

Size-of-source Effect in Infrared Thermometers with Direct Reading of Temperature

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Abstract The size-of-source effect (SSE) for six infrared (IR) thermometers with direct reading of temperature was measured in this work. The alternative direct method for SSE determination, where the aperture size is fixed and the measurement distance is varied, was used in this study. The experimental equivalence between the usual and the alternative direct methods is presented. The magnitudes of the SSE for different types of IR thermometers were investigated. The maxima of the SSE were found to be up to 5 %, 8 %, and 28 % for focusable, closed-focus, and open-focus thermometers, respectively. At 275 °C, an SSE of 28 % corresponds to 52 °C, indicating the severe effect on the accuracy of this type of IR thermometer. A method to realize the calibration conditions used by the manufacturer, in terms of aperture size and measurement distance, is discussed and validated by experimental results. This study would be of benefit to users in choosing the best IR thermometer to match their work and for calibration laboratories in selecting the technique most suitable for determining the SSE.

Keywords Infrared thermometers with direct reading of temperature · Radiation thermometry · Size-of-source effect

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1 Introduction

Radiation thermometers are widely used because of their advantages over contact thermometers, such as fast response, avoidance of contamination, and wide temperature measurement range. These thermometers are designed to collect thermal radiation emitted from the measured object by a detector; therefore, an optical system is needed. When using an IR thermometer, the field of view of the thermometer should be covered by the physical size of the object measured. The size of the field of view depends on the design of the optical system and is normally defined by the distance-to-spot-size ratio (D:S ratio). Unfortunately, imperfections in the optical system cause scattering of radiation into and out of the ideal path and also diffraction of radiation within the optical system, resulting in aberration of the optics. Consequently, some radiation from outside the nominal field of view is incident on the detector and some radiation from within the nominal field of view is scattered away from the detector. This leads to the actual field of view being ill-defined and the measured signal being influenced by the object size, the so-called size-of-source effect (SSE).

There are generally three methods to determine the SSE in radiation thermometers [1,2]. In the first method, the direct method, the radiation thermometer measures a uniform source with a well-defined aperture larger than the nominal field of view. By varying the aperture size, the dependence of the measured signal on source size can be observed. In the second method, the indirect method, a black spot with a size slightly larger than the nominal field of view is used to block the direct radiation from the target. Again, using different sized apertures surrounding the black spot, the variation in the signal can be observed, giving an indication of the SSE. In the last method, the scanning method, the radiation thermometer is scanned across a circular or rectangular-slit source with a width slightly larger than the nominal field of view. The SSE can be determined by accumulating signals with distance from the center of the source.

For high-accuracy narrow-band thermometers, the SSE has been widely studied [1–7], and this knowledge has been used to improve the SSE in thermometer design. Values of SSE as low as 7×10^{-5} can be achieved [7]. On the other hand, not much data for the SSE in handheld IR thermometers with direct reading of temperature have been published; therefore, the range of the SSE magnitude is still a question. In particular, the different magnitudes of the SSE among three types of thermometer, i.e., open-focus, closed-focus, and focusable thermometers [8], has not been studied. The indirect and the scanning methods are not suitable for determining the SSE in direct-reading IR thermometers due to the low level of radiation scattered into and out of the nominal field of view compared to the resolution of such instruments.

Saunders [9,10] proposed an alternative direct method to measure the SSE in handheld IR thermometers, with emphasis on open-focus thermometers, in which the measurement distance is varied instead of the aperture size. Using this technique, there is no requirement for any extra equipment, which is beneficial for calibration laboratories and users. However, while the equivalence of the alternative and the usual direct techniques for the SSE determination was experimentally verified for open-focus thermometers [9], this has not been done for focusable and closed-focus thermometers.

Measurements of the SSE are not only important for applying temperature corrections and calculating uncertainties, but can also be used to determine the manufacturer's calibration conditions; i.e., the aperture size and measurement distance used when the manufacturer put the temperature scale onto the device. This can be determined by observing the conditions that minimize the corrections of the IR thermometer [9]. For recalibration of the device, it is recommended that the measurement conditions are the same as those used by the manufacturer.

In this work, six handheld direct-reading IR thermometers from several suppliers were studied. The SSEs of all the thermometers were measured and compared; i.e., benchmarked to present the variation of the SSE in different types of handheld IR thermometers. Experiments to demonstrate the equivalence of the two approaches for the direct method were carried out for closed-focus and focusable thermometers. In addition, determinations of the manufacturers' calibration conditions are illustrated and confirmed by experimental results. This information would be beneficial for calibration laboratories for method validation and recalibration, and for users for the selection of IR thermometer to achieve a desired accuracy.

2 Measurements

2.1 Measurement Apparatus

Six direct-reading IR thermometers were used in this study. The equipment originated in USA, Japan, and China. Table 1 presents the specifications of each instrument. A flat plate blackbody (FP BB) was used as a heat source to determine the SSE in the IR thermometers. The diameter of the flat plate was 152.4 mm, and the surface emissivity was 0.95 in the spectral range of the IR thermometers studied. The flat plate's temperature measured by its indicator was calibrated radiometrically. The calibration results were used to correct the value measured by the indicator to obtain the actual temperature of the FP BB. Another source, a cavity blackbody (BB), was also used for determining the SSE and for calibrating the IR thermometers; it had a 60-mm-diameter aperture and an effective emissivity of 0.993. The temperature of the cavity BB was measured by a calibrated platinum resistance thermometer (PRT). Seven square aperture plates, 150 mm \times 150 mm in size, with circular apertures of diameter 25 mm, 30 mm, 40 mm, 50 mm, 60 mm, 70 mm, and 80 mm cut into them, were used with the blackbodies when variation in aperture size was required. The apertures were inserted into a holder with a 30-mm-opaque rim on each side. The aperture plates and their holder were blackened. The temperature of the plates and its holder were not controlled, but they were monitored by a surface thermometer.

2.2 Measurement Method

Two of the IR thermometers, IRT1 and IRT2, were selected to study the conformity between the alternative and the usual direct SSE measurement methods for closed-focus and focusable thermometers, respectively. Each of these IR thermometers was

Table 1 Specification of IR thermometers with direct reading of temperature used in this work

IR thermometer number	IRT1	IRT2	IRT3	IRT4	IRT5	IRT6
Temperature range (°C)	-30 to 900	-50 to 1,000	-50 to 1,000	-32 to 535	-50 to 330	-20 to 400
Optical system	Closed-focus	Focusable	Focusable	Open-focus	Open-focus	Open-focus
Spectral range (µm)	8 to 14	8 to 13	8 to 13	5 to 14	8 to 14	Open-focus
Distance/Spot (D:S)	60:1 ^b	40:1	40:1	12:1	12:1	Not stated ^a
Minimum distance	-	700 mm	700 mm	-	-	12:1
Emissivity	Adjustable	Adjustable	Adjustable	Adjustable	0.95 (Fixed)	Adjustable

^a The spectral range of IRT6 was assumed to be (8 to 14) µm in this work

^b At the focal point, 1150 mm from target, the diameter of the spot size is 19 mm

used to measure the temperature of the two different blackbody sources (cavity BB and FP BB), which were both set to 275 °C. The laboratory room temperature was controlled at 23 °C ± 2 °C. In all measurements, the instrumental emissivity of all the IR thermometers was set to 0.95.

For the usual direct method, the measurements were made at a fixed distance from each blackbody, namely 560 mm for IRT1 and 700 mm for IRT2. The measurement distance was defined from the aperture to the lens of the IR thermometers. The aperture size of the blackbodies was varied by placing the aperture plates with selected aperture size in the holder located in front of the blackbodies. The distance between the blackbodies and the aperture plates was 100 mm to reduce the influence of thermal radiation from the blackbodies. For each aperture size, IRT1 and IRT2 were used to measure the blackbody temperatures 5 times each. At each time, the blackbody temperatures, indicated by the PRT for the cavity BB and the indicator for the FP BB, were recorded.

In contrast with usual direct method, for the alternative direct method the temperature measurements of the blackbodies were made without aperture plates in place, so that effectively the aperture size was fixed at 60 mm for the cavity BB and 152.4 mm for the FP BB. Instead of varying the aperture size, the measurement distance between the blackbodies and the thermometers was varied, in the range 100 mm to 5000 mm, depending on nominal spot size of the thermometer and the aperture size of the heat source used. As above, temperatures read by IRT1 and IRT2 were recorded 5 times together with the temperature of the blackbodies. We note that for the measurements, the IR thermometers were moved horizontally and vertically (X and Y axes) to get the maximum reading. For the case of IRT2, the focus of the thermometer was also adjusted to achieve the maximum reading.

For IRT3 to IRT6, the SSE was measured using just the alternative direct method, and only the FP BB was used as a heat source. The process for the measurements was the same as described above.

To validate the manufacturers' measurement conditions, IRT1 and IRT2 were calibrated in the range from 50 °C to 450 °C. The cavity BB with the 60-mm-diameter aperture was used as the source. The measurement distances were 560 mm and 1500 mm for IRT1 and IRT2, respectively.

3 Results and Discussions

3.1 Validation of the Alternative Direct Method

When analyzing the measurement results, the IR thermometer readings measured for different blackbody conditions, i.e., emissivity and temperature, cannot be directly compared. Instead, we present the results in terms of a correction, C , which is the temperature difference between the blackbody temperature, t_{BB} , and the IR thermometer readout, t_{IR} :

$$C = t_{BB} - t_{IR}. \quad (1)$$

As the emissivity of the cavity BB was not the same as the instrumental emissivity setting on the IR thermometers, a correction to t_{BB} for the case of the cavity BB was

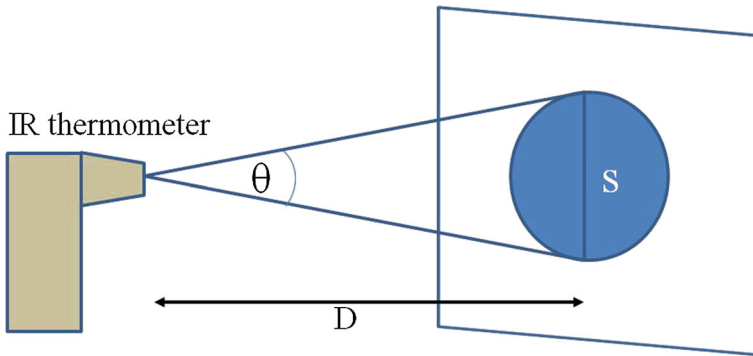


Fig. 1 Diagram illustrating the angular target size of a target of diameter S for an IR thermometer viewing the target at a distance D

required. This was calculated using the method in Refs [11–13]. The temperature of the aperture plate was found to be up to $50\text{ }^{\circ}\text{C}$ when the 25-mm aperture was placed in front of the FP BB. However, no correction was applied for this effect because this temperature increase over ambient temperature affects the signal of the IR thermometer by only 0.27 %, which is much smaller than the SSE of the thermometers. In addition, the aperture plates had no measurable effect on the temperature of the blackbodies themselves.

To present the measurement results, the correction will be plotted as a function of the angular target size, θ , which characterizes the relationship between aperture diameter, S , and measurement distance, D , as shown in Fig. 1. The angular target size can be calculated as

$$\theta = 2 \tan^{-1} \left(\frac{S}{2D} \right). \quad (2)$$

Figure 2a, b presents the corrections of IRT1 and IRT2, respectively, for both the usual and the alternative direct methods for the two different types of blackbody. The uncertainty of the measurements is estimated to be $1.2\text{ }^{\circ}\text{C}$. The measurement results illustrate how the correction depends on angular target size. The effect in IRT1 is found to be 2 times larger than the effect in IRT2. Good agreement of all measurement results can be observed, especially in the case of IRT1. For IRT2, the corrections diverge for angular target sizes larger than 5° , with a temperature difference of about $0.7\text{ }^{\circ}\text{C}$. This is most likely evidence that the SSE changes slightly as the lens is moved during focusing. There may also be a contribution from the focus effect [14], where the throughput changes with focusing if the aperture stop is not correctly located. The results show the experimental equivalence of the SSE data between the usual and the alternative direct methods for fixed-focus instruments and validate the simpler alternative direct method for assessing SSE, which was first outlined in [9] for open-focus devices. This method can be used with both cavity BBs and FP BBs.

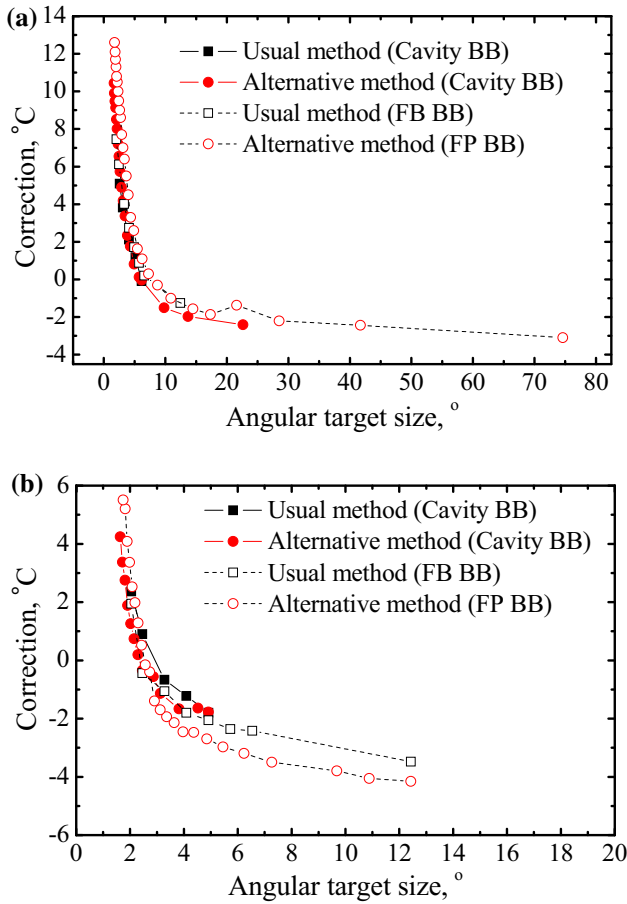


Fig. 2 Correction as a function of angular target size for (a) IRT1, and (b) IRT2

3.2 Benchmarking of the SSE in Direct-Reading IR Thermometers

For determination of the SSE, Eq. 16 in Ref. [9] is used. The SSE, σ , of the direct method is determined as the ratio of the thermometer signal for a given aperture size, $S_\theta(T)$, to the signal for the maximum aperture size, $S_{\theta_{\max}}(T)$, with each signal corrected for the background radiation, $S(T_{\text{amb}})$, at the ambient temperature, T_{amb} :

$$\sigma = \frac{S_\theta(T) - S(T_{\text{amb}})}{S_{\theta_{\max}}(T) - S(T_{\text{amb}})}. \tag{3}$$

The background radiation is negligible in our case as the measured temperature is higher than 200 °C [15]. For the IR thermometers used in this study, access to the nonlinear signal of the thermometer is not possible. The signals, $S(T)$, however, can be obtained by using the Sakuma–Hattori approximation [16]:

$$S(T) = \frac{C}{\exp\left(\frac{c_2}{AT+B}\right) - 1}, \tag{4}$$

where assuming the spectral responsivity of the IR thermometer is approximately rectangular in shape [9],

$$A = \lambda_0 \left(1 - \frac{\Delta\lambda^2}{2\lambda_0^2}\right), \tag{5}$$

$$B = \frac{c_2\Delta\lambda^2}{24\lambda_0^2}, \tag{6}$$

and C can be assumed to be 1. $\Delta\lambda$ is the width of the spectral responsivity and λ_0 is the center wavelength.

The SSE of all thermometers studied is shown in Fig. 3. For IRT2 and IRT3, the values of σ are very close to each other, so a magnified scale for these two thermometers is shown in the inset of the figure. It should be noted that IRT2 and IRT3 have the same physical aspects and the same specifications, but are branded from different companies. However, we suppose that they have the same original equipment manufacturer, as evidenced by the SSE data. The SSE presented in terms of σ is used to indicate how the IR thermometers respond to different sized sources. For example, $\sigma = 0.98$ at 2° means 98 % of incident radiation falls within an angular field of view of 2° and the remaining 2 % originates from larger angles. Alternatively, it can be said that the SSE = 2 %.

In Fig. 3, the variation of the SSE from thermometer to thermometer can be observed. To sort the IR thermometers by the SSE, they can be classified into three

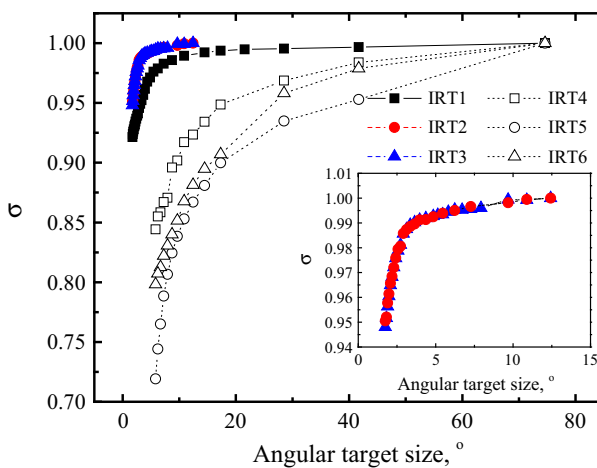


Fig. 3 The SSE for IRT1 to IRT6 determined by the alternative direct method. The inset shows IRT2’s and IRT3’s SSE data with a magnified scale

different groups, related to the optical system of the thermometers. The focusable thermometers IRT2 and IRT3 are subject to a smaller SSE, with an SSE of 5 % at $\sim 2^\circ$. This is in the same range as the commercial radiation thermometer studied in Ref. [15], but is three times higher than an accurate IR thermometer [17]. For IRT1, a closed-focus thermometer, the SSE is up to 8 % at $\sim 2^\circ$; however, this is better than for the group of open-focus thermometers. The SSE of IRT4, IRT5, and IRT6 can rise up to 16 %, 28 %, and 21 %, respectively, at $\sim 6^\circ$. For IRT5 (the worst of these), the SSE could affect the measured temperature by up to 52°C at 275°C , indicating the dramatic influence of the SSE. The data in Fig. 3 would be useful for users deciding on the selection of an appropriate thermometer.

3.3 Determination of Manufacturer's Calibration Conditions

For best use of the device, the user should measure objects with the same angular target size as the source used by the manufacturer when the device was initially calibrated; otherwise, an additional correction due to the SSE should be applied (which may be large). This also applies when recalibrating the device. To determine the calibration conditions used by the manufacturer, measurements of the SSE of the device should be carried out. The angular target size that makes the correction close to zero indicates the calibration conditions of the manufacturer.

Here, we consider the SSE measurements as shown in Fig. 2a, b. The results indicate that the corrections of the devices are close to zero for angular targets of $\sim 6.13^\circ$ and $\sim 2.29^\circ$ for IRT1 and IRT2, respectively. It can be assumed that these are the calibration conditions of the manufacturers. To validate this assumption, both devices were calibrated at these angular target sizes over the temperature range 50°C to 450°C . The calibration results are presented in Figs. 4 and 5 for IRT1 and IRT2, respectively. The corrections of IRT1 and IRT2 are close to zero as expected over the whole temperature range, except the results at 400°C and 450°C for IRT2. The validation here

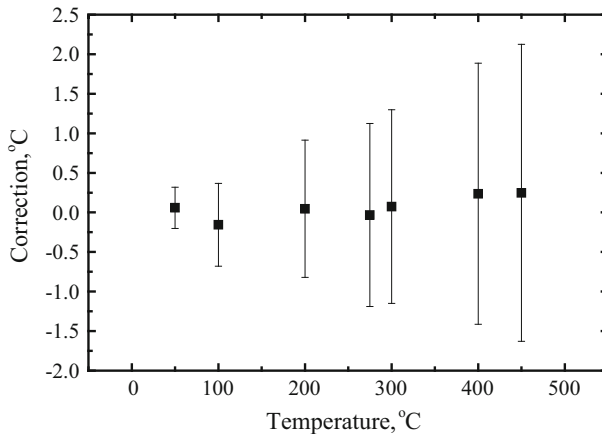


Fig. 4 Calibration results of IRT1 with 6.13° angular target size

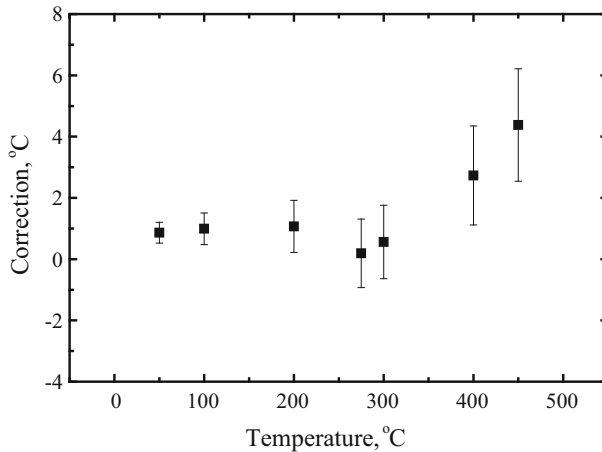


Fig. 5 Calibration results of IRT2 with 2.29° angular target size

would assist the calibration laboratory to select the correct conditions for calibration.

4 Conclusion

The alternative direct method to measure the SSE was studied in this work. The results indicate the equivalence of the alternative and the usual direct method. The SSE for six direct-reading IR thermometers was measured. The magnitude of the results depends on the optical system used. In the worst case, an SSE of 28 % was found in an open-focus thermometer, while SSE values of 5 % and 8 % were found in the focusable and closed-focus thermometers, respectively. The technique to determine the manufacturer's calibration conditions, i.e., aperture size to measurement distance ratio, was demonstrated and validated by experimental data. The work would have benefits for users and calibration laboratories in selecting thermometers suitable for their work and for choosing a suitable approach for evaluating the SSE.

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