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Round-Robin Test of Heat Flux Sensors

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Abstract The first intercomparison on the density of heat flow-rate measurements has been organized by MKEH (Hungarian Trade Licensing Office, Metrology Division) within the framework of EUROMET (Project No. 426). This round-robin test gives evidence about the measurement capabilities of the local realizations of a density of a heat flow-rate scale up to $100\,\mathrm{W \cdot m^{-2}}$. Two types of heat flux plate sensors differing in their size were circulated among partner laboratories. Each one of the six partners calibrated the sensors using its own calibration system, a guarded hot plate or a heat flow meter apparatus. This article compares all the results of the round-robin test and gives the mutual differences among the partners. The participants could benefit from the measurement results by improving, in case of need, their calibration methods and procedures and by reducing their uncertainties. The impact of this comparison will go directly to the users in industry.

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1 Introduction

Heat flux sensors can be calibrated using different calibration systems such as a guarded hot plate or a heat-flow meter apparatus. This article presents the first inter-comparison on the density of heat flow-rate measurements which has been initiated by the EUROMET Technical Committee for Thermometry. The comparison includes six participants.

The objective of this round-robin test was to give evidence about the measurement capabilities of the local realizations of a density of a heat flow-rate scale up to $100\,\mathrm{W \cdot m^{-2}}$ and to clarify the need of reducing the measurement uncertainties. Taking into consideration that the project compares calibrations of heat flux meters, the presentation is effectuated in terms of sensor sensitivity.

The heat flux sensors are calibrated by determining the sensitivity coefficient of the output voltage with respect to the heat flux through the sensor.

Considering the uncertainty, which characterizes the quality of these measurements, the terms of the GUM required for this purpose were extended by the instrument-and-sample-specific corrections [1–3].

2 Measurements

Two types of heat flux plate sensors having different dimensions, electrical resistance, sensitivity, thermal conductivity and here denoted as “NL” and “HU” were circulated among five (NL) and two (HU) partner laboratories, respectively [4–6]. Particulars of the heat flux sensors can be found in Table 1.

The calibrations were effectuated with the use of the same method in different equipment.

The densities of heat flow-rate determinations were made by placing one of the circulated heat flux sensors between a heater plate and an isothermal cold plate, which are maintained at known temperatures. On its lateral face, the sample is surrounded by edge insulation. The hot plate dissipates the constant electric input power as the heat flow rate, which on its way to the cold plate traverses the sample as homogeneously as

Table 1 Particulars of the heat flux sensors

Sensor	No. 1 “NL”	No. 2 “HU”
Model	PU 43 T	OMH 1
Dimensions	ϕ 100 mm × 1 mm	300 mm × 300 mm × 3.5 mm
Sensitive area	ϕ 55 mm	100 mm × 100 mm
Sensitivity	$0.17\,\mathrm{mV \cdot m^2 \cdot W^{-1}}$	$(5\text{ to }9)\,\mathrm{\mu V \cdot m^2 \cdot W^{-1}}$
Electrical resistance	7000 Ω	6 Ω to 24 Ω
Max. temperature	60 °C	100 °C
Thermal conductivity	$0.2\,\mathrm{W \cdot m^{-1} \cdot K^{-1}}$ to $0.3\,\mathrm{W \cdot m^{-1} \cdot K^{-1}}$	$0.3\,\mathrm{W \cdot m^{-1} \cdot K^{-1}}$ to $0.4\,\mathrm{W \cdot m^{-1} \cdot K^{-1}}$
Cable length	2 m	2 m

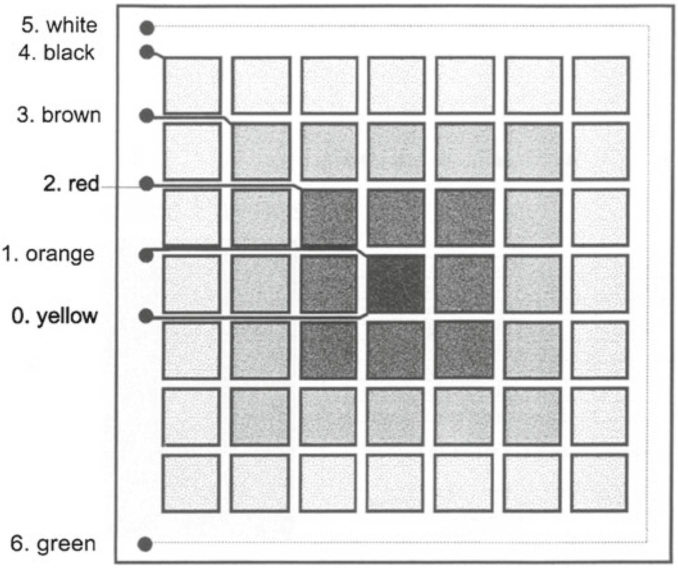

Fig. 1 Heat flux sensor "HU" (reference dimensions: 100 mm × 100 mm)

possible. The known heat flow leads to a temperature drop across the sample which is the measure of its thermal conductivity [1]. To promote good thermal contact between the specimen and the hot and cold plates, rigid specimen materials are coupled to both plates by the use of a contact medium or pressing force.

Each one of the six partners calibrated one or both of the sensors, depending on the dimensions of their measurement apparatus, at nominal densities of heat flow rates of $10\,\mathrm{W \cdot m^{-2}}$, $50\,\mathrm{W \cdot m^{-2}}$, and $100\,\mathrm{W \cdot m^{-2}}$, using its own calibration system, a guarded hot plate, or a heat flow meter apparatus. Measurements were performed at nominal temperatures of 20 °C and 30 °C. The first and last measurements were effectuated by the pilot laboratory MKEH.

Adjustment of the desired heat flow rate was achieved by modifying the temperature difference between the upper and lower parts of the sensor, for a given nominal temperature.

The calibration of the heat flux sensors was done using the following recommendations: ISO 9869:1994(E), ISO 8302:1991, ISO 8301:1991, and ISO 7345:1987.

The heat flux sensors are illustrated in Figs. 1 and 2.

3 Results

The calibration procedure used involved the determination of the sensitivity coefficient of the output voltage with respect to the heat flux through the sensor.

The measurement results are grouped considering the two types of heat flux sensors and the two different nominal temperatures.

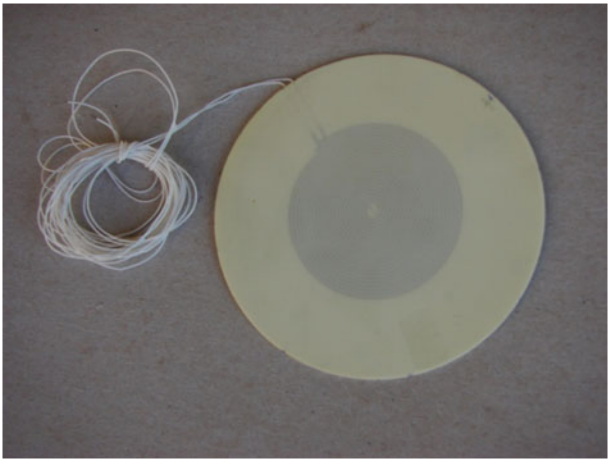

Fig. 2 Heat flux sensor “NL” (reference diameter: 55 mm)

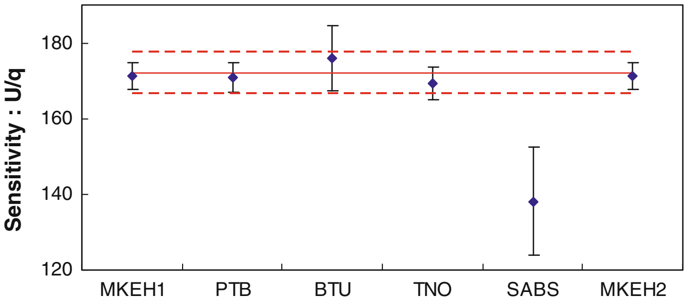

Fig. 3 Results of the participants for the calibration of the sensor “NL,” nominal temperature of 20 °C, nominal density of heat flow rate of $10\,\mathrm{W \cdot m^{-2}}$

The sensitivity coefficient was obtained by the following equation:

$$S_{\mathrm{lab}} = \frac{U_{\mathrm{lab}}}{q_{\mathrm{lab}}}$$

where U_{lab} is the voltage of the heat flux sensor output measured by each partner and q_{lab} is the density of heat flow rate given by the participants.

The results are composed of the realized density of heat flow-rate values, of reading values of the sensor output, and of the calculated sensitivity values which are specific for one type of sensor.

Figures 3, 4, 5, 6, 7, and 8 present some examples of the reported results and their combined expanded uncertainties given by the partner laboratories. Uncertainties are given for the coverage factor $k = 2$. A detailed presentation of the measurement results can be found in the project report [7].

The uncertainties are associated with the heat flux transducer output (resolution and calibration of the differential voltmeter (dvm), calibration of the voltage reference, the

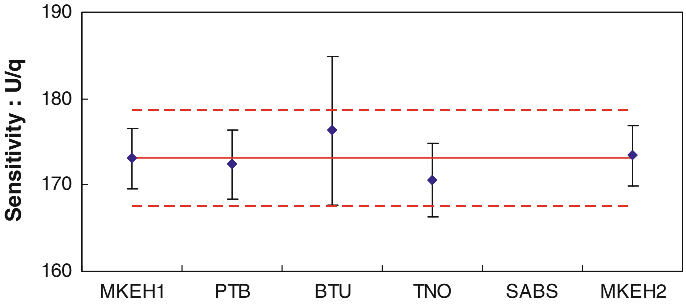

Fig. 4 Results of the participants for the calibration of the sensor "NL," nominal temperature of 20 °C, nominal density of heat flow rate of 50 W · m^{-2}

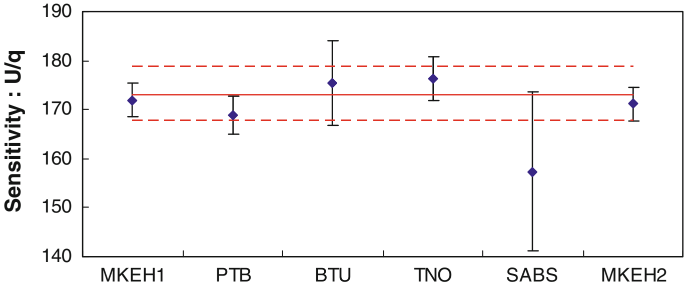

Fig. 5 Results of the participants for the calibration of the sensor "NL," nominal temperature of 30 °C, nominal density of heat flow rate of 50 W · m^{-2}

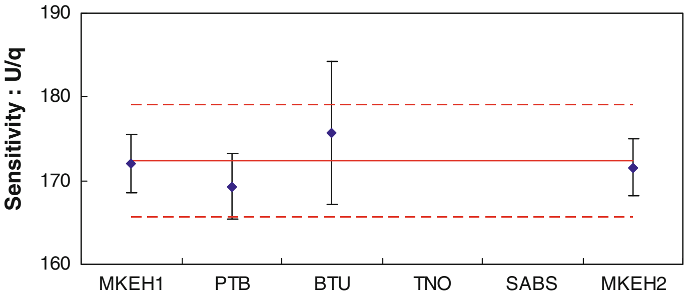

Fig. 6 Results of the participants for the calibration of the sensor "NL," nominal temperature of 30 °C, nominal density of heat flow rate of 100 W · m^{-2}

averaging resolution), the heater area (length and width measurement, calibration and resolution of calipers), the measurement of power (resolution and calibration of dvm, voltage reference, and standard resistor), miscellaneous factors (heat losses), the absolute temperature (thermocouple calibration), and the fixed heat flux offset.

In order to establish the uncertainty budget, the uncertainty contributions are extended by the instrument-and-sample-specific corrections [1,3].

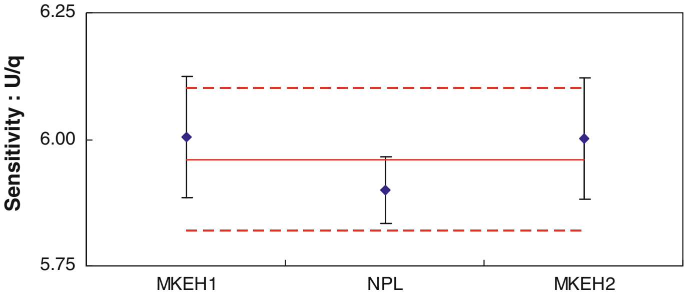

Fig. 7 Results of the participants for the calibration of the sensor "HU," nominal temperature of 20 °C, nominal density of heat flow rate of 100 W · m^{-2}

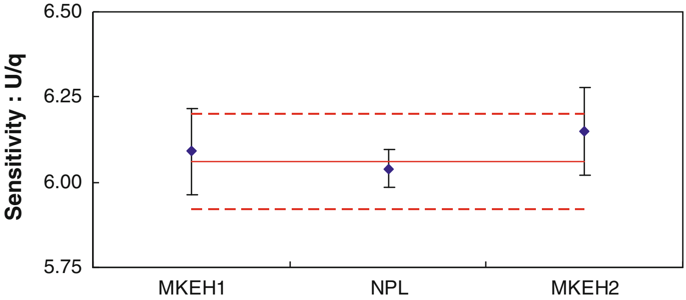

Fig. 8 Results of the participants for the calibration of the sensor "HU," nominal temperature of 30 °C, nominal density of heat flow rate of 50 W · m^{-2}

There are two major sources of experimental error, systematic and random effects. The systematic measurement errors are compounded from apparatus-specific errors and specimen-specific errors. The apparatus-specific errors consist, for example, of the imbalance error, the edge heat loss error of the hot plate, the edge heat loss error of the sample, and indirect temperature measurements with thermocouples [1]. The specimen-specific errors consist, for example, of the thermal expansion of the sample, the contact resistance error, the temperature jump due to mechanical contact, and the exchange of radiation. Other sources of uncertainty are due to variations of the geometry of the sample, of the temperature differences, and of the heat flow. The characteristics of each apparatus and the detailed uncertainty evaluations are presented in the project report [7].

The Euramet reference values (ERV) were evaluated according to the mean (Table 2) [7]. Taking into consideration the limited number of participants, the mean seems to yield the most reasonable reference value.

In particular, the results of the SABS laboratory are not satisfactory, because, due to an inaccurate calibration procedure, their sensitivity coefficient is not constant for each temperature and for each density of the heat flow rate (Fig. 3). For this reason, their results are not included in the evaluation of the ERV values and their uncertainties.

Table 2 Summary of ERV values and uncertainties for sensor NL and sensor HU

Nominal temperature (°C)	Nominal density of heat flow rate ($W \cdot m^{-2}$)	Sensor NL		Sensor HU	
		ERV value ($\mu V \cdot W^{-1} \cdot m^2$)	U_{ERV} ($\mu V \cdot W^{-1} \cdot m^2$) $k = 2$	ERV value ($\mu V \cdot W^{-1} \cdot m^2$)	U_{ERV} ($\mu V \cdot W^{-1} \cdot m^2$) $k = 2$
20	10	171.86	5.49	6.18	0.46
30	10	172.43	5.43	5.99	0.25
20	50	173.06	5.49	6.00	0.16
30	50	173.14	5.48	6.06	0.14
20	100	173.07	6.73	5.96	0.14
30	100	172.33	6.70	6.05	0.13

4 Conclusion

The participating NMIs are offering calibrations for heat flux meters. For this reason there is an urgent need for demonstrating the equivalence between them, which makes this comparison important.

Six institutes took part in the comparison; their representative results are presented in this article. Each one of the six partners calibrated the sensors using its own calibration system, a guarded hot plate, or a heat flow meter apparatus. These calibration facilities used as standards assured that uniform and reliable measurements lead to comparable results.

In spite of the diversity of the calibration procedures and of the characteristics of each apparatus, the measurement results in most cases show good agreement.

These investigations led to a better approach for the density of heat flow-rate measurements and improvements in the calibration methods and procedures. A broadening cooperation among laboratories should provide a more consistent and standardized uncertainty evaluation. The degree of equivalence, resulting from this comparison and presented in the report, can be used in reviewing the calibration and measurement capabilities (CMCs) of the participants.

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