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Experimental Method Calibration (MECr): A new relative method for heat flux sensor calibration.

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Abstract:

Heat flux sensor calibration is often expensive, but it is also a fundamental step to obtain valid results. According to the needs, several calibration procedures could be considered. If experimental interpretations focus on heat flux values comparison rather than true values, a relative calibration with high accuracy can be performed. This paper focuses on a new relative calibration-type method of heat flux sensors (HFSs). In general, the HFSs were originally (even recently) factory and in-house-calibrated, but this method was used to calibrate them to an exact common reading to help in performing accurate experiments and eliminating errors that could result from differences between the HFSs. The developed methodology was adapted from a secondary calibration-type (i.e., absolute) generalization. This method aimed to present a simple, low cost, and accurate way to calibrate heat flux sensors. The proposed calibration method was relative, which means that it did not use any calibration reference. However, an absolute calibration adaptation of this method can easily be performed. In the method presented in this paper, calibration was made via sensor sensitivity correction. The experiment consisted of imposing an identical and homogeneous heat flux across four heat flux sensors during a sufficiently long time to be able to statistically subtract any unwanted influences, such as convective and radiative variation. More precisely, temperatures and heat flux levels of 30-35 °C and 60-70 $W.m^{-2}$, respectively, were used. Then, new sensor sensitivity values were found by basic statistical data manipulations. Although the focus of this methodology was for contenting thermopile-based HFSs that used differential temperature measurements, the set-up can be adapted for other types of HFSs. In this paper, the set-up, its conception, and guidelines for using this method are presented.

Keywords:

Relative calibration, Comparative calibration, Secondary calibration, Absolute calibration, Heat flux sensors, Wall heat transfer.

1. Introduction

Heat exchange is a common physical phenomenon. Everyday examples, from building heat transfer (e.g., heat island effect [1]) to agriculture and medicine (e.g., transpiration) are experienced by systems and living things alike. Conduction heat exchange is characterized by atomic and molecular excitation within a material from a higher to a lower temperature that can be measured experimentally by heat flux sensors (HFSs).

For the integrity and credibility of any experimental activity, it is crucial to exercise care during sensor installation before each experiment, despite the fact that this goal is demanding and relatively expensive because of the instrumentation that is needed for precise calibration. In fact, HFSs calibration without specific instrumentation may not be accurate, even though precise. In some cases, only good precision is needed, and then relative calibration is sufficient. Considering the previous comment, the current study focuses on a simple recalibration method (a relative method) based on the comparison of four coplanar HFSs. This method’s design and performance are described and analyzed in the following sections.

2. Objective of the study

Review of the HFS calibration literature in building physics suggests that no methodology defines any relative calibration method. However, relative calibration exists in other physics fields, such as particles physics or astronomy [2]. Therefore, only absolute calibration is defined in building physics. The method presented in this paper attempts to fill this deficit in the open literature. More precisely, the present paper focuses and proposes an experimental method that is used to find, after data extrapolation, sensor-specific calibration coefficients to be applied to the sensor sensitivities furnished by the sensor manufacturers. This experimental method is located in the first position of the global calibration methodology (Fig. 1).

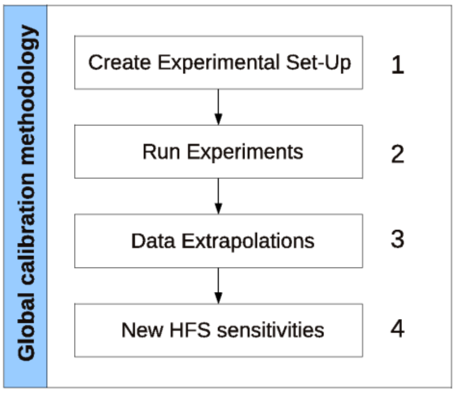

Fig. 1. Global calibration methodology

3. Prologue: calibration and HFS theory

3.1 Calibration definition

Calibration of differential HFSs can be achieved by either one or a combination of conduction, convection or radiation methods, depending on the experimental needs. Our method described herein, achieves calibration of HFSs to a common averaged value to assist in accurate experiments using multiple meters. In fact, all HFS have some degree of inaccuracy even if they have just been factory calibrated. (This can be easily verified by comparing new HFSs' readings.) An absolute calibration allows the sensor to find the true value of the measurement, whereas, a relative calibration allows several sensors to find a common value. In both calibrations, accuracies can be defined by their results compared to the ideal value (which is respectively the true or 'common' value defined previously). In the presented methodology, only averaged data were used. The sensor-specific coefficients allow a modification of the accuracy of the HFSs making their readings closer to the true value.

An absolute calibration method can be characterized as primary or secondary [5], whereas the relative calibration method is only secondary (comparative). A primary calibration is defined as a method where the sensor is calibrated from a comparison between the sensor results and the known environmental characteristic specifically applied to it. Whereas, a secondary (comparative) calibration is defined as a method where the sensor is calibrated comparatively to a previously calibrated sensor. This reference sensor is called a secondary standard [5]. Considering error accumulation, and in comparison to the primary calibration, the secondary method is intrinsically less accurate.

Finally, HFS calibration is complex because the sensors are very sensitive to heat transfer modes and minor experimental variations (e.g., air flow around the sensor and/or emissivity of surfaces surrounding the sensor) [3,9].

3.2. HFS succinct presentation

HFSs use several different technologies (e.g., thermopile, liquid crystal thermal system, etc.) and different configurations (e.g., foil thermopile, micro-sensor thermopile, wire-wound thermopile, etc.). For the purposes of this paper, only planar sensors based on spatial temperature gradient will be presented [3,6] (Fig. 2 [4]).

A heat flux sensor is a sensor that provides an output voltage (E) as a linear function of the intensity of a heat flux across a material. HFSs based on spatial temperature gradient technology use transducers that are embedded into a polymeric matrix placed between two conductive plates [3] (Fig. 2 [4]). The transducer uses a thermopile that produces an electrical voltage as a function of the temperature difference between the two sides of the polymeric matrix whose operation is based on the Seebeck effect" [5]. The thermopile is composed of several thermocouples that are connected in series, which respond to the local temperature difference across the polymeric matrix. The output signal E of this transducer is simply a multiple of the number of differential thermocouple (hot and cold junction values difference) [6]. The output signal is defined by Equation 1, where N_j is the number of thermocouple junctions, S the Seebeck coefficient ($V \cdot K^{-1}$) and ΔT the temperature difference (K) [3]:

$$E = N_j \cdot S \cdot \Delta T , \qquad (1)$$

This transducer is called thermopile or differential transducer, and the sensor is called a differential HFS. Figure 2 presents a HFS using a thermopile based on spatial temperature gradient measurement. This technology was first reported in 1942 by Martinelli et al. [7] and expressed in terms of heat flux by:

$$\varphi = k \cdot E \qquad (2)$$

Where φ is the heat flux ($W \cdot m^{-2}$), k ($W \cdot m^{-2} \cdot mV^{-1}$) represents the sensor's specific sensitivity and E is the voltage output (mV). In this context, calibration is made by sensitivity parameter setting, which is the k value in Equation 2. This value is sensor specific, calibration conditions specific [8], and time evolving (over several months). A well-calibrated HFS sensitivity is a key requirement to achieving good results.

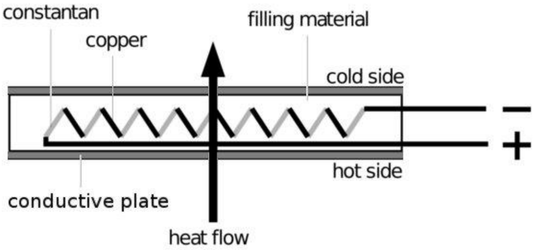

Fig. 2. HFS based on a differential transducer, was adapted from [4].

4. MECr: A new method of relative calibration

MEC is the acronym for "Experimental Method Calibration" ("Méthode Experimentale pour la Calibration" (in French)). It defines a secondary absolute calibration generalization. The generalization main characteristics build upon the radiative calibration components of Murthy [9], the comparative calibration components of Holmberg [8], and the secondary standard utilization by Gifford [10, 11]. This general method, MECr, can be used for relative calibrations, whereas the absolute method would be denoted MECa. The MECr is presented in the following sections.

4.1. Principles

The MECr allows a comparison of four similar[1] and coplanar HFSs homogeneously insulated, with one being denoted the factory-calibrated reference HFS. Experimental data are corrected in function of a predefined selected value (herein referred to as "ideal value"), which is defined in terms of HFSs values[2]. These corrections, once applied to the sensitivities of the HFS 'i' give the new HFS calibrations (4). The previously cited 'correction' consists of a ratio application. This ratio is sensor specific and composed by the quotient of equation (3) where 'm' and 'id' represent the measured and ideal values, respectively.

$$\varphi_{id} = \varphi_m \bullet \left(\frac{\varphi_{id}}{\varphi_m} \right) = \varphi_m \bullet Ratio \;, \qquad (3)$$

$$k_i^{new} = k_i^{old} \bullet Ratio_i \;, \qquad (4)$$

This correction is only valid if the data are influenced homogeneously. In reality, sensors are influenced by their locations. As explained previously, this influence comes from air movement and/or enclosing surfaces emissivity (e.g., convection and/or radiation) which are inhomogeneous. To determine these influence differences, the experiment must be conducted four times with each sensor in each possible location (Fig. 3 and A2).

This experiment multiplication involves an issue of environmental influences. Unless experiments are conducted in a highly-controlled area, which is not compatible with a low-cost approach, experiment’s environmental factors and their evolutions, such as room air and surface temperatures, draft velocity, and relative humidity impact the HFS reading.

Therefore, there are two key influences: location and environment. These influences are corrected statistically (Step 3 Fig.1) in this method. Following this methodology, all the HFSs are corrected, resulting in the new sensitivities coefficients (k_i^{new}).

For reference, the MECr method can also be adapted from relative to absolute calibration, or MECa. For this, a secondary standard HFS is used as reference instead of the HFS average. The secondary standard takes the place of one of the four HFSs. Mathematically there is no modification involved; the only modification appears in the choice of ideal value.

4.2. Limits and hypothesis

4.2.1. Limits

The experiment design can lead to some decisions that could potentially limit its use.

The experiment was designed for planar sensors based on spatial temperature gradient (Fig. 2). Nevertheless, an experimental set-up modification can be performed to use HFS from other technologies or configurations.

According to Zarr [5], absolute calibration with a secondary standard would lead to an uncertainty of about 10%.

Removing HFSs influences differences increases the uncertainty by error propagation, which are only calculable from experimental data, although the main part of the error comes from the random convection and radiation influences which cannot be removed because they are unknown. These errors can be reduced by draft, convection, and radiation reduction around the sensors.

4.2.2. Hypothesis

During HFS calibration some assumptions were made, which could be reduced by knowledge of both the set-up and methodology.

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[1] This results in a calibration which remains correct even if the mode transfer repartition evolves.

[2] HFS values are derived from steady-state data averages.

All HFSs in this experiment were assumed to have the same reading characteristics. In this case, for identical conditions, even if different from the calibration conditions, the calibrated HFSs should give the same reading. This involves the calibration validity over all the full specific range of measurements allowed by the HFSs.

According to Holmberg [8], "calibration coefficients are sensitive to the following parameters: sensor mounting, type of applied flux (convection versus radiation), magnitude of applied flux, contact resistance, (…). This means that the same sensor can have widely different calibration coefficients depending on the calibration set-up,". Holmberg concludes that, "For this reason, in situ sensor calibration is always desired if possible." The present method is not an in situ method, but calibration is made on similar HFSs. However, as long as every HFS is surrounded by identical influences, the relative calibration would produce sensitivity coefficients (k) that would provide more accurate heat flux values regardless of set-up.

For sensor calibration at elevated temperatures, it was demonstrated that there is a dependence of the heat flux sensitivity on sensor temperature [3]. According to Zarr [5], heat flux sensitivity values are also dependent on sensor temperature at low and moderate temperatures in the range of 10-50°C. This dependence, however, is weak; therefore, sensitivities are only slightly affected by HFS temperature dependence. To minimize this effect, the HFSs are kept away from the heat source. In a relative (i.e., comparative) calibration, this effect is not an issue because it is assumed to be the same for every HFS.

Zarr [5] shows also that HFS responses can be approximated as a linear function of the heat flux with a deviation of less than ±3%. More precisely, HFS responses can be approximated as a linear function without bias term. Therefore Equation 2 is confirmed and the experimental power source location can be freely chosen. This decision was made considering the maximum flux density allowed by the used HFS and the error involved by anisotropic convection and radiation heat transfer.

4.3. Set-up configuration

The calibration set-up was composed by a vertical steel plate ($38 \times 59 \times 0.8$ cm^3) homogeneously covered with black heat paint and back-lit by an infrared bulb lamp (250 W at a distance of 46 cm) centered in the middle of the steel plate. This configuration allowed to assume the plate as an isotropic secondary source (Fig. 3 and A1), which can be also assumed as a blackbody. It is assumed that a blackbody effectively absorbs over the entire wavelength range and emitted homogeneously in a range[3] from 0.4 to 25 µm that was assumed to be Lambertian.

On the other side of the steel plate (at 7 cm) (also centered in the middle of the plate) , two pieces of Polymethyl-methacrylate (PMMA) ($30 \times 30 \times 0.9$ cm^3) were attached by screws. Between these PMMA pieces, four heat flux sensors ($5 \times 5 \times 0.8$ cm^3) were placed side-by-side with a space of 5 mm between each. For a better contact, the HFSs were lightly pressed against the PMMA by eight small plastic screws which allowed a constant clamping pressure. Contact was also improved by the application of a thermo-conductive paste, which helped by avoiding microscopic air spaces that would increase the thermal resistivity [8]. Type T thermocouples (gauge 24) were installed on both sides of the PMMA plate and on the steel plate. This was done to check the history of temperatures during the experiment and to monitor and control the temperature tolerance of the HFS) (Fig. A2).

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[3] For a body at 283K, first Wien law gives a maximum emissivity at λ=10.23µm.

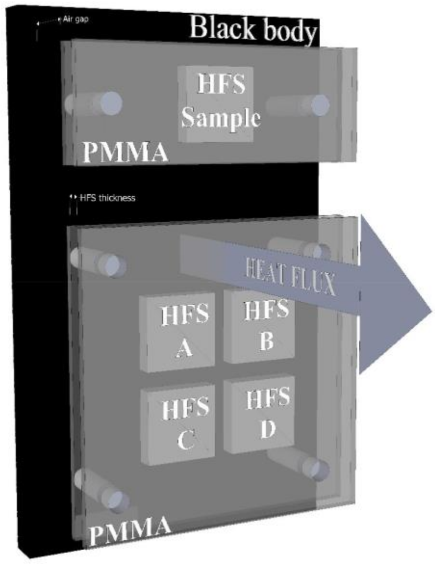

Fig. 3. Figure of the relative and comparative calibration set-up.

To obtain a more homogeneous flux from the steel plate, the HFSs were not in contact but located at 7 cm assuming Lambertian properties (Fig. 3 and A3) Therefore, the three heat transfer modes impacted the results. These modes allowed us to define the influence notion in this specific context. An influence is a physical property, such as set-up or environment characteristics, that modifies the heat flux reading by the HFS. Without influences, the heat flux reading should be an isotropic radiative heat flux from the steel plate. In relative calibration, influences are not an issue, as long as they impact homogeneously every HFS. From the set-up considerations, conductive and radiative heat transfer modes could be assumed as isotropic on the four HFS, but not the convective mode. This is the case because the HFS were 7 cm away from the steel plate thereby creating an air-convective pattern. To reduce and homogenize the convection influence, a thermal-resistive but far-infrared transmissive material was chosen to protect the HFSs (Fig. 3). A similar solution, using a glass window to minimize the convective effects, was proposed by Bryant [14]. Considering the fragility of this material in relation to the experimental needs, glass windows were not chosen for use. With a low thermal conductivity of 0,19 $W \cdot m^{-1} \cdot K^{-1}$, and an Izod impact of 0.160 $J \cdot cm^{-1}$ (respectively found by ASTM method C177 and D256), a PMMA plate was suitable for this use [15].

Note: The far infrared (10.23µm) PMMA absorptivity was unknown. However, experimental data showed heat flux values around 60-70 $W \cdot m^{-2}$ for a heating source composed of an IR lamp consuming 250 W. Considering bulb lamp thermal losses, radiative losses (view factors) and convective losses associated with the heat source, the experimental range value permitted an assumption of a low PMMA absorptivity around 10 µm.

As explained in the previous section, four experiments were conducted to cancel the location influence. This lead to adding a second environmental influence typically characterized by the environmental variation between these experiments. To cancel this influence, a fifth heat flux sensor, continuously located above a PMMA plate, was used as a sample to compare the environmental influence variations between these four experiments, and then subtract these influences to the respective HFS values (Fig. 3 and A2).

To summarize, this experiment was conducted in a closed room with natural roof air-extraction to avoid unwanted convection.

4.4. Methodology

The methodology used can be split in three key parts: 1) set up base, 2) first experiments, and 3) remaining experiments. The last three experiments were made after HFSs location modification consisting of a π/2 rotation of the two PMMA board contenting the HFSs. The first steps must be done only one time regardless of the number of HFSs.

Set-up base:

1) Cover the clean and isotropic steel surface homogeneously with black heat paint.
2) Drill four holes into the steel to attach PMMA plate.
3) Screw steel surface on vertical wood sticks.
4) Install the HFS sample between two PMMA plates with conductive paste.
5) Screw PMMA contenting HFS sample, on vertical wood sticks, above the HFSs location.
6) Install a thermocouple (type T) on each HFSs PMMA plate (sensor side).
7) Install a thermocouple (type T) on the centre of the steel plate.
8) Install an infrared bulb light (250 W_e) at 50 cm, orthogonally, from the centre of the steel plate.

First experiment:

1) Install the four HFSs side-by-side between the two PMMA plates using thermo-conductive paste[4].
2) Bolt the PMMA plates and create a constant and homogeneous clamping pressure on the HFSs.
3) Bolt the PMMA plates containing the HFSs at 7 cm to the steel plate.
4) Connect all sensors to the data logger.
5) Initiate data acquisition (t=0).
6) Turn on heat lamp (t=5 min).
7) Stop the lamp and data acquisition (t=10 h, and 05 min).
8) Analyze data.

Second to fourth experiments:

1) Unbolt the PMMA plates containing the HFSs and turn 90 degrees clockwise.
2) Bolt the PMMA plates containing the HFSs in their new locations.
3) Initiate data acquisition (t=0).
4) Turn on heat lamp (t=5 min).
5) Stop the lamp and data acquisition (t=10 h and 05min).
6) Analyse data.

4.5. Multi-set Calibration

If more than four sensors were to be calibrated, several sets of experiments have to be conducted. The methodology consists of taking one sensor as reference (that is, as the ideal value), and keep it in every set of HFSs. After every set calibration, a post-calibration correction, based on the reference sensor's average calibration-coefficients, is applied. This correction is identical to the influence correction methodology (12). Because of the reference sensor, a multi-set calibration involves a 25% increase in experimental time compared to the one-set calibration.

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[4] Allow 5 mm minimum distance between each HFS. The thermo-conductive paste has to be used homogeneously and in thin layers.

(*Note*: Intrinsically, in an absolute calibration mode, a multi-set calibration does not need any calculation between each set.)

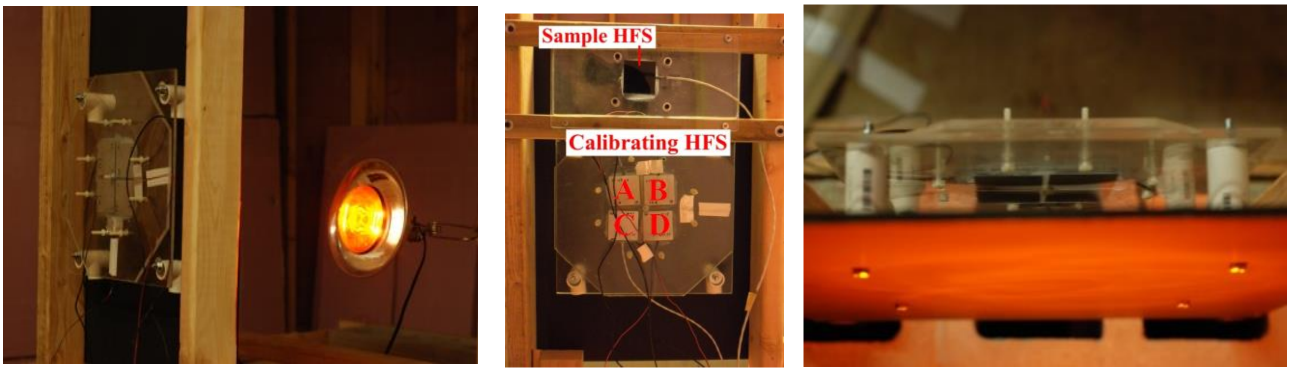
5. Conclusion

The objectives of this relative calibration method was to calibrate four heat flux sensors in a simple and inexpensive manner, but with good accuracy. This simple experimental methodology allowed us to check the first goal. But concerning accuracy, the random convection and/or radiation influence can significantly increase the uncertainty; therefore, this goal was not fully completed. Note, that this field calibration method was used to calibrate HFSs that were already factory and in-house-calibrated, but may have lost some of their calibration, or had arrived from the manufacturer with some relative differences.

Without the random influences, this method produces acceptable accuracy. Future research will focus on set-up optimization to avoid any random environmental influences and reduce the uncertainty.

Experiments following this methodology have been successfully conducted. Additional work to determine the random convection and radiation influence significance and the methodology accuracy quality are also being conducted.

Appendix A



Pictures of the experimental set-up.

Fig. A1, A2, A3. Posterior view, set-up with HFS sample and top view of the Set-up, respectively.

Nomenclature

List of symbols

Latin symbols

E	HFS Voltage in Volts
T	Temperature in K
S	Seebeck coefficient in V.K^{-1}
k	Calibration sensitivity in W.m^{-2}.mV^{-1}
W_e	Watt electric in W
N_{HFS}	Number of HFS to calibrate

Greek symbols

φ	Heat Flux in W.m^{-2}

Subscripts and superscripts

a	Absolute
r	Relative

List of Acronyms

MEC	Experimental Calibration Method
HFS(s)	Heat Flux Sensor(s)
PMMA	PolyMethyl-MethAcrylate
ASTM	American Society for Testing and Materials

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