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A New Method to Determine the Size-of-Source Effect

M. Bart · E. W. M. van der Ham · P. Saunders

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Abstract This article introduces a new technique for measuring the size-of-source effect in radiation thermometers. It is based on scanning a thermometer across an aperture and extracting the size-of-source effect data from the residual signal, and is similar to the commonly used indirect method. The method has several advantages including speed, an ability to cover wide angles, and amenability to automation, at the expense of some added mathematical complexity. Results compare favorably with the frequently used indirect method of measuring the size-of-source effect.

Keywords Field of view · Radiation thermometry · Size-of-source effect

1 Introduction

The accuracy of radiation thermometry measurements is affected by a large number of environmental and instrumental effects, including the emissivity and reflectivity of the target object, reflected radiation from surrounding objects, atmospheric absorption, and the operating wavelength and temperature of the radiometer.

The most important instrumental factor, governing the accuracy of radiation thermometry measurements is the size-of-source effect (SSE) [1–3]. Ideally, the optical system of a radiation thermometer focuses all of the radiant energy from the target onto a detector. However, imperfections, scattering, and diffraction in the optical

M. Bart · P. Saunders (✉)
Measurement Standards Laboratory of New Zealand, Industrial Research Ltd, P.O. Box 31-310, Lower Hutt, New Zealand
e-mail: p.saunders@irl.cri.nz

E. W. M. van der Ham
Nederlands Meetinstiuut – van Swinden Laboratorium, Delft, The Netherlands

system of the thermometer cause some radiation from outside the field of view (FOV) to be detected, and some radiation from inside the field of view to be lost. This introduces errors into the measurement that depend on the angular size of the target and the temperature distribution of nearby objects. In high-quality industrial radiation thermometers, the effect may be as little as a few degrees Celsius; in thermal imaging systems, it may be as large as 40°C.

The effect is well known to the measurement community [1–11] and most laboratories make measurements of the effect and apply corrections to improve accuracy. The two methods currently used for assessing the SSE, colloquially called the direct and indirect methods, measure different quantities: the direct method measures the scattering into and out of the field of view, whereas the indirect method measures only the scattering into the field of view.

The SSE impacts on both the calibration and use of radiation thermometers. During calibration, the thermometers are exposed to blackbody-radiation sources of a relatively small angular extent. This has two consequences. Firstly, the signal does not include scattering from high angles, and secondly, the calibration is dependent on the diameter of the source (hence, size-of-source effect). SSE is currently the largest source of uncertainty in calibrations [3], and is currently an active area of research with respect to both the design of thermometers, and measurements and correction of the SSE [1–11]

In practical applications, the targets for radiation thermometers are typically larger than during the calibration and are often surrounded by hotter objects. In extreme cases, especially with thermal imaging systems, the errors can be many tens of degrees. When it is considered that reaction rates and material lifetimes in high-temperature industrial processes can halve or double with a 15°C change in temperature, it can be seen that the SSE is potentially a large problem. Thus, detailed measurements of the SSE are required to assess the impact of SSE on the utility of industrial radiation thermometers.

This article introduces a new method of measuring the SSE by scanning a thermometer across a narrow slit and collecting data, as a function of the viewing angle, rather than the source diameter. The new method proposed here effectively trades complexity of equipment for some added complexity in data analysis. Once validated, it will offer a faster and lower-cost method with the ability to assess the SSE at large angles and the potential for automation.

2 SSE Methods

2.1 Indirect Size-of-Source Measurements

The indirect method is a popular and sensitive method of measuring the SSE at national metrology institutes [1,4,6–8]. In this method, the radiation thermometer is sighted at a large variable-diameter diffuse radiation source, such as an integrating sphere, where the radiation from the FOV of the thermometer has been blocked using an obscuration. The residual signal detected by the thermometer is the radiation scattered from outside the nominal FOV. The relative residual signal is plotted against the radius of the source to give the SSE curve. Apart from being a labor intensive technique, there are several documented sources of error that originate from using this measurement method, including reflections between the front element of the thermometer and the central obscuration, optical misalignment, and poor sensitivity for direct-reading radiation thermometers [4]. The method also fails to provide any information about radiation lost from the nominal field of view. Furthermore, in the laboratory, the angular size of the radiant source is small, typically 10–20°, compared to the large angular size of the radiant source encountered in many industrial applications. This method cannot be applied to low-resolution direct-reading instruments because the signal is usually too small.

2.2 Direct Size-of-Source Measurements

Direct measurements of the size-of-source effect involve taking a source of uniform radiance and measuring the thermometer response with increasing aperture size. The signal, normalized to unity at the maximum aperture size, is plotted as a function of aperture diameter. An integrating sphere or large-diameter blackbody is usually used in the implementation of this method. This method has the advantage over the indirect method in that it can be applied to low-resolution direct-reading thermometers, but otherwise is not as sensitive and is more susceptible to noise than the indirect method. With the direct method, the measured radiation includes the effects of scattering both into and out of the field of view of the thermometer. In the laboratory, the angular size of the radiant source is normally less than 5°, which is very small compared to the >90° angular extent of the radiant source encountered in some industrial applications.

2.3 Scanning Method

The scanning method introduced here involves scanning a thermometer over a narrow radiant source, the same width as the measurement spot, and examining the residual signal collected from outside the specified field of view. The integrated response of the residual thermometer is a measure of the SSE.

This method has the advantage of having high resolution and being very fast, but a precision translation stage is required. A disadvantage of this technique is its relative insensitivity, making it susceptible to noise and difficult to apply to low-resolution direct-reading thermometers. In general, this technique is applicable to the same class of instruments as the indirect method.

In order to validate the scanning method and relate the results to the indirect method, a transform needs to be carried out on the indirect SSE data. Consider Fig. 1; in the indirect method, each contributing annulus, such as the one shown in light gray, is assumed to have radial symmetry. Each annulus can be broken up into a series of areas each with the same width as the slit, shown in dark gray. The area of a chord, A, with height h, for any circle of radius R, is

$$A(R,h) = R^2 \cos^{-1}\left(\frac{R-h}{R}\right) - (R-h)\sqrt{2Rh-h^2}. \tag{1}$$

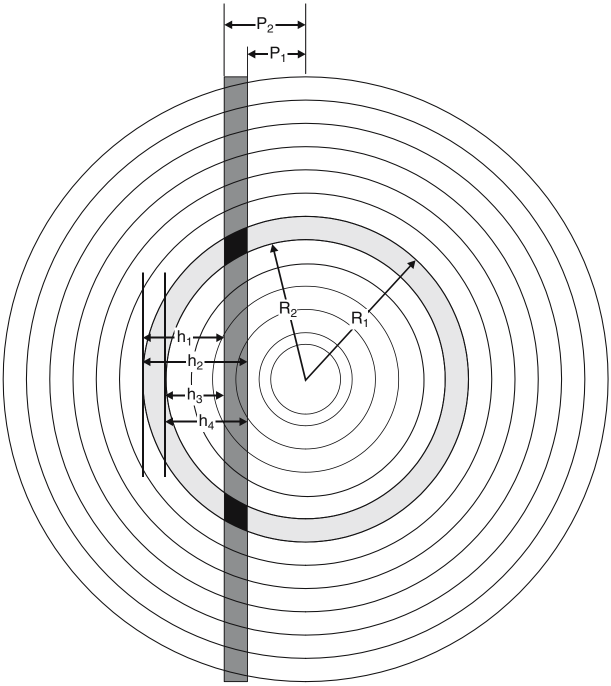

Fig. 1 Graphical representation of parameters used to transform indirect SSE results to the scanning method

By using this relation repeatedly, it is possible to determine the relative area of any segment in the annulus, for example, the one shown in black on Fig. 1. The sum of the segments along the slit then gives the relative contribution to the SSE for every slit position.

The h values can be determined from the slit positions P_1 and P_2 using Eqs. 2–5 below, where P_1 is the distance to the inside edge of the slit and P_2 is the distance to the outside edge of the slit from the center of the thermometer's FOV, as show in Fig. 1.

$$h_1 = R_1 - P_2 \quad (2)$$

$$h_2 = R_1 - P_1 \quad (3)$$

$$h_3 = R_2 - P_2 \quad (4)$$

$$h_4 = R_2 - P_1 \quad (5)$$

The contribution to the total signal for any segment, i, is then given as

$$S_i = \frac{[A(h_2, R_1) - A(h_1, R_2)] - [A(h_4, R_2) - A(h_3, R_2)]}{\pi\left(R_1^2 - R_2^2\right)} \times \left[SSE_{\mathrm{Ind}}(R_1) - SSE_{\mathrm{Ind}}(R_2)\right]. \quad (6)$$

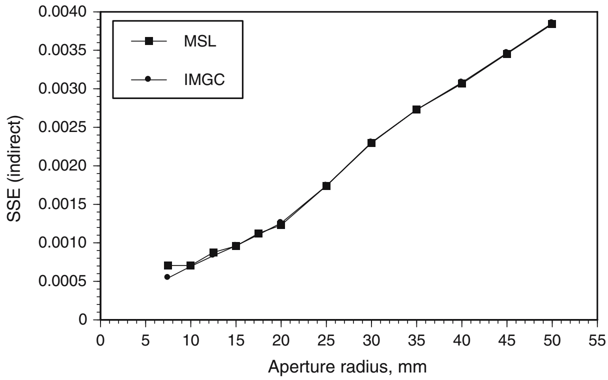

Fig. 2 MSL and IMGC indirect SSE data, taken five years apart

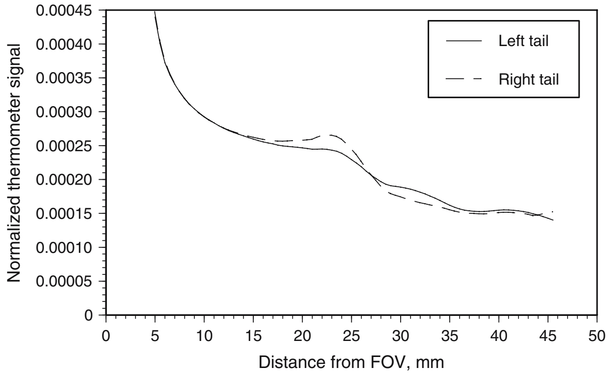

Fig. 3 Residual signal detected from outside of the specified 5 mm FOV of the thermometer

The contribution from each segment S_i for each P_1 position is then summed to give the transformed indirect SSE signal.

3 Results

The IMGC-TS2 thermometer is used as a primary radiation thermometer at MSL in New Zealand and has been well characterized at Istituto di Metrologia "Gustavo Colonnetti" in Italy (IMGC) (now Istituto Nazionale di Ricerca Metrologica (INRIM)) and at MSL. The thermometer operates at a wavelength of 1.6 μm and uses a temperature-controlled InGaAs detector. The measurement spot is specified as a 5-mm diameter circle, at 585 mm from the objective lens, giving an angular field of view of 0.49°.

Measurements of the SSE of the IMGC-TS2 thermometer using the indirect method, carried out at IMGC and MSL, are shown in Fig. 2. The measurements at MSL were made in 2005, and the IMGC measurements were made in 2000. The agreement between the two laboratories is extremely good, and shows a very good long-term stability of the SSE in this thermometer.

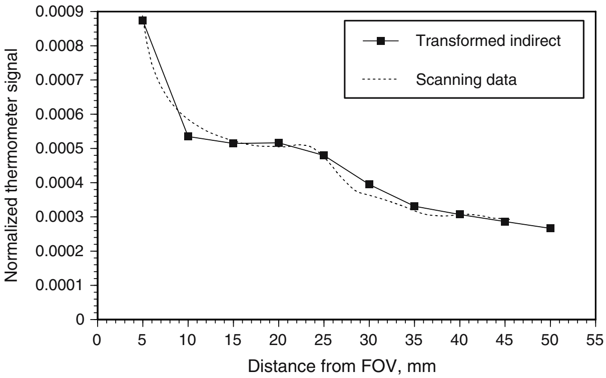

Fig. 4 Indirect residual SSE data after applying the transform, and scanning data

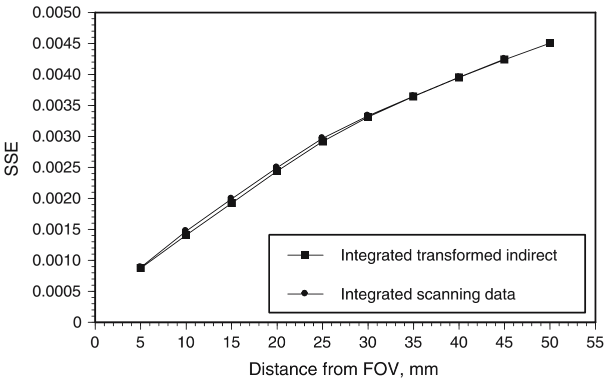

Fig. 5 Traditional SSE response for rectangular apertures obtained by integrating the curves in Fig. 4

For the scanning method, the thermometer was scanned across a 130 mm high, 5 mm wide slit, which was placed in front of a large-diameter integrating sphere. Figure 3 shows the residual signals from the left and right tails of the scan, as a function of position from the center of the slit. The data have been normalized to the integrating sphere radiance, by dividing each point by the signal measured directly from the center of the slit. The curve shows that the SSE behavior of the thermometer is quite symmetrical, suggesting that scratches or asymmetric defects are not the predominant cause of the SSE in this case.

The SSE data obtained using the scanning technique is compared in Fig. 4 to that from the indirect method. The scanning data is the sum of the two tails given in Fig. 3, and the indirect curve is obtained by transforming the data of Fig. 2 using the method outlined in Sect. 2.3. The data for each method are in excellent agreement, giving confidence that the scanning and indirect methods produce the same result.

Figure 5, which presents the same data as Fig. 4, but in a more traditional manner, shows the total signal obtained by integrating the data of Fig. 4. This gives an equivalent SSE for a series of rectangular apertures, each 130 mm high with the width increasing in 5 mm steps. The different aperture shapes explain the differences between Figs. 2 and 5.

4 Discussion and Conclusions

The scanning method introduced here shows promise as a simple technique, equivalent to the indirect method, to determine the SSE. The scanning method has several advantages over the indirect method, including speed and the ability to produce high-resolution angular data at much larger effective radii than the indirect method. The technique is also well suited to automation, which is difficult to apply to the indirect technique.

Further research is required to simplify the transformation between the indirect and scanning methods, and to find the inverse transform. In addition, further experiments could be performed to determine the effect of changing the height of the slit to map out the complete angular response of a thermometer in the viewing plane for a more complete characterization. A long-term goal is to automate SSE measurements for industrial thermometers.

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