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New Vacuum Blackbody Cavity for Heat Flux Meter Calibration

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Abstract In the field of thermal radiation measurements, blackbody cavities are commonly used as reference standards for the calibration of heat flux meters. Applying the energy balance equation to the closed system including the cavity and the sensor, it is possible to predict the heat flux density absorbed by the heat flux meter. Calibration procedures developed at Laboratoire National de Métrologie et d'Essais (LNE) in recent years have allowed us to propose practical solutions for heat flux meters working below $100\,\mathrm{kW \cdot m^{-2}}$. The best relative uncertainties ($k = 2$) over the range of (10–100) $\mathrm{kW \cdot m^{-2}}$ vary from 1.7 % to 3 %. During previous studies, three major facilities were constructed, each one with the objective to respond to different technical problems considering the measuring principle of these heat flux sensors. Following this approach, the sensitivity of these meters to radiation, the sensitivity to radiation and convection, and also the influence of the size of the source or of the positioning of the sensor (horizontally, vertically, etc.) have been investigated. As an outcome of this recent experience, a new vacuum blackbody cavity has been set up. As well as the possibility to calibrate at very low irradiance, there are also some substantive improvements in heating, thermal performance, and calibration methodology. After a summary of the state of the art of calibration methods and their limits, the article presents the preliminary results of the characterization obtained with this new facility for which the objective is to reduce the uncertainties by at least a factor of two for heat flux densities lower than $20\,\mathrm{kW \cdot m^{-2}}$.

Keywords Blackbody cavity · Calibration · Gardon gauge · Heat flux density · Heat flux meter · Irradiance · Schmidt-Boelter gauge · Uncertainty

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1 Introduction

A good heat flux measurement requires accurate calibration of the sensor against metrological references. Depending on the final need requested by the end-user, two methods are commonly applied to calibrate such heat flux meters, absolute and comparative methods:

(1) the absolute method is based on the calibration of a heat flux meter irradiated by a calculable heat flux generated by means of a radiant source and
(2) the comparative method is based on the calibration of a heat flux meter, whose electrical response is unknown, against a calibrated standard radiometer or standard heat flux meter.

These two calibration methods are performed at Laboratoire National de Métrologie et d'Essais (LNE) and applied daily at the laboratory for research and transfer traceability [1,2].

Three main facilities have been successively developed at LNE in recent years. The investigation of a new primary standard facility recently developed at the laboratory is presented here. This setup is dedicated to absolute calibration and is at the present time newly characterized for low heat flux density (about $20\,\text{kW}\cdot\text{m}^{-2}$). The initial calibration uncertainty budget assessment and the application constraints of such a method of calibration are discussed.

2 Brief State of the Art

Measurements of heat flux are nowadays numerous, and the technologies developed vary according to the field of application, standards, and regulations (e.g., building, industrial processes, fire tests, solar, defense, aerospace, etc.).

For very high heat flux density measurements greater than $1000\,\text{kW}\cdot\text{m}^{-2}$, such as for solar applications, Gardon-type gauges, radiometers, or calorimeters are calibrated against solar concentrating systems [3–6].

In the range of (0–70) $\text{kW}\cdot\text{m}^{-2}$, such gauges are also commonly used in the field of fire engineering. Usually, blackbody cavities are implemented to calibrate the sensors in such a range. The discussion is limited to applications with relatively low to medium thermal heat flux obtained by means of radiant heat sources thermally controlled with temperatures up to 1000 °C. The main facilities of the national metrology institutes or fire research laboratories are listed in Table 1.

In France, at the national metrology institute, LNE, calibrations of Gardon, or Schmidt-Boelter type heat flux meters intended for measurements of heat flux density lower than $100\,\text{kW}\cdot\text{m}^{-2}$ are carried out using either a primary standard method (level 1) or by means of a secondary standard method (level 2). The first metrological level consists of absolute measurements of the measurand relating to the measuring instrument. The comparison method constitutes the second metrological level.

Table 1 Example of heat flux meter calibration facilities of National Metrology Institutes

Country National Metrology Institute	Radiant source Range Temperature/Heat flux density	Calibration method (Range) [Reference]
France LNE	(1) VBBC (Vacuum blackbody cavity) (2) SBBC (Spherical blackbody cavity) Oxidized cavities : Up to 1173 K / up to 100 $kW \cdot m^{-2}$	Radiometric and Heat transfer modeling Up to 70 and 100 $kW \cdot m^{-2}$ [1,2]
Italy INRIM	Cylindrical heat-pipe blackbody (oxidized Inconel walls) operating in air and vacuum. In this case, both the heat-pipe blackbody and the meter are enclosed within a vacuum-tight stainless-steel tube. 673–1273 K/12 to 150 $kW \cdot m^{-2}$	Radiometric and Heat transfer analysis [7]
Sweden SP	Spherical furnace with cooling device housing the heat flux meter/ Type S thermocouple Up to 1273 K/2–100 $kW \cdot m^{-2}$	Radiometric and Heat transfer analysis (2–85 $kW \cdot m^{-2}$) [8,9]
USA NIST	(1) Two gas-purged VTBB (Variable temperature cylindrical blackbodies) 973–2923 K/3350 $kW \cdot m^{-2}$ (2) Spherical blackbody, with a Type S thermocouple up to 1373 K or 1446 K for shorter duration/0–200 or 250 $kW \cdot m^{-2}$	Radiometric ECR (Electrically calibrated radiometer) traceable to NIST HACR—High accuracy cryogenic radiometer via Si detectors and QED—Quantum efficiency detector (1–55 $kW \cdot m^{-2}$) [10–12]

2.1 Absolute Method

At LNE, the absolute method consists of generating a thermal heat flux density by means of a characterized variable-temperature blackbody cavity. The heat flux density is calculated using a model. This method is realized in two versions.

The first version, historically the oldest one applied at the laboratory (since the end of the 1980s), consists of implementing and calculating the radiative and convective heat transfer from a radiant source, operating at atmospheric pressure and thermally controlled, within which the heat flux meter constitutes one zone of the closed surface of the system. This work led the laboratory to study various source geometries (flat, cylindrical, and spherical). Currently, a cavity blackbody with spherical geometry (SBBC, spherical blackbody cavity) realized by the engineering and design department of LNE is still in operation.

The second version, developed during the nineties, consists of a thermally controlled blackbody with a cylindrical geometry operating under vacuum (VBBC, vacuum blackbody cavity). The third generation of this VBBC is described later.

2.2 Comparison Method

This method has been applied by the laboratory since the beginning of the 1990s using a facility with two measuring sections. The first bench enables, by comparison to a standard heat flux meter traceable to the primary devices (exploiting the metrological performance of the spherical blackbody SBBC), the calibration of any heat flux meter operating in the same heat flux density range. The second bench consists of a mechanically and thermally controlled radiant source and of a turntable platform supporting the secondary standard and the heat flux meters to be calibrated. This device makes it possible to carry out calibrations by comparison with thermal heat-transfer configurations similar to the conditions of use of the end-users.

3 Description of the Calibration Facility

3.1 General Description

A cylindrical blackbody cavity operating under vacuum is used to irradiate the gauge to be calibrated. The blackbody cavity is heated by a four-zone electrical furnace. The distribution of temperature along the cavity is measured with 13 Type S thermocouples. The pressure inside the blackbody cavity can vary between atmospheric pressure and 1 Pa. Figure 1 shows a schematic of the vertical cross section of the furnace and the blackbody cavity.

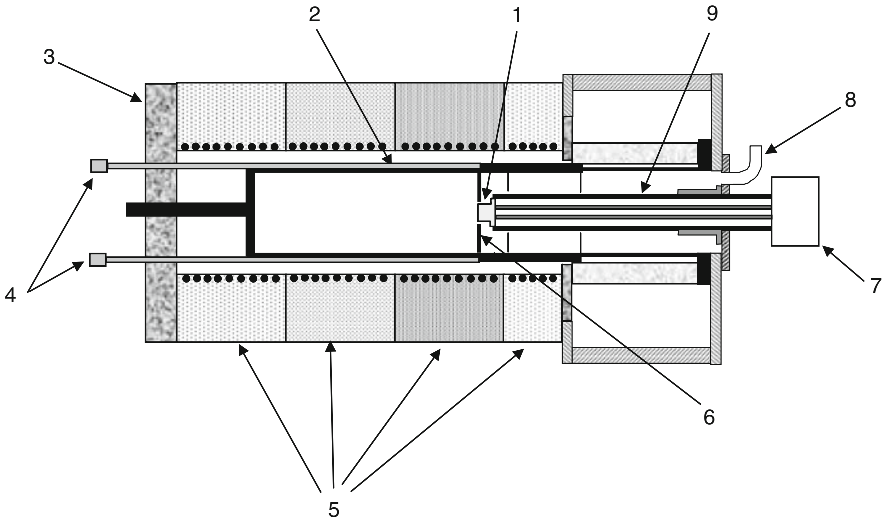

Fig. 1 Schematic picture of a vertical cross section of the furnace and the blackbody cavity: (1) heat flux meter; (2) blackbody cavity; (3) thermal insulation; (4) temperature sensors; (5) heating elements; (6) diaphragm; (7) case for connecting the heat flux meter; (8) pipe to pump the air outside the cavity; (9) heat flux meter holder

3.2 Description of the Main Elements

3.2.1 Blackbody Cavity

The cavity is a metal cylinder 420 mm long with a diameter of 162 mm. It is made of refractory steel, and the walls are 14 mm thick. Two longitudinal square-profile grooves were machined along the cylinder for the sensors that measure the distribution of temperature along the cylinder. The cavity walls were oxidized by heating in air to get a stable layer of oxide with a high emissivity. At the bottom of the cavity, a metallic rod is used to support the cavity. Without that rod, the cavity would be overhanging and could collapse at high temperature. A diaphragm (metallic ring), made of stainless steel, closes the blackbody cavity around the heat flux gauge. The diaphragm leaves a space around the gauge to pump the air from the cavity.

3.2.2 Heat Flux Gauge Holder

The heat flux gauge holder is a double-walled metal tube that is water-cooled. The holder, fixed on a carriage, supports the gauge, and protects the heat flux meter signal wires and the pipes from the high temperatures. Another important function of the holder is to provide airtightness with the body of the heat flux meter. The heat flux meter body is tightened onto the holder with a gasket. A low pressure inside the cavity can be reached only if the body of the heat flux meter is airtight, which is the case for most heat flux meters. Different mechanical adapters can be used for the different types of existing heat flux meters (with or without flange, with a threaded body, etc.).

3.2.3 Furnace

The furnace is a four-zone electrical furnace. The temperatures of the four zones are controlled independently to obtain uniformity of temperature along the cavity. The temperature of the furnace can be controlled from 23 °C to 900 °C. The temperature of each heating element is controlled by a thermocouple placed between the heating element and the cavity cylinder. The vacuum inside the cavity is obtained using a pumping system made up of a rotary vane pump and a turbo-molecular pump. The pressure is measured by means of a Pirani gauge. The lowest pressure that can be reached is about 1 Pa.

3.2.4 Temperature Measuring Chain

Five Type S thermocouples are used to measure the temperature along the cylinder of the cavity. Two other Type S thermocouples are used to measure the temperature of the bottom of the cavity, and another one is used to measure the temperature of the diaphragm. An ice bath is used as the reference temperature for the thermocouples.

4 Calculation of the Heat Flux Density

The heat flux density is the sum of the incident irradiance and of the convective heat flux density.

4.1 Calculation of the Irradiance

The irradiance produced by the blackbody in the opening plane of the cavity where the heat flux meter is placed is calculated using the "radiosity" technique [13]. This technique is applied to the cavity limited by the cylinder, the bottom of the cylinder, the front side of the heat flux meter, and the diaphragm. The blackbody cavity is divided into virtual elementary small surfaces assumed to be isothermal. The temperature of each elementary surface is measured directly or approximated. This method enables computation of the radiation exchanges among all the elementary surfaces considering the multiple reflections inside the cavity. The resulting irradiance on each elementary surface can then be calculated, particularly the one on the sensitive surface of the heat flux meter. The main assumptions are perfect diffusion of the reflection, Lambertian emission (radiance independent of the direction) of each elementary surface, and constant spectral emissivity of each surface for all wavelengths. The emissivities of the inner surface of the cavity, of the front side of the heat flux meter (copper body and absorbing element), and of the diaphragm must be known to calculate the irradiance. The normal spectral emissivities of two samples, made of the same metals as the cavity and the diaphragm and oxidized by heating in air, were measured using the emissometer described in [14]. The quasi-normal spectral emissivities of the surfaces of a heat flux meter were measured using the reflectometer described in [15]. The total hemispherical emissivities of the surfaces were calculated using the results of normal or quasi-normal spectral emissivity measurements. The procedure for calculation involves integration over all wavelengths and extrapolation over all directions. The total hemispherical emissivities are, respectively, 0.89, 0.85, 0.1, and 0.92 for the inner surfaces of the cavity, the diaphragm, the copper body of the heat flux meter, and the absorbing part of the sensor.

The variations of temperature along the cavity are quite low (1 °C at 50 °C, 3 °C at 150 °C, 4 °C at 300 °C, 4 °C at 500 °C, 5 °C at 800 °C); thus, the irradiance on the heat flux meter is very close to that of a perfect blackbody at a temperature equal to the mean temperature of the cavity. A good approximation of the irradiance on the heat flux meter is then given by the relation,

$$I = 5.67 \times 10^{-8}\, T_{\text{cav}}^{4} \tag{1}$$

where T_{cav} is the average temperature of the cavity. Table 2 gives the irradiances corresponding to different temperatures.

4.2 Calculation of the Convective Heat Flux Density

The sensitive element of the heat flux meter is heated by the radiation of the cavity and also by the air. Indeed, the air in the cavity is almost at the same temperature as

Table 2 Range of irradiance and proportion of convective heat flux

Average temperature of the cavity (°C)	Irradiance on the heat flux meter ($W \cdot m^{-2}$)	Proportion of convection in the total net heat flux density (%)	
		Pressure = 100 Pa	Pressure = 101,300 Pa
100	1,099	18.4	52.7
150	1,818	16.8	50.1
200	2,842	14.4	46.1
300	6,119	9.5	36.4
400	11,642	5.9	27.1
500	20,260	3.8	19.5
600	32,956	2.6	13.9
700	50,851	2.0	10.0
800	75,201	1.7	7.2
900	107,398	1.6	5.3

the walls of the cavity. Thus, the signal delivered by the heat flux meter is proportional to the sum of the irradiance and of the convective flux density. A model has been established to calculate the convective heat flux density on the sensitive surface as a function of the temperature and of the air pressure [16].

The convective heat flux density has been calculated by solving numerically the Navier–Stokes equations in the cavity. The assumptions made are: the air is a perfect gas, the Boussinesq assumption is used to calculate the density variations, the flow is laminar, the air remains Newtonian even at low pressure, and the air is perfectly transparent to radiation. Figure 2 shows the variation of the conductive heat flux density with pressure for a temperature of 500 °C. Three regimes of convection can be defined, depending on the pressure. From atmospheric pressure to 10^4 Pa, the convective heat flux decreases rapidly with pressure. This is due to the decrease of the buoyancy with pressure. From 10^4 Pa to 10^2 Pa, the convective heat flux varies weakly with pressure. In fact, in that pressure range, convection is almost nonexistent and conduction is the principal mode of heat transfer from the air to the heat flux meter. From 10^2 Pa to 1 Pa, the regime is still conductive, but the decrease of pressure causes important variations in the properties of air. In that pressure range, the effects of discontinuity in the vicinity of the walls increase when the pressure decreases. Table 2 gives the proportion of convective flux in the total net heat flux density for two pressures in the temperature range of the cavity.

5 Measurement Procedure

The heat flux meter is tightened onto the holder and inserted inside the cavity. The blackbody cavity is heated at the required temperature until the temperature is stable. Some cycles of measurement are repeated with atmospheric pressure inside the cavity. A cycle of measurement consists of measuring the signals of the 13 thermocouples, the signal of the heat flux meter, and the pressure inside the cavity. A measurement cycle lasts 30 s. The measurement of the heat flux meter signal and the measurement

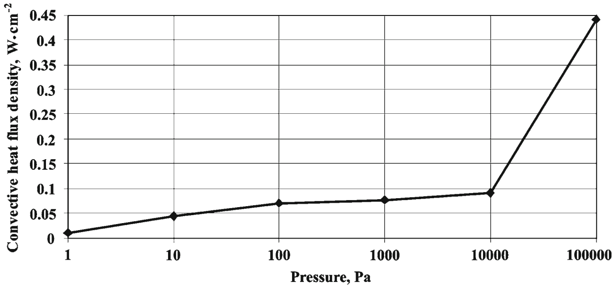

Fig. 2 Variations with pressure of the convective heat flux density calculated using the theoretical model. The temperature of the cavity is 500 °C

of the pressure are made consecutively to have better correlation between the heat flux meter signal and the pressure. The temperatures are much less correlated with the pressure. The pumping system is put into operation and the measurement cycles are repeated as quickly as possible. However, during a measurement cycle (30 s), the pressure in the cavity can decrease significantly. The pumping is stopped when the measured pressure reaches about 5 Pa. Then, the pressure increases slowly with time and measurement cycles are repeated until the pressure reaches 500 Pa. The heat flux density on the heat flux meter is calculated for each measurement cycle.

It must be noted that, practically, some heat flux meters show aberrant response at low pressure. The relative variations of the response with pressure are very different from those predicted by the model used for the calculation of the convective heat flux. Thus, at the end of each measurement at low pressure, the relative variations of the response of the heat flux meter with pressure are compared to the variations predicted by the "convection" model. The relative variations are calculated by reference to the signal measured at atmospheric pressure. Figure 3 shows an example of such a comparison. When the difference between the relative signal and the relative curve given by the model is >2.5 % in the pressure range 10^4 Pa to 10^2 Pa, the results at low pressure are considered to be false. In that case, the heat flux meter is calibrated at atmospheric pressure by comparison to another calibrated heat flux meter. We cannot explain the aberrant response of some heat flux meters at low pressure, although we suspect mechanical constraints due to the difference of pressure between the front and the back sides of the flux meter or small air leakages in the vicinity of the flux meter to be the sources of the aberrant behavior of some flux meters at low pressures.

6 Uncertainty Analysis

The sources of uncertainties on the heat flux are:

– the uncertainty related to the simplified model used to calculate the irradiance,
– the uncertainty related to the model used to calculate the convective flux,
– the uncertainties of the temperature measurements of the cavity walls,
– the uncertainty of the emissivity of each part of the cavity,
– the uncertainty of the dimensions of the surfaces of the cavity, and
– the uncertainty of the air pressure inside the cavity.

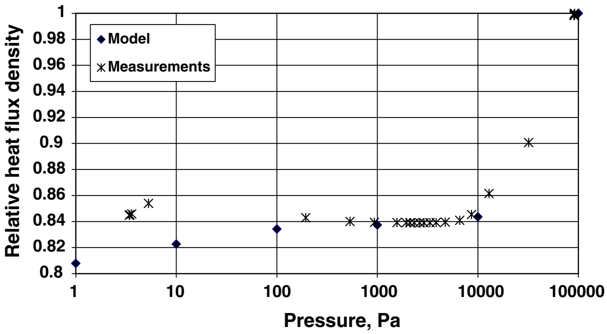

Fig. 3 Comparison of the relative variation of the calculated heat flux density with the relative variation of the real signal. The temperature of the cavity was 500 °C

6.1 Uncertainty of the Model Used to Calculate the Irradiance on the Heat Flux Meter

The model to calculate the irradiance is based on the radiosity technique. This technique is a simple tool to calculate the radiative fluxes exchanged between the elementary surfaces constituting the cavity, but it is based on the following assumptions:

- the reflections are perfectly diffuse,
- the emissions from the surfaces are Lambertian (radiance independent of the direction), and
- the elementary surfaces are isothermal.

It is not easy to evaluate directly the uncertainty related to the model. It would be necessary to set up a more realistic model to consider the diffusion (bidirectional reflectance function) of the surfaces. Modeling by ray tracing is quite computationally complex to set up. The surface that directly radiates the heat flux meter is the inner surface of the metallic cylinder; the emissivity of that surface is quite high (0.89). A significant change in the emissivity of the cavity induces only a very small change in the irradiance on the heat flux meter. Assuming an emissivity of the cavity of 0.65 instead of 0.89 produces a relative variation of the irradiance on the heat flux meter of <0.3 %. The weak variation of the calculated irradiance with the emissivity of the cavity walls allows us to conclude that the directional and spectral variations of the emissivity of the cavity walls are not critical to the use of the radiosity technique. The relative standard uncertainty of the calculated irradiance related to the radiosity technique is assumed to be 0.3 %.

6.2 Uncertainty of the Model used to Calculate the Convective Heat Flux Density Incident on the Heat Flux Meter

The convective heat flux density is calculated using a theoretical model (Sect. 4.2). It is very difficult to directly measure the convective heat flux density. Some heat flux meters show relative variations of the response at low pressure very different from the variations predicted by the model. As explained in Sect. 5, the behavior of the heat flux meter at low pressure is validated by a comparison of its relative response curve to the relative curve predicted by the model (Fig. 3). When the relative difference between the two curves in the pressure range from 10^4 Pa to 10^2 Pa is >2.5 %, the calibration results at low pressure are considered invalid. Thus, the relative standard uncertainty of the total heat flux density due to the model used to calculate the convective heat flux density is 1.3 %. That uncertainty is much more related to the behavior of the heat flux meter at low pressure than to the theory used to calculate the convective heat flux.

6.3 Measurement Uncertainty of the Cavity Internal Surface Temperature

The standard uncertainty of the temperature due to the measurement of the voltage and the calibration of the thermocouple is 0.7 K. The thermocouples are located in grooves machined along the external side of the cavity. The heat flux meter holder is cooled by water at ambient temperature, creating a heat leak for the cavity; the heat transfer between the cavity and the holder is by radiation. The cavity is attached to the frame at ambient temperature by a section of refractory steel tube, generating a heat leak by conduction. The heat leaks are located at one end of the cavity; thus, the temperature drop through the wall is not uniform along the cavity. The heat leaks have been modeled; a temperature offset of 5 °C was calculated for a cavity temperature of 800 °C by considering that the heat leaks are located on a 20 cm long section of the cavity. The offset of temperature through the wall for that section can be linearized and is then given by the following relationship:

$$\Delta T_{\text{wall}} = \frac{\left(T_{\text{cavity}} - 20\right) \times 5}{(800 - 20)} \tag{2}$$

where ΔT_{wall} is the temperature offset and T_{cavity} is the average temperature of the cavity.

The temperature offset is not uniform along the cavity; thus, a systematic correction of temperature is not applied to all the measured temperatures. The standard uncertainty due to the temperature offset is approximated by $\frac{1}{2}\Delta T_{\text{wall}}$ considering the distribution function as Gaussian.

6.4 Uncertainty of the Emissivity of the Cavity Walls

The spectral normal emissivities were measured in the spectral range from 1 μm to 13 μm with an expanded uncertainty lower than 0.03. The total hemispherical emissivities were calculated using the normal spectral emissivity values according to methods described in [17]. The uncertainty of the total hemispherical emissivity was calculated by combining the uncertainty of measurements, the uncertainty for the extrapolation of emissivity for wavelengths longer than 13 μm, and the uncertainty for the extrapolation of the hemispherical emissivity from the normal emissivity. For wavelengths longer than 13 μm, the spectral emissivity was assumed to be constant and equal to that at 13 μm. The standard uncertainties of the total hemispherical emissivities are <0.05. The influence of those uncertainties on the irradiance incident on the heat flux meter is calculated using the radiosity model. The blackbody effect of the cavity makes the irradiance almost insensitive to the uncertainty of the emissivities. For the temperature range from (150 to 900) °C, the relative variation of the irradiance incident on the heat flux meter is <0.09 % when the emissivity of the cavity varies from 0.79 to 0.89. The variations are higher for low temperatures than for high temperatures.

6.5 Uncertainty of the Air Pressure Inside the Cavity

The response of the heat flux meter is measured in a pressure range of 100 to 10,000 Pa for which the variations of the convective heat flux with pressure are weak (see Fig. 3). The relative standard uncertainty of the measured pressure is 10 %. Thus, the standard relative uncertainty of the heat flux density (irradiance and convection) due to the uncertainty of the pressure is 0.2 %.

6.6 Application: Example for a Gardon-Type Heat Flux Meter

To summarize, Table 3 gives the uncertainty budget for the calibration of a Gardon-type heat flux meter at a heat flux density of $18\,\mathrm{kW \cdot m^{-2}}$ (cavity temperature of 480 °C). The measured sensitivity was $5.218 \times 10^{-7}\,\mathrm{V \cdot W^{-1} \cdot m^2}$. The right column gives the relative standard uncertainty of the measured sensitivity due to each source of uncertainty. The significant uncertainty sources are, in order of importance, the model to calculate the convection and the measurement of the temperatures of the cavity walls. We point out to the reader that the overall combined standard uncertainty of the sensitivity is the square root of the sum of the squares of each standard uncertainty on the sensitivity, appearing in the right column. The relative expanded uncertainty of the sensitivity, calculated with the coverage factor $k = 2$, is 3.2 %, with the major contribution being the convective heat flux modeling component.

7 Conclusion

As a result of the experience gained over the past 10 years, improvements have been made to the vacuum blackbody cavity for absolute calibration of heat flux meters typically used in fire research laboratories as well as in combustion research laboratories. Consequently, a new vacuum blackbody cavity was recently designed and built at LNE with the objective to improve calibration uncertainties, particularly for heat flux densities lower than $20\,\mathrm{kW \cdot m^{-2}}$.

The radiant source is a primary blackbody radiation standard. This absolute calibration method is commonly practiced at the laboratory and was more recently applied in a round-robin study of total heat flux gauges used by fire laboratories.

This new facility is now operating and enables calibration of a gauge working in the range of (0–20) $\mathrm{kW \cdot m^{-2}}$, at low pressure (about 100 Pa), with no risk of damage to the coating of the sensor, and with a better repeatability and reproducibility than previous versions. This result and observation clearly point out the need to investigate

Table 3 Example: budget of uncertainty for the calibration of a Gardon-type heat flux meter at a heat flux density of 18 $kW \cdot m^{-2}$

Source of uncertainty	Value	Standard uncertainty	Standard uncertainty on the sensitivity ($V \cdot W^{-1} \cdot m^2$)	Standard uncertainty on the sensitivity (%)
Signal of the heat flux meter	9.405×10^{-3} V	0.055×10^{-3} V	2.2×10^{-9}	0.43
Model to calculate the irradiance	17237.94 $W \cdot m^{-2}$	52 $W \cdot m^{-2}$	1.5×10^{-9}	0.29
Model to calculate the convection	785.8 $W \cdot m^{-2}$	216 $W \cdot m^{-2}$	6.3×10^{-9}	1.2
Temperatures of the cavity walls	470 °C[a]	1.6 K	4.3×10^{-9}	0.83
Emissivities of the cavity walls		0.05	1.04×10^{-10}	0.02
Areas of the surfaces of the cavity		0.7 %[b]	0	0.00
Pressure of air inside the cavity	100 to 10,000 Pa	5 %[b]	1.04×10^{-9}	0.20
Temperature of the cooling water	20 °C	0.5 °C	1.0×10^{-9}	0.20
Flow rate of the cooling water	60 $kg \cdot h^{-1}$	2.5 $kg \cdot h^{-1}$	5.2×10^{-10}	0.10
Measured sensitivity	5.218×10^{-7} $V \cdot W^{-1} \cdot m^2$	8.2×10^{-9} $V \cdot W^{-1} \cdot m^2$		1.6

[a] Average value
[b] Relative standard uncertainty

in more detail this particular component which contributes more than one-third of the total uncertainty. Results are in a good agreement with those obtained with the previous calibration set-up.

This research project is part of efforts devoted to improving the heat flux meter calibration methods with respect to the ISO-Plan in progress within the framework of ISO/TC 92 devoted to fire standards [9,18–21] or standards developed at the European stage [22].

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References

1. J.-R. Filtz, I.Wetterlund, M. Öhlin, M. Lièvre, T. Lemaire, J. Myllymäki , T. Valin, in *Proceedings of TEMPMEKO 2004, 9th International Symposium on Temperature and Thermal Measurements in Industry and Science*, Solar Thermal 2000, ed. by D. Zvizdić (FSB/LPM, Zagreb, Croatia, 2004), pp. 757–764
2. J.-R. Filtz, P. Ridoux, in *Proceedings of METROLOGIE 95, 7th International Metrology Congress*, ed. by MFQ/Collège Métrologie (Nîmes, France, 1995), pp. 195–201

3. J. Ballestrin, M. Rodriguez-Alonso, J. Rodriguez, I. Canadas, F.J. Barbero, L.W. Langley, A. Barnes, Metrologia **43**, 495 (2006)
4. A. Ferriere, B. Rivoire, in *Proceedings of the 10th SolarPACES, International Symposium on Solar Thermal Concentrating Technologies, Solar Thermal 2000*, ed. by H. Kreetz, K. Lovegrove, W. Meike (Sydney, Australia, 2000), pp. 233–240
5. A. Ferriere, J.-F. Robert, J. Kaluza, A. Neumann in *Proceedings of the 10th SolarPACES, International Symposium on Solar Thermal Concentrating Technologies*, *Solar Thermal 2000*, ed. by H. Kreetz, K. Lovegrove, W. Meike (Sydney, Australia, 2000), pp. 247–253
6. A. Ferriere, B. Rivoire, Solar Energy **72**, 187 (2002)
7. T. Ricolfi, F. Lanza, in *Proceedings of TEMPMEKO 2004, 9th International Symposium on Temperature and Thermal Measurements in Industry and Science*, ed. by D. Zvizdić (FSB/LPM, Zagreb, Croatia, 2004), pp. 903–908
8. P. Andersson, I. Wetterlund, Uncertainty in heat flux calibrations performed according to NT FIRE 050, SP Report 2001:34, Boras, Sweden (2001)
9. Fire tests—Calibration and use of heat flux meters ISO/TS 14934-2: primary calibration methods
10. W.M. Pitts, A.V. Murthy, J.L. de Risc, J-R. Filtz, K. Nygård, D. Smith, I. Wetterlund, Fire Safety J. **41**, 459 (2006)
11. A.V. Murthy, B.K. Tsai, R.D. Saunders, J. Res. Natl. Inst. Stand. Technol. **105**, 293 (2000)
12. B.K. Tsai, C.E. Gibson, A. V. Murthy, E.A. Early, D.P. Dewitt, R.D. Saunders, *Heat Flux Sensor Calibration*, (National Institute of Standards and Technology Special Publication, 250–65, 2004), 37 pp
13. R. Siegel, J.R. Howell, *Thermal Radiation Heat Transfer* (McGraw-Hill, New York, 1972), pp. 235–250
14. J. Hameury, High Temp.-High Press. **30**, 223 (1998)
15. J. Hameury, B. Hay, J.R. Filtz, Int. J. Thermophys. **26**, 1973 (2005)
16. D. Blay, D. Lemonnier, M. Rafieivand, Etalonnage des capteurs radiatifs dans la cavité corps noir cylindrique du LNE, contract CNRS-ENSMA-LET- BNM-LNE no 983009, Final report, Poitiers, Futuroscope (2000)
17. M. Rubin, D. Arateh, J. Hartman, Int. Comm. Heat Mass Transfer **14**, 561 (1987)
18. Fire tests—Calibration and use of heat flux meters ISO/TS 14934-1: general principles
19. Fire tests—Calibration and use of heat flux meters ISO/TS 14934-3: secondary calibration methods
20. Fire tests—Calibration and use of heat flux meters ISO/TS 14934-4: guidance on the use of heat flux meters in fire tests
21. Fire testing: Method for the use and calibration of radiometers to be used for the measurement of irradiation and/or total heat flux in fire resistance and reaction to fire testing, EGOLF—The European Group of Official Laboratories for Fire testing—Standard Method, EGOLF/SM/4 1998
22. British Standard Method for Calibration of radiometers for use in fire testing, BS 6809 (1987)