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Size-of-Source Effect Difference Between Direct and Indirect Methods of Radiation Thermometers

X. Hao · Z. Yuan · X. Lu · W. Zhao

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Abstract The size-of-source effect (SSE) of radiation thermometers is generally determined using direct and indirect methods. The present paper describes the difference in the SSE obtained using the two methods. Three thermometers at different SSE levels, namely, 1.5×10^{-4}, 1.05×10^{-3}, and 2.44×10^{-3}, are selected. SSEs with 5 mm to 96 mm aperture diameters are higher in the indirect than in the direct method. Three factors contribute to this difference: the light reflection from the inside face and edge of the aperture to the black spot, the relay reflections from the thermometer and background, and the decreased radiance caused by obstruction of light by a black spot. Thus, the difference in the SSEs results from the difference in the principle of the two methods and not from the SSE levels of the thermometers themselves. The difference is negligible to be considered in a number of radiation thermometers, but they must be taken into consideration in top-level intercomparisons.

Keywords Direct method · Indirect method · Radiation thermometer · Size-of-source effect

1 Introduction

The size-of-source effect (SSE) is a significant contributor to the error and uncertainty in radiation thermometry measurements, both in laboratory standard calibrations and

X. Hao (✉) · Z. Yuan · X. Lu
Division of Thermometry and Materials Evaluation, National Institute of Metrology,
Beijing 10013, China
e-mail: haoxp@nim.ac.cn

W. Zhao
University of Science and Technology Beijing, Beijing, China

industrial temperature measurements [1–3]. It represents the dependence of the radiometer or radiation thermometer on the environment surrounding the target area. The SSE has been extensively studied with the widespread application of radiation thermometers in many national metrology institutes (NMIs) [4–7], including the National Institute of Metrology (NIM) [8,9]. The SSE results from the diffraction and scattering of radiation and from the optical imperfections and aberrations within the optical system of radiation thermometers [10,11] and contributes to the uncertainty in temperature measurements. The correction and calculation methods for this uncertainty have been discussed several times [12–15]. The signals must be corrected to a common aperture size if more than one blackbody is used during calibration or if comparisons are performed between different blackbodies. Two methods for measuring the SSE, the direct [16] and indirect methods [17], are available. These two methods measure slightly different quantities, and published comparisons of their equivalence have not been entirely conclusive [18,19]. The two measurement methods have several differences in terms of equipment and methods used to process the results.

In the present paper, three radiation thermometers at different SSE levels were used to determine the differences between the direct and indirect methods. The characteristics of the two methods were investigated, and the area of application was analyzed.

2 Instruments and Methods

A radiation thermometer with a 660 nm center wavelength has been established and improved into several types since 1990 at the National Institute of Metrology (NIM) of China. Compared with the older type of radiation thermometer (RT9031), the new radiation thermometer (RT9032) has a smaller volume, lighter weight, and high portability. RT9032s with 660 nm and 900 nm center wavelengths (RT9032-660 and RT9032-900, respectively) have been set-up at the NIM since 2008.

The SSE of three thermometers was determined. The RT9032-660 and RT9032-900, as well as the KE LP4 with a 650 nm center wavelength, were all equipped with a Si photodiode. The characteristics of the three thermometers are listed in Table 1.

Table 1 Radiation thermometer specifications

	RT9032-900	RT9032-660	LP4
Temperature range (°C)	600–2000	800–3000	677–3527
Center wavelength (nm)	900	660	650
FWHM (nm)	20	10	10
Focus distance (mm)	150	150	143
Field stop (mm)	0.33	0.33	0.25
Resolution (°C)	0.001	0.001	0.001
Measurement distance (mm)	700	700	700
FOV diameter (mm)	1.21	1.21	0.97

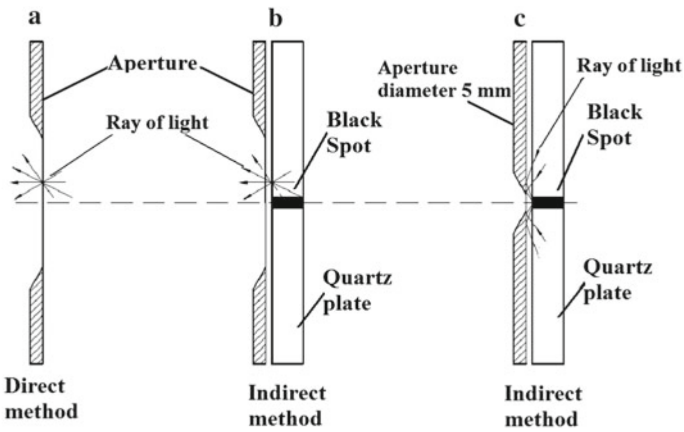

Fig. 1 Schematic diagram of the SSE measurement system: (*a*) direct method, (*b*) indirect method with a large aperture, and (*c*) indirect method with a 5 mm aperture diameter

The radiance source is an integrating sphere with an 800 mm inside diameter and 96 mm exit port aperture diameter. The diffused reflection layer in the integrating sphere is Teflon and has a reflectance of approximately 0.98. The sphere has six halogen lamps (21 V, 150 W) around the port, which has a uniformity of $\pm 5 \times 10^{-4}$ over an area of 48 mm × 48 mm of the exit port [20]. The black-coated integrating sphere has six apertures with diameters ranging from 5 mm to 96 mm. A quartz plate with a black spot (2 mm or 4 mm in diameter) at its center was held at the exit port behind the aperture in the indirect method. A small Si photodiode detector monitored the change in the radiance within the sphere and made adjustments for each aperture change.

The direct method employed a large area that integrated the sphere as the radiance source, which was powered with a constant current power supply. The sketch of the thermometer as it focuses on the center of the aperture plate of the source is shown in Fig. 1a. The signal, which was normalized to unity at the maximum aperture size, was plotted as a function of the aperture diameter. The result of the direct method was calculated using the following equation:

$$\sigma(d, d_0) = \frac{v(L, d)}{v(L, d_{\max})} \tag{1}$$

where $\sigma(d, d_0)$ is the SSE at the aperture with diameter d_0 to d, d is the diameter of the uniform radiance source, $d_{\max}$ is the maximum diameter of the uniform radiance source, and $v(L)$ is the radiance of the source.

In the indirect method, the thermometer was focused on the aperture of an integrating sphere with a field of view smaller than the spot, as shown in Fig. 1b. The spot was a cavity coated with high-emissivity black painting. The indirect method result was calculated using the following equation:

$$\sigma(d, d_0) = 1 - \frac{v(L, d_{\max}) - v(L, d)}{v(L)} \tag{2}$$

where $\sigma(d, d_0)$ is the data of SSE at the aperture with diameter d_0 to d, d is the diameter of the uniform radiance source, d_{max} is the maximum diameter of the uniform radiance source, and $\upsilon(L)$ is the radiance of the source.

3 Results

The SSE of RT9032-900, RT9032-660, and LP4 were determined using the two methods. The SSE of each thermometer was measured three times, and the average is plotted in Figs. 2, 3, and 4. All data obtained from the direct and indirect methods were calculated using Eqs. 1 and 2, respectively, and were returned to 100 % at the 96 mm diameter aperture.

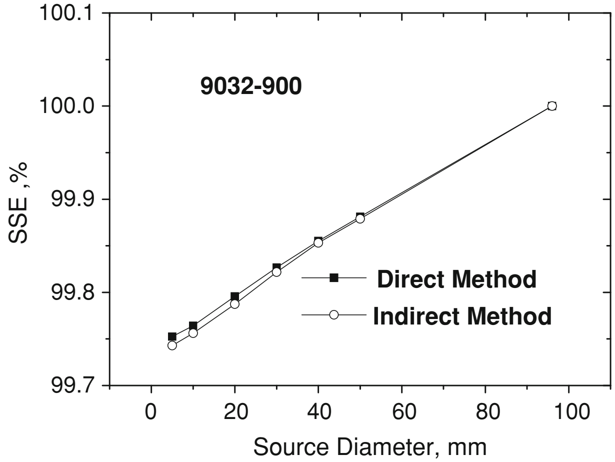

Fig. 2 Plots of the RT9032-900 SSE results of the two methods with 5 mm to 96 mm aperture diameters

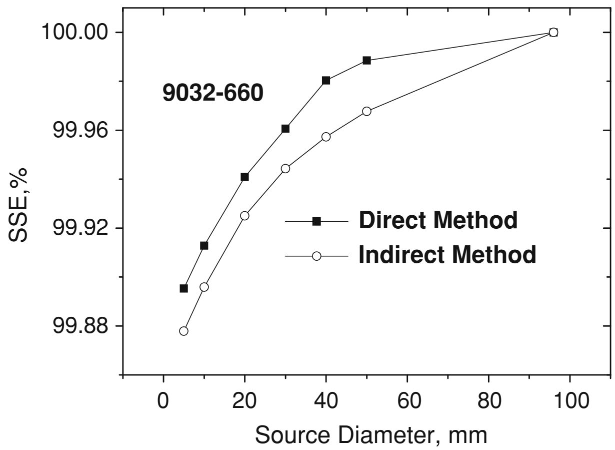

Fig. 3 Plots of the RT9032-660 SSE results of the two methods with 5 mm to 96 mm aperture diameters

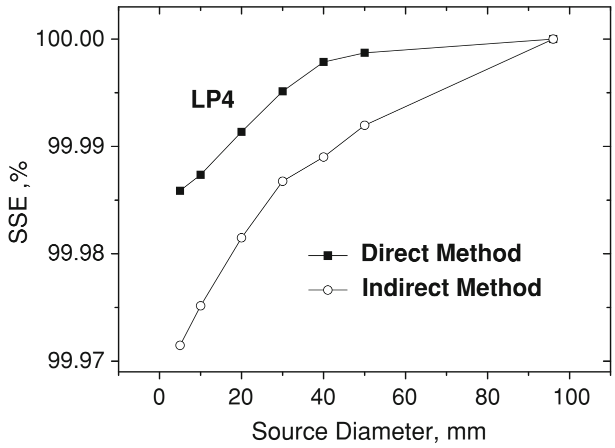

Fig. 4 Plots of the LP4 SSE results of the two methods with 5 mm to 96 mm aperture diameters

Table 2 SSE increments of RT9032 and LP4 with 5 mm to 96 mm source diameters measured using the direct and indirect methods

Measurement method	RT9032-900	RT9032-660	LP4
Direct method (%)	0.244	0.105	0.015
Indirect method (%)	0.257	0.122	0.029
Difference (%)	0.013	0.017	0.014

Difference = indirect − direct

The apertures with different diameters were separately placed at the exit of the integrating sphere. For the 5 mm to 96 mm aperture diameters, the SSEs of LP4, RT9032-660, and RT9032-900 obtained using the direct method are 0.015 %, 0.105 %, and 0.244 %, respectively, whereas those from the indirect method are 0.029 %, 0.122 %, and 0.257 %, respectively, with a black spot 2 mm in diameter. The three thermometers are at three different SSE levels: RT9032-900 at the lowest, RT9032-660 in the middle, and LP4 at the highest. An obvious difference is observed in the indirect method compared with the direct one with an aperture diameter of 5 mm to 96 mm, especially when the SSE level is higher by approximately 0.015 % (the average SSE difference for each thermometer). All data are shown in Table 2. The slope of the plots from the indirect method with an aperture diameter of 5 mm to 20 mm is different from that of the direct method. The slope of the plots with an aperture diameter of 40 mm to 96 mm is higher in the indirect than in the direct method, especially in RT9032-660 and LP4.

4 Discussion

The SSE results of the three thermometers at three levels using the two methods are different. The SSE measured using the direct method is smaller than that using the indirect one. Three main factors contribute to the difference in the results.

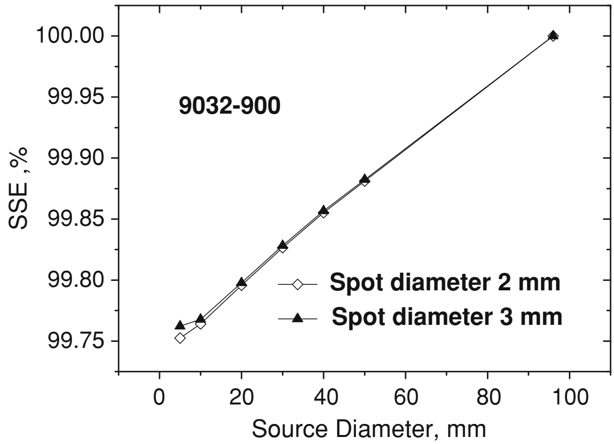

Fig. 5 Plots of the RT9032-900 SSE results of the indirect method with black spots 2 mm and 4 mm in diameter

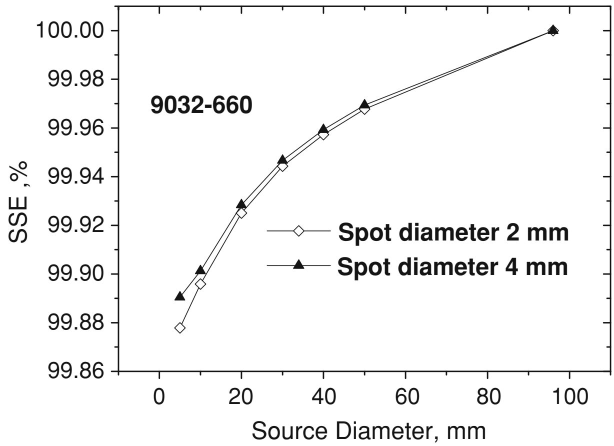

Fig. 6 Plots of the RT9032-660 SSE results of the indirect method with black spots 2 mm and 4 mm in diameter

First, light from the integrating sphere inside the face and edge of the aperture is reflected into the black spot in the indirect method, as shown in Fig. 1c. The reflected light illuminates the black spot, thereby decreasing the size of the aperture. A much smaller aperture size results in a much shorter distance between the edge of the aperture and the black spot. Thus, the SSE in the indirect method is higher than in the direct method. The SSE measurement using the indirect method with a black spot 4 mm in diameter was performed to confirm this finding.

The SSEs with black spots 2 mm and 4 mm in diameter are shown in Figs. 5, 6, and 7. The slope of the plot of the RT9032-900 SSE with apertures 5 mm to 20 mm in diameter is smaller with the 2 mm to 4 mm spot diameter (Fig. 5). A similar result was obtained for RT9032-660 and LP4 (Figs. 6 and 7). However, the SSE of the LP4 with a 4 mm spot diameter is bigger at the aperture 5 mm in diameter than that at the

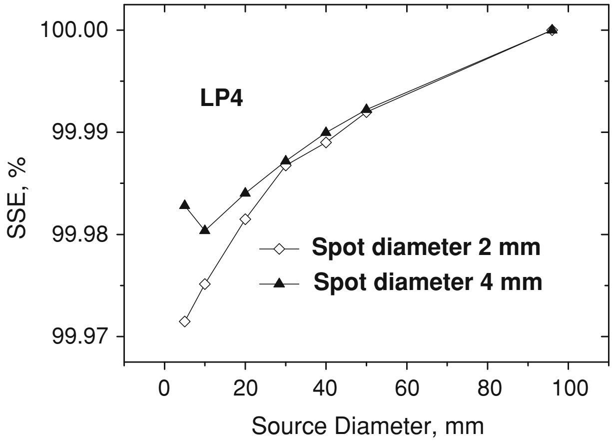

Fig. 7 Plots of the LP4 SSE results of the indirect method with black spots 2 mm and 4 mm in diameter

Table 3 SSE of RT9032 and LP4 with 5 mm to 96 mm source diameters measured using the indirect method

	RT9032-900		RT9032-660		LP4	
Aperture diameter (mm)	5	10	5	10	5	10
Spot diameter 2 mm (%)	99.753	99.764	99.878	99.896	99.971	99.975
Spot diameter 4 mm (%)	99.762	99.768	99.890	99.901	99.983	99.980
Difference (%)	0.009	0.004	0.012	0.005	0.012	0.005

Difference = (4 mm spot diameter) − (2 mm spot diameter)
All data were returned to 100 % at the 96 mm diameter of the source

aperture 10 mm in diameter (Fig. 7). SSEs and the different aperture and spot diameters are listed in Table 3. Although the three thermometers are at three SSE levels, the difference is the same. The difference (difference = $SSE_{4\,mm\,spot} - SSE_{2\,mm\,spot}$) is approximately 0.011 % (the average of the SSE difference for each thermometer) at the 5 mm aperture diameter and 0.005 % at the 10 mm aperture diameter (Table 3). The light reflected by the inside face and edge of the aperture into the black spot contributes to the difference in the slope of the plot with a 5 mm to 20 mm aperture diameter.

Second, the relay reflections from the thermometer and background into the black spot also affect the results. The relay reflections increase with increasing aperture diameter when the indirect method is used to measure the SSE. More relay reflections enter the black spot as the diameter of the aperture increases. The slope of the plot using the 40 mm to 96 mm diameter aperture is bigger in the indirect method than in the direct method, especially in RT9032-660 and LP4. The SSE also increases because of the principle of measurement, which indicates the absence of any relationship with the SSE level of the thermometer. However, the slope of the plot obviously changes for thermometers at high SSE levels.

Third, the radiance measurement signal $\nu(L)$ is decreased by the black spot in the indirect method, as shown in Fig. 1b. The field of view of the thermometer is moved around the black spot to measure the radiance signal $\nu(L)$. The radiance of the source decreases because the black spot obstructs the light from the integrating sphere, resulting in a decrease in the value of $\nu(L)$ and an increase in the SSE calculated using Eq. 1. Thus, the radiance obstruction near the black spot is the third reason for the difference in the results.

The three above-mentioned factors are the primary reasons for the difference in the results, but other factors also contribute. Thus, the difference in the SSEs results from the difference in the principle of the two methods and not from the SSE levels of the thermometers themselves. This difference is negligible to be considered in a number of radiation thermometers, but they must be taken into consideration in top-level intercomparisons.

5 Conclusions

A difference in the SSE results of the direct and indirect methods is observed. This difference may be significant enough to become part of the uncertainty in the results of top-level intercomparisons.

The SSE obtained through the indirect method is higher than that from the direct method. Three factors contribute to the difference in the SSE, namely, the reflection from the inside face and edge of the aperture into the black spot, the relay reflections from the thermometer and background, and the obstruction of the sphere by the black spot, which results in radiance reduction.

The three thermometers at different SSE levels were chosen to evaluate the difference between the direct and indirect methods. The difference is constant for a known SSE measurement system, and is affected by the source, source window with a black spot, aperture, holding of aperture, background, etc. The thermometer with a small SSE must be considered when the direct method is used to avoid non-ideal factors.

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