Heat flux sensor technology:
printed thermopile conductors vs. *etched-and-plated*

Hukseflux' foil heat flux sensors contain full-metal "etched-and-plated" thermopile conductors. Competing models use thermopile conductors made by printing metal-filled inks. Testing at Hukseflux has revealed potential shortcomings, in particular the instability of heat flux sensors manufactured using metal-filled inks. A sensor that is not stable does not reliably perform an accurate and repeatable measurement. Users may detect stability issues by monitoring the electrical resistance of the heat flux sensor.*

Figure 1 *a flexible heat flux sensor on a tube surface measuring heat flux between the tube and its environment.*

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.

Printed flex circuits

Printed flexible circuits are commonly used in many applications. The electrically conductive inks used in these circuits consist of a plastic base-material filled with small conducting particles, typically copper, nickel or silver. Using an electrical circuit with through-holes and filling up alternate holes with two different conductive inks, you may construct a thermopile, see Figure 3. See also US patent 10 393 598.

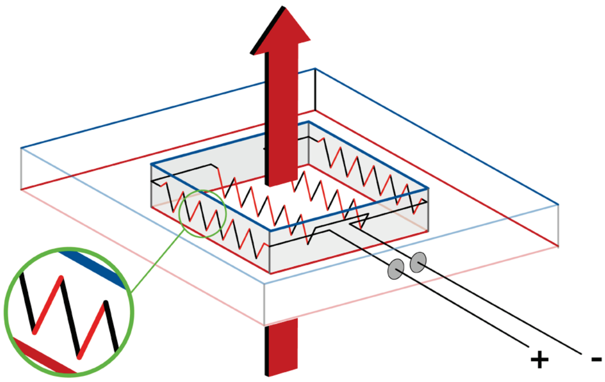

Figure 2 *heat flux sensor principle: the sensor contains a thermopile consisting of an alternating pattern of two metal alloys.*

* Experiments were carried out on Hukseflux FHF series models, as well as sensors purchased from a leading supplier of printed heat flux sensors. The test results may not be applicable to sensors produced by other manufacturers or when improving manufacturing technology.

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Hukseflux
Thermal Sensors

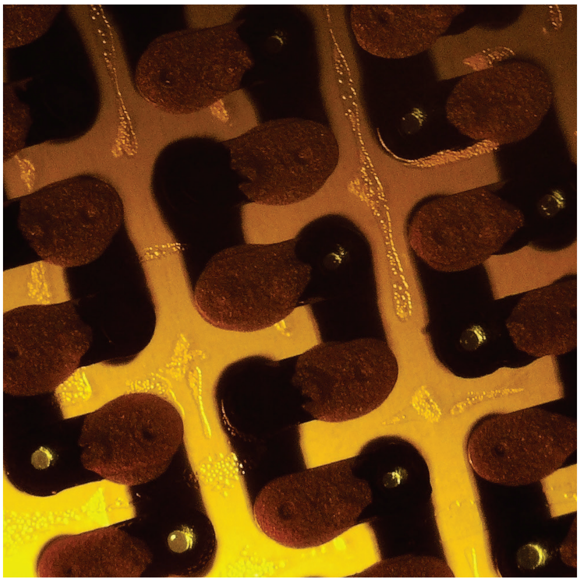

Figure 3 *close-up of a heat flux sensor with a thermopile created using printing technology. Two different metal-filled electrically conducting inks are printed into through-holes.*

Etching and plating

Etching and plating technologies use a metal foil as base-material. By etching material away, and locally plating with another metal, you may construct a thermopile, see Figure 4.

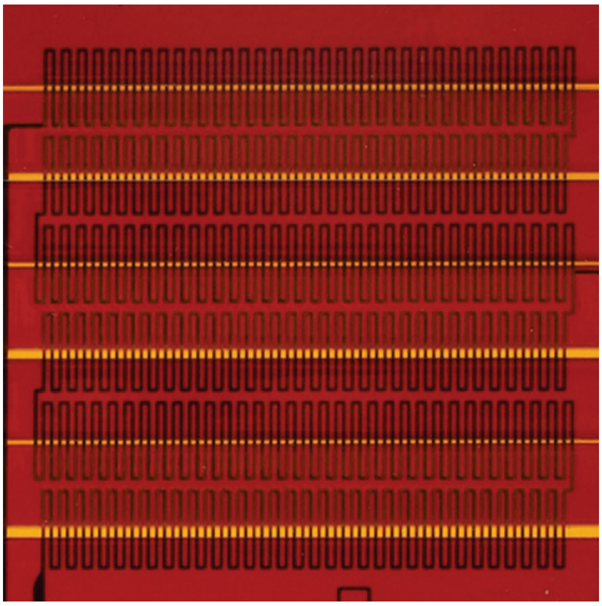

Figure 4 *close-up of a heat flux sensor with a thermopile created using etching and plating technology. A continuous full-metal trace is locally plated and woven through the plastic base material of the sensor.*

Differences: sensor stability

The differences between the two technologies were revealed in two experiments. They address potential issues with sensor stability, i.e. change in sensitivity.

- stability under high temperature exposure
- stability under bending

An unstable sensor grows increasingly unreliable with time and use. As a result, its uncertainty of the sensitivity, as given in the calibration certificate is no longer valid. To put test results in perspective: the calibration uncertainties of all sensors involved are 5 %. An instability of just a few percent is significant.

Test results

The sensitivities of the sensors were tested at 20 °C after 1-time bending around a pipe of 25 x 10^{-3} m radius, and after 24 hours of exposure to high temperatures. Sensors were first exposed to 120 and later to 150 °C. The 150 °C is above the rated operating range for printed sensors and only serves to present an indication what may happen during long-term exposure within the rated 120 °C range. The changes of sensitivity were all relative to an initial measurement by Hukseflux at 20 °C and were all performed on a flat surface. 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 absolute accuracy is not a factor.

sensor technology	test	permanent change of sensitivity	permanent change of resistance
	[name]	[(V/(W/m²)/(V/(W/m²)]	[Ω / Ω]
etched	bending radius 25 x 10^{-3} m	not detectable (< 3 %)	< 2 %
printed	Bending radius 25 x 10^{-3} m	-7 %	+11 %
etched	120 °C	not detectable (< 3 %)	< 2 %
printed	120 °C	+ 6 %	+ 250 %
etched	150 °C	not detectable (< 3 %)	< 2 %
printed	150 °C	+ 16 %	+ 1200 %

Table 1 *test of stability of the sensitivity and the internal resistance of heat flux sensors based on two manufacturing technologies. Tests were performed before and after 24-hour exposure to high temperatures and before and after bending. Sensors are all rated for long-term use up to 120 °C, and sold as "flexible", which was confirmed by the sellers: "suitable for bending up to 1.25 x 10^{-3} m radius". Changes are all relative to those at the start of the test, positive values indicating a higher value after testing.*

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Conclusions

- sensors based on the etching and plating manufacturing technology are stable under bending and high temperature exposure within the rated operating range
- sensors based on metal-filled inks must be treated with care and may have stability issues, even under mild exposure.
- sensors based on metal-filled inks may have different failure mechanisms under bending and under exposure to high temperatures. Comparing test results resistance increases in all tests while sensitivity increases in one test and sensitivity decreases in the other.

Figure 5 *example of a heat flux sensor stable under bending and high temperature exposure*

Discussion

Full-metal thermopiles, such as the ones employed by Hukseflux, are inherently stable. There is a long experience with the manufacturing technology of etched-and-plated metal traces and with the plastic base material and glues. The same technology is employed in electric heater manufacturing, which have a solid reputation for stability.

Metal-filled ink application is widespread, however limited to cases that changes of physical properties are acceptable. They are mostly employed as simple conductors, not as critical to a measurement. Many of these inks require curing, and we suspect the instability during high temperature exposure is caused by curing effects (chemical reaction of materials). Inks depend on metal particle-to-particle connections for their electrical conductance. When bending sensors based on metal-filled inks, the instability noted may be caused by these particle-to-particle connections loosening or breaking up.

Recommendations

Monitoring the electrical resistance of a heat flux sensor is a powerful tool to detect potential stability issues. A stable sensor has a stable electrical resistance. There is no one-to-one relationship between electrical resistance and sensitivity, however if electrical resistance changes there is a high probability that sensitivity changes as well.

About Hukseflux

Hukseflux Thermal Sensors makes sensors and measuring systems. Our aim is to let our customers work with the best possible data. Many of our products are used in support of energy transition and efficient use of energy. We also provide services: calibration and material characterisation. Our main area of expertise is measurement of heat transfer and thermal quantities such as solar radiation, heat flux and thermal conductivity. Hukseflux is ISO 9001 certified. Hukseflux products and services are offered worldwide via our office in Delft, the Netherlands and local distributors.

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