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Methodology for spectral emissivity measurement by means of single color pyrometer

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ABSTRACT

The application of non-intrusive optical devices, such as infrared pyrometers able to measure the temperature of surfaces, makes possible the evaluation of emissivity curve of the tested materials at different temperature values. In this paper the authors propose a methodology for the spectral emissivity measurement by means of a single color pyrometer providing a semi-empirical formula, obtained experimentally at CIRA's laboratory. The semi-empirical formula allows to know the actual emissivity value of the sample's surface for whatever emissivity value set up on the pyrometer. The agreement between the experimental emissivity and the emissivity predicted by semi-empirical formula was verified.

1. Introduction

The measurement of the temperature of the material's surface solicited by thermal loads, has always been the target of experiments developed in laboratory.

The development of optical devices operating in the infrared region of the spectrum has given the opportunity to measure temperatures up to several thousands of kelvin. In fact the use of non-contact devices such as pyrometers or thermocameras has given the possibility to measure temperatures of the material's surface without the insertion of temperature sensors in the samples. The only problem occurring with this type of application is the knowledge of the material's surface characteristics, in particular the emissivity.

Purpura et al. [1] have performed a technique to determine the experimental emissivity of a material during a test in the PWT-SCIROCCO by comparing the temperature values obtained by a thermocamera operating with the known emissivity and by a dual color pyrometer. They have found an increasing of about the 10% of the material's emissivity during the development of the test campaign.

The use of a dual color pyrometer to determine the temperature of the sample was performed also by Teodorescu et al. [2], to measure the spectral emissivity of nickel by a Fourier transform infrared spectrometer. But in that analysis the sample was located in a vacuum chamber, so it was not considered the oxidation influence on emissivity. The introduction of dual color optical devices has allowed the temperature measurement by-passing the knowledge of the material's emissivity and considering the material as a gray-body in the two operating wavelengths λ.

The use of thermocouples to calibrate a pyrometer to measure the temperature of a sample was performed by Hagqvist et al. [3], which determined that the temperature uncertainty was less than 2.5%. In that analysis the sample was located in air at ambient pressure so the effect of oxidation phenomena was considered. The use of thermocouples, and the effect of surface oxidation, were described also by Shi et al. [4] to affect the spectral emissivity.

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To evaluate the spectral emissivity values, the authors were performed experiments in air at ambient pressure on metallic sample using optical single color pyrometers, at different wavelengths and temperatures. In particular, a sample of OFHC Copper was installed on a quartz beam and then inserted inside the graphite spherical cavity of a black body in the temperature range from 400 °C to 900 °C. A K-type thermocouple was installed in the sample to measure its temperature. This temperature was assumed as the temperature of the entire sample in the hypothesis of uniform temperature distribution. The hypothesis of uniform temperature distribution was assessed by a preliminary CFD analysis in steady state condition. By combining the temperatures measured by the pyrometers and by the thermocouple, the spectral emissivity of the sample's surface as function of temperature at three different wavelengths was determined, maintaining fixed the emission angle.

The authors have been provided a semi-empirical formula, obtained experimentally at CIRA's laboratory for three different of pyrometer's models, that allows to know the value of the emissivity $\varepsilon_{\lambda,th}$ of the sample's surface for whatever emissivity value $\varepsilon_{\lambda,SC}$ set on the pyrometer. Furthermore, the $\varepsilon_{\lambda,th}$ was compared with the experimental emissivity value, $\varepsilon_{\lambda,\exp,}$ that was evaluated directly by changing the emissivity value on the pyrometer until the temperature provided by pyrometer was equal to the ones provided by the thermocouple. The agreement between the experimental emissivity determined and the emissivity predicted by semi-empirical formula was verified.

2. Equipment used for the investigation

To carry out the investigation, a blackbody with spherical cavity was used. As shown in Fig. 1, the sample was installed on a quartz holder with an inner pipe for the passage of a K-type thermocouple to measure the temperature of the sample.

The blackbody is a MIKRON M305 with a temperature range of 100–1000 °C and error equal to ±0.2% RDG + 1 °C. The pyrometer system is consisting of one IMPAC device and two MIKRON ones. The IMPAC pyrometer is the IGAR-12LO with focusable optics MB10, operating at $\lambda_1 = 1.52$ µm and $\lambda_2 = 1.64$ µm, at a temperature range 300–1000 °C, error equal to ±0.5% RDG + 1 °C. The pyrometer is controlled by a remote PC and operates both in single and dual color modes. The MIKRON pyrometers are both the M67S model operating in single color mode only, at a temperature range 400–800 °C with $\lambda = 1$–1.16 µm, while the other is operating at temperature range 600–1000 °C with $\lambda = 0.78$–1.06 µm; the error is equal to ±0.5% FS, or ±1 °C whichever is greater.

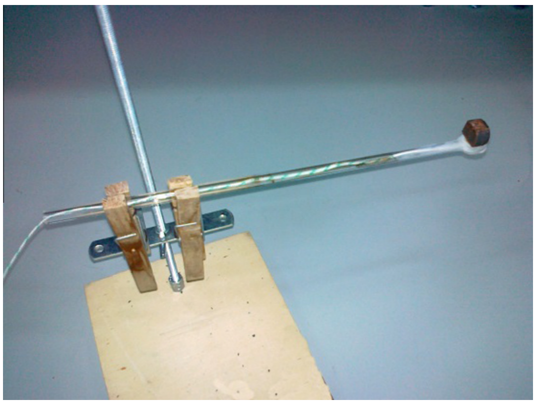

Fig. 1. Sample installed on the support.

The sample is of OFHC copper, with nominal surface emissivity equal to 0.80. In Fig. 2 (on the right side) it is possible to observe the presence of a little hole, ∅ 3 mm and 3 mm in depth located on the lower flat face, in order to allow the insertion of the K-type thermocouple for the measurement of its temperature. The K-type thermocouple measures in the range of temperature −200 to 1100 °C with an error of ±2.5 °C or 0.0075 ∗ T (°C) and its wire is protected by insulation material. The end of the thermocouple is the sensor and it is at direct contact with the inner material of the sample.

3. Mathematical approach and experimental setup

3.1. Mathematical approach

An infrared thermometer (IRT) consists of two parts, the optical system and the detector. The output of the detector may be different depending on the wavelength, and it is proportional to the amount radiated by the target at the specific wavelength. The calibration function of the thermometer, that is the thermometer output U, varies with the temperature and wavelength. $U(T)$ is the integral of the Plank's law that in the Wien's hypothesis, can be written as:

$$U(T) = kC_1 \int_{\lambda_1}^{\lambda_2} \lambda^{-5} \varepsilon^{-\frac{C_2}{\lambda T}} d\lambda \tag{1}$$

with C_1 the first radiation constant $3.7415 \cdot 10^{-16}$ W/m^2, C_2 the second radiation constant $1.43879 \cdot 10^{-2}$ m · K, and k is a constant depending on the construction of the thermometer.

At a single temperature or over a narrow range of temperatures, the calibration function may be expressed as:

$$U(T) = \varepsilon_\lambda k T^{\frac{C_2}{LT}} \tag{2}$$

where T is the temperature of the target with emissivity ε_λ, and $L = L(T)$ is a characteristic of the thermometer defined during the calibration.

Now, let assume as "a" the ratio:

$$a = \frac{U(T)}{k} = \varepsilon_\lambda T^{\frac{C_2}{LT}} \tag{3}$$

which is constant when the target is at a fixed temperature.

Hence, by setting a blackbody at a fixed temperature T_{BB}, and pointing the optical thermometer (pyrometer) at the center of the opening of the black body cavity, it is possible to measure the corresponding temperature at the given emissivity $\varepsilon = 0.995$. So, the $a(T)$ and $L(T)$ functions