory to reflect radiation
ACCESSORIES	
Hand-held read-out unit	LI19 handheld read-out unit / data logger NOTE: LI19 does not measure temperature, only heat flux and does not support self-test functionality
Separate black stickers	BLK sticker to absorb radiation, to be applied by the user
Separate gold sticker	GLD sticker to reflect radiation, to be applied by the user

3.2 Dimensions of FHF05SC series

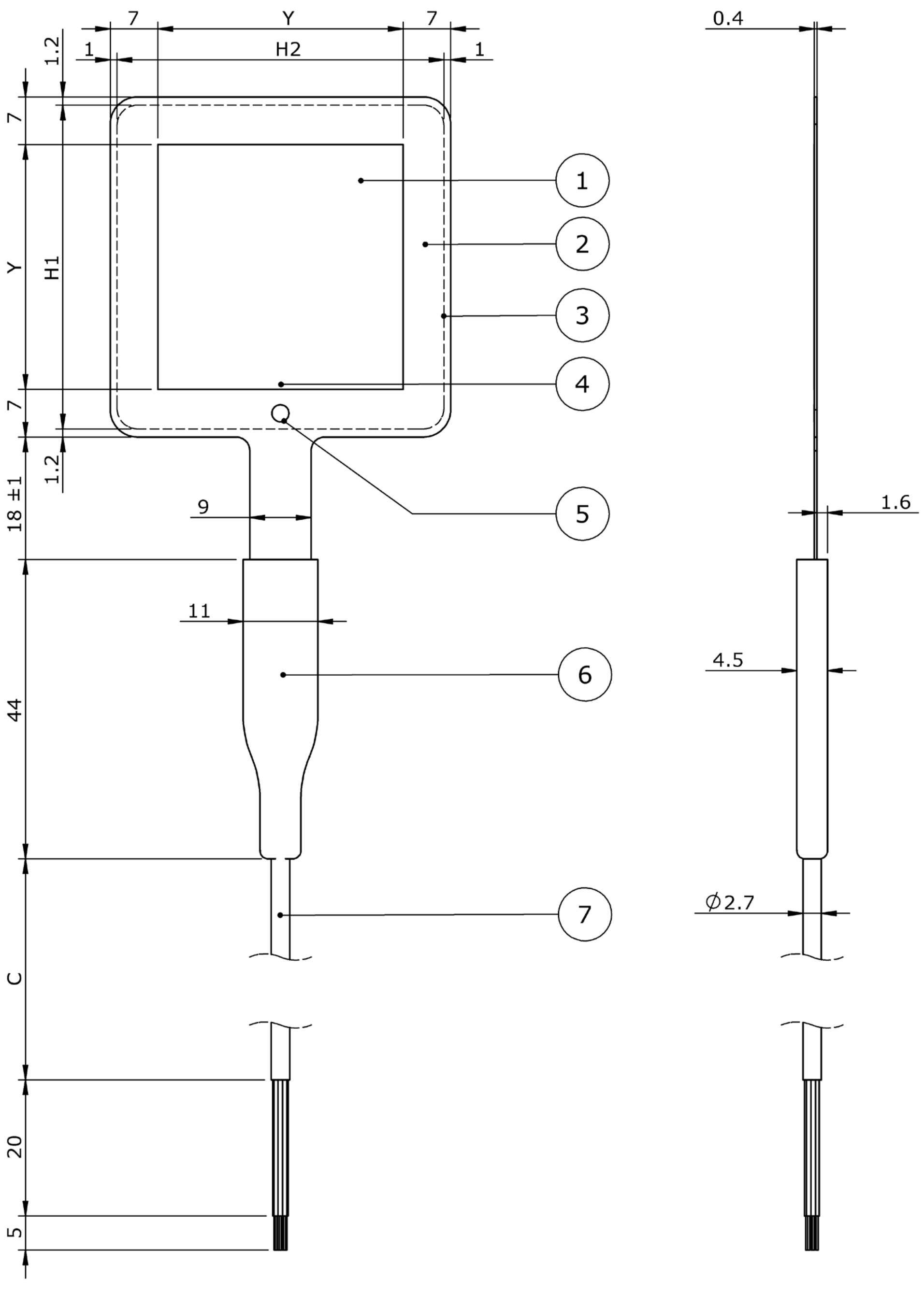


Figure 3.2.1 *FHF05SC series models -50X50 and -85X85 heat flux sensor; Y = 36 or 70, H1 = 47.6 or 82.6 and H2 = 48 or 83. All dimensions in x* 10^{-3} *m.*

(1) sensing area with thermal spreaders
(2) passive guard
(3) contour of the heater area for self-test
(4) type T thermocouple
(5) dot indicating frontside
(6) potted cable connection block for strain relief
(7) wires, standard length C = 2 m

4 Standards and recommended practices for use

FHF05SC sensors should be used in accordance with recommended practices.

There are no ISO, ASTM or IEC standards with recommended practices for use of heat flux sensors like FHF05SC.

4.1 Heat flux measurement in industry

FHF05SC series 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 model FHF05SC-85X85 foil heat flux sensor being installed for measurement on an object. The sensor is mounted on a well-prepared flat surface.*

5 Installation of FHF05SC sensors

Before performing a measurement, and permanently installing a heat flux sensor, we recommend to extensively test the heat flux sensor and the entire measuring system.

For example,

- confirm the functionality and measurement accuracy of the temperature sensor in a temperature bath
- confirm the functionality and accuracy of the heat flux measurement in a separate experiment, for example using electrical heaters such as those of the HTR series and a heatsink

In such experiments you may select a temperature and a heat flux sensor to serve as references and determine deviations relative to this reference.

5.1 Why to avoid air gaps

The thermal conductivity of air is in the order of 0.02 W/(m·K). Therefore, even small air gaps are significant thermal resistances.
The thermal conductivity of plastic or thermal paste is in the order of 0.2 W/(m·K), so for the same thickness, thermal resistance is a factor 10 lower.
Take for example a 0.05×10^{-3} m, air gap. This has a thermal resistance of 20×10^{-4} K/(W/m^2). This may be compared to around 10×10^{-4} K/(W/m^2) for FHF sensors, so a small air gap produces an increase of thermal resistance of respectively 200 % for FHF.
Using a filler of 0.05×10^{-3} m, with a thermal conductivity around 10 times higher than that of air, the thermal resistance is reduced to 2.5×10^{-4} K/(W/m^2). The contribution of the thermal resistance reduces to about 20 % .

From this example, you can also see that it is not necessary to use high-thermal conductivity tapes. Using a thin normal tape is enough.

An air gap may not only lead to a higher thermal resistance for conductive heat, but also to an entirely different radiation balance. An air gap is a "resistance" (a radiation screen) for radiative transfer. If it is filled-up, it is no resistance any longer. Watch out in case radiative (far infra-red) heat flux is significant. In that case, the presence of an air gap may be the dominant source of errors, because a sensor with an air gap acts as a radiation shield, reducing local radiative transfer by a theoretical maximum of 50 %.

5.2 Site selection and installation

Table 5.2.1 *Recommendations for installation of FHF05SC series 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	we recommend using > 2 sensors per measurement location. This redundancy also improves the assessment of the measurement accuracy
Mounting	when mounting a FHF05SC model, keep the directional sensitivity in mind orient the heater away from the object on which it is mounted heat flux from the backside (side with heater) to the frontside (side with dot) generates a positive voltage output signal to achieve the highest accuracy temperature measurement fix the connection block to the object of interest so that the temperature of the cable connection block remains as close as possible to that of the heat flux sensor (see appendix on the accuracy of the temperature measurement)
Surface cleaning and levelling	create a clean and smooth surface of at least the outer dimensions of the sensor in use
Mechanical mounting: avoiding strain on the sensor to wire transition	during installation as well as operation, the user should provide proper strain relief on the cable so that the cable connection block is not exposed to significant force first, install the sensor by providing strain relief on the connection block and after that install the wires including additional strain relief
Short term installation	to avoid air gaps, we recommend thermal paste or glycerol for short-term installation use tape to mount the sensor on the surface. If possible, tape only over the passive guard area (surrounding the sensing area). See Figure 5.2.1 use tape to mount the cable connection block of the sensor usually, the cable is fixated with an additional strain relief, for example using a cable tie mount as in Figure 5.2.1
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 at 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

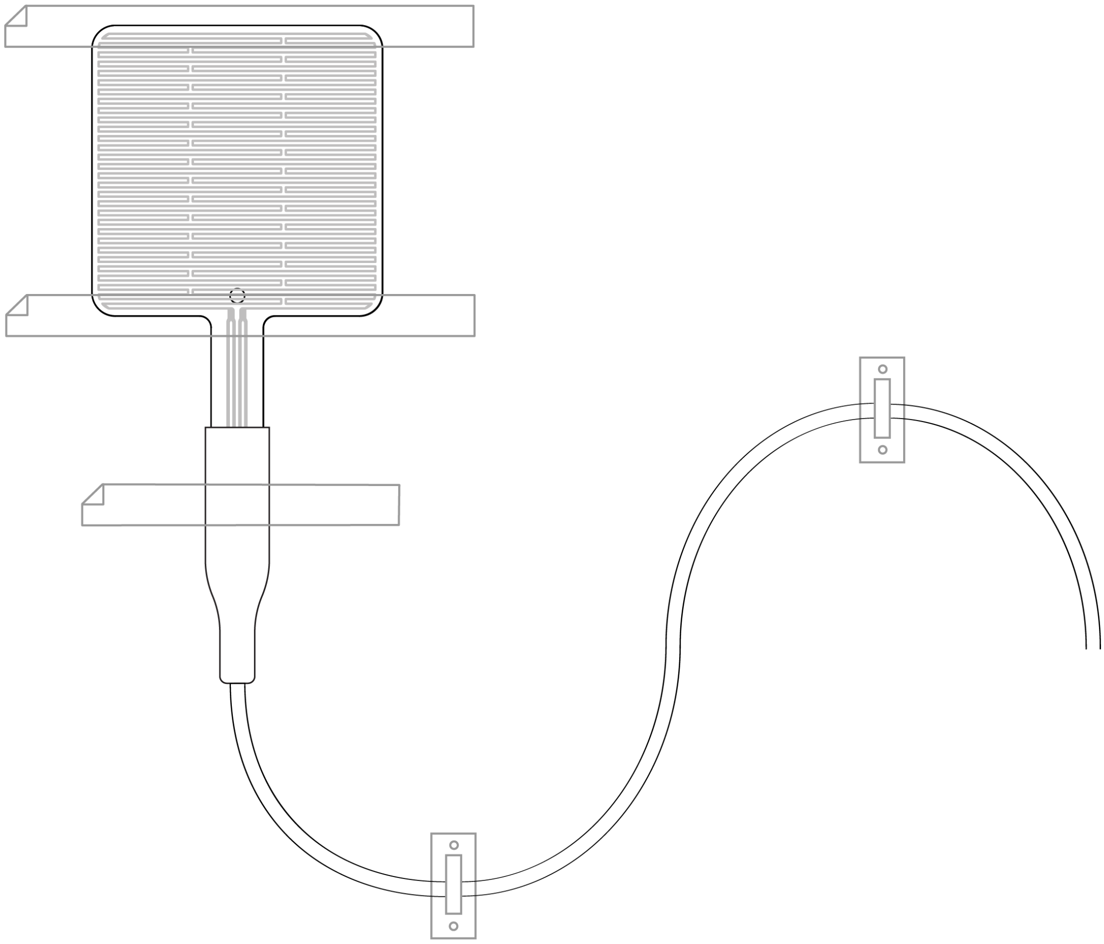


Figure 5.2.1 *Installation of model FHF05SC-50X50 using tape to fixate the sensor and the connection block. Extra strain relief on the wires is provided using cable tie mounts equipped with double-sided tape as an adhesive. As indicated in Table 5.1.1, tapes used for mounting the sensor are preferably 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 we are viewing the backside (heater side) and that the other side, the frontside, is attached to the object on which the sensor is mounted, as explained in Chapter 2.*

Table 5.2.2 *Options for mounting heat flux sensors. Materials may act to position the sensor, but also to fill up airgaps.*

product	**duration**	**temperature range**	**functionality**	**comments**
[type]	**[time]**	**[˚C]**	**[description]**	**[description]**
single sided tape	temporary or permanent	-260 to 150	positioning only	Positioning only, use with other fillers such as thermal paste TESA 51408 orange masking tape most commercially available Kapton tapes are suitable
silicone glue	Permanent Potentially removable	-45 to 200	positioning and gap filling	most commercially available silicone glues are suitable DOWSIL 3145 silicone sealant Before silicone hardens the sensor is typically held in position using a tape
High temperature epoxies	Permanent Not removable	to 300	positioning and gap filling	Duralco 4460 adhesive epoxy
glycerine	Short term	to 120	gap filling only	filler only for quick experiments; glycerine can be obtained at the local pharmacy. It is safe to use and easily dissolves in water.
toothpaste	Short-term (days)	40	gap filling only	filler only, use with other positioning such as single sided tape water-based most commercially available toothpastes are suitable
thermal paste	Weeks	to 177	gap filling only	filler only, use with other positioning such as single sided tape silicone oil-based DOW CORNING heat sink compound 340

5.3 Installation on curved surfaces

The flexibility of the FHF05SC sensor foils makes them perfectly suitable to be installed on singly curved surfaces. The sensor foil can be bent around any axis.

Figure 5.3.1 *Bending of model FHF05SC-50X50 foil heat flux sensor, in this image on a pipe.*

When measuring on curved surfaces, the same recommendations of the previous chapter apply, except that the use of thermal paste is recommended over glycerol. 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 5.3.1 *Extra recommendations for installation of FHF05SC series foil heat flux sensors on curved surfaces.*

Bending	sensor foil can be bent in all directions
Rated bending radius	≥ 15 x 10^{-3} m
Effect on sensitivity	no significant influence on sensitivity

5.4 Electrical connection

5.4.1 Electrical diagram

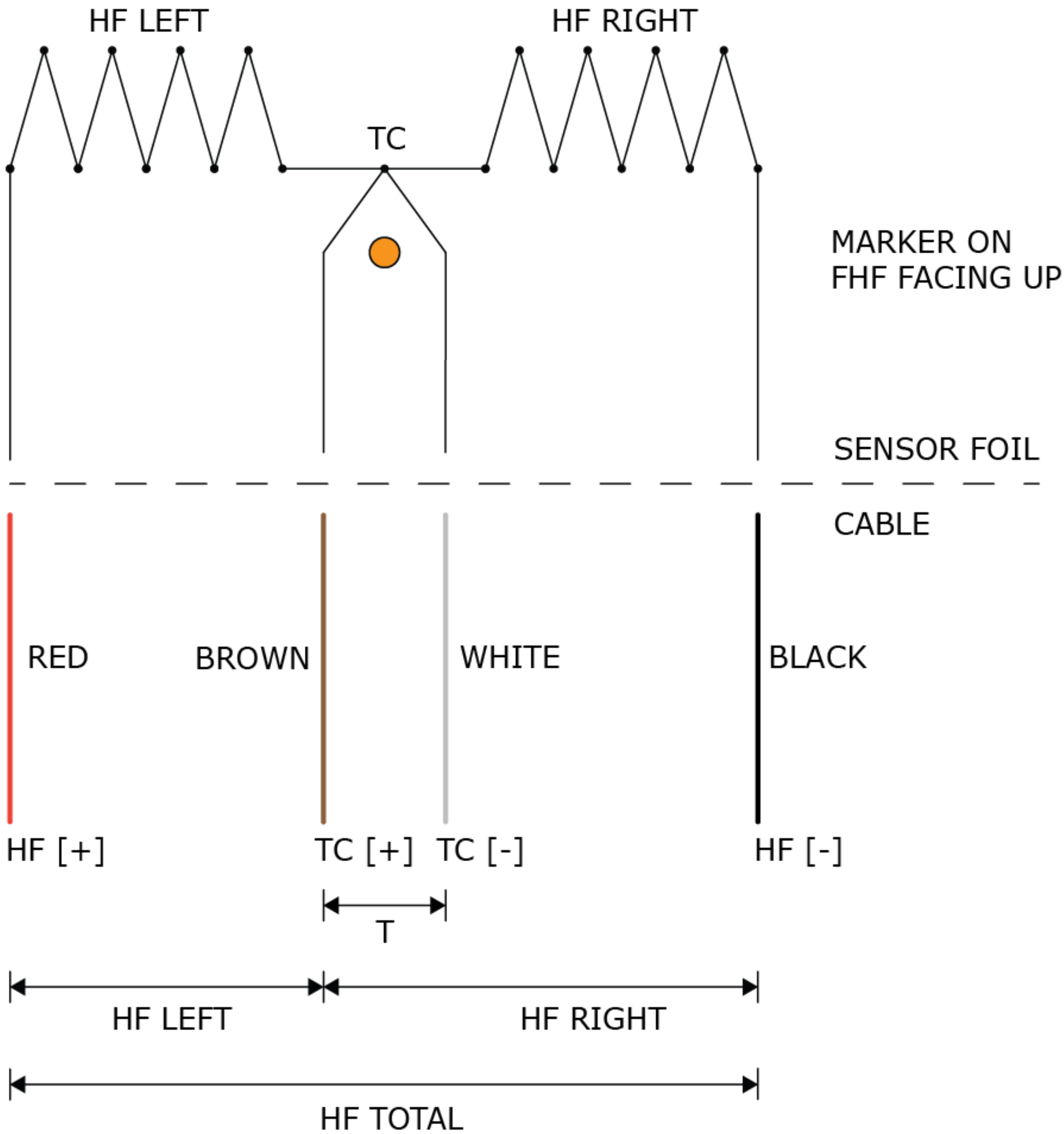


Figure 5.4.1.1 *Electrical diagram of sensor foil and cable of FHF sensors.*

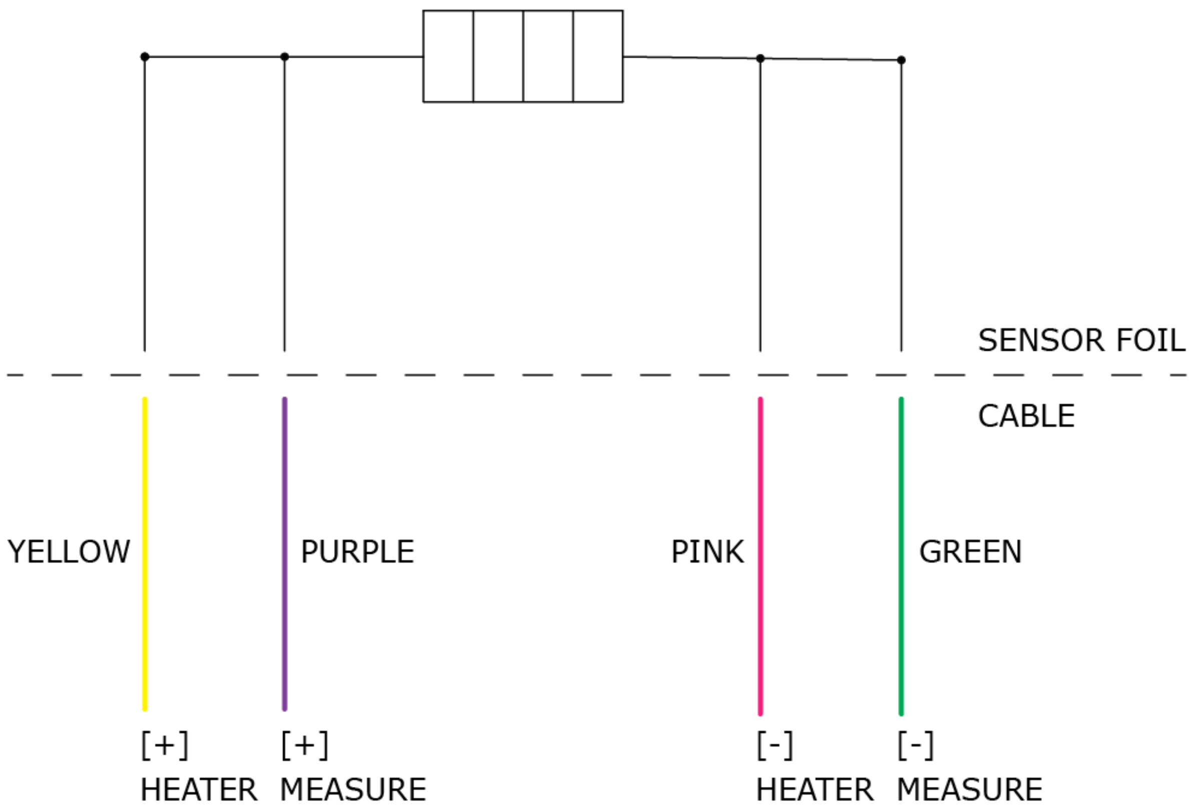


Figure 5.4.1.2 *Electrical diagram of heater foil of FHFSC sensors.*

5.4.2 Normal connection

FHF05SC series has one bundled cable. It contains two sets of wires, one set for the heat flux signal, and one set for the heater.

To read out the heat flux sensor, an FHF05SC sensor should be connected to a measurement system, such as a voltmeter, an amplifier, a data logger or a data-acquisition (DAQ) system. The FHF05SC's electrical connections are explained in the electrical diagrams above and the table below. FHF05SC's heat flux and temperature sensors are passive sensors that do not require any power. FHF05SC's heater does require power and must either be switched on and off, or be connected to a programmable DC power supply.

Cables and wires may act as a source of distortion by picking up capacitive noise. We recommend keeping the distance between a data logger or amplifier and the sensor as short as possible. For cable extension please refer to the appendix on this subject.

Table 5.4.2.1 *The electrical connection of FHF05SC.*

WIRE	FHF05SC
Red	heat flux signal [+]
Black	heat flux signal [−]
White	thermocouple type T [−]
Brown	thermocouple type T [+]
Yellow	heater power [+]
Purple	heater measure [+]
Pink	heater power [−]
Green	heater measure [−]

The sensor serial number and sensitivity are shown on the FHF05SC's product certificate and at the end of FHF05SC's cable.

⚠ CAUTION

Do not put a voltage of more than 0.1 V over 2 wires that connect to the same side of the heater: the yellow and purple wire on one side of the heater, or the pink and green wire on the other side of the heater.
The traces on the heater foil may overheat and get damaged beyond repair.

NOTICE

Putting more than 24 Volt across the sensor wiring can lead to permanent damage to the sensor.

NOTICE

The heat flux sensor and thermocouple are electrically connected inside the FHF sensor foil. In the hardware used for measurement of the sensor output, do not electrically short-circuit (part of) the heat flux signal and thermocouple; this will reduce signal output by 50 %.

To apply power to the FHF05SC series heater, it should be connected to a 12 V power supply.

The heat generated by the heater can be accurately determined by measuring the heater voltage and current in a four-point measurement. To this end, the heater has a four-wire connection. A voltmeter should be used to measure the voltage between heater measure [+] and [-]. Working either with formula 5.4.2.1 or 5.4.2.2, either

- an ammeter should be used to measure the current through the heater power [+] and heater power [-], using I and V to estimate the heater power, or
- a voltage lower than 24 VDC should be applied to the heater power [+] and heater power [-], using V and R to estimate the heater power

To measure the power P_{heater}, the heater can be connected in several different ways, measuring:

- heater voltage and current, $P_{heater} = U_{heater} \cdot I_{heater}$ (Formula 5.4.2.1)
- heater voltage and known heater resistance, $P_{heater} = U_{heater}^2 / R_{heater}$ (Formula 5.4.2.2)
- heater current and known heater resistance, $P_{heater} = I_{heater}^2 \cdot R_{heater}$ (Formula 5.4.2.3)

This heater requires a switched or controlled power supply. Typically, it is connected to a 12VDC power supply with a solid-state relay.

5.4.3 Increasing sensitivity and spatial coverage- connecting multiple sensors in series

Multiple heat flux sensors may be electrically connected in series. By making a connection, the resulting output becomes the sum of the output of the individual sensors. The sensitivity then is the sum of the sensitivities of the individual sensors.
The resulting measurement is then representative of the heat flux over the area covered by the sensors and may also be representative for the area between the sensors.

$$\Phi = U/(S_1 + S_2) \quad \text{(Formula 5.4.3.1)}$$

and

$$U = U_1 + U_2 \quad \text{(Formula 5.4.3.2)}$$

Table 5.4.3.1 *The electrical connection of two FHF05SC heat flux sensors, 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 [−]	
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 [−]	

The serial number and sensitivity of the individual sensors are shown on the FHF05SC series product certificate and on the sticker.

For the temperature measurement, users may consider:

- to read out one thermocouple only
- to put several thermocouples in parallel (so feeding several thermocouple wires to one input channel). The temperature reading will then be the weighted average of the signals. Weighting is by 1/R with R the electrical resistance. In case cables are equally long, with the same conductor diameters, this will result in a normal average.

Heaters may also be put electrically in series.

5.4.4 Connection to read out half signals

See Figure 5.4.4.1: heat flux sensors in FHF05SC can be connected to read out only the heat flux through the left half of the sensing area or the heat flux through the right half of the sensing area. This feature may be used for quality assurance purposes; if the sensor is correctly installed, a constant percentage (usually close to 50 %) of the signal will be generated by the left – and right. If the two 50 % signals are read out, the sensor's brown wire is typically connected to a thermocouple input, and from there, two copper wires may be used to connect the same signal to the two 50 % heat flux millivolt readout inputs.

NOTE: in case the user works with voltage measurements in which the [-] is connected to ground, use the 100 % and "right" 50 % signals only, and do not use the "left" configuration. These then share the same ground as the heat flux sensor [-]. Connecting the "left" as well, would create a short-circuit over the right signal, so that only the left signal is measured.

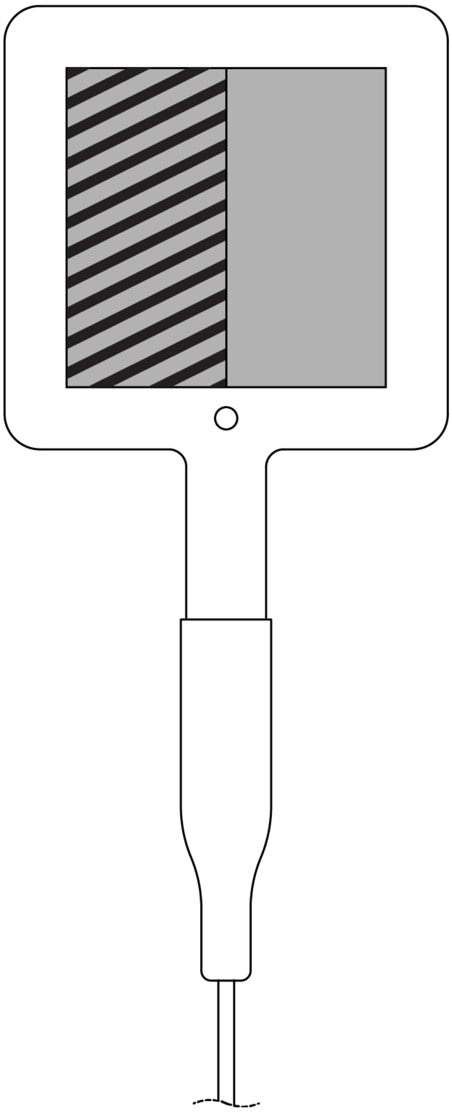


Figure 5.4.4.1 *FHF05SC-50X50 with left half indicated by diagonal lines.*

Table 5.4.4.1 *The electrical connection of FHF05SC 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 [−]	

Table 5.4.4.2 *The electrical connection of FHF05SC for left 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 [−]	

Table 5.4.4.3 *The electrical connection of FHF05SC for right 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 [−]	

5.5 Requirements for data acquisition / amplification

The selection and programming of data loggers 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 FHF05SC sensors are available. In case a program for similar instruments is available, this can be used. All FHF05SC's can be treated in the same way as other heat flux sensors and (analogue) thermopile pyranometers.

NOTICE
Do not use "open circuit detection" when measuring the heat flux sensor and thermocouple output signals.

Table 5.5.1 *Requirements for data acquisition and amplification equipment for FHF05SC 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) select your data logger voltage range setting carefully, based on the heat flux sensor sensitivity and the expected heat flux level. setting your data logger voltage range too high may lead to a low resolution and large offsets, not allowing you to detect changes at low heat flux levels. setting your data logger voltage range too low may lead to overranging, leading to a cap in measured heat flux level or temperature, or leading to datalogger measurement errors.
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.
Heater power supply	typically by a DC power supply with a voltage output in the 12 VDC range. In most cases, 5 W power is sufficient. Preferably with the capability to measure current as well.
Switching heater power	typically with a solid-state relay
Measuring heater voltage and current	there are several possibilities to measure heater power. Depending on the method users may measure voltage, current or both. When measuring the power supply voltage: typically around 12 VDC, preferably with a 1 % or better uncertainty. When measuring heater current: typically in the 0.1 to 0.3 A range, preferably with a 1 % or better uncertainty.

6 Maintenance and trouble shooting

6.1 Recommended maintenance and quality assurance

FHF05SC series 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 FHF05SC series. If possible, the data analysis is done daily.*

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. Set acceptance intervals for temperature and heat flux and compare measured data to these acceptance intervals.
2	6 months	inspection	inspect sensor for wear, cable and wire condition, clamping of conductors at the data acquisition, inspect sensor mounting, inspect the location of installation. Look for repeating (day-night, seasonal) patterns in measurement data. Try to explain these patterns.
3	2 years	Validation and recalibration	validation by comparison to a calibration reference sensor in the field, see the following paragraph about validation and calibration. recalibration by the sensor manufacturer
4	2 years	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. Set acceptance intervals for temperature and heat flux and compare measured data to these acceptance intervals.

6.2 Trouble shooting

Table 6.2.1 *Trouble shooting for FHF05SC sensors.*

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 cable and wires. Check the data logger program, in particular if the right sensitivity is entered. FHF sensor sensitivity and serial number are shown on the product certificate and at the end of the FHF's cable. Check the electrical resistance of the sensor between all wires. In many cases, this can be done on the screws of the clamps of the signal wires. In other cases, it is necessary to disconnect signal wires from the data acquisition. See the following tables for the nominal electrical resistances per wire combination. Measure resistances first with one polarity, then reverse the polarity. Actual resistance values may vary from one sensor to the other sensor and with cable length. The typical resistance of the copper wiring (red, brown and black wires) is 0.3 Ω/m, for the constantan wiring (white wire) this is 6.5 Ω/m. Infinite resistance indicates a broken circuit; zero or a lower than 1 Ω resistance indicates a short circuit.
The heat flux 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 100×10^{-3} VDC range or lower. Expose the sensor to heat. Exposing the backside (the side without the dot) to heat should generate a positive signal between the red [+] and black [-] wires, doing the same at the frontside (the side with dot), the sign of the output reverses. Check the data acquisition by replacing the sensor with a spare unit.
The heat flux sensor signal is unrealistically high or low	Check the wire condition. Ensure that the wires clamp on the metal conductor and not (partly) on the plastic cladding of the wires. Disconnect heat flux signal wires from data acquisition. Check the data acquisition by applying a 1×10^{-6} V source to it in the 1×10^{-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. Check the data logger voltage range settings. - a voltage range setting that is too high lead to a low signal resolution and high offsets. - a voltage range setting that is too low can cause the sensor signal to cap at a maximum level of generate data logger errors. Check for possible interference between the heat flux signal and thermocouple output. The heat flux signal and thermocouple are electrically connected inside the heat flux sensor. An electrical short-circuit between (part of) the heat flux signal and thermocouple, which may occur if they are both grounded, can reduce heat flux signal output by 50 %. - with the thermocouple wires connected, disconnect the heat flux signal wires from the data acquisition and observe the behaviour of the thermocouple reading. - with the heat signal wires connected, disconnect the thermocouple signal wires and observe the behaviour of the heat flux signal. - make sure the thermocouple measurement and heat flux/voltage measurements have no open circuit detection. If this is activated, disable it.

Table 6.2.1 *Trouble shooting for FHFSC sensors (started on previous page).*

The heat flux or temperature sensor signal shows unexpected variations	Check the presence of strong sources of electromagnetic radiation (radar, radio). Check the condition of the sensor wires. Check if the wires are not moving during the measurement. If available on your data logger, turn on 50 Hz or 60 Hz noise filtering. Ground your data logger.
The temperature measurement shows unrealistic values	Check if the thermocouple type T is selected in the data logger program. Check if a correct reference temperature is selected in the program. 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. The typical resistance of the copper wiring is 0.3 Ω/m, for the constantan wiring this is 6.5 Ω/m. Typical resistance should be the nominal thermocouple resistance of 2.5 Ω plus 6.8 Ω for the total resistance of the two wires of each metre (back and forth). Infinite resistance indicates a broken circuit; zero or a lower than 1 Ω resistance indicates a short circuit. Make sure the temperature of the connection block remains as close as possible to that of the heat flux sensor. See appendix on temperature measurement accuracy for more information. Check the program settings, signal range settings and sampling speed of your data logger. Please ask the data logger provider to comment on the data files. Do not use open circuit detection on your data logger. In FHF05 sensors the thermocouple is electrically connected to the heat flux sensor. Some older data loggers do not properly handle such electrical connection. Disconnect the heat flux signal wires from the data acquisition to see if this is the cause of the problem. Check the connection of the thermocouple wires to the data logger. Ensure that the wires clamp on the metal conductor and not (partly) on the plastic cladding of the wires. Do not ground the thermocouple [-]. Only heat flux [-] should be connected to ground if needed. If the [-] minus signals of both the heat flux and the temperature are connected to ground, the heat flux senor is partly, 50 %, short-circuited and the signal will be reduced by around 50 %. Make sure that the sensor does not pick up electrical noise by external sources (e.g., heavy machinery like heaters or air conditioners blowing hot or cold air over the sensor).
Check heater	Check the electrical resistance of the sensor between all wires. See Table 6.2.2 and Table 6.2.3 for the nominal resistance per wire combination. Actual resistance values may vary with sensor and with cable length. The typical resistance of the wiring is 0.2 Ω/m. Infinite resistance indicates a broken circuit; zero or a lower than 1 Ω resistance indicates a short circuit.

Table 6.2.2 *Indicative electrical resistances between wires for FHF05SC-50X50 with standard cable length.*

WIRE	Red	Black	White	Brown	Yellow	Purple	Pink	Green
Red	x	280 Ω	155 Ω	140 Ω	> 1 MΩ	> 1 MΩ	> 1 MΩ	> 1 MΩ
Black		x	155 Ω	140 Ω	> 1 MΩ	> 1 MΩ	> 1 MΩ	> 1 MΩ
White			x	15 Ω	> 1 MΩ	> 1 MΩ	> 1 MΩ	> 1 MΩ
Brown				x	> 1 MΩ	> 1 MΩ	> 1 MΩ	> 1 MΩ
Yellow					x	1	120	120
Purple						x	120	120
Pink							x	1
Green								x

Table 6.2.3 *Indicative electrical resistances between wires for FHF05SC-85X85 with standard cable length.*

WIRE	Red	Black	White	Brown	Yellow	Purple	Pink	Green
Red	x	1100 Ω	565 Ω	550 Ω	> 1 MΩ	> 1 MΩ	> 1 MΩ	> 1 MΩ
Black		x	565 Ω	550 Ω	> 1 MΩ	> 1 MΩ	> 1 MΩ	> 1 MΩ
White			x	15	> 1 MΩ	> 1 MΩ	> 1 MΩ	> 1 MΩ
Brown				x	> 1 MΩ	> 1 MΩ	> 1 MΩ	> 1 MΩ
Yellow					x	1 Ω	40 Ω	40 Ω
Purple						X	40 Ω	40 Ω
Pink							x	1 Ω
Green								x

6.3 Validation and calibration

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 validation – that is, making sure the sensor is fit for purpose - is possible by comparison to a calibration reference sensor, which is usually mounted side by side or alternatively on top of the field sensor.

Hukseflux's main recommendations for field validations 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 validation or calibration experiment, using the integrated heater.

7 Appendices

7.1 Appendix on cable and cable extension

FHF05SC sensors are equipped with a cable containing eight wires. Seven copper wires (red, brown, black, purple, yellow, pink and green wire) and one constantan wire (white). Standard cable length is 2 m. It is possible to order FHF05SC with longer cable lengths or without cable.

Cables and wires 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 FHF05SC series wires may be extended without problem. If done properly, the sensor signal, although small, will not significantly degrade because the sensor electrical resistance is very low (which results in good immunity to external sources) and because the voltage measurement circuit of the data logger has a high impedance. There is no current flowing, and there are no resistive losses.

Cable, wire and connection specifications are summarised below.

Table 7.1.1 *Preferred specifications for cable extension of FHF05SC series.*

Cable and wiring	Extend the red, brown, black, purple, yellow, pink and green wire with the copper wires. Extend the white wire with the constantan wire. For the constantan wire, use the right alloy for type T thermocouple measurements: $Cu_{55}Ni_{45}$ For constantan and copper, use either Standard grade type T according to ASTM E230 or IEC 60584 Class 2. Use of thermocouple extension cables is permitted, because for type T these have nominally the same composition as thermocouple cables. Standard cable as supplied by Hukseflux: 7 x copper and 1 x constantan wire, AWG 28, solid core, bundled with an PFA sheath
Separate cable	available in 2, 5 or 10 m length longer cables may be offered as a "special" order.
Extension sealing	make sure any connections are sealed against humidity ingress
Conductor resistance	< 0.3 Ω/m (copper wire)
Cable outer diameter	typically 2.7 x 10^{-3} m
Length	cables and wires should be kept as short as possible, in any case the total wire length should be less than 100 m
Connection	either use gold-plated waterproof connectors, or solder the conductors and shield of the extension cables to those of the original sensor cable, and make a waterproof connection using heat-shrink tubing with hot-melt adhesive. when using connectors for extending the thermocouple wires, either use dedicated type T thermocouple connectors, or use connectors with a heavy metal housing in which no temperature differences occur, or put the connection in an enclosure in which no temperature differences occur.

7.2 Appendix on using FHF05SC sensors with BLK – GLD sticker series

BLK black and GLD gold stickers are accessories for the heat flux sensors of the FHF05 series and FHF05SC series. A sensor equipped with a BLK black sticker is sensitive to both radiative and convective heat flux. A sensor equipped with a GLD gold sticker reflects radiation and measures convective heat flux only. To calculate the radiative heat flux, subtract the two measurements.

There are BLK – GLD stickers for every sensor model in FHF05 series and FHF05SC series.

BLK – GLD stickers are designed to be applied by the user. Optionally, it is also possible to order FHF05(SC) with stickers pre-applied at the factory.

For more details, see the BLK – GLD sticker series user manual.

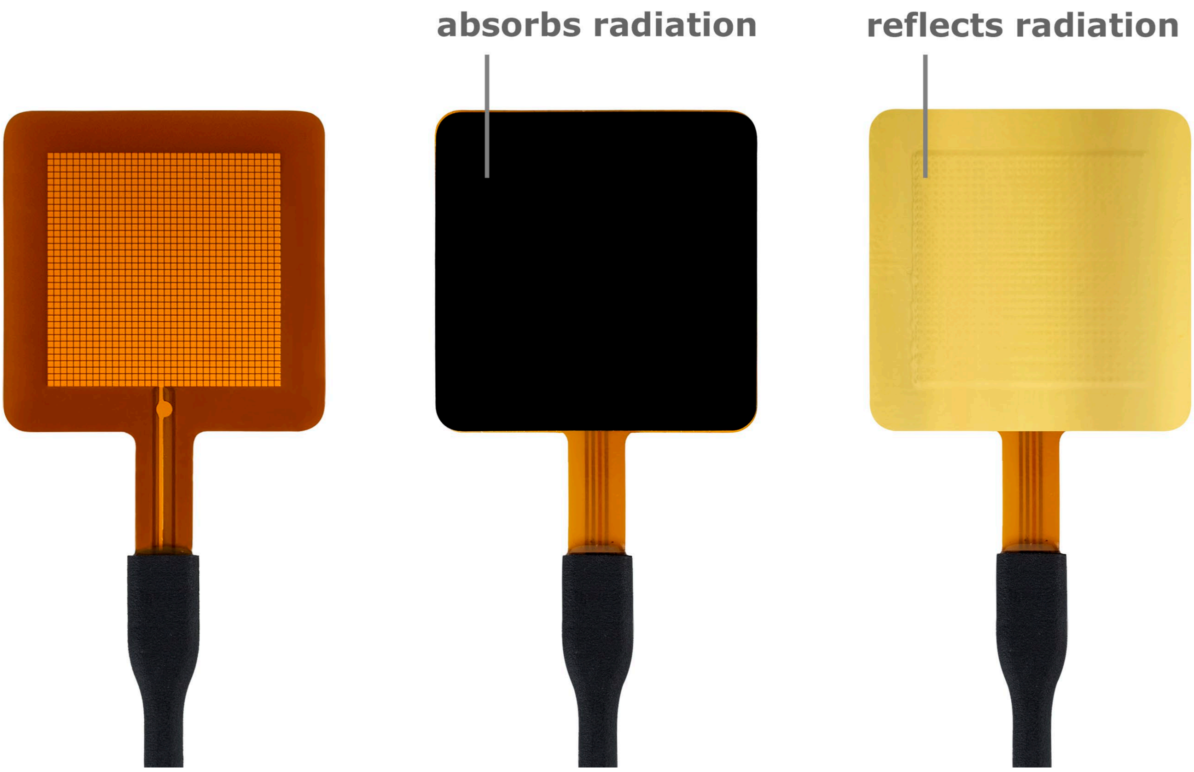


Figure 7.2.1 *FHF05SC-50X50 heat flux sensor: with BLK-5050 and GLD-5050 stickers.*

Table 7.2.1 *Recommendations for use of FHF05SC heat flux sensors with BLK – GLD stickers.*

Mounting	when mounting a BLK or GLD sticker on an FHF05SC sensor, keep the directional sensitivity in mind heat flux from the back side to the front side (side with dot, side without the heater) generates a positive voltage output signal.
Mounting on curved surfaces	apply BLK – GLD stickers before mounting the sensor
Location	avoid direct exposure to the sun
Effect on sensitivity	BLK-GLD stickers have no significant influence on sensitivity

7.3 Appendix on standards for calibration

The standard ASTM C1130 – 21 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 HFPC 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 - 21.

Table 7.3.1 *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 - 21 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

7.4 Appendix on calibration hierarchy

FHF05SC's 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 HFPC method follows the recommended practice of ASTM C1130 - 21. 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.

7.5 Appendix on correction for temperature dependence

The sensitivity of an FHF05SC sensor depends on the temperature of the sensor. The temperature dependence of FHF05 series is specified as < 0.2 %/°C.

The calibration reference temperature is 20 °C.

Users who measure at temperatures that deviate much from 20 °C or who 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 following measurement function:

$$\Phi = U/(S \cdot (1 + 0.002 \cdot (T - 20))) \qquad \text{(Formula 7.5.1)}$$

with Φ the heat flux in W/m², U the FHF05 series voltage output in V, S the sensitivity in V/(W/m²) at 20 °C and T the FHF05 temperature. The coefficient of 0.002 or 0.2 [%/K] is the best estimate Hukseflux currently has of the temperature dependence of sensitivity.

S is shown on the product certificate and at the end of FHF05's cable.

7.6 Appendix on measurement range for different temperatures

The measurement range of FHF05SC sensors 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 rated temperature for continuous use of +120 °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).

$$T = T_{heatsink} + \Phi \cdot R_{thermal,A} \quad \text{(Formula 7.6.1)}$$

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

$$\Phi_{maximum} = (120 - T_{heatsink})/R_{thermal,A} \quad \text{(Formula 7.6.2)}$$

Table 7.6.1 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.

NOTE: calculated values are based on thermal resistance of the sensor only. We assume that the thermal resistance of any glue layer is negligible.

Table 7.6.1 *Measurement range for different heat sink temperatures.*

HEATSINK TEMPERATURE	MEASUREMENT RANGE
20 °C	54 x 10^3 W/m²
40 °C	45 x 10^3 W/m²
60 °C	38 x 10^3 W/m²
80 °C	29 x 10^3 W/m²
100 °C	20 x 10^3 W/m²
120 °C	12 x 10^3 W/m²

7.7 Appendix on temperature measurement accuracy

All FHF's have an integrated thermocouple to measure the temperature of the object under test. This thermocouple then performs a separate secondary measurement, in addition to the main heat flux measurement.

The uncertainty of the temperature measurement is the sum of the thermocouple measurement uncertainty (a sensor property) + the voltage measurement uncertainty of the electronics + the reference junction measurement uncertainty. The reference junction uncertainty and the uncertainty of the electronics should be part of the specifications of electronics. Please note the latter two are often ignored, because their contributions are typically small.

The FHF sensors are equipped with a cable containing thermocouple extension wires with an uncertainty specified as a type T thermocouple, IEC 60584-1:2013 class 2 or ASTM. They consist of a brown positive copper (Cu) wire and a negative white constantan ($Cu_{55}Ni_{45}$) wire. The contribution of thermocouple properties to the measurement uncertainty is 1 °C or ± 0.75 % (whichever is larger) of the temperature differences between the cold joint T_2 and the sensor cold junction T_3 (see Figure 7.8.1).

For most applications, we may assume that the cold junction uncertainty is negligible and that the temperatures T_1 and T_2 are identical.

The total expanded measurement uncertainty becomes, as stated in the specifications:

$u_c(T) = (1\ °C \text{ or } \pm 0.75\ \% \cdot \Delta T_2)$ (Formula 7.7.1)

However, if you want more detail: in the FHF sensor itself, the thermocouple junction (T_1) located at the object under test consists of copper and constantan traces that are extended from the connection block to the edge of the heat flux sensor sensitive area. These traces have slightly different Seebeck coefficients compared to normal thermocouple materials, which results in a higher measurement uncertainty of ± 5 % for temperature differences between T_1 and T_2 junctions.

The total expanded measurement uncertainty becomes:

$u_c(T) =$

cold junction uncertainty + $5\ \% \cdot \Delta T_1 + (1\ °C \text{ or } \pm 0.75\ \% \cdot \Delta T_2)$ (Formula 7.7.2)

It is clear from formula 7.8.2 that the accuracy is best, i.e., within the 2 % range, if T_1 is kept close to the temperature T_2, so that ΔT_1 = 0. If the temperature measurement is critical, consider using a separate more accurate temperature sensor.

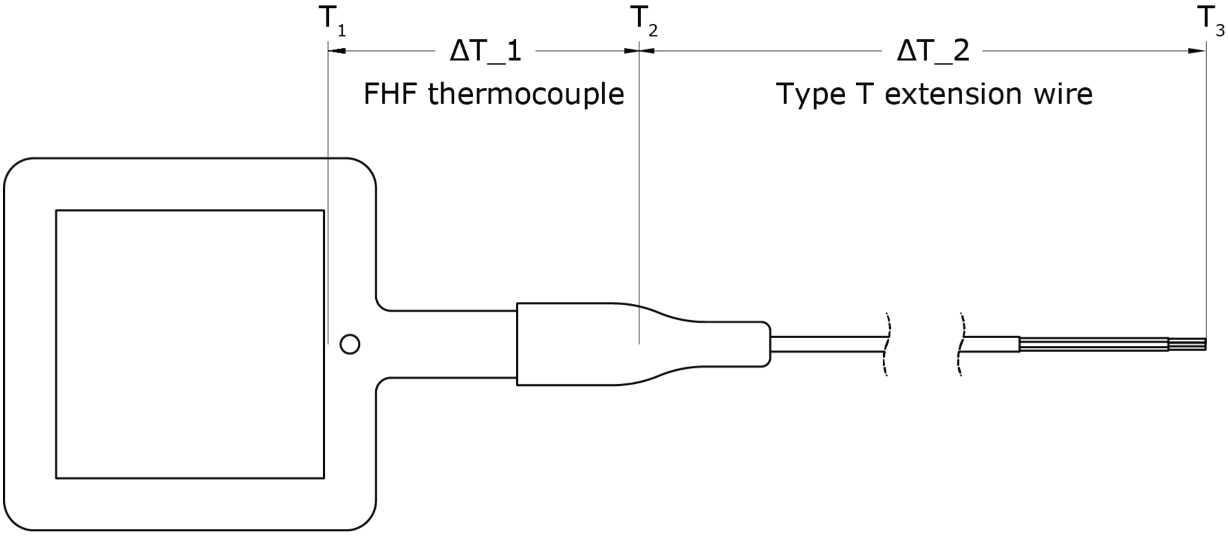


Figure 7.7.1 *Model FHF with its thermocouple junctions. To minimise temperature measurement uncertainty, please make sure that ΔT_1 is close to zero.*

7.8 Appendix on use of FHF sensor foils at low temperatures to -200 °C

FHF users have employed the FHF05, FHF05SC and FHF06 sensor foils in cryogenic conditions, below the rated temperature of -70 °C. Although use at lower temperatures is possible, Hukseflux does not specify the use down to -200 °C formally because the application of any sensors, not just these, at such temperatures is always high-risk. Use at a temperature lower than -70 °C is at the user’s own risk.

NOTICE
At temperatures lower than the rated -70 °C FHF05, FHF05SC and FHF06 sensor foils may become stiffer and more brittle than in the rated temperature range. Use of these foils at these temperatures is possible, but at the user’s own risk.

Practical experience at temperatures < -70 °C:

- Hukseflux tested the FHF05 sensor foils at -80 °C and found no issues
- FHF05 sensor foils have been used in liquid natural gas (-160 °C) conditions without problem

Directions for use at temperatures < -70 °C:

- use the sensor foil only, not the cable connection block
- the cable connection block between foil and cable is potted and not rated for lower temperatures than -70 °C. At lower temperatures use the sensor foil only, not the cable connection block.
- the FHF sensor foils are made using Kapton etched foil technology. The materials used are Kapton (polyimide), acrylic glue (not for FHF06) plus the metals of the sensor. This technology is generally considered suitable for use down to -200 °C.
- at temperatures below – 70 °C the sensor foil of FHF will become rigid and brittle. It is important not to change the sensor position at low temperatures, because it will likely break the sensor. At low temperatures, the FHF sensor foil loses its flexibility, but besides this, the sensors work just as normal.
- users may order the standard FHF cable as a separate item. This is made of PFA; its temperature rating is -200 to + 260 °C.
- users may solder signal wires to the foil by themselves following the directions in the manual of the sensor. If needed, seal the soldered connections using suitable potting material.
- if you expect small signals and want to know if a sensor still functions or if you want to monitor the stability, you can use the FHF05SC sensors. The heater materials are the same as the foil sensor. Soldering is also similar. The -SC version is available only for certain FHF05 sensor sizes.
- the sensitivity of the FHF sensors at low temperatures may become very low. Temperature dependence is around < 0.2 % / °C. So, at -200 °C, you have 64 % of the sensitivity left compared to the calibration reference situation at room temperature. Users may correct for temperature dependence of the sensitivity with the approximation of the manual of the sensor. This uses a temperature dependence of the sensitivity of + 0.2% / °C. If needed, for higher accuracy, Hukseflux can determine the sensitivity from +50 to -30 °C, which users can then extrapolate to the temperature of their application. This is an additional service available at extra cost.
- use of optional BLK black stickers is limited to -40 °C. However please note that in the infra-red, the normal Kapton sensor surface behaves as a black emitter and absorber, so you may not need a black sticker.
- use of the optional GLD gold stickers is limited to -185 °C.

7.9 Appendix on use of FHF sensor foils under vacuum conditions

FHF users have successfully employed the FHF05, FHF05SC and FHF06 sensor foils under vacuum conditions. Hukseflux does not specify the use under vacuum conditions, because the application of any sensors, not just these, under vacuum is always high-risk. Use under vacuum conditions is possible but at the user's own risk.

NOTICE
Use of FHF05, FHF05SC and FHF06 sensor foils under vacuum conditions is possible, but at the user's own risk.

Directions for use under vacuum:

- use the sensor foil only, not the cable connection block
- the cable connection block between foil and cable is potted with an epoxy. The epoxy may outgas under vacuum. The sensor foils do not outgas.
- the FHF sensor foils are made using Kapton etched foil technology. The materials used are Kapton (polyimide), acrylic glue (not for FHF06) plus the metals of the sensor. This technology is generally considered suitable for use under vacuum. The outgassing is specified for the FHF06 foil.
- under vacuum the sensors work just as normal.
- users may order the standard FHF cable as a separate item. This is made of PFA which is formally rated for use under vacuum
- users may solder signal wires to the foil by themselves following the directions in the sensor manual. If needed, seal the soldered connections using suitable potting material.
- Model FHF06 sensor foil has a formal outgassing specification (low outgassing, 0.36 % total mass loss, 0.01 % collected volatile condensable material (CVCM) as per NASA-JSC).

7.10 Appendix on long-term use in condensing -, wet - and underwater conditions

FHF users have employed the FHF05, FHF05SC and FHF06 sensors in condensing, wet and underwater conditions, also for periods of many years and at high water pressure. However, Hukseflux formally specifies such use under IP67 for short - 30 minutes - duration and at a limited pressure - 0.5 m of water - only. Long-term application under wet conditions is possible, but always high-risk and at the user's own risk.
Examples of successful application are:

- buried in the soil, exposed to rainwater
- in a high-pressure water vessel as part of a simulated service test for deep-sea pipelines (sensor foil only, not the cable connection block and not the sensor cable). In most cases, users make their own connection to the sensor foil.
- mounted on the wall of a house, frequently exposed to rainwater

NOTICE
Use of FHF05, FHF05SC and FHF06 sensors under wet conditions beyond IP67 (0.5 m depth and 30 minutes exposure) is possible, but at the user's own risk.

Directions for use under wet conditions are:

- the sensor foil materials and the materials of the potted cable connection block can absorb a limited amount of water only. However, as a result of exposure to this absorbed water over a long term the alloys in the sensor foil and conductors in the cable may slowly corrode. Corrosion may result in loss of sensitivity. Corrosion may be noticed by measuring changes of electrical resistance, because corrosion leads to increase of the electrical resistance.
- the sensor cable is not waterproof. It is open at the cable end. Operating in wet conditions, in case of damage to the cable and/or wire cladding the conductors may be directly exposed to water. In most cases, exposure to water has no effect; electrical resistance of water tends to be high. However, in case water conducts for example if it contains salts, this may lead to ground loops or loss of signal.
- users should perform regular inspections of the sensor and the cable condition
- users may solder signal wires to the sensor foil by themselves following the directions in the sensor manual. In case of exposure to water, seal the soldered connections using suitable potting material.

7.11 Appendix on use of FHF sensor foils under pressure

Hukseflux specifies the use of FHF05 sensor foils to 8 bar uniform pressure. For model FHF06 this specification is 25 bar uniform pressure. This pressure may result from air or fluids under pressure or be mechanical pressure in case the sensor is clamped.

NOTICE
Use of FHF05, FHF05SC sensor foils above 8 bar pressure and FHF06 sensor foils above 25 bar pressure is possible, but at the user's own risk.

During the manufacturing process of our FHF05 sensors, an 8 bar pressure is used for the lamination process on the foil. So, the rated operating condition of 8 bar specification is safe. Previous, very similar heat flux sensors were manufactured at 40 bars. Thus, Hukseflux has reasonable confidence in the performance of the foils up to 40 bar, but any use above 8 bar is at the user's own risk.

The FHF06 sensor is manufactured under much higher pressure levels and does not contain acrylic glue layers. It is much stiffer and can be used up to 25 bar.

Directions for use under pressure:

- the pressure specification applies to the sensor foil only, not the cable and not the cable connection block
- the pressure specification applies to uniform pressure only; avoid exercising mechanical pressure at one point on the foil
- users may solder a signal wires to the sensor foil by themselves following the directions in the sensor manual. In case of exposure to water, seal the soldered connections using suitable potting material.

7.12 EU declaration of conformity

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

hereby declare under our sole responsibility that:

Product model	FHF05SC series, all models
Product type	Heat flux sensors

conform with the following directive(s):

2011/65/EU, EU 2015/863	The Restriction of Hazardous Substances Directive

This conformity is declared using the relevant sections and requirements of the following standards:

Hazardous substances	EU RoHS2 (2011/65/EU) and EU 2015/863 amendment known as RoHS 3

Eric HOEKSEMA
Director
Delft, 15 November 2022