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Infrared thermometers for small wires drawing

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ABSTRACT

This work describes the design of two contactless thermometers based respectively on a total radiance and two-color pyrometry scheme, developed to measure the temperature of a small brass coated steel wire during wire drawing. In this critical condition, wire oscillation and relevant insertion errors do not allow using commercial contact or contactless sensors. Thus, ad hoc pyrometers optical layouts have been designed in order to minimize sensitivity to the wire oscillations and emissivity changes. Moreover, performances associated to different infrared detectors have been compared using as figure of merit the achieved measurement uncertainty simulating typical disturbances, i.e. the background temperature variation, the slope of the wire's emissivity and the effect of the atmosphere transmittance. Finally, the uncertainty budgets were drawn, evidencing the limitations of the proposed methods and identifying the best configuration for both developed instruments.

1. Introduction

Temperature measurement without any contact between the sensor and an observed object is a clear advantage in case the target size is so small that even with the smallest thermometers (e.g. miniature thermocouples or RTDs) the loading effect due to the sensor becomes unacceptable. Anyway, contactless temperature measurement is generally a difficult task since final accuracy relies directly on the knowledge of many parameters such as the object emissivity, the background temperature, the medium spectral transmissivity and on the condition that the emitting source fills completely the sensor Field of View (FOV) [1–7]. Total emissivity is difficult to predict since in general it depends on temperature and might change because of the local state of oxidation, cleanliness or roughness of the observed surface [2]. These criticalities are present in the analyzed case study, i.e. wire drawing, since the manufacturing process requires soaps as lubricants and the wire emissivity varies because of the material inhomogeneity or local oxidation. Thus, usage of common total radiance pyrometers would lead to large measurement errors. Moreover, the wire size (between 0.1 and 1 mm) is generally smaller than the measurement spot of any standard pyrometer or infrared camera [6]. This leads to measurement errors because beside the wire's emission some radiance from the background scene is collected as well, and averaged with the source one. Finally, significant transversal oscillations of the wire are present during wire drawing and brass coating deposition process. In case of wire oscillations, radiative coupling between the source and the sensor is not stable, leading to fluctuations of the measured temperature or to a SNR (Signal to Noise Ratio) worsening.

Thus, two contactless temperature measurement systems have been developed to overcome the drawbacks of the standard pyrometers in the intended application and minimize the achievable uncertainty in measuring the temperature of small wires with large oscillations and emissivity changes. The expected improvements with respect to off the shelf instruments derive from purposely

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designed optical layouts and an optimal choice of the pyrometers detectors.

Modeling and layouts of the two pyrometers are summarized in Section 2 whereas Section 3 draws the uncertainty budgets of the instruments, discussing the achieved results. The manuscript is eventually concluded in Section 4.

2. Material and methods

2.1. Theoretical background

The output, O, of an infrared detector corresponding to a source at a given temperature T can be evaluated as follows:

$$O(T) = \int_{\lambda_{min}}^{\lambda_{max}} R(\lambda) GR\, E_{n\lambda}(T) d\lambda \quad (1)$$

where λ_{max} and λ_{min} are respectively the maximum and minimum wavelengths of the detector range, GR the radiative coupling factor between source and detector, $R(\lambda)$ the detector responsivity and $E_{n\lambda}(T)$ is the source spectral radiance.

Conversely, temperature measurement with two-color pyrometer requires evaluating the ratio between the heat fluxes at two different wavelengths. Thus, the ratio of the signals measured by the two detectors ideally gives:

$$\frac{O_1}{O_2} = \frac{GR_1\, R_1(\lambda_1)\varepsilon(\lambda_1)\, \lambda_2^5 \left(e^{\frac{C_2}{\lambda_2 T}} - 1\right)}{GR_2\, R_2(\lambda_2)\varepsilon(\lambda_2)\, \lambda_1^5 \left(e^{\frac{C_2}{\lambda_1 T}} - 1\right)} \quad (2)$$

The measured temperature can be derived in a simple form from Eq. (2) under the assumption that the source emissivity is a smooth function, and so, takes the same value at the two adjacent wavelengths and the detectors responsivities and radiative exchange factors with the wire are the same:

$$T = \frac{\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right) C_2}{\ln\left(\frac{O_1\, \lambda_1^5}{O_2\, \lambda_2^5}\right)} \quad (3)$$

Moreover, Eq. (3) is valid under the assumption that the exponential term in Eq. (2) is at least one order magnitude larger than one. The latter hypothesis is fully satisfied within the investigated wavelength range, i.e. between 0.5 and 5 μm, and for the analyzed temperatures (from 200 °C to 800 °C), which are representative of the drawing process. Extension to higher temperatures is limited, for the two-color pyrometer by the validity of Eq. (3), as previously mentioned. Reduction of the minimum temperature is possible but in practice limited to the ambient one because of signal to noise ratio worsening in common IR detectors.

2.2. Optical layout design

A Monte Carlo ray tracing software has been used to develop pyrometers radiative models. The model includes infrared sensor active area, mirrors, wire and an enveloping box. Fig. 1 shows the conceptual scheme of the instruments optical layouts. The first configuration has been developed for the total radiance pyrometer. This exploits one planar diffusive mirror to reflect the wire radiance so that without any focusing optics, the detector collects also the reflected power while insensitivity against wire oscillation should be achieved. The planar mirror was replaced in the two-color pyrometer by parabolic reflectors. These focus the wire emission on the detector, achieving higher SNR with respect to the total radiance configuration. Moreover, the internal surfaces of the optical cavity (mirrors and envelope box) were reflective (in the IR range) to convey most of the power to the detectors.

Candidate optical configurations have been compared on the basis of the radiative efficiency and sensitivity to the wire oscillations. Thus, the radiative exchange factors (hereafter named GRs) between wire and detector have been computed in nine different positions, as evidenced in Fig. 2, simulating an oscillation amplitude of 0.5 mm. This value was measured during a preliminary test.

The optical properties of the used materials are reported in Table 1. In particular, the coating for the total radiance pyrometer is sand blasted aluminum whereas vacuum deposited gold is used in the two-color configuration. Ray-tracing is performed starting from a mesh of the optical elements. In order to identify the maximum mesh size for each optical component to grant computational stability, some preliminary radiative analyses were run.

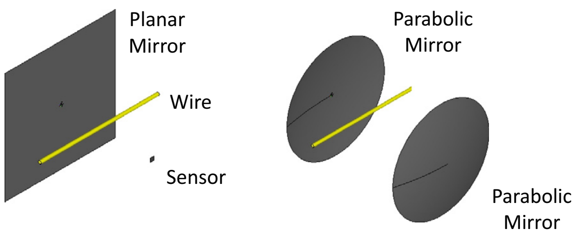

Fig. 1. Conceptual schemes of the instruments optical layouts; (left) total radiance configuration, (right) two-color pyrometer. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

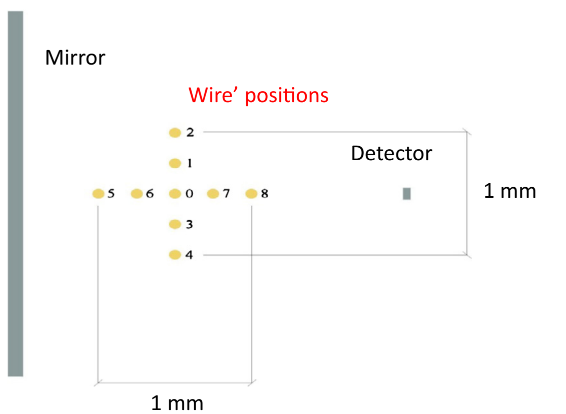

Fig. 2. Wire positions to simulate oscillation during wire drawing.