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The Influence of Distance and Focus on the Calibration of Infrared Radiation Thermometers

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Abstract If a radiation thermometer is calibrated by measuring the temperatures of two cavities having different geometries, sometimes discrepancies arise between them, even though their emissivities are close to that of a blackbody. The origin of such discrepancies may result from the size-of-source effect, and in the distance-to-target effect for those thermometers that offer focusing capability. Examples include: (a) out-of-focus image changes the reading: different focus settings produce different results and (b) measurements taken at different distances produce different results. These effects are discussed, their contribution to the measurement uncertainty is evaluated, and some recommendations are made for practical blackbody cavities or radiators to reduce such effects.

Keywords Blackbody cavity · Emissivity · Field-of-view (FOV) · Infrared · Radiation thermometer · Size-of-source effect · Wideband radiation thermometer

1 Introduction

Many times, the requested temperature range for the calibration of a radiation thermometer requires the use of more than one blackbody cavity. It is expected that the measured error obtained by using such cavities is the same and independent of them, but sometimes this is not what is observed. This indicates that the results are subject to influence variables that are different for each cavity.

For fixed-focus radiation thermometers, it is believed that the reproducibility of the results is assured as long as the required "distance to target/target diameter" ratio is

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fulfilled. However, this is often not the case. Instead, the readings depend on the cavity diameter and the distance from the thermometer to the target. For some thermometers, there is no distance range over which the displayed value remains constant.

When a thermometer offers the means to focus on the target, the out-of-focus image from the cavity bottom may affect the measured radiance. The opposite is also true: measuring the radiance by focusing on the bottom of the cavity may be affected by the out-of-focus image of the opening.

We present three cases, two related to the distance-to-source effect and one related to using two different cavities to cover the calibration range. The distance effect has already been studied for standard pyrometers by several researchers [1], but their behavior is much different from fixed-focus, low-accuracy thermometers. The size-of-source effect of a thermometer similar to the one with focusing studied in this work is described in [2], and the distance effect for this thermometer, related to its size-of-source effect, has been described in [3].

2 Distance Effect for Fixed-Focus Wideband Radiation Thermometers

We calibrated two wideband radiation thermometers, one with a field-of-view (FOV) specified as an 8:1 distance-to-target diameter ratio and the other with a 50:1 ratio, by measuring the radiance temperatures of a 65 mm diameter, 17 cm long cylindro-conical cavity designed to operate between 50 °C and 550 °C. The calibration consisted of measuring the cavity's radiance temperatures with the thermometer under test and comparing the measured values with the temperatures obtained with a calibrated platinum resistance thermometer (PRT) inserted 16 cm into a well drilled in the cavity's cylindrical wall.

Considering the FOV of each thermometer, the cavity diameter yields maximum measurement distances of 52 cm and 325 cm, respectively, to produce a signal that is 90 % or 95 % of that obtained with respect to positions where the thermometer-to-cavity distances are such that the FOV is totally filled by radiation emerging from the cavity's opening, and where the readings should remain constant. At longer distances, the thermometers' sensors are underfilled and the readings are correspondingly affected. Our results are presented in Fig. 1. They show that the error changes linearly with distance, although the effect is less significant for the 50:1 FOV thermometer, and the slope depends on the temperature value, i.e., the error increases as the temperature rises. It was found that the recommendation to use a cavity having an opening with a diameter twice that defined by the thermometer's FOV [4] is insufficient to ensure invariant readings, as would be expected for distances <26 cm for the 8:1 FOV thermometer and 162.5 cm for the one with 50:1 FOV, when using a cavity with a 6.5 cm diameter opening.

2.1 Contribution of the Thermometer's Angular Responsivity to the Distance Effect of Fixed-Focus Thermometers

In order to know the effect of the thermometer's angular responsivity on the variations shown in Fig. 1, temperature readings at several distances were calculated for a

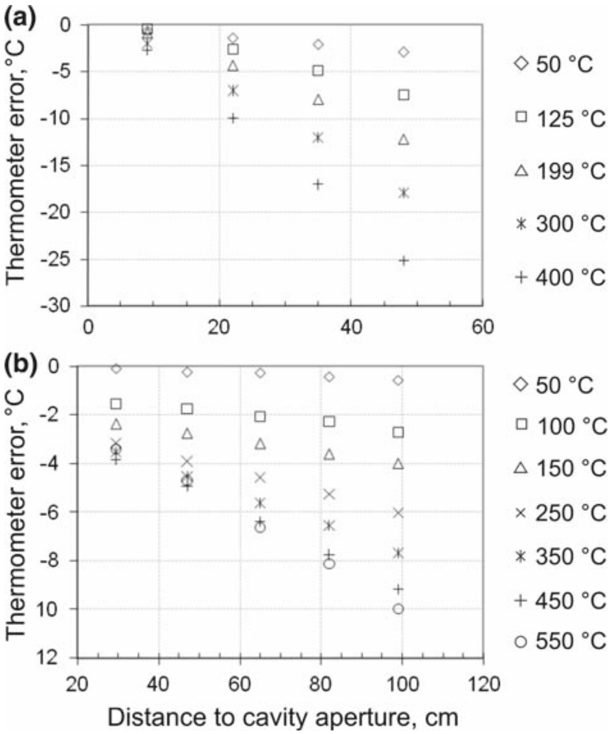

Fig. 1 Measured errors for two wideband radiation thermometers as a function of distance to the calibration source. Thermometers have different FOV angles: (**a**) 8:1 and (**b**) 50:1

hypothetical thermometer having a spectral responsivity from 8 μm to 14 μm and an angular responsivity as shown in the left frame of Fig. 2, as published for a thermometer with a distance to target/target diameter ratio equal to 12.32 [5]. In our calculations, it was assumed that the readings were taken by measuring the 65 mm diameter opening of the cylindro-conical cavity described in Sect. 2, and having the temperature deviations shown in Fig. 3 along its radii and surrounded by a circular panel 160 mm in diameter. The temperature profiles that define the deviations seen in Fig. 3 were measured as described in Sect. 4.1. It was also assumed that the surrounding panel has a temperature gradient that increases slightly and linearly from its perimeter to the circle that defines the cavity's opening. The edge temperature of the panel is assumed to be close to that of the laboratory, increasing to a maximum of 46 °C near the cavity opening. These values resemble those measured in an actual situation.

The graph in the center of Fig. 2 shows the temperature profile "observed" (arising from the calibration cavity and its surroundings) by the hypothetical thermometer as a function of its FOV when placed 75 cm from the cavity opening. At this position, the distance and the cavity's outer diameter define a FOV of 5° that is wider than the angle where the thermometer's angular responsivity exhibits a large slope. This field changes when the thermometer-to-target distance changes, yielding different values for the total signal.

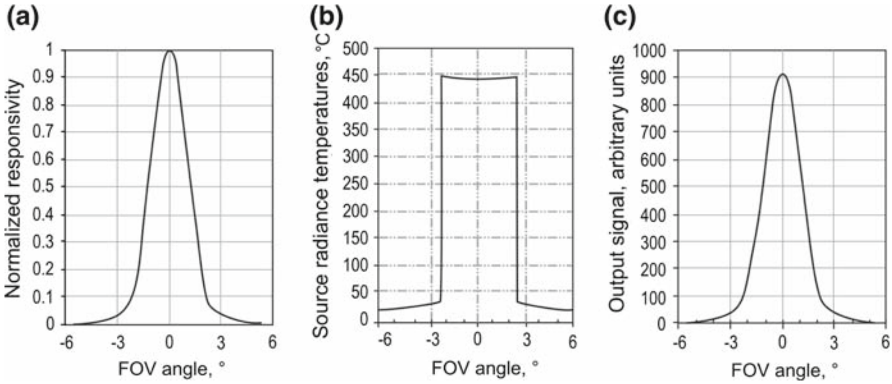

Fig. 2 (**a**) Assumed normalized responsivity of a wideband radiation thermometer, (**b**) assumed temperature profile of the cavity and its surroundings, as seen by the thermometer when placed 75 cm from the cavity opening, and (**c**) calculated output signal when the cavity temperature is 450 °C and the thermometer is 75 cm from the cavity opening

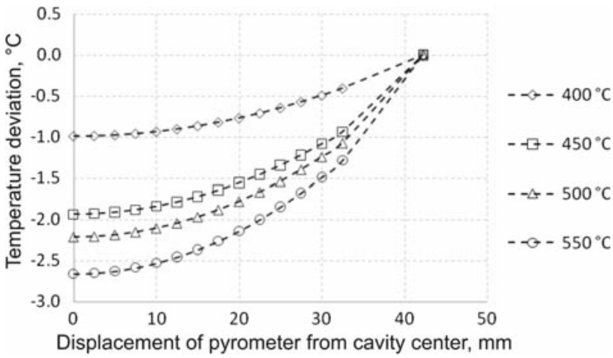

Fig. 3 Average deviations of measured radiance temperatures for four radii along the bottom wall of the cylindro-conical cavity as measured with the LP2 pyrometer. Position at 42 mm corresponds to the location where the well was drilled into the cavity's cylindrical wall for a contact thermometer

The calculated temperatures were obtained by dividing the observed field into small sections and summing their radiances to determine the total signal produced by the thermometer sensor. For each of these sections, the power per unit area was calculated as a function of its temperature and multiplied by the sensor's normalized angular responsivity, shown at the left of Fig. 2, appropriate to the angle to which each section corresponds.

The exitance value for each section was obtained by integrating Eq. 1 [6] between the wavelength limits of the thermometer's response band:

$$L_\lambda(\varepsilon_\lambda, T_s, T_w, T_d) = \varepsilon_\lambda L_\lambda(T_s) + (1 - \varepsilon_\lambda) L_\lambda(T_w) - L_\lambda(T_d) \tag{1}$$

In its general form, Eq. 1 is the algebraic sum of the spectral radiances that contribute to the signal from the thermometer's sensor, some of them affected by the emittance of the measured object, and evaluated at each wavelength of the spectrum transmitted through its optical system. $L_\lambda(T)$ denotes the spectral radiance of a blackbody for temperature T and wavelength λ, T_s is the temperature of the object being measured, ε_λ is the spectral emittance of the object, T_w is the temperature of the surrounding walls whose radiance is reflected to the thermometer when the object is not a blackbody, and T_d is the temperature of the thermometer's internal walls that are assumed to be at the same temperature as the thermometer's detector (the sensor). All temperatures are expressed in kelvin.

The panel to the right of Fig. 2 shows the resulting output signal as a function of the FOV, calculated for a cavity temperature of 450 °C and a distance of 75 cm. Table 1 contains the calculated values for an assumed cavity temperature of 450 °C. The results obtained at 15 cm were used as the reference for the deviations calculated at other distances. These deviations are not the thermometer error but arise from the measurement conditions.

Figure 4 shows the calculated deviations for the four assumed calibration temperatures. In this exercise, it was observed that the temperature profile of the cavity's surrounding panel contributes to the deviations only when the cavity opening underfills the thermometer's field of view, i.e., at distances greater than 32 cm.

Table 1 Theoretical temperature deviations at 450 °C (value at 15 cm distance used as reference)

Distance to cavity (cm)	Output signal (arbitrary units)	Fraction (%)	Deviation from reference (°C)
15	925.8	100.0	0.0
22	925.9	100.0	0.0
30	926.0	100.0	0.0
50	861.6	93.1	−20.8
75	770.6	83.2	−51.0
100	676.1	73.0	−83.4

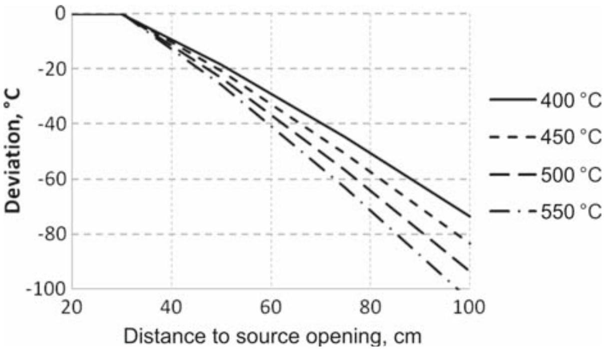

Fig. 4 Calculated deviations for a hypothetical thermometer as a function of the distance to the source and the observed field of the cylindro-conical cavity, and including its surroundings at longer distances

3 Distance and Focus Effect of a Radiation Thermometer with Focusing

For our experiment, we calibrated a thermometer with a FOV of 1 °, corresponding to a solid angle of 2.39×10^{-4} sr, and a focusing range from 50 cm to infinity. Its response band is from 8 μm to 13 μm [7]. The cavity used was the one described in Sect. 2. The thermometer was calibrated from 50 °C to 550 °C. Table 2 shows the calibration results as a function of distance when the radiation thermometer was focused on the cavity opening. For the results shown in Table 3, the focused target was the cavity's bottom wall, with a similar set of distances and the same temperature range.

As observed in Fig. 5, the effect due to the change in the distance between the cavity and the thermometer is different from that shown in Fig. 1 for fixed-focus

Table 2 Calibration results with the focus at the cavity opening

Calibration temperature (°C)	Thermometer measurement error as a function of distance (°C)					
	50 cm	62.5 cm	75 cm	87.5 cm	100 cm	112.5 cm
50.2	−0.4	−0.2	−0.2	−0.1	−0.2	−0.2
100.2	−0.7	−0.2	0.0	0.1	0.0	−0.2
150.1	−2.0	−1.4	−1.2	−1.1	−1.2	−1.7
200.0	−3.1	−2.1	−1.9	−1.7	−1.9	−2.3
250.0	−4.1	−3.0	−2.9	−2.3	−2.5	−3.0
299.9	−4.9	−3.9	−3.4	−3.0	−3.2	−3.9
349.9	−6.0	−4.5	−4.0	−3.9	−3.9	−4.9
400.0	−7.1	−5.3	−5.0	−4.7	−5.0	−5.7
450.1	−8.0	−6.2	−6.0	−5.3	−5.9	−6.8
500.2	−9.1	−7.3	−7.1	−6.3	−6.7	−7.9
550.4	−11.1	−8.5	−8.3	−7.6	−8.1	−9.2

Table 3 Calibration results with the focus at the cavity's bottom wall

Calibration temperature (°C)	Thermometer measurement error as a function of distance (°C)							
	50 cm	60 cm	70 cm	80 cm	90 cm	100 cm	110 cm	120 cm
50.2	−0.3	−0.2	−0.1	−0.1	0.0	0.0	0.0	−0.1
100.2	−0.5	−0.1	0.0	0.2	0.3	0.3	0.2	0.0
150.1	−2.0	−1.5	−1.4	−1.1	−0.9	−0.8	−1.1	−1.3
200.1	−2.9	−2.2	−1.8	−1.7	−1.6	−1.4	−1.7	−2.0
250.1	−4.0	−3.1	−3.1	−2.3	−2.1	−2.1	−2.2	−3.1
300.0	−4.6	−4.0	−3.8	−3.0	−2.9	−3.0	−3.2	−4.0
349.9	−5.8	−4.9	−4.4	−3.9	−3.9	−3.9	−4.2	−4.8
399.9	−6.8	−5.6	−5.0	−4.9	−4.3	−4.2	−5.0	−5.8
450.1	−8.0	−6.4	−6.1	−5.5	−5.1	−5.1	−6.0	−7.0
500.1	−8.6	−7.3	−7.1	−6.6	−6.1	−6.1	−6.9	−8.0
550.2	−10.4	−8.6	−8.2	−7.8	−7.2	−7.2	−8.1	−9.0

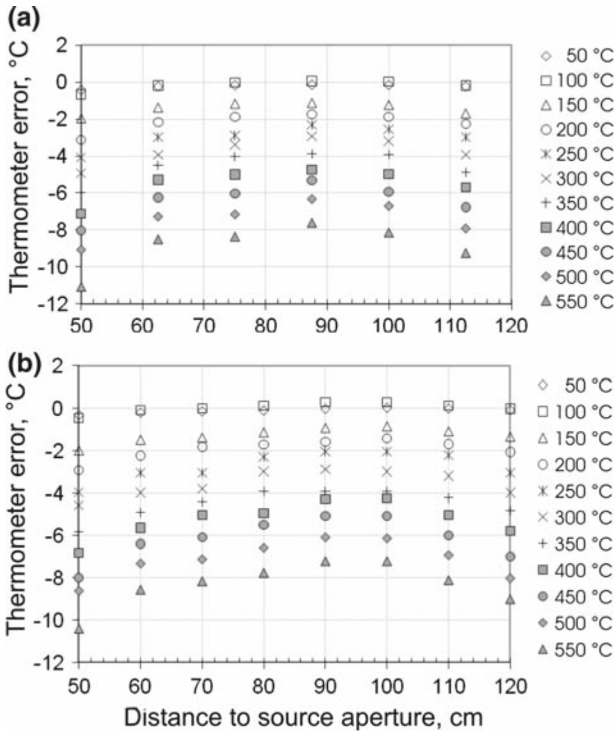

Fig. 5 Thermometer error determined by measuring the radiance temperatures of the cylindro-conical cavity: (**a**) focusing on the cavity opening and (**b**) focusing on the center of the bottom wall

thermometers. Figure 5a shows the results with the focus on the cavity opening, and Fig. 5b shows the results with the focus on the center of the bottom wall.

For the thermometer with focusing, there exists a region between 85 cm and 95 cm where the thermometer error is less sensitive to changes of the measuring distance. Differences in the results for changing the focal plane are not evident in Fig. 5. Table 4 summarizes the differences of the measurements at 50 cm and 100 cm, due to this change of target focus, where:

$$\begin{aligned}\text{Error difference} &= \text{error when focusing on the opening}\\ &\quad -\text{error when focusing on the bottom}\end{aligned}$$

In Fig. 6, the values given in Table 4 are plotted. The lack of uniformity in the differences at 300 °C and 350 °C at 100 cm could be due to the automatic change of the thermometer's resolution from 0.1 °C to 1 °C above 200 °C.

4 Discrepancies in Calibration Results When Using Different Cavities

In another set of experiments, the thermometer with focusing described above was calibrated at different distances by measuring the radiance temperatures of two different

Table 4 Differences in the measurement error from focusing on two visual fields of the radiating source: cavity opening and bottom wall

Wall temperature (°C)	At 50 cm (°C)	At 100 cm (°C)
50.2	−0.1	−0.2
100.2	−0.2	−0.3
150.1	0.0	−0.4
200.0	−0.2	−0.5
250.0	−0.1	−0.5
299.9	−0.4	−0.2
349.9	−0.1	0.0
399.9	−0.3	−0.7
450.1	−0.1	−0.8
500.2	−0.4	−0.6
550.3	−0.6	−0.9

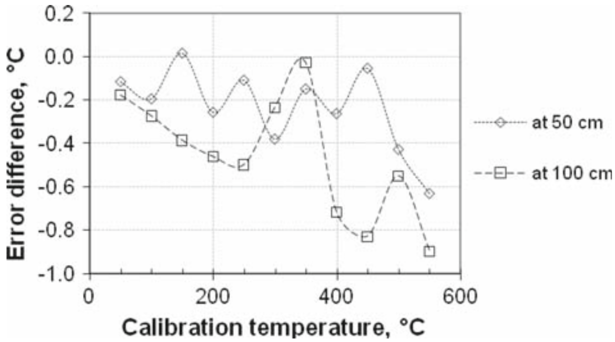

Fig. 6 Differences in the measurement error from focusing on two visual fields of the radiating source (cavity opening and bottom wall) for working distances of 50 cm and 100 cm

cavities. One cavity was described in Sect. 2. The other is the well of a potassium-filled heat-pipe furnace with a working range from 400 °C to 1000 °C. As indicated in Sect. 2, the reference temperatures for the first cavity are measured by a PRT inserted in its wall. For the second one, the reference temperatures are the measured values from an LP2 pyrometer.

The results are shown in Fig. 7, with both the thermometer under calibration and the reference pyrometer focussed on the openings. Besides the effects already described, we found other influence variables that affect the calibration results:

- Temperature gradients in the cylindro-conical cavity, indicated by the temperature profiles shown in Fig. 3
- Focusing of the LP2 pyrometer

4.1 Temperature Gradients Inside the Cavity

The measured temperature of the cavity wall depends on the PRT insertion depth. Measurements made by changing the thermometer position indicate that there is a

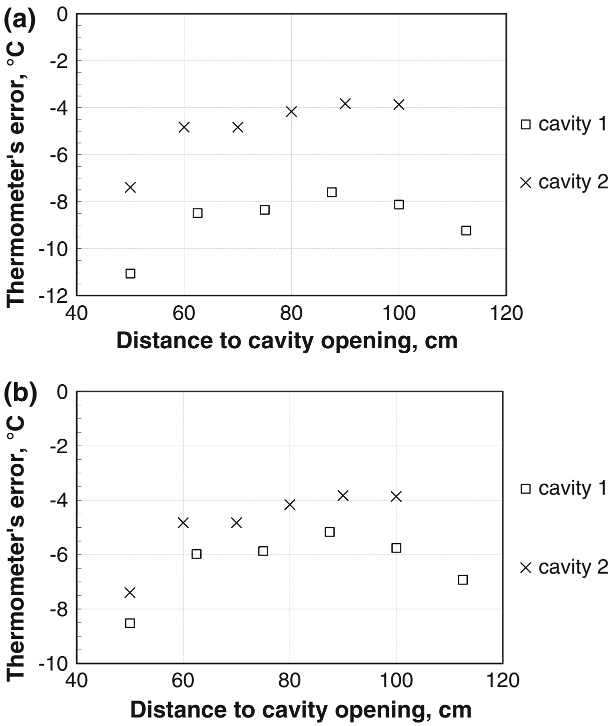

Fig. 7 Calibration results at 550 °C for the thermometer with focusing for two different cavities: (**a**) with uncorrected values of the cylindro-conical cavity, identified as no. 1 and (**b**) after correcting the measured values for temperature gradients that exist across the bottom wall of cavity 1. Cavity no. 2 is the well of a heat-pipe furnace

warmer region located between 12 cm and 16 cm inside the opening, with a maximum difference of 0.6 °C at 550 °C.

A significant temperature gradient was observed across the conical wall at the bottom, indicating that its center is colder than its perimeter, which is closer to the heater. The deviations shown in Fig. 3 were obtained by measuring the radiance temperatures along four different radii across the cavity's bottom wall, each rotated 45 ° with respect to one another from 0 °C to 135 °C, by translating the LP2 pyrometer from the cavity center to its edge. It is important to remark that the temperature of the thermometer well drilled into the cylindrical wall as measured by the LP2 pyrometer differs from that measured inside the well with a resistance thermometer.

In Fig. 7a, it is evident that the calibration results are different for different cavities. If the results obtained with the cylindro-conical cavity (number 1 in Fig. 7) are corrected for the temperature gradients that exist in its bottom wall, the differences are reduced but not eliminated, as observed in Fig. 7b. The results obtained with the heat-pipe furnace cavity (number 2 in Fig. 7) are the same in (a) and (b).

4.2 Focusing of the Standard Pyrometer

The measured radiance temperature of the heat-pipe cavity depends on the selected focal plane: the entrance aperture, the bottom of the heat pipe, or any place between them. Sakuma et al. [1] reported the distance and size-of-source effects of a pyrometer similar to the LP2 used in this study.

Visual focusing of the pyrometer is not recommended, because this depends on the visual capabilities of the user. Instead, we use the focus setting that produces the sharpest temperature profile at the cavity edges, by measuring along the diameter of the cavity opening and plotting the photocurrent output of the pyrometer as a function of its position.

4.3 Emissivity of Cavities

In this study, the measured objects are calibration cavities with emissivities assumed equal to one at all wavelengths within the response band of the thermometers. The effective cavity emissivities seem to be close to one according to various verifications. For the cylindro-conical cavity, these include a theoretical determination based on [8] using the values of the measured temperature profile at 500 °C along its cylindrical wall and the intrinsic emissivity of the paint that coats its inner wall (values between 0.9 and 0.95). For the heat-pipe furnace above 650 °C, we find agreement of the radiance temperatures at the working wavelengths of the LP2 pyrometer (652 nm and 912 nm) when sighted on its entrance. Differences of 0.3 °C at 650 °C and <0.1 °C at 950 °C indicate that the spectral emissivity is 0.99 ± 0.01. Also, for the heat pipe cavity, an approximate calculation of its emissivity, based on the cavity dimensions and the intrinsic emissivity of heavily oxidized Inconel with emissivities between 0.81 and 0.97 [9,10], indicates that is close to one.

5 Discussion

Distance and focus effects influence the calibration results of radiation thermometers of the types presented in this paper. It is observed that the calculated deviations obtained with the angular responsivity function of Fig. 2 are similar to that of the measured thermometer error in Fig. 1, suggesting that the distance effect is related to the angular responsivity. However, the results of the theoretical exercise indicate that, close to the source, a region exists where the readings should remain unaffected when the distance is changed. Such a region has not been observed by us when we calibrate fixed-focus thermometers. The curves shown in Fig. 4 may not resemble the actual distance effect of these thermometers, which instead seem to be linear functions, but in this exercise only the responsivity and the distance were considered in the calculations and there are other factors that contribute to the deviations, such as aberrations produced by the thermometers’ lenses.

In the case of the thermometer with focusing, it was observed that changing the focus yields different results. It is a common practice to focus on the cavity opening, but we were interested in knowing how the results are affected when focusing on a different target, such as the cavity bottom. Our results with this thermometer differ from those shown in [3] for a thermometer of the same kind. In [3], the distance effect behaves similarly to what we described here for a fixed-focus thermometer.

When calibrating the thermometer with focusing using two different cavities, it was observed that temperature gradients in the cylindro-conical cavity are responsible for the discrepant results shown in Fig. 7, indicating that the temperature measured within its wall requires correction. After attempting this, we were able to reduce the differences but not eliminate them. Correction for the size-of-source effect to take into account the different diameters of the cavities may be required to place the measurements on the same footing.

6 Uncertainties

Uncertainties estimated before taking into account distance and focus effects mentioned here include those values given as "normal" in [11] for the calibration scheme of measuring a variable temperature blackbody in the 50 °C to 500 °C temperature range, excluding the uncertainty due to drift of the thermometers under calibration and those due to the resolution and scattering of thermometer readings. Thermometers giving readings directly as temperature values are precluded in [11], but we assume that the uncertainty values given there are correlated with those of the thermometers studied here. Uncertainties above 500 °C for the 8 μm to 14 μm spectral band are not covered in [11], but a similar treatment was given here for our uncertainty estimations at 550 °C.

In the calibration of the thermometer with focusing, the uncertainty includes the size-of-source effect of the thermometer. The combined uncertainties appear in columns with the "Before" heading, in Tables 5 and 6. When the LP2 pyrometer is used

Table 5 Uncertainties for the calibration of the fixed-focus radiation thermometers presented in this paper for $k = 1$

Calibration temperature (°C)	Before (°C)	Distance effect uncertainty (°C)		Final (°C)	
		(FOV = 8:1)	(FOV = 50:1)	(FOV = 8:1)	(FOV = 50:1)
50	±0.26	±0.03	±0.00	±0.26	±0.26
100	±0.25	–	±0.01	–	±0.25
125	±0.25	±0.07	–	±0.28	–
150	±0.25	–	±0.01	–	±0.25
200	±0.26	±0.17	–	±0.31	–
250	±0.23	–	±0.02	–	±0.23
300	±0.37	±0.24	–	±0.44	–
350	±0.39	–	±0.03	–	±0.39
400	±0.42	±0.33	–	±0.53	–
450	±0.37	–	±0.04	–	±0.37
550	±0.58	–	±0.05	–	±0.58

Table 6 Uncertainties in the calibration of the radiation thermometer with focussing presented in this paper for $k = 1$

Calibration temperature (°C)	Before (°C)		Uncertainty from focusing (°C)	Final (°C)
	Standard: PRT	Standard: LP2		
50	±0.28	–	±0.01	±0.28
100	±0.26	–	±0.03	±0.26
150	±0.29	–	±0.04	±0.29
200	±0.25	–	±0.05	±0.25
250	±0.49	–	±0.06	±0.49
300	±0.48	–	±0.07	±0.49
350	±0.49	–	±0.08	±0.50
400	±0.51	–	±0.09	±0.52
450	±0.56	–	±0.10	±0.57
500	±0.61	–	±0.11	±0.62
550	±0.70	±0.70	±0.13	±0.71

as the reference standard, the uncertainty also includes that of the working wavelength, the reference temperature, and the nonlinearity of the detector.

Table 5 gives the estimated "final" uncertainties in the calibrations of the fixed-focus thermometers at those fixed distances used as examples in this paper, after taking into account the uncertainties due to the distance and focus effects described here. Table 6 gives the corresponding uncertainties for the thermometer with focusing. The contributions to the uncertainty from the distance and focus effects were estimated for a distance uncertainty of ±2 cm and a focal distance uncertainty of ±5 cm. When performing the calibration at fixed distances, their contribution to the final uncertainty is marginal for the thermometer with FOV of 50:1. The situation is different for thermometers with FOVs of the order of 10:1, or wider, at calibration temperatures higher than 200 °C, where the uncertainty due to distance should be part of the uncertainty budget.

7 Conclusions

Reference conditions for distance and focus are necessary to improve the reproducibility of the calibration results of radiation thermometers, with either a fixed or variable focus. Such conditions should be declared in the calibration report.

For fixed-focus thermometers, we propose that the distance be that where the thermometer "sees" a source larger than twice the diameter calculated from the "distance to target/target diameter" ratio specified by the manufacturers, or 1 m as recommended in [4] when such a ratio yields a greater distance.

For thermometers with focusing capability, a distance where the results have the least sensitivity to changes in distance could be experimentally determined and used for the calibration. For the cases shown in Fig. 5, we found that this distance was approximately (90 ± 5) cm.

The uncertainties of the calibrations carried out at fixed distances will not substantially be reduced with those aforementioned reference conditions. The challenge is to improve the reproducibility of the calibration results with different cavities or different distances. To achieve that goal, the use of such conditions for distance and focusing and the augmentation of the required diameter for the cavities indicated in [4] are mandatory.

During the use of these thermometers, it would be desirable as good practice to overfill the FOV with a wider field than that indicated by the manufacturer, as deduced from the graphs of this study. In order to ensure correct results, the user should be advised to use the thermometer under conditions close to that of the calibration (same distance and diameter of the measured field). If these conditions are not repeated during the use of the calibrated thermometers, the user should estimate the additional uncertainties that will arise.

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