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INFLUENCE OF SIZE OF SOURCE EFFECT ON ACCURACY OF LWIR RADIATION THERMOMETERS

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Abstract

Determining the size of source effect of a radiation thermometer is not an easy task and manufacturers of these thermometers usually do not indicate the deviation to the measured temperature due to this effect. It is one of the main uncertainty components when measuring with a radiation thermometer and it may lead to erroneous estimation of the actual temperature of the measured target. We present an empiric model to estimate the magnitude of deviation of the measured temperature with a long-wavelength infrared radiation thermometer due to the size of source effect. The deviation is calculated as a function of the field of view of the thermometer and the diameter of the radiating source. For thermometers whose field of view size at 90% power is approximately equal to the diameter of the radiating source, it was found that this effect may lead to deviations of the measured temperature of up to 6% at 200ºC and up to 14% at 500ºC. Calculations of the temperature deviation with the proposed model are performed as a function of temperature and as a function of the first order component of electrical signal .

Keywords: size of source effect, radiation thermometer, temperature, field of view.

1. Introduction

In the calibration of radiation thermometers and in technological and industrial applications where non-contact temperature measurements are required, one of the main uncertainty components is the *size of source effect* (SSE) [1]. The SSE is inherent in *radiation thermometers* (RT) and is caused by diffraction, scattering, reflections and aberrations of their optical components [2]. This originates from the fact that part of the radiation coming from regions outside the field of view specified by the manufacturer reaches the detector while part of the radiation within the focal zone does not.

Estimation of the SSE function can be carried out with direct, indirect or scanning methods [3], but there is not a normalized one that is versatile enough to cover all types of RTs [4]. Moreover, in most industrial applications these experimental methods are impractical and the equipment and conditions needed to carry out this kind of characterization is difficult to implement. Due to the above, many users of radiation thermometers either neglect this kind of effects or do not have the possibility of estimating the deviation of the measured temperature due to the SSE. Therefore, a deviation of the measured temperature exists and the temperature uncertainty budget is underestimated.

We present an empiric model that enables to estimate the magnitude of deviation of the measured temperature value due to the SSE for each radiating source whose diameter is at least equal to the thermometer field of view.

The model is based on the known parameters of most commercial LWIR (*Long-Wavelength Infrared*) RTs and on the experimental results where it has been found that most RTs have

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a specified field of view that covers around 90% of the radiation received by the detector coming from the focused region [5].

In the next sections we show the proposed model and the temperature deviations due to this effect calculated directly and as a function of the first order component of signal variation . The behaviour is shown for different temperatures and different cavity diameters and fields of view.

2. Model

When coming from a finite radiating source, part of the radiation hitting the thermometer comes from the surroundings. Ideally, to ensure that all the radiation received by the thermometer comes from the selected target, one would choose a source of infinite area. As one decreases the area of the source, part of the radiation that reaches the detector will come from regions other than the source. If the ratio of energy coming from a finite source and energy coming from an infinite source is known, for different source sizes, it is possible to find a function that describes the behaviour for any source size. This function is called SSE function and is commonly denoted by σ. It has been found experimentally that for a source with a diameter $D > 5d$, where d is the field of view of an RT at 90% power, the signal at the output of the detector reaches a maximum and the signal remains basically constant when the source diameter is increased [6].

The model we propose estimates the SSE function of an RT from the experimental values of the fraction of radiation coming from the focal zone of the RT.

In general, for most RTs, especially the commercially available ones, it has been found that the field of view specified by the manufacturer encompasses 90% of the radiation coming from the radiating source and that if the source diameter is doubled the RT encompasses around 95% of the radiation [6].

Taking the above into account, we propose the following expression for the SSE function:

$$\sigma(D/d) = 1 - \frac{2^{-\frac{D}{d}}}{5}, \qquad D \geq d\,, \tag{1}$$

where D is the radiating source diameter and d is the RT field of view specified at 90%.

Figure 1 shows a plot of (1) as a function of ratio D/d.

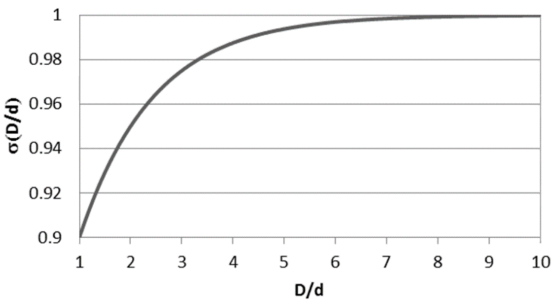

Fig. 1. Expression of the proposed SSE as a function of the source diameter/ field of view ratio, (1).

In Fig.1 the proposed SSE function can be further visualized. It takes a value of 0.9 when $D/d = 1$ and 0.95 for $D/d = 2$. When $D/d > 5$ the contribution of the SSE (less than 0.6%) is basically negligible. In the next subsections we describe an analytical procedure to calculate the deviations of the temperature measured with a RT by using (1).

2.1. Temperature deviations due to SSE for direct temperature reading thermometers

For temperatures below 1000ºC the signal of an RT is well described by the Sakuma-Hattori equation [7]:

$$S(T) = \frac{C}{e^{\frac{c_2}{AT+B}} - 1}, \tag{2}$$

where $c_2 = 0.0014388$ m·K is a value in the ITS-90 assigned to the second radiation constant and A, B and C are constants determined after calibration.

The signal generated at the output of the RT is a result of a fraction of radiation coming from the target and a fraction coming from the surroundings,

$$S(T) = \sigma S(T_i) + (1-\sigma)S(T_a) \text{ for } n = 1, \ldots, N, \tag{3}$$

where $S(T_i)$ is the signal coming from the target at temperature T_i and $S(T_a)$ is the signal coming from the surroundings at temperature T_a.

From (2) and (3) the deviation $\Delta T = T - T_i$ of the measured temperature, due to SSE, is expressed as follows:

$$\Delta T = \frac{c_2}{A}\left\{\ln\left[1 + \frac{1}{\dfrac{\sigma}{e^{\frac{c_2}{AT_i+B}} - 1} + \dfrac{1-\sigma}{e^{\frac{c_2}{AT_a+B}} - 1}}\right]\right\}^{-1} - \left(T_i + \frac{B}{A}\right). \tag{4}$$

By using (4) it is possible to estimate the deviation of the measured temperature due to the SSE for direct temperature reading RTs.

2.2. Temperature deviations due to SSE for direct temperature reading thermometers

Sometimes it is more useful to calculate the temperature variation as a function of the measured signal variation, following a procedure similar to that in [7]. In general, this relation is given by:

$$\Delta T = \frac{1}{\left.\dfrac{dS}{dT}\right|_{T=T_i}}\Delta S + \frac{1}{2!\left.\dfrac{d^2S}{dT^2}\right|_{T=T_i}}(\Delta S)^2 + \ldots + \frac{1}{n!\left.\dfrac{d^2S}{dT^2}\right|_{T=T_i}}(\Delta S), \tag{5}$$

where $\Delta S = S(T) - S(T_i)$ and $d^nS/dT^n\big|_{T=T_i} \neq 0$ for $n = 1,2,3\ldots\infty$.

If the signal at the output of the RT is not very deviated from the signal that should be obtained at temperature $T_i, \Delta S \approx 0$, it is possible to approximate the temperature variation taking only the first-order components on the right hand side of (5).

The first derivative that appears in (5) is given by:

$$\frac{dS}{dT} = \frac{Ac_2}{(AT+B)^2}\frac{S(T)}{1 - e^{-\frac{c_2}{AT+B}}}. \tag{6}$$

From (3) the relative variation of the measured signal due to SSE is given by:

$$\frac{\Delta S}{S(T_i)} = (\sigma - 1)\left(1 - \frac{S(T_a)}{S(T_i)}\right). \tag{7}$$

Inserting (6) and (7) into (5) we obtain the variation of temperature due to SSE for thermometers with the electrical output signal as the first-order component:

$$\Delta T_1 = -\frac{(AT_i + B)^2}{Ac_2}\left(1 - e^{-\frac{c_2}{AT_i + B_i}}\right)(\sigma - 1)\left(1 - \frac{S(T_a)}{S(T_i)}\right). \tag{8}$$

Although parameters A and B are still present in (8), this formula can be used to estimate the changes in temperature as a function of changes in electrical signal due to the SSE on measurements with a radiation thermometer.

3. Results

The plots shown below are for RTs operating in the wavelength range from 8 to 14 µm. The values of A and B are calculated as a function of the nominal upper and lower working wavelengths of the RT, as given in [8]. In this case A = 9.61 µm and B = 151 µm·K.

Figure 2 shows the variations in temperature as a function of the ratio D/d for different temperatures, calculated from the proposed model of the SSE. The (4) refers to direct temperature reading RTs, whereas (8) – to thermometers with the electrical output signal.

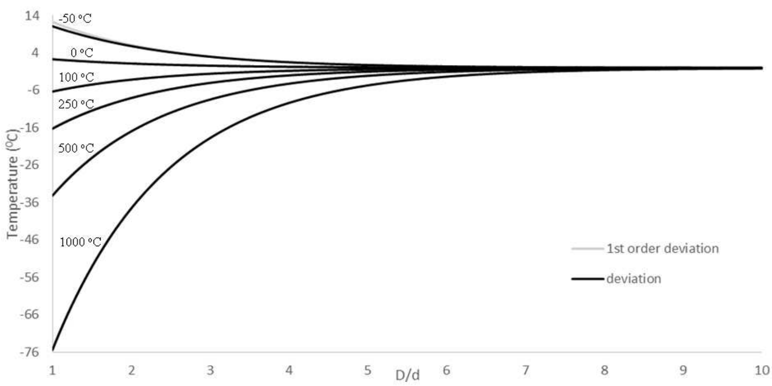

Fig. 2. The deviation of the temperature value due to SSE as a function of the *D/d* ratio, calculated from (4) for direct reading RTs and from (8) (the first order approximation) for RTs with the electrical output signal.

It can be seen in Fig. 2 that for a typical RT calibration at 250ºC, the SSE can lead to deviations of temperature of up to 16ºC. Also, for the *D/d* ratio value slightly larger than one, the SSE is not negligible, as is commonly suggested [8].

It can also be appreciated that the first-order approximation is not valid at low temperatures. This indicates that it is necessary to take into account higher order components in ΔS as temperature decreases, for RTs with the output signal. In Fig. 3 the variation calculated directly is compared with the one obtained by the first-order approximation, both as a function of temperature.

Figure 3 shows that the temperature from which the first-order approximation is valid is around –50ºC. As an example, thermometers with the spectral response in the 8 µm – 14 µm range have a temperature working range from –50ºC to 1000ºC. For this type of thermometers the first-order approximation is sufficient to estimate the temperature variation due to SSE.

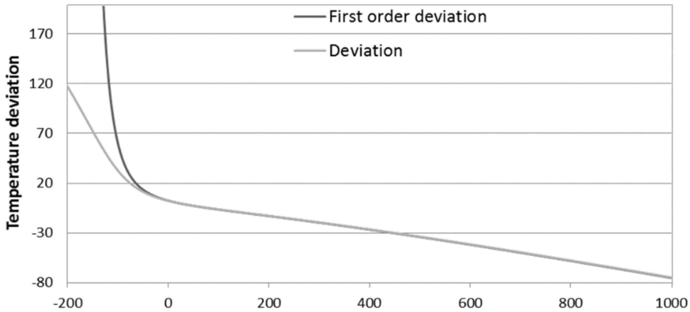

Fig. 3. Comparison of the calculated temperature deviation due to size of source effect for direct reading thermometers (4) and the one obtained by the first order approximation for thermometers with the electrical output signal (8). The room temperature was assumed to be 21ºC.

To estimate how accurate are the temperature deviations calculated with the proposed model from the real measurement results, Table 1 shows a comparison of the results calculated with the proposed model and the experimental results obtained from [4] for the SSE function of an RT with a 4.4 mm field of view specified at 90% power. Table 2 shows a similar comparison with the measurements performed in our laboratory of the SSE of a radiation thermometer with a nominal 1.8 mm field of view at 90% power.

Table 1. The normalized difference between the theoretical SSE function (σ_T) obtained from the proposed model and the SSE obtained experimentally (σ_E) from [4].

D/d	40ºC $\frac{\sigma_E-\sigma_T}{\sigma_E}$	133ºC $\frac{\sigma_E-\sigma_T}{\sigma_E}$	533ºC $\frac{\sigma_E-\sigma_T}{\sigma_E}$
2.2	2.8%	–0.3%	–1.0%
2.4	3.1%	1.4%	1.0%
2.6	2.8%	1.5%	1.1%
3.1	2.5%	1.4%	1.1%
3.5	1.9%	1.1%	0.8%
4.4	1.3%	0.8%	0.6%
5.5	0.7%	0.3%	0.1%
6.7	0.2%	0.1%	–0.1%
8.9	0.0%	0.0%	–0.1%

Table 2. Normalized difference between the theoretical SSE function (σ_T) from the proposed model with the SSE obtained experimentally (σ_E) for the Raytek thermometer 1.8 mm field of view at 90% power.

D/d	985ºC $\frac{\sigma_E-\sigma_T}{\sigma_E}$
1.35	6.6%
2.71	2.5%
5.42	0.2%
8.13	0.0%
13.55	0.0%

Similarly to the procedure followed for the two thermometers shown above, the model was tested with the radiation thermometers shown in Table 3. The relative deviation for these thermometers, $\frac{\sigma_E - \sigma_T}{\sigma_E}$, is within 6%, with the target placed at the focusing distance and the field of view considered as appearing in the table below.

Table 3. The list of commercial IR thermometers tested in our laboratory with the proposed model.

Brand and model	Spectral response (µm)	Emissivity	Distance to target (mm)	Field of view* (mm)
Craftsman 50466	6 to 14	Fixed at 0.95	100	13
Extech 42540	6 to 14	Adjustable 0.1 to 1	320	20
Extech 42545	8 to 14	Adjustable 0.1 to 1	640	13
Fluke 62 Max	8 to 14	Adjustable 0.1 to 1	640	13
Fluke 68	8 to 14	Adjustable 0.1 to 1	300	19
Fluke 574	8 to 14	Adjustable 0.1 to 1	300	6 **
Omega OSXL450	7 to 18	Fixed at 0.95	153	26
Omega OSXL653	5 to 14	Adjustable 0.1 to 1	250	34
TPI 384	7 to 14	Adjustable 0.1 to 1	150	20

* at 90% power;
** closed focus option.

We want to notice that the purpose of the presented model is not to give exact corrections to the measured temperature with a radiation thermometer. Its usefulness is now apparent in actual measurements with an RT, in the field or the laboratory. If the user does not have information about the SSE function to make the proper corrections to its measurements, (1) enables to estimate the magnitude of deviation of the measured temperature due to the SSE. It follows from Table 1 that the estimated theoretical values obtained by using the proposed model are accurately showing a relative deviation between 0.1% and 7% with respect to the experimental measurements with an RT.

We also notice that, although we concentrated here on LWIR radiation thermometers, the model can be extended on thermometers with different working wavelengths.

4. Conclusions

An empiric model for estimating the deviations of temperature measured with a radiation thermometer due to the size of source effect was presented. By knowing the field of view provided by the manufacturer and the diameter of the radiating source, it was shown how to use the proposed model to estimate the magnitude of deviation of the temperature measurements. We presented analytical expressions for both types of thermometers, those with direct temperature readings and those with the electrical output signal.

The practical usefulness of the proposed model was illustrated with examples of thermometers with the spectral responsivity in the 8–14 µm range.

We notice that the presented model can be useful for secondary laboratories or users that either do not have the equipment suitable to measure the size of source effect or do not have the information required to estimate the uncertainty due to this effect.

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