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Citation: [AIP Conference Proceedings](#) **1734**, 130003 (2016); doi: 10.1063/1.4949213

View online: <http://dx.doi.org/10.1063/1.4949213>

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# Pyrometric Method for Measuring Emittances at High Temperatures

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**Abstract.** In this work an alternative method for emittance determination based on pyrometric measurements is presented. The measurement procedure has been applied to AISI 310S steel samples in the Plataforma Solar de Almería vertical axis solar furnace SF5. The experimental results show that emittance increases with increasing temperature and decreases with increasing wavelength. This behaviour is in agreement with experimental results obtained by other authors. Analysis of tests has revealed a good repeatability (1%) and accuracy (< 2%) of this measurement procedure.

## INTRODUCTION

Many industrial and scientific applications need to know the effectiveness of material surfaces in emitting energy as thermal radiation. Quantitatively, emittance (emissivity) is the ratio of the thermal radiation from a surface to the radiation from an ideal black body at the same temperature as given by the Stefan–Boltzmann law. The terms emittance and emissivity are often used interchangeably. There is, however, a technical distinction. Emissivity refers to the properties of a material; emittance to the properties of a particular object. The total thermal radiant energy emitted by an ideal black body is a function only of its absolute temperature. On the contrary, thermal radiant energy emitted by real material surfaces depends on many factors such as temperature, surface roughness, wavelength and viewing angle [1]. Emittance therefore depends on the same factors and may theoretically range from 0 to 1 but in real material surfaces usually varies from approximately 0.1 to 0.95.

In the last years, both experimental and analytical studies on the emittance measurement at low temperatures have been done and nowadays different approaches are possible [2, 3, 4]. Unfortunately many of these approaches are not applicable when working at high temperatures. In this case, there are more sophisticated methods based on the measurements of the temperature and the total or spectral radiance of the sample [5, 6].

In this work, an alternative method for emittance determination based on pyrometric measurements is presented. The measurement procedure has been applied to steel samples AISI 310S in the Plataforma Solar de Almería (PSA) vertical axis solar furnace SF5 [7].

## METHOD FOR EMITTANCE MEASUREMENT

Pyrometers and infrared cameras are non-contacting devices intercepting and measuring, in a certain wavelength band, thermal radiation emitted from an object to determine surface temperature. Emittance of a real surface in this wavelength band is:

$$\varepsilon_{\Delta\lambda}(T) = \frac{\int_{\lambda_1}^{\lambda_2} L_{\lambda}(T) d\lambda}{\int_{\lambda_1}^{\lambda_2} L_{b\lambda}(T) d\lambda} = \frac{\int_{\lambda_1}^{\lambda_2} \varepsilon_{\lambda}(T) L_{b\lambda}(T) d\lambda}{\sigma T^4 F_{\text{BAND}}(T)} \quad (1)$$

Where  $L_{b\lambda}$  is the black body spectral radiance,  $L_{\lambda}$  is the spectral radiance from the real surface and  $\sigma$  is the Stefan–Boltzmann constant.  $F_{\text{BAND}}(T)$  is the fraction of the total emissive thermal power emitted at a given temperature  $T$  in a spectral band  $\Delta\lambda=\lambda_1-\lambda_2$ :

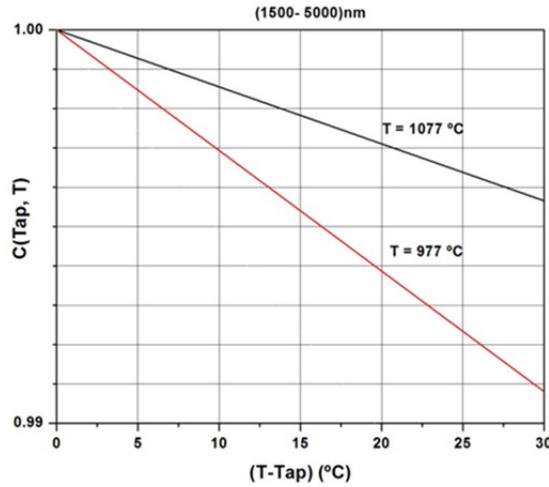
$$F_{\text{BAND}}(T) \equiv \frac{\int_{\lambda_1}^{\lambda_2} L_{b\lambda}(T) d\lambda}{\int_0^{\infty} L_{b\lambda}(T) d\lambda} = \frac{\int_{\lambda_1}^{\lambda_2} L_{b\lambda}(T) d\lambda}{\sigma T^4} \quad (2)$$

Setting the emissivity value of the pyrometric device at a constant value  $\epsilon_{\lambda}(T) = \epsilon_{\text{ap}}$ , and assuming that  $T_{\text{ap}}$  and  $T$  are very close:

$$\epsilon_{\Delta\lambda}(T) = \frac{\sigma \epsilon_{\text{ap}} T_{\text{ap}}^4 F_{\text{BAND}}(T_{\text{ap}})}{\sigma T^4 F_{\text{BAND}}(T)} = \frac{\epsilon_{\text{ap}} T_{\text{ap}}^4}{T^4} \quad (3)$$

Where  $T_{\text{ap}}$  is the apparent temperature supplied by the pyrometric device when an apparent emittance  $\epsilon_{\text{ap}}$  is fixed and  $T$  is the true or real temperature of the sample surface.

Some simulations of  $C(T_{\text{ap}}, T) = F_{\text{BAND}}(T_{\text{ap}})/F_{\text{BAND}}(T)$  reveal how this relationship may differ slightly from 1 under certain conditions and equation 3 then only would be an approximation.



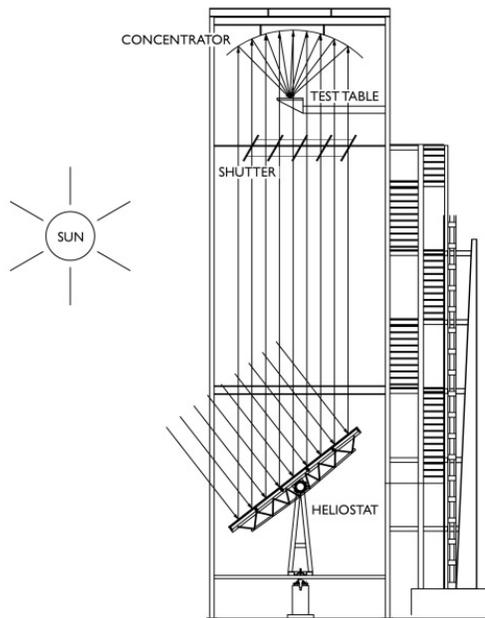
**FIGURE 1.** Factor  $C(T_{\text{ap}}, T)$  versus  $T-T_{\text{ap}}$ . Spectral range (1500-5000) nm

In the case to be described in this work, the temperature difference  $(T-T_{\text{ap}})$  is always less than 30 Celsius degrees and the deviation of the factor  $C$  from the unit is less than 1%, then equation 3 can be applied properly (Fig. 1).

## PSA VERTICAL AXIS SOLAR FURNACE SF5

The highest energy levels possible with a solar concentrating system are reached in solar furnaces, where concentrations of over 10000X have been attained. A solar furnace essentially consists of a flat solar-tracking heliostat, a parabolic collector mirror, an attenuator or shutter and the test zone located in the concentrator focus (Fig. 2). The flat collector mirror, or heliostat, reflects the solar beams on the parabolic dish, which in turn reflects them on the test area in its focus. The amount of incident light is regulated by the shutter located between the concentrator and the heliostat. A test table movable in three directions (East-West, North-South, up and down) places the test samples in the focus with great precision. The main advantage of vertical axis solar furnaces is that the samples are deposited, without the need of any fixation, on a horizontal plane where they can be treated directly in the focus.

This PSA vertical axis solar furnace SF5 is able to deliver up to 5 kW power at peak concentration ratios exceeding 7000 and focus size 25 mm diameter approximately. This solar furnace [7] has one 25 m<sup>2</sup> heliostat. The reflective surface of the heliostat, which is made up of 25 non-concentrating flat facets of 1 m<sup>2</sup> with reflectivity higher than 0.95 %, continuously tracks the solar disk and reflects its parallel vertical beams onto the concentrator.



**FIGURE 2.** Solar Furnace SF5 diagram

The concentrator dish, which concentrates the incident light from the heliostat, multiplying the radiant energy in the focal zone, is the main component of the solar furnace (Fig. 2). Its optical properties especially affect the irradiance distribution at the focus. It consists of 54 hexagonal, 25 cm radius facets of 1623.78 cm<sup>2</sup> surface. Its contour is quasi circular with 3.5 m diameter and a total area of 8.77 m<sup>2</sup>. For economic reasons, the facets are all identical, spherical curvature with a focal distance of 2 m and radius of curvature 4 m, double the focal distance.

The total energy in the focus is proportional to the radiation that passes through the louvered shutter, which is made up of 11 slats of 4 m long and 0.5 m wide under the test table, at 14 m above ground level. The slats are driven by a gear motor assembly which transmits its rotary movement to them through the straps, with a regulation accuracy of 0.1°. In the closed position the blades form an angle of 47.5° with the vertical, while fully open the angle is 0°. The attenuator can be operated manually from the control panel and in automatic mode from the control computer Data Acquisition System (DAS).

## EXPERIMENTAL SET-UP AND RESULTS

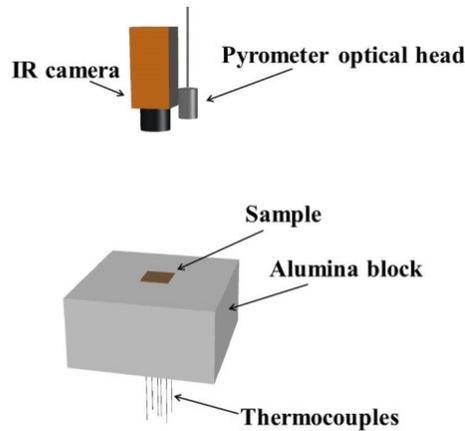
A commercial pyrometer based on an InGaAs photo diode infrared detector and a narrow band-pass filter allows working on 1400 nm [8]. A commercial IR camera based on an InSb detector works in the 1500-5000 nm spectral range and a software-controlled filter wheel enables the centered band-pass filters to be used on three additional narrow wavelength bands 1900, 3320 and 4720 nm [9].

Narrow bands centered on 2700 and 4300 nm should be excluded from this study as they represent strong atmospheric absorption bands of radiance which will distort the pyrometric temperature measurement and will cause a miscalculation of the emittance. The absorption band centered on 2700 nm is caused by the environment humidity and carbon dioxide, and the other one centered on 4300 nm is due to the single action of carbon dioxide.

Both instruments are perpendicularly placed at a distance of 1.5 m from the steel sample, intercepting and measuring thermal radiation emitted in the normal direction from a circle of approximately 10 mm diameter in the center of the sample surface (Fig. 3).

IR camera and pyrometer have been previously calibrated in front of a blackbody for the different filters at the same set-up distance and temperature range. A sample (40 x 40 mm, 3 mm height) of austenitic stainless steel for high temperatures, AISI 310S, is embedded in an alumina block (200 x 200 mm, 100 mm height) to achieve stationarity in thermodynamic variables. A group of first class type K thermocouples, 1.5 mm diameter x 500 mm long metallic sheath, allow measuring temperatures of alumina block and sample with an accuracy of  $\sigma_1 = \pm 0.004$  T

( $375\text{ °C} \leq T \leq 1000\text{ °C}$ ), according to the standard. Two of these thermocouples are embedded in the center of the back face of the sample at 0.8 mm of the interesting front face surface and separated 5 mm. The average temperature supplied by these two thermocouples is assumed as the real temperature of the sample surface in stationary conditions. This temperature measurement has an associated standard uncertainty  $\sigma_{av}$ .

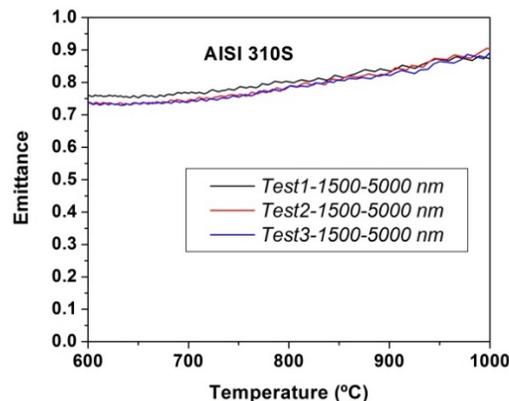


**FIGURE 3.** Overview of the experimental setup

A Testo<sup>®</sup> 608-H2 thermohygrometer allows continuous measurement of relative humidity ( $\pm 2\%$ ) and ambient temperature ( $\pm 0.5\text{ °C}$ ) close to the test table while a pressure transducer GMDU<sup>®</sup> measures the atmospheric pressure ( $\pm 0.2\%$ ).

This set-up is placed at the focus of the 5 kW PSA vertical axis solar furnace SF5 in order to reach very high temperatures in a few seconds on samples. After reaching the desired maximum temperature of  $1100\text{ °C}$ , the shutter closes totally to prevent solar influence and cool the sample. Moreover, the ambient radiation reflected from the sample can be considered negligible due to the high temperature of the sample. Measurements performed during cooling of the sample are considered for determining the emittance. Assuming a fixed value of 1 for the apparent emittance of pyrometric devices as a close value to the real emittance, tests have been performed using equation 3. The summary of results obtained for different tests is presented in the figures 4 and 5.

Figure 4 shows the high repeatability (1%) of the measurement procedure. Figure 5 is obtained by selecting tests performed with different band-pass filters and taking emittance values at the same temperature but with different wavelengths. The data show that AISI 310S emittance increases with increasing temperature (Fig. 4 and 5) and decreases with increasing wavelength (Fig. 5). Would expect a change in the position of the peak in the spectral emittance changing temperature but low spectral resolution does not allow this. These results are consistent with the limited data available in the literature [6].



**FIGURE 4.** Emittance vs. Temperature

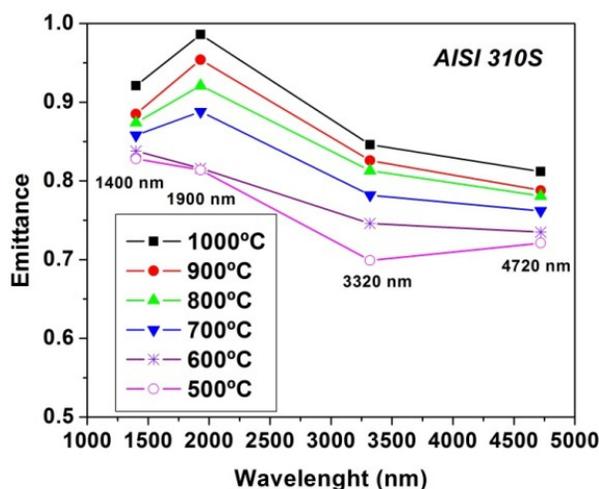


FIGURE 5. Emittance vs. Wavelength at high temperatures

The sample suffers an oxidation process during the first tests to reach 1100°C in a few seconds. The repeatability of the measures in the following tests indicates the durability of the surface properties of the sample. The austenitic stainless steel 310S (UNS S31008/AISI310S) composition has about 25% Cr, 0.6% Si and 20% Ni. This quality is known for its behavior of corrosion resistance at high temperature. The additions of carbon are optimized in order to improve its deformation resistance. The steel can easily be welded. AISI 310S is projected for high temperature applications, up to 1100°C, in oxidizing atmospheres. The image of the samples before and after the tests (Fig. 6) shows severe oxidation process after exposure to the extreme conditions ( $20\text{ }^{\circ}\text{C} \leq T \leq 1100\text{ }^{\circ}\text{C}$ ).



FIGURE 6. AISI 310S samples, before (left) and after solar tests (right)

## ANALYSIS OF UNCERTAINTIES

Although material surface emittance depends on various factors, equation 3 shows that this dependence is explicitly only to the absolute temperature of the surface  $T$  which has an associated uncertainty  $\Delta T$ . From equation 3, it can obtain an explicit expression for emittance uncertainty considering that  $\epsilon_{ap}$  is a chosen quantity that determines the value of  $T_{ap}$ :

$$\Delta\epsilon_{\Delta\lambda}(T) = \left| \frac{\partial\epsilon_{\Delta\lambda}}{\partial T} \right| \Delta T = \frac{4\epsilon_{ap}T_{ap}^4}{T^5} \Delta T \quad (4)$$

The measurement of this temperature has three sources of uncertainty due to the location of the thermocouples and their properties:

1. Instrumental uncertainty  $\sigma_I$ : The thermocouples used are first class type K which means their measurements have an uncertainty of  $\sigma_I = \pm 0.004 T$  ( $375 \text{ }^\circ\text{C} \leq T \leq 1000 \text{ }^\circ\text{C}$ ), according to the current standard.
2. Standard uncertainty  $\sigma_{av}$ : When considering surface temperature,  $T$ , as the average of two temperature measurements made with two nearby thermocouples, the average temperature is associated with a standard uncertainty.

$$\Delta T = \pm \sqrt{\sigma_I^2 + \sigma_{av}^2} \quad (5)$$

3. Systematic uncertainty  $\Delta T_{sys}$ : Two thermocouples are embedded in the center of the back face of the sample at 0.8 mm of the interesting front face surface and separated 5 mm. The average temperature supplied by these two thermocouples is assumed as the real temperature of the sample surface in stationary conditions despite being a measurement on the back of the sample which means a systematic uncertainty associated to the surface temperature to be determined and corrected.

Specific tests were carried out under conditions of thermodynamic stationarity and the thermal evaluation has been performed [10, 11] by means of a commercial computational fluid dynamics software (Fluent®). This analysis shows a small temperature difference ( $\Delta T_{sys} < 3^\circ\text{C}$ ) between the front and back surfaces of the AISI 310S steel sample embedded in an alumina block, being temperature slightly lower at the front due to external cooling process (Fig. 7) and the temperature difference linearly dependent on the temperature in the working range considered ( $\Delta T_{sys} = 0.0018 T + 0.5073$ ,  $R^2 = 0.9971$ ). This temperature difference depends mainly on sample temperature, sample thickness, and thermal conductivity of the sample material. This result can be generalized, this systematic uncertainty is very low when the thermal conductivity of the material is high and the temperature is measured near the surface [10].

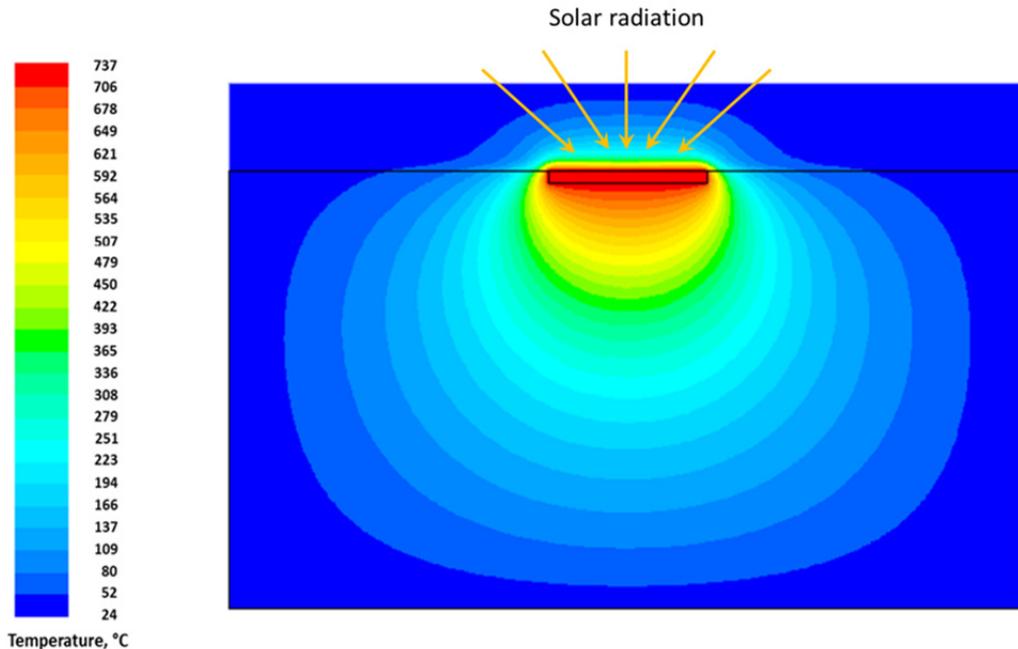
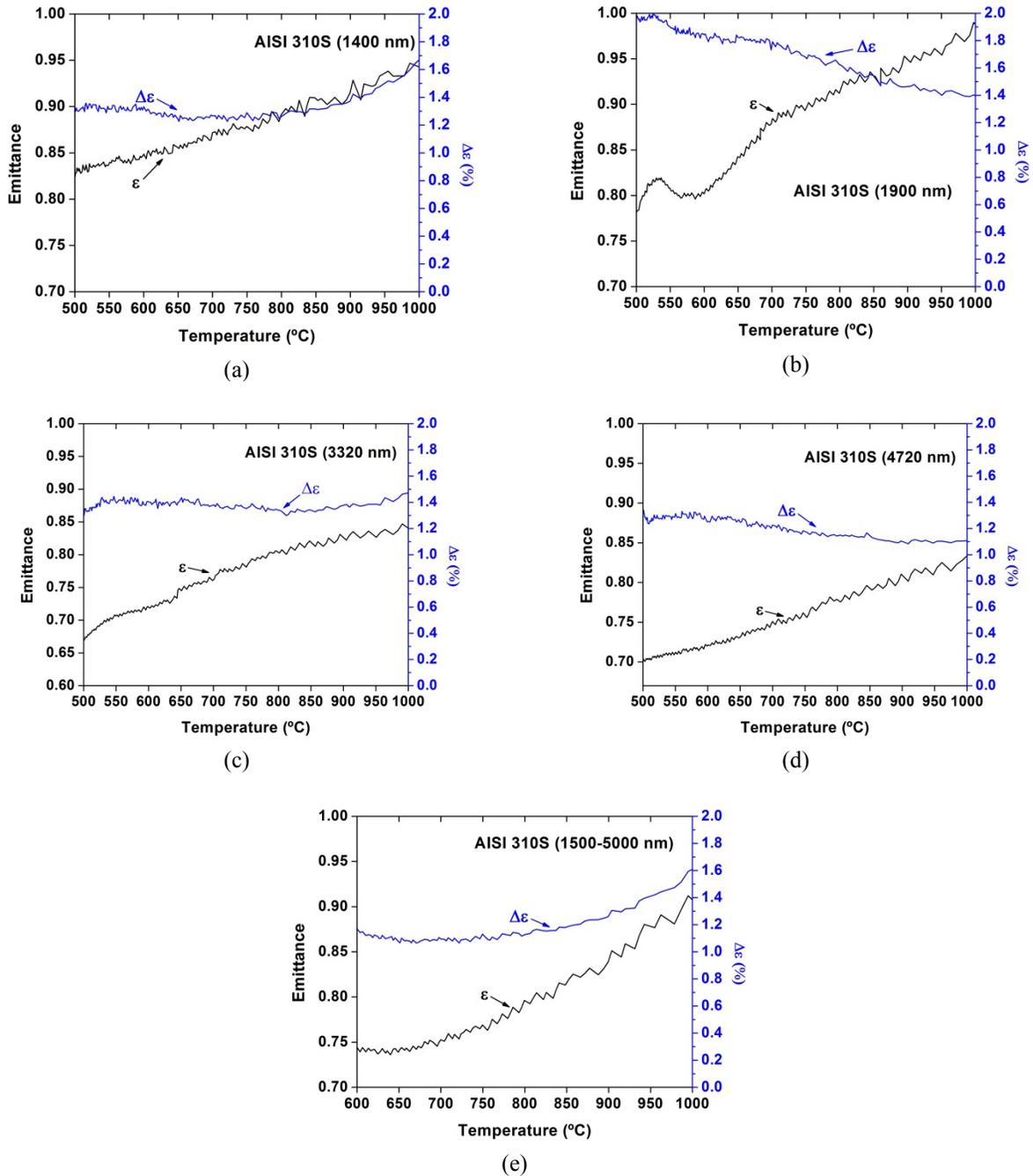


FIGURE 7. Temperature distribution 2D on both sides of the AISI 310S steel sample

Emittance and its uncertainty are then obtained by considering this systematic uncertainty of temperature and applying equations 3, 4 and 5 accordingly.

Figure 8 shows the emittance values and uncertainty (< 2%) for steel AISI 301S sample depending on the temperature at different spectral ranges. The data show that the emittance of AISI 301S sample increases with increasing temperature for all considered wavelengths. The behavior of uncertainty in emittance with temperature depends on the peculiarities of each test, which are determined by the factor  $(T_{ap}^4/T^5) \Delta T$  in equation 4.



**FIGURE 8.** AISI 301S steel emittance and emittance uncertainty vs. temperature at (a) 1400 nm, (b) 1900 nm, (c) 3320 nm, (d) 4720 nm, and (e) 1500-5000 nm

## CONCLUSIONS AND OUTLOOK

In this work an alternative method for emittance determination based on pyrometric measurements is presented. The measurement procedure has been applied to AISI 310S steel samples in the PSA vertical axis solar furnace SF5, which has proved to be an ideal scenario for this purpose. The data show that emittance increases with increasing temperature and decreases with increasing wavelength, which is in agreement with experimental results obtained by other authors. Analysis of tests has revealed a good repeatability (1%) and accuracy (< 2%) of this measurement procedure.

It should be mentioned the oxidation process that suffers the sample during the first tests to reach 1100 °C in a few seconds. The repeatability of the measures in the following tests indicates the good response of the surface properties of the sample. Tests could be performed in vacuum atmosphere to avoid oxidation of the sample. In this case, it could be obtained emittance of the sample at wavelengths compatible with the transmittance of the enclosure.

## ACKNOWLEDGEMENTS

Financial support by the SFERA-II project (Grant Agreement no. 312643, WP12: Pyrometric temperature measurement methods for high-concentration solar facilities and solar simulators; WP13: Determination of physical properties of CSP materials under concentrated solar irradiation) from the Research Infrastructures Activity in the 7th Framework Programme of the European Union is gratefully acknowledged <http://sfera2.sollab.eu>. We also thank J. Galindo from PSA for their help and contribution during assembly work and operation. Financial support provided by the Education Ministry of Chile Grant PMI ANT 1201 and CONICYT/ FONDAP/ 15110019 "Solar Energy Research Center" SERC-Chile as well.

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