

Heat flux sensor technology:

why use sensors with low thermal resistance and with spreaders

Heat flux measurement is not easy. On a macroscopic level: the presence of a sensor potentially affects the local heat flux. For a representative measurement: use a sensor with a low thermal resistance. Also, the environment of the sensor - the thermal conductivity of the surrounding material - acting at a microscopic level, potentially affects the sensitivity of heat flux sensors. This is why Hukx's sensors have "spreaders"; thin metal foils covering the thermopile, creating an environment for the internal thermopile sensor that does not depend on the way it is installed. Tests* confirm superior performance.



Figure 1 Model FHF05-85X5 heat flux sensor on a pipe to study heat losses.

Heat flux sensors

Heat flux sensors measure a temperature difference across a thin layer of material. They typically employ a thermopile, which is manufactured by creating an alternating pattern of two dissimilar conductors, generally metal alloys. See Figure 2.

* Experiments were carried out on Hukx HFP01 and FHF05-50X50 models, as well as sensors purchased from a leading supplier of printed heat flux sensors with thermopiles based on electrically conductive inks, and a sensor model employing a semiconductor thermopile. The test results may not be applicable to sensors produced by other manufacturers or when improving manufacturing technology.

Macroscopy: thermal resistance

On a macroscopic level: a heat flux sensor has a certain thermal resistance.

- Mounted on a surface, the sensor always represents an additional resistance.
- Surrounded by a material, the sensor may locally increase or decrease thermal resistance.

Users should ask themselves what consequences this has for their measurement.

To avoid making measurement errors due to thermal resistance, Hukx takes the following countermeasures:

- Use high-thermal-conductivity materials (HFP01 ceramics-plastic composite).
- Use thin sensors (FHF series)
- Use guards (non-sensitive parts) around the central heat flux sensor to avoid edge measurements, where errors are highest (HFP01 and FHF05 series).

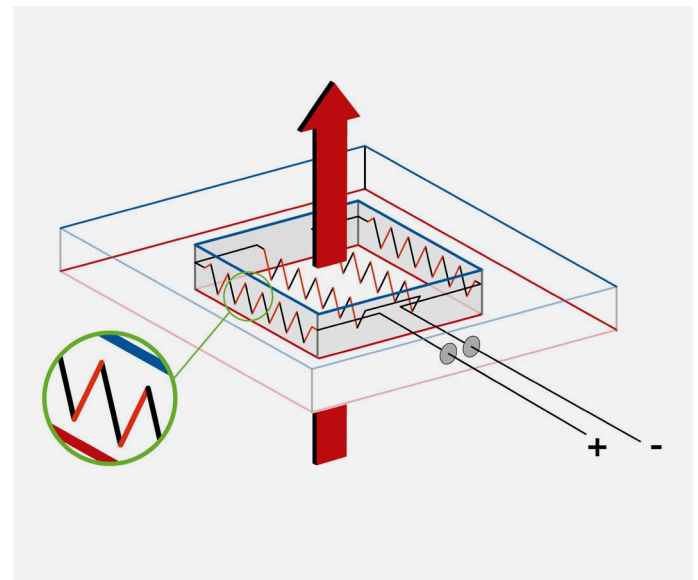
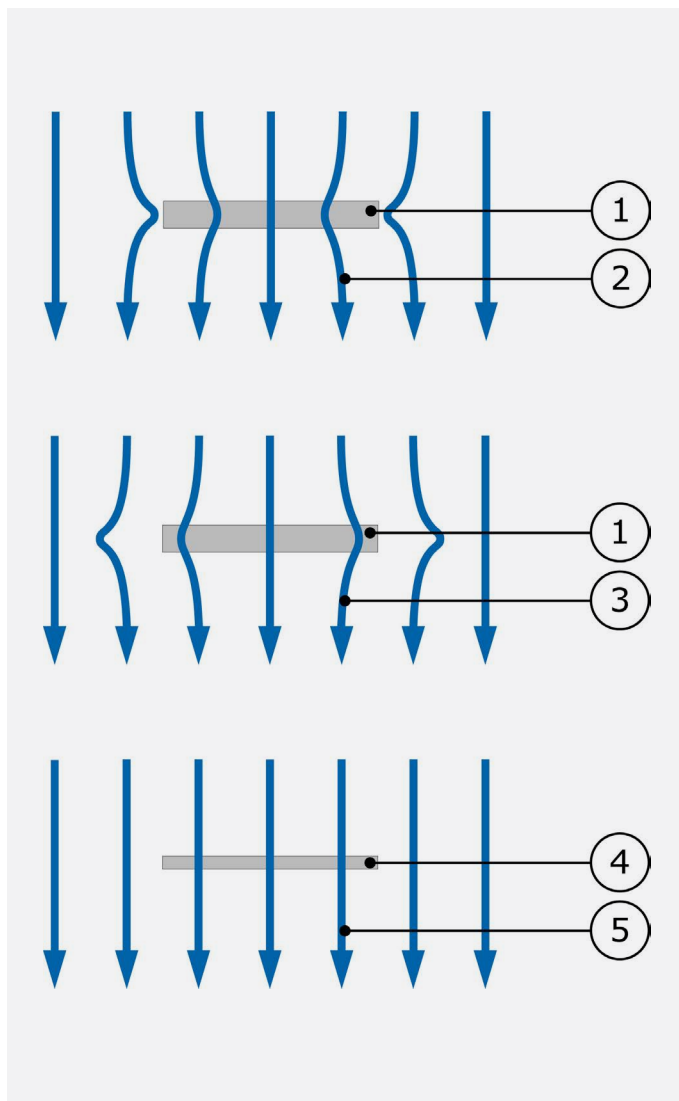


Figure 2 Heat flux sensor principle: the sensor contains a thermopile consisting of an alternating pattern of two metal alloys.

Microscopy: spreaders and thermal conductivity dependence

Inside a heat flux sensor, you will find a thermopile, typically embedded in plastic material, see Figure 2. The traces of the thermopile are electrical conductors, which typically will also conduct heat quite well. Seen from the outside, a sensor may look like "A" in Figure 5. "Spreader" are thin metal foils covering the thermopile. There may be one large spreader as in "B", or multiple small spreaders like "C". To explain the benefits of using spreaders, we zoom in on the sensor as in Figure 4, and focus on microscopic effects:

Figure 3 Macroscopic view of a heat flux sensor (1), in a heat flux field (2). The upper picture shows a sensor that has higher thermal conductivity than its environment. Heat then tends to flow towards the sensor. The measurement result is an overestimation of the actual (undisturbed) heat flux. The center picture shows a sensor (1) with lower thermal conductivity than its environment. Heat flux (3) at the point of measurement (center of sensor) is lower than in the undisturbed situation. The bottom picture shows a relatively thin and well conducting sensor (4), leading to an almost undisturbed heat flux and small measurement error.

We make a distinction as in Figure 5:

- A: A sensor without a spreader; the thermopile may be visible and is directly exposed.
- B: Sensors with a single large spreader of well conducting metal foil (applied in Hukx models HFP01).
- C: Sensors with multiple small spreaders (applied in all Hukx models of FHF05 series and FHF06).

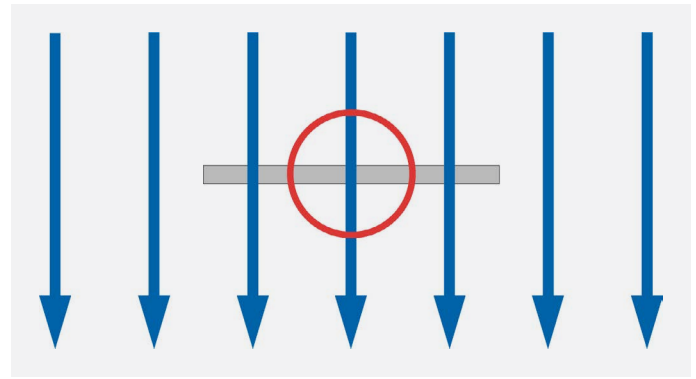


Figure 4 To explain microscopic effect we zoom in on a section of the heat flux sensor. This detail can be seen in Figure 7.

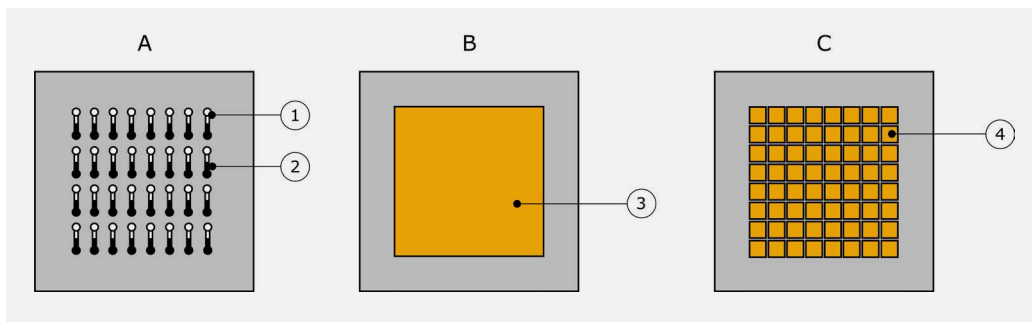


Figure 5 A: sensor without a spreader. One thermopile alloy (1), other thermopile alloy (2) In B and C, the thermopile is covered by spreaders. B: sensor with a single large spreader (3) C: sensor with multiple small spreaders (4).

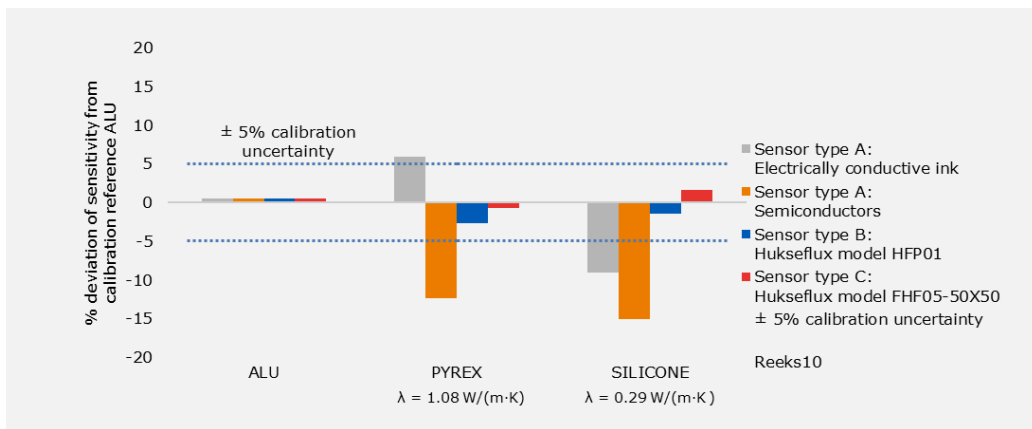


Figure 6 Thermal conductivity dependence of three sensor types. Two "type A" sensors were tested: one with a thermopile made of electrically conductive inks and the other made of semiconductors. The calibration uncertainty is 5%. Sensor type A makes up to 15% error when the thermal conductivity of the environment changes. Errors made with type B and C sensors are negligible.

In Figure 7 you can see what happens at a microscopic level to the heat flux:

- A1: A sensor without a spreader surrounded by a material with high thermal conductivity will measure a heat flux that is too high; the path of least resistance for heat is through the metal thermopile materials. The high thermal conductivity of the surrounding material offers an easy path sideways, and the thermopile is exposed to a relatively high flux.
- A2: A sensor without a spreader surrounded by a material with low thermal conductivity will measure a heat flux that is too low.

- B, C: In sensors with a single spreader or multiple small spreaders, the thermopile sensor is always exposed to the same environment i.e., the spreader. Heat arriving from outside the sensor there is no path of least thermal resistance.

The result is that sensor model A will have a sensitivity that depends on the thermal conductivity of the surrounding material.

Thermal conductivity dependence

Thermal conductivity dependence is an intrinsic property of a heat flux sensor that its sensitivity depends on the thermal conductivity of the surrounding material. This is expressed as % change of sensitivity, either absolute or per [W/(m·K)] change of thermal conductivity. Thermal conductivity dependence is reported relative to the sensitivity at the calibration reference condition, mounted on a metal heat sink. There are no standardized experiments to perform tests. The results presented are therefore “comparative” only.

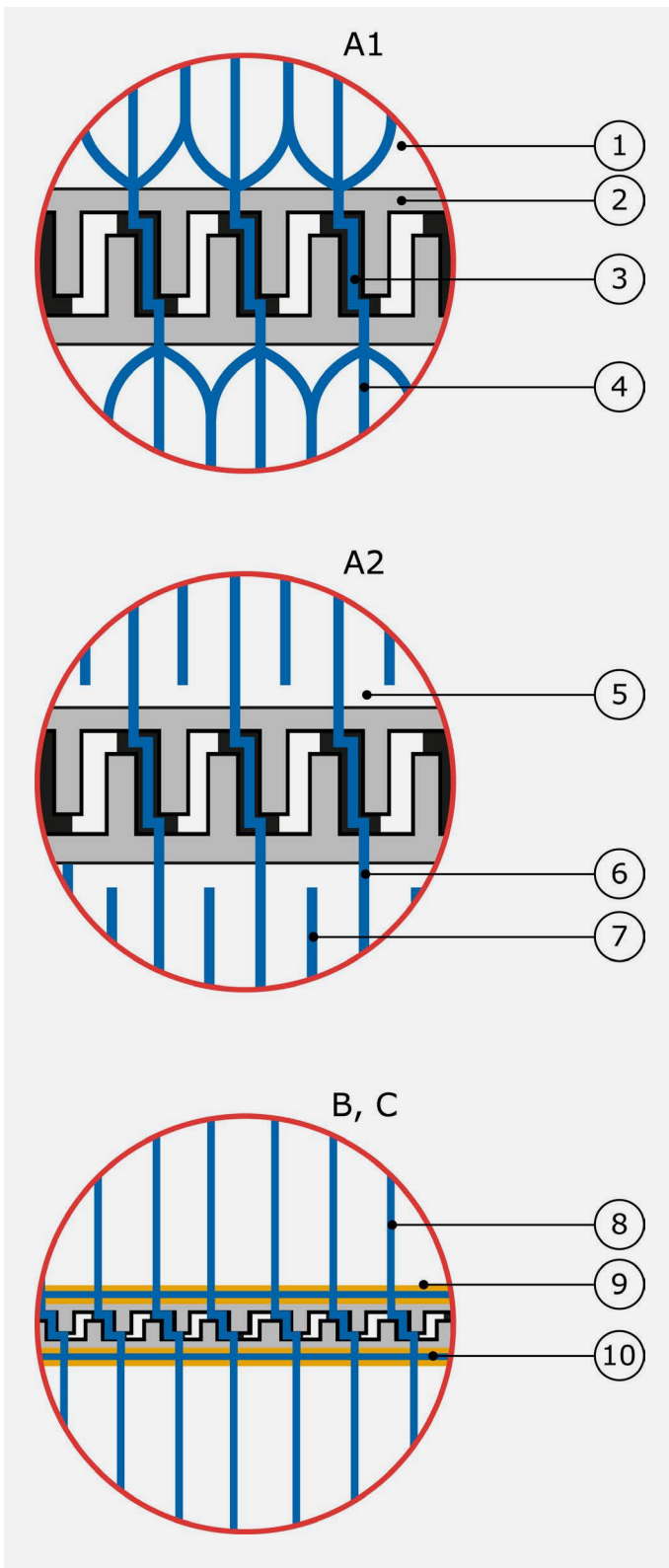


Figure 7 Microscopic effects in heat flux sensors. Upper picture: sensor (2) in a well conducting environment (1); the heat (4) chooses a preferential path (3) through the sensor. Centre picture: in a less conducting environment (5), the heat flux (7) experiences a higher thermal resistance. Bottom picture, in a sensor with a spreader, the well conducting spreader (9) conducts all heat (8) in-plane (10), creating a constant environment for the thermopile.

Test results

The sensitivities of the sensors were tested under different conditions. The reference condition is mounted on aluminum, the other conditions surrounded by Pyrex (glass) and silicone (plastic) create an environment with different thermal conductivities.

Of sensor type A (Figure 5), thermopiles made with two different manufacturing techniques from leading suppliers were tested: the first based on electrically conductive inks and the second based on semiconductor materials. The test results are presented in Figure 6. When determining the sensitivity, the capability to measure changes has a reproducibility in the order of 1%, asserting that changes of 3% can meaningfully be detected. In this experiment the calibration uncertainty is set at $\pm 5\%$. Test results show a very significant thermal conductivity dependence of sensors of type A, while the error types B and C are much smaller than the calibration uncertainty.

Conclusions

- When used under conditions different from the calibration reference conditions (conditions for which the calibration is valid) heat flux sensors without spreaders may make large measurement errors because of their thermal conductivity dependence.
- Use of sensors with spreaders reduces this risk. Measurement errors become negligible.

Discussion

Sensors with spreaders of type B and type C such as the FHF series supplied by Hukx, have a negligible thermal conductivity dependence. By contrast, type A sensors produce large errors when used in an environment different from the one in which it was calibrated. Figure 7, A1 and A2 schematically show what is happening on microscopic scale in these sensors. The spreaders, large or small, will create a constant environment for the thermopile (Figure 7B, C). Testing shows no significant difference between the use of one large spreader or multiple smaller ones (Figure 5, B and C). Using multiple small spreaders, like in Hukx's FHF series, has the benefit of higher flexibility than when using one single large spreader.

Recommendations

- To avoid errors, use of heat flux sensors with spreaders such as Hukx models (FHF05 series, FHF06 and HFP01) is highly recommended.
- Whatever the application, use of sensors with a low thermal resistance is beneficial, provided that the sensitivity does not become too low.
- Heat flux sensors of which the individual thermocouples are visible to the eye are inherently unreliable; they will have a large thermal conductivity dependence and cannot be trusted to provide an accurate measurement in other environments than the calibration environment.

About Hukx

Hukx is the leading expert in measurement of energy transfer. We design and manufacture sensors and measuring systems that support the energy transition. We are market leaders in solar radiation and heat flux measurement. Customers are served worldwide through our headquarters in the Netherlands, and locally owned representative sales offices in the USA, Brazil, India, China, Southeast Asia, and Japan.

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