Measurement 87 (2016) 126–137

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Characterisation and laboratory investigation of a new ultraviolet multi-wavelength measuring system for high-temperature applications

M. Battuello *, F. Girard

Istituto Nazionale di Ricerca Metrologica (INRIM), Strada delle Cacce 91, Torino, Italy

ARTICLE INFO

Article history:
Received 12 February 2015
Received in revised form 9 March 2016
Accepted 11 March 2016
Available online 17 March 2016

Keywords:
Radiation thermometry
Multi-wavelength
Emissivity

ABSTRACT

In the framework of the HiTeMS project of the European Metrology Research Pogramme (EMRP) a new multi-wavelength device for measurement of high temperatures in industrial applications was developed at INRIM. The apparatus takes advantage of the ultraviolet operation with working wavelengths from 350 nm up, which reduces the possible errors connected with the multi-wavelength approach. The instrument has been characterised in terms of optical and electronic behaviour and some laboratory trials were carried out to verify the reliability of the multi-wavelength approach. The true temperature of a blackbody source at 1300 °C with optical windows of unknown spectral transmittance interposed has been defined. By applying an approach that allows a result to be accepted when a threshold limit is reached, it was found that, when an acceptable result can be obtained, errors are comprised within less than 1% of the temperature of the source. Three others single-band thermometers, at 508 nm, 650 nm and an IR broadband 0.8–1.1 μm, were also used to the purpose of a comparison. It has been found that, when the multi-wavelength approach is applicable, it provides generally better or in few cases, at worst similar results of corrected single-wavelength thermometers.

1. Introduction

Radiation thermometry is a non-contact method, hence it is robust and, in principle, suitable for high-temperature applications in a broad spectrum of industries. However, it is well known that when radiation thermometers are used in practical applications outside laboratories the uncertainty rapidly increases because of the measurement environment. The unknown emissivity of the surface under investigation is the most common source of uncertainty, but also unknown absorption along the optical path or the transmission of possible protective windows used in the measurement setups may play an important role. Many attempts have been made over the years to overcome these problems, but no generally applicable method has been devised. If we refer to the emissivity issue, but the reasoning is the same for the other influencing parameters, increasing the number of measuring wavelengths, and provided that some assumptions on the emissivity behaviour are done, it is possible, in principle, to derive the real temperature of a surface from the spectral radiances measurements.

The approach can be implemented by means of different experimental methods. Before the advent of the array detectors, it was common practice to split/select the incoming radiation by means of optical filters with the consequent limitation of operating at few and fixed working wavelength bands. Nowadays the use of array detectors allows to realize a device to be used directly as a

* Corresponding author. Tel.: +39 011319738.
E-mail address: m.battuello@inrim.it (M. Battuello).

http://dx.doi.org/10.1016/j.measurement.2016.03.024
0263-2241/

multi-wavelength thermometer with a high degree of flexibility both in terms of number and position of the working wavelengths bands. However, in practice these advantages are not sufficient to make the multi-wavelength approach a reliable one for operations in the Visible–Near Infrared (VIS–NIR), i.e., in spectral ranges normally used for measurement of temperatures around 1000 °C or less. The attempts made to develop practical thermometers were not satisfactory because of the unreliability of the results. A dependence of the results on the specific material under measurement was found and there was no practical means to know the extent of the possible errors.

However, an analysis of the measuring principle of the multi-wavelength thermometry, suggested the opportunity to investigate the possible advantages in extending the operating wavelengths down to the ultra-violet. The multi-wavelength approach essentially is an extrapolation process towards $\lambda \to 0$ of measurement data obtained in a defined spectral range. Such considerations may suggest that by reducing the extrapolation range it should be possible to reduce the errors. Based on this assumption simulations were performed and consistent improvements were found [1]. On such basis, INRIM developed for the High Temperature Metrology for Industrial Applications (HiTeMS) project of the European Metrology Research Programme (EMRP) a flexible multi-wavelength measuring system for high temperature applications. The instrument was constructed to be operated in a spectral range comprised between 350 nm and 950 nm.

Functionality tests and measurements have been performed in different setup conditions in order to characterise the device. The tests referred both to the electronic and optics-related characteristics of the device. The characterisation evidenced some limitations, particularly referred to the electronics. The linearity of the gain ratios and exposure times of the CCD detector strongly depends by the wavelength. Such a behaviour makes difficult to manage signals with large dynamic range as those available when wide spectral regions are analysed and consequently an alternative operative approach was devised to overcome these electronic drawbacks. However, an important outcome of the characterisation was the extremely high sensitivity of the device that open to lower temperatures operation with respect to the originally expected limits. It has been found that the MWT can be operated at temperatures as low as 1300 °C with the originally set spectral limits, i.e., 350–950 nm, and even down to 900 °C if the minimum operating wavelength is increased to 500 nm.

The paper will briefly discuss the measurement principle, will describe the apparatus, its characterisation and some laboratory investigations simulating industrial trials aimed to compare the results with those obtainable with common single-wavelength radiation thermometers at different wavelengths.

2. Discussion of the measurement principle

An analysis of the measurement principles can be found in [1]. In radiation thermometry when N measuring wavelengths are used a general representation with a system of N equations with $N+1$ unknowns can be derived and by conveniently using the Wien's approximation of the Planck's equation:

$$L_{\lambda_i,T}(\varepsilon_{\lambda_i}) = \varepsilon_{\lambda_i} c_1 \lambda_i^{-5} \exp\left(-\frac{c_2}{\lambda_i} T\right) \tag{1}$$

where $i = 1,\ldots N$ is the number of wavelengths used, λ is the wavelength, $c_1 = 1.1911 \times 10^{-16}\ \mathrm{W\ m^{-2}\ sr^{-1}}$ and $c_2 = 1.4388 \times 10^{-2}\ \mathrm{m\ K}$ are the first and second radiation constant, respectively, T is the temperature in kelvin and $\varepsilon_{\lambda i}$ are the spectral emissivities. By assuming the emissivity to be a function of the wavelength with no more than $N-1$ coefficients, the system of equations will contain no more than N unknowns and consequently can be analytically solved. As suggested by Coates [2] the following polynomial expression with a degree $M \leqslant N-2$ can be used to describe the emissivity behaviour:

$$\ln\ \varepsilon_\lambda = \sum_{j=0}^{j=M} a_j \lambda^j \tag{2}$$

The spectral radiances can be written down in a straight way and all the following calculation process can be consequently greatly simplified. By combining Eqs. (1) and (2) the following equation can be obtained:

$$Y_i = \frac{c_2}{T} - \lambda_i \sum_{j=0}^{j=M} a_j \lambda_i^j \tag{3}$$

where

$$Y_i = \lambda_i[-\ln L_{\lambda,T}(\varepsilon_\lambda) + \ln c_1 - 5\ln \lambda_i] \tag{4}$$

are the measured radiance terms. Consequently, the temperature and the emissivity can be simultaneously derived by solving the system of equations described above.

In practice, searching for the value of temperature T in the Eq. (3) corresponds to search for the value of the function Y_i when the wavelength λ tends to zero:

$$\lim_{\lambda \to 0}\left(\frac{c_2}{T} - \lambda_i \sum_{j=0}^{j=M} a_j \lambda_i^j\right) \tag{5}$$

and the Eq. (3) assumes the form:

$$T = \frac{c_2}{Y_i} \tag{6}$$

The calculation procedure appears to be as an extrapolation process towards lim $\lambda \to 0$. The system of equations to be solved can be expressed and written in a matrix form, as shown in the Section 5.2.

3. Description of the multi-wavelength measuring system

The multi-wavelength measuring system has been based on a 1024 × 256 elements CCD silicon detector (HJY model Syncerity^{TM}) and an automated spectrometer (HJY model MicroHRauto) coupled together to form a complete spectrometric system. Both devices are produced and commercially available from Horiba Scientific. In addition