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SIZE OF SOURCE EFFECT OF A TRANSFER REFERENCE THERMOMETER SUITABLE FOR INTERNATIONAL COMPARISONS NEAR TO ROOM TEMPERATURE

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Abstract − We measured the size-of-source-effect (SSE) of a transfer reference thermometer (TRT) for the low-temperature mode with the spectral range from 8 μm to 14 μm by using the direct method. The measurements were carried out for various blackbody temperatures from 10 °C to 300 °C. The size of source changed from 10 mm to 80 mm in diameter. Taking the radiation from the masked area of the aperture plate and its surroundings into account, we observed that the SSE curves measured at various temperatures overlaps well. The SSE functions show a two-step saturation behaviour unusually. Excluding the data obtained near the room temperature, the values of the SSE functions agrees within 0.05 %.

Keywords: radiation thermometry, size of source effect, international comparison

1. INTRODUCTION

Now radiation thermometry is widely being used near room temperature. The SSE is one of the most important systematic errors in calibration of a radiation thermometer and its application to a practical temperature measurement. As the temperature range decreases and the sensing wavelength increases, the uncertainty is getting more important. Especially when the national metrology laboratories are to compare the radiance temperature scale by measuring the blackbodies with different aperture diameters, the SSE might be one of key factors limiting the agreement so that it should be known to make the correction.

The SSE has been defined as dependence of the detector signal of a radiation thermometer on the diameter of a target such as a blackbody with a spatially uniform radiance source. In the geometrical point of view, the detector does not collect the radiation from outside the nominal target size defined by the field-of-view (FOV). The FOV is determined by the optics and the detector size of the radiation thermometer at the target plane. In practical, however, the intensity of the detector signal is increased by emission from outside the nominal target size due to aberrations of the optics, light scattering inside or outside the instrument, multiple reflections on relevant surfaces, and diffraction at the system apertures [1, 2]. Diffraction of these causes mainly contributes to the SSE and is critically dependent on the wavelength and the field stop size of the thermometer.

In this study, we measured the SSE of the TRT for the low-temperature (LT) range with the spectral range from 8 μm to 14 μm by using the direct method [3-5]. The measurements were carried out for various blackbody temperatures from 10 °C to 300 °C. The SSE functions were incorporated to take an averaged function and know a degree of agreement. Because the TRT has been used as a transfer standard for the EUROMET comparison, the averaged SSE function will be useful for an international comparison in the future.

2. MEASUREMENT EQUATION

In low temperature region, The SSE measurement requires a blackbody and circular aperture plates with different openings. These aperture plates are placed in front of the blackbody to act as apertures of the blackbody. The thermometer under test is co-axially focused on the center of the aperture plate to measure the output signal or readout for each aperture plate. Since the aperture plate& holder is set to the temperature T_b of the surroundings (see section 3.1) it effectively acts as a plate of infinite extension with an aperture of diameter D, and held at room temperature T_b.
We denote the actual signal generated by the source at the temperature T, encompassed by the aperture plate of infinite extension, with an aperture of diameter D, and held at room temperature T_b, as $S(D,T,T_b)$. We denote the signal generated by the (virtual) source of infinite extension and held at the temperature T as $S(\infty,T) \equiv S(T)$. We denote the signal generated by the (virtual) source at the temperature T, encompassed by the aperture plate of infinite extension, with an aperture of diameter D, and held at a temperature of 0 K, as $S(D,T,0) \equiv S(D,T)$.

The SSE function $\sigma(D)$ at a certain diameter D is defined as: [3]

$$\sigma(D) \equiv \frac{S(D,T)}{S(\infty,T)}. \tag{1}$$

From the notation, we obtain:

$$S(D,T,T_b) = S(D,T,0) + S(D,0,T_b). \tag{2}$$

By the definition (1),

$$S(D,T,0) = \sigma(D) \cdot S(T), \text{ and} \tag{3a}$$

$$S(D_m,T,0) = \sigma(D_m)\cdot S(T), \tag{3b}$$

Combining (2) and (3) yields:

$$\sigma(D) = \{S(D,T,T_b) - S(D,\ 0,T_b)\}\ /\ S(T), \text{ and} \tag{4a}$$

$$\sigma(D_m) = \{S(D_m,T,T_b) - S(D_m\ ,0,T_b)\}/\ S(T). \tag{4b}$$

Dividing (4a) by (4b) gives:

$$\frac{\sigma(D)}{\sigma(D_m)} = \frac{S(D,T,T_b) - S(D,0,T_b)}{S(D_m,T,T_b) - S(D_m,0,T_b)} \tag{5}$$

From (2), we obtain:

$$\begin{aligned} S(D,T_b,T_b) &\equiv S(T_b) \\ &= S(D,T_b,0) + S(D,0,T_b) \\ &= \sigma(D)\cdot S(T_b) + S(D,0,T_b) \end{aligned} \tag{6}$$

and

$$S(D,0,T_b) = \{1 - \sigma(D)\}\cdot S(T_b). \tag{7}$$

Substituting (7) into (5) yields:

$$\frac{\sigma(D)}{\sigma(D_m)} = \frac{S(D,T,T_b) - \{1-\sigma(D)\}\cdot S(T_b)}{S(D_m,T,T_b) - \{1-\sigma(D_m)\}\cdot S(T_b)}. \tag{8}$$

Because the SSE is usually measured as a function of source diameter D in the finite range of which diameter is less than D_m, the truncated SSE was introduced as: [3]

$$\sigma(D,D_m) \equiv \frac{S(D,T)}{S(D_m,T)} = \frac{\sigma(D)}{\sigma(D_m)}. \tag{9}$$

From (8) and (9), we can finally obtain:[6]

$$\sigma(D,D_m) \equiv \frac{S(D,T,T_b) - S(T_b)}{S(D_m,T,T_b) - S(T_b)}, \tag{10}$$

which is the same equation as in the reference[3]. Using Eq. (10), we can obtain the SSE values from the thermometer signals measured at various diameters and blackbody temperatures.

3. MEASUREMENT SETUP

3.1. Blackbody and aperture plates

The SSE measurement setup consists of two blackbodies, aperture plates and the plate holder with water-cooling. The blackbody (MIKRON, model: 385) has an aperture of 100 mm in diameter and emissivity of 0.9997 over the temperature range from 5 °C to 95 °C. The cavity is immersed in a stirred bath of deionized fluid and controlled with a set point resolution of ± 2 mK. The temperature stability and uniformity are ± 2 mK and ± 5 mK, respectively. Spectral emission is known to be essentially flat from 3 µm upwards [7].

The other blackbody (Isotech, Model: Gemini R) having an aperture of 65 mm in diameter can be set to 0.1 °C over the temperature range from 30 °C to 550 °C. The blackbody was used for the measurement over 95 °C. Its emissivity is known to be greater than 0.995. Temperature stability and uniformity are better than ±0.1 K.

To measure the SSE, we prepared 14 aperture plates with different opening sizes as shown in Fig.1. They include a dummy plate without an opening. These plates were made of 5 mm thick polyacetal resin with low thermal conductivity to avoid warming by radiation and convection from the blackbody. The aperture plate holder with 110 mm opening diameter and 10 mm in thickness was made of copper and cooled to room temperature, (24±0.3) °C, by circulating water, effectively resulting in an aperture plate of infinite extension, with an aperture D, and held at room temperature. These aperture plates and its holder were blackened by Nextel® paint with emissivity of 0.975 over the wavelength range from 8 µm to 14 µm. The aperture holder was placed at 30 mm distance apart from the front of the blackbodies. Finally, the front of the aperture plate was placed at 45 mm apart from the front of the blackbodies.

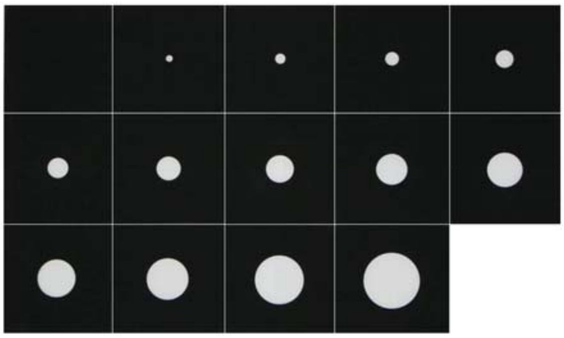

Fig. 1. Aperture plates darkened with Nextel® paint.

3.2. Reference thermometer under test

The TRT (Heitronics, Germany, Model TRT-2) operates in two temperature ranges: LT ranges from -50 °C to 300 °C and the medium temperature (MT) ranges from 150 °C to 1,000 °C. While the spectral range is from 8 µm to 14 µm for the LT range, it centers at 3.9 µm with a bandwidth of 0.4 µm for the MT range. The TRT uses a pyroelectric detector and zinc selenide lens to cover the spectral range from 3 µm to 15 µm. FOV in diameter is 5.8 mm at the measuring distance of 390 mm for the MT range and 7.4 mm at the measuring distance of 420 mm for LT range, respectively.

The TRT can display the output in terms of temperature or radiation intensity. The intensity output is acquired using a computer via a RS-232C interface controlled by home-made software. The response time of 3 s is chosen for the best temperature resolution of 0.02 °C.

To our knowledge, the TRT have the best temperature resolution and precision of the radiation thermometers commercially available. It is reason why the TRT has been used as the transfer standards in the EUROMET comparison and is being considered as the transfer standard in the future APMP comparison.

4. RESULS

We decided to set the aperture plate temperature to 24 °C since the ambient temperature is controlled at (24±0.3) °C. Before measuring the SSE, we inserted an aperture plate into the holder and keep it in the blocked part of the holder until the aperture plate temperature is stabilized to 24°C. Usually after 5 min, the aperture plate was moved so that its center is aligned to the center of the plate holder.

The TRT signal was acquired in terms of radiation intensity with a response time of 3 s for the best resolution.

We took 5 readings for each aperture plate within only 30 s to avoid temperature rise of the aperture plate by radiation and convection flow from the blackbody. The measurement proceeded as increasing the aperture diameter. Ten sets of data for each aperture plate were obtained to take the averages. The measurement was carried out for various blackbody temperatures from 10 °C to 300 °C.

Figure 2 shows the normalized signal $S(D,T,T_b)/S(60,T,T_b)$ of the TRT in the LT range for 8 different blackbody temperatures. The aperture diameters were changed from 9.8 mm to 80 mm. The signals were normalized with respect to the signal for the diameter of 60mm. The signals include the radiance contribution from the aperture plate.

At the blackbody temperature of 24°C, the signal intensity was nearly same for every aperture plate as we expected. It is because in any case the source + aperture plate& holder act as a source at temperature T_b and of infinite extension. At temperatures of 10 °C and 20 °C below the ambient, the signal intensity was increasing as the diameter was getting smaller since the radiation from aperture plates is stronger than that from the blackbody. For temperatures above 24 °C, reversely, the signal intensity was decreasing as the diameter was getting smaller. As the blackbody temperature increased, the signal intensity became closer and closer since the radiation from the blackbody became more dominant compared to that of the aperture plate. Finally they will coincide when the radiation from the aperture plate can be neglected.

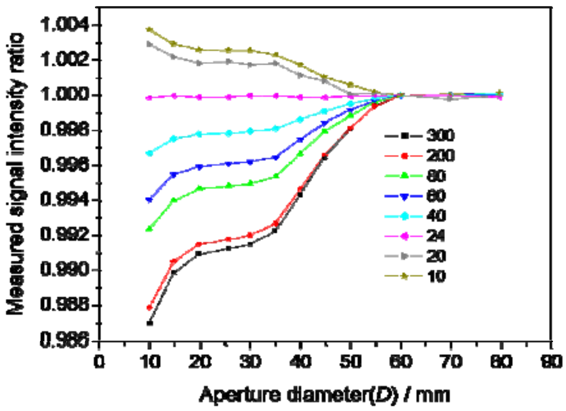

Fig. 2. Normalized TRT signal intensity for LT range with respect to the intensity for the aperture diameter of 60 mm.

Fig. 3 shows the truncated SSE of the TRT for the LT range, corrected for background radiation, obtained from Eq. (10), where D_m is chosen as 60 mm. It is reduced from data in Fig. 2 and the thermometer signals $S(T_b)$ obtained by measuring the black plate without opening at every temperature setting of the blackbody.

We excluded the data obtained at 24 °C in Fig. 3 because it is trivial. Even if the SSE functions obtained near the ambient temperature such as at 10 °C and 20 °C shows large scatter, the curves overlaps well. The large scatter occurs because their signal intensities are comparable to that of the aperture plate. Therefore, we also excluded these data in taking the averaged SSE function.

All curves show a clear two-step saturation behaviour which occurs near 20 mm and near 60 mm. In general, the signal is expected to show saturation after the source size becomes comparable to the minimum target size (7.4 mm in our case). The second increase and saturation of the SSE in Fig. 2, however, indicates that there exists another critical size which influences the SSE. We are investigating the origin of this two-step saturation by varying the effective size of the objective lens (40 mm in diameter) and by calculating the diffraction in the measurement geometry. Also interreflection effects between the optical components of the TRT may influence the shape of the SSE curve.[8]

The value of SSE curves above 40 °C agrees with each others over the diameter range from 9.8 mm to 80 mm. The agreement is within 0.05% in terms of standard deviation, which is equivalent to 30 mK at the room temperature. The averaged SSE function will be given for correction when the TRT will be used as a transfer standard of international comparisons.

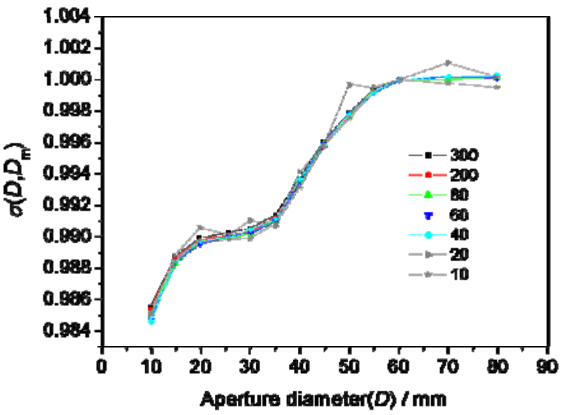

Fig. 3. Truncated SSE of TRT for LT range corrected with the background signal from aperture plates.

5. CONCLUSIONS

The size-of-source effect (SSE) of the TRT is measured by the direct method using blackbodies and apertures whose temperature is carefully controlled. We confirmed that all experimental conditions are well under control by observing constancy of the SSE curve obtained at the ambient temperature condition. We measured the SSE for the blackbody temperature from 10 °C to 300 °C. Correcting for the background radiation of the aperture plate&holder and of the surroundings, we observed that the truncated SSE functions obtained for various source temperatures overlapped well. Excluding the data near the ambient temperature, the values of the SSE curve agrees within 0.05 % in terms of relative standard deviation.

To our knowledge, the TRT have the best temperature resolution and precision of the radiation thermometers commercially available. It is being considered as the transfer standard in the future APMP comparison. When the TRT will be used as a transfer standard of an international comparison, the averaged SSE function will be very useful information which will be given to the participants for correction.

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