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MEASUREMENTS OF THE SIZE OF SOURCE FOR PYROMETERS DIRECTLY INDICATING IN TEMPERATURE

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Abstract – The calibration of radiation thermometers requires knowledge of the target size effect on the thermometer output, namely the size of source effect (SSE). The measurement of an instrument SSE allows to calculate a correction, or an estimation for this source of uncertainty. For a correct determination of SSE it is necessary to use large aperture radiation sources of uniform spectral radiance. We show here an experimental system to measure SSE at high temperature (up to 600 °C) with an enough large aperture of broad band radiation thermometer with output in terms of temperature.

Keywords: SSE, large aperture, high temperature

1. INTRODUCTION

The signal from a radiation thermometer (RT) can be shown experimentally to depend on the target size. At different distances, a RT will have different nominal target sizes, depending on the field of view defined by the optics. Ideally, a correct measurement is performed when the nominal field of view is completely filled by the target to be measured. In practice, this is not possible due to the limitations of the optics of a RT. As a result of the inclusion of radiation originating outside the nominal target area and the loss (e. g. scattering) of radiation originating from within it, the temperature indicated will depend on the size of the source. This phenomenon is known as the size-of-source effect, or SSE. The SSE is a consequence of radiation scattering by dust particles, reflections between lens surfaces, diffraction, and aberrations in the optical system of a RT [1].

Usually, two methods are used to measure SSE: the direct and the indirect method [2], [3]. In the direct method, the radiation thermometer is focused on a circular aperture placed in front of a stable radiation source, usually a blackbody. The SSE at the radius r, $\sigma(r)$, is determined as the ratio between the signal $S(r,L)$ at the radius r and the signal $S(\infty,L)$ at the infinite radius:

$$\sigma(r) = \frac{S(L,r)}{S(L,\infty)} \tag{1}$$

For a correct determination of the SSE, it is necessary to use a radiation source of uniform spectral radiance with an aperture much larger than the nominal target size of the RT.

Many radiation thermometers, especially the commercial thermometers, which operate in the infrared spectrum, have a large nominal target size (e.g. ∅ 10 mm), so they are calibrated with typically ∅ 30 mm radiation sources (calibration radius r_c = 15 mm). In order to measure the SSE, we need radiation sources enough large for these thermometers. Even more, if we have a large aperture radiation source at high temperature (high enough to allow the background radiation being neglected), we will be able of establish any dependence of the SSE on the temperature of the source.

2. EXPERIMENTAL SETUP

The equipment used to measure the SSE by the direct method consists of a home-made high aperture blackbody working up to 600 °C (see figure 1)

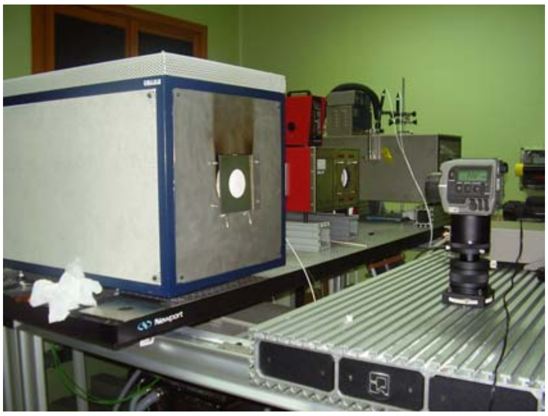
The blackbody cavity is cylinder-conical and it is made of stainless steel painted with pyromark®. The dimensions of the cavity are:

- 40 cm long
- cone angle of 120º
- aperture diameter of 7 cm (more details are given in figure 1)

This blackbody cavity is inserted in a three zone furnace. The stability and the uniformity of the furnace have been measured with a type K thermocouple and they are shown in figure 2.

The thermocouple is placed between the cavity and the ceramic cylinder of the furnace and can be inserted across the front of the furnace or across the back of the furnace, in order to avoid the conduction lost.

A HP3458A has been user to measure the electromotive force (emf) of the thermocouple.



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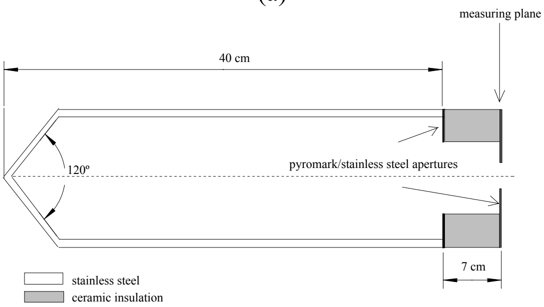

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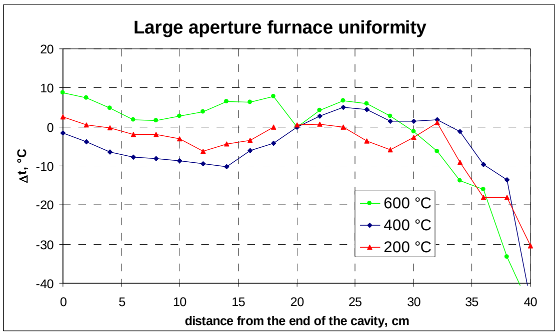
Fig. 1. Large aperture furnace used to measure SSE. (a) The furnace (b) The blackbody placed inside the furnace.



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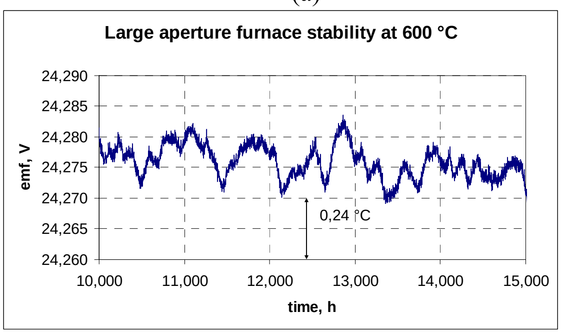

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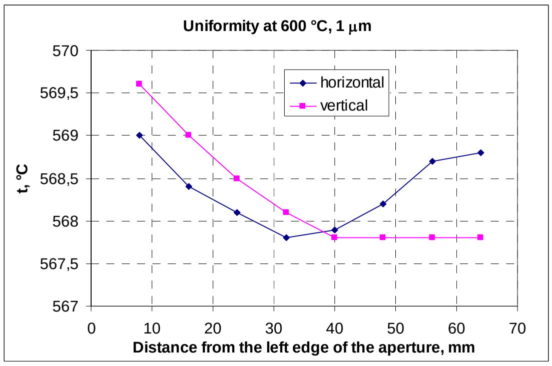
Fig. 2. (a) Large aperture furnace uniformity at 200 °C, 400 °C and 600 °C. (b) Large aperture furnace stability at 600 °C

The radiation uniformity at the aperture was measured for the 70 mm aperture diameter at 600 °C and the results obtained at 1 µm and 10 µm wavelengths are shown in Fig. 3.

The SSE has been measured for two RT:

- LAND C300 with an effective bandwidth of 8 – 13 µm (central wavelength of 10,5 µm) and a nominal target radius of 4,5 mm at a distance of 48 cm between the source and the RT lens.

- RAYTEK RAYMX4PCFS with a effective bandwidth of 8 – 14 µm (central wavelength of 11 µm) and a nominal target radius of 3 mm at a distance of 30 cm between the source and the RT lens.



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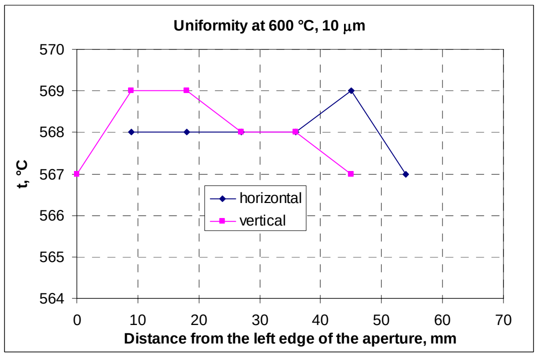


(b)

Fig. 3. Radiation uniformity for the 70 mm aperture. (a) 1 µm (b) 10 µm.

3. RESULTS

In order to ease the use of the SSE results for the customers, (1) can be referred to the calibration source radius r_c = 15 mm:

$$\sigma(r, r_c) = \frac{S(L, r) - S(L, r_c)}{S(L, \infty)} \qquad (2)$$

where $S(L,r_c)$ is the thermometer signal measured with an aperture of radius equal to the calibration source radius.

Commercial infrared thermometers usually have no access to the signal of the detector, but they display the temperature measured instead. So, using Planck law, we can express (2) as:

$$\sigma(r,r_c)=\frac{\frac{1}{e^{c2/\lambda T(r)}-1}-\frac{1}{e^{c2/\lambda T(r_c)}-1}}{\frac{1}{e^{c2/\lambda T(\infty)}-1}} \qquad (3)$$

where $T(r)$, $T(r_c)$ and $T(\infty)$ are the temperature measured in kelvin for apertures of radius r, r_c and ∞, respectively, and it is assumed that the variation of the effective emissivity with radius can be neglected.

In practice, we cannot realize infinite radius, so in the calculus below, it will be consider the measurement done at the aperture of maximum radius.

The expression of the combined standard uncertainty for $\sigma(r,r_c)$ is obtained from (3) using the law of propagation of uncertainties:

$$u^2(\sigma(r,r_c))=s_1{}^2u^2(r)+s_2{}^2u^2(r_c)+s_3{}^2u^2(T(\infty))+ + s_4{}^2u^2(T(r_c))+s_5{}^2u^2(T(r)) \qquad (4)$$

Where the sensitivity coefficients s_1, s_2, s_3, s_4 and s_5 are:

$$s_1=\frac{\partial\sigma}{\partial r}=-a\times b\times e^{b\times(r_c-r)} \qquad (5)$$

$$s_2=\frac{\partial\sigma}{\partial r_c}=a\times b\times e^{b\times(r_c-r)} \qquad (6)$$

$$s_3=\frac{\partial\sigma}{\partial T(\infty)}=\sigma\frac{\frac{c_2}{\lambda T^2(\infty)}e^{c2/\lambda T(\infty)}}{e^{c2/\lambda T(\infty)}-1} \qquad (7)$$

$$s_4=\frac{\partial\sigma}{\partial T(r_c)}=\frac{-1}{\left(e^{c2/\lambda T(r_c)}-1\right)^2}\frac{\frac{c_2}{\lambda T^2(r_c)}e^{c2/\lambda T(r_c)}}{\left(e^{c2/\lambda T(\infty)}-1\right)^{-1}} \qquad (8)$$

$$s_5=\frac{\partial\sigma}{\partial T(r)}=\frac{1}{\left(e^{c2/\lambda T(r)}-1\right)^2}\frac{\frac{c_2}{\lambda T^2(r)}e^{c2/\lambda T(r)}}{\left(e^{c2/\lambda T(\infty)}-1\right)^{-1}} \qquad (9)$$

For obtaining (5) and (6) it has been used a fit of the experimental data to the equation:

$$\sigma(r,r_c),\% = a\times(1-e^{b\times(r_c-r)}) \qquad (10)$$

The precision of the fit when taking the nominal values of temperatures defined in (3) is small enough so that it can be neglected in the uncertainty calculus.

The values obtained in the fits for both thermometers are:

Table 1.- Parameters of equation (10) obtained for both thermometers

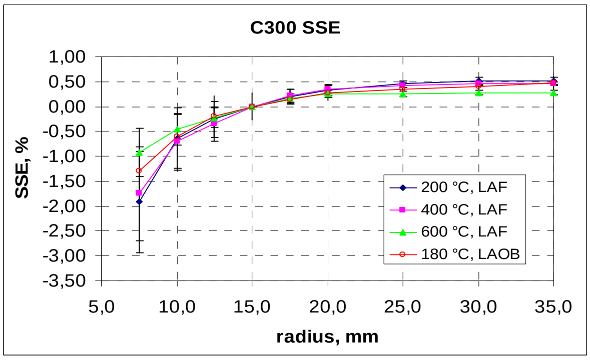
	C300 RT		RAYTEK RT	
	a	***b***	***a***	***b***
200 °C, LAF	0,456	0,214	0,751	0,199
400 °C, LAF	0,463	0,207	1,052	0,170
600 °C, LAF	0,298	0,189	0,933	0,190
180 °C, LAOB	0,432	0,187	0,581	0,322

The uncertainties are estimated as:

- $u(r_c)$, $u(r)$: standard uncertainty due to the aperture radius. It is a combination of: the error due to the measurement of the actual radius of the aperture, the difference between the actual radius and the effective radius (defining the radius of a source of uniform radiance, inducing a thermometer signal, equal to the signal, as observed for the actual, non uniform source) calculated for the blackbody aperture and the uncertainty of the calculation of the effective radius. It has been obtained a combined uncertainty of 0,75 mm.
- $u(t(\infty))$: Standard uncertainty of the measurement of the temperature for the maximum radius aperture. It has been considered the lack of radiation uniformity of the blackbody. The maximum variation of the temperature at the aperture for 10 µm thermometers is 3 °C.
- $u(t(r_c))$, $u(t(r))$: Standard uncertainty of the measurement of the temperature for the aperture. It has been consider the maximum of: furnace stability at the measurement temperature or the thermometer resolution. As they are rectangular distributions the maximum value is divided by √12

The results obtained for the LAND RT at 200 °C, 400 °C and 600 °C are shown in figure 4 and for the RAYTEK RT are shown in figure 5. Lines between points only connect data, they do not represent equation (10)

To validate the method used, the thermometers have been measured using another large aperture blackbody available at the laboratory: a blackbody inserted inside an oil bath. The background radiation has been neglected again. The results are shown in figure 4 and 5, too.



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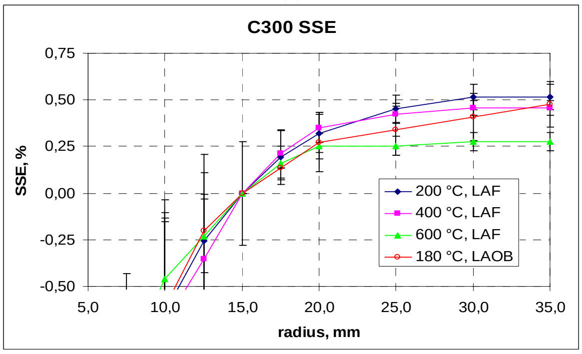

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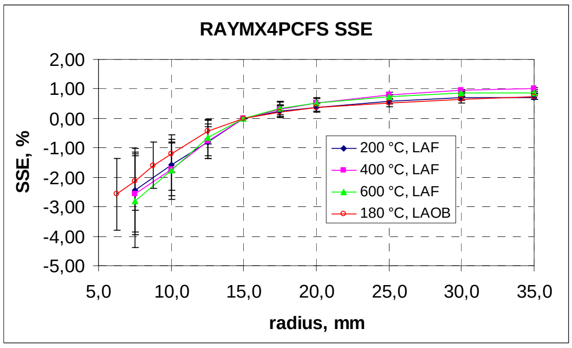
Fig. 4. Results of SSE for C300 RT. LAF: large aperture furnace; LAOB: large aperture oil bath. (b) is a zoom of (a).



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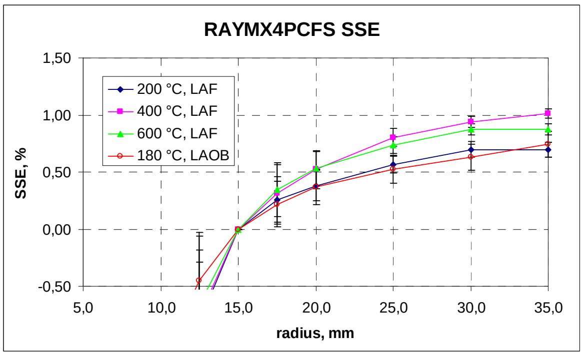

(b)

Fig. 5. Results of SSE for RAYTEK RT. LAF: large aperture furnace; LAOB: large aperture oil bath. (b) is a zoom of (a).

As we can see in figures 4(a) and 5(a), we measure nearly the same SSE at different temperatures, except for the smallest radius. It seems that SSE is higher when temperature is lower for LAND RT and when temperature is higher for RAYTEK RT, but, because of the large uncertainty (calculated with (4)) involve at smaller radius and the intrinsic error of the measurement method (i.e. different measurements at different blackbodies at the same temperature), we can not conclude this behaviour surely.

At figures 4(b) and 5(b), we can see that the uncertainty calculated with (4) is too low, because the results at the two blackbodies at the same temperature do not overlap. So, an additional uncertainty component due to the method should be added.

4. CONCLUSIONS

It has been measured the SSE of 10 μm commercial radiation thermometers with a large aperture blackbody (70 mm aperture diameter) at high temperature (up to 600 °C). The method has been validated using another large aperture blackbody working up to 180 °C.

It has been developed an uncertainty calculus for SSE.

For the thermometers used in the measurements (LAND C300 and RAYTEK RAYMX4PCFS), SSE does not depend on the temperature, considering the uncertainty calculated and the intrinsic error of the method (i.e. different measurements at different blackbodies at the same temperature).

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