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Optimal wavelengths obtained from laws analogous to the Wien's law for monospectral and bispectral methods, and general methodology for multispectral temperature measurements taking into account global transfer function including non-uniform emissivity of surfaces

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HIGHLIGHTS

- Criteria allowing selecting wavelengths minimizing measurement error on the temperature.
- Optimal wavelengths obtained from laws analogous to the Wien's law for mono-spectral and bi-spectral methods.
- General methodology for multi-spectral temperature measurements of surfaces exhibiting non-uniform emissivity.

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ABSTRACT

In this paper, it is shown how to select the optimal wavelengths minimizing the relative error and the standard deviation of the temperature. Furthermore, it is shown that the optimal wavelengths in mono-spectral and bi-spectral methods (for a Planck's law) can be determined by laws analogous to the displacement Wien's law. The simplicity of these laws can thus allow real-time selection of optimal wavelengths for a control/optimization of industrial processes, for example. A more general methodology to obtain the optimal wavelengths selection in a multi-spectral method (taking into account the spectral variations of the global transfer function including the emissivity variations) for temperature measurement of surfaces exhibiting non-uniform emissivity, is also presented. This latter can then find an interest in glass furnaces temperature measurement with spatiotemporal non-uniformities of emissivity, the control of biomass pyrolysis, the surface temperature measurement of buildings or heating devices, for example. The goal consists of minimizing the standard deviation of the estimated temperature (optimal design experiment). For the multi-spectral method, two cases will be treated: optimal global and optimal constrained wavelengths selection (to the spectral range of the detector, for example). The estimated temperature results obtained by different models and for different number of parameters and wavelengths are compared. These different points are treated from theoretical, numerical and experimental points of view.

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1. Introduction

These last years in parallel with industrial development, optical measurement methods were increasingly used in various fields, for measuring space and/or time distributions of temperature in extreme conditions such as Tokamaks [1,2], semi-transparent materials [3], reflective materials [4–8], thermal characterization at high temperatures [9,10], or for the industrial control/applications [11,12], for example. These methods presents the advantage of being weakly intrusive and allow performing remote measurement, which are usually done by infrared cameras, quantum detectors, or photomultipliers in the case of measurements at shorter wavelengths [13,14]. The measurement difficulties are numerous, such as taking into account the reflection on the sample, or spatial and temporal variations of the emissivity of the material, making it non-uniform over the sample surface, especially at high temperature where significant oxidation phenomena can occur [15]. One solution is to make a measurement by a multi-spectral method [3–8,11–22]. Even if the idea is interesting,

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Nomenclature

φ	flux, W
M°	emittance, W m^{-3}
C_1	constant of Planck's law: 3.741e−16 W m^2
C_2	constant of Planck's law: 14388e−6 m K
e	error
f	global spectral transfer function
TNL.TXY	multi-spectral method based on the flux ratio and the Wien's approximation
TNL.Tabc	multi-spectral method based on the flux given by the Planck's law
$\{a, b, c\}$; $\{X, Y\}$	parameters of the global spectral transfer function, respectively for the models *TNL.Tabc* and *TNL.TXY*
T	temperature, K or °C
T_{ij}	temperature calculated from the wavelengths filters λ_i, λ_j
$\propto$	proportional
$\equiv$	identical to/equivalent to
min	minimum
argmin	argument of the minimum
cov	covariance matrix $[\![1; N]\!]$ Set of integers from 1 to N

Greek symbols

ε	emissivity
λ	wavelength, m
χ	sensitivity
σ	standard deviation
$\Delta\lambda_{\min}$	wavelength separation criterion
β	parameter vector
$\boldsymbol{X}$	sensitivity matrix

Indices, exponents and other symbols

λ	spectral, or wavelength
m	mean
i, j, k	number of filter
T	temperature
opt	optimal
φ	flux
Planck	based on the Planck's law
Wien	based on the Wien's approximation
MP	relative to the optimal wavelength for mono-spectral measurements and for the flux defined by the Planck's law
MW	relative to the optimal wavelength for mono-spectral measurements and for the flux defined by the Wien's approximation
BP	relative to the optimal wavelengths for bi-spectral measurements and for the flux defined by the Planck's law
BW	relative to the optimal wavelengths for bi-spectral measurements and for the flux defined by the Wien's approximation
exp	experimental
bi	relative to bispectral measurements or methods

its implementation is tricky because of the difficulty to choose the adapted wavelengths λ_i, the number of wavelengths and/or emissivity model, as illustrated by the state-of-the-art realized by [7,16]. Indeed, they must be chosen "close enough" to overcome emissivity variations of the material, but not "too close" to obtain an uncertainty on the measured temperature lowest as possible [19].

The objective of this paper is to present some criteria allowing selecting wavelengths minimizing measurement error on the temperature. In particular, it is shown that there is equivalence between minimizing the relative error on the temperature, maximizing the flux sensitivity to the temperature, or minimizing the standard deviation of the temperature. Furthermore, it is shown that the wavelengths that minimize the standard deviation of the estimated temperature in mono-spectral and bi-spectral methods (without the Wien's approximation, i.e. for a Planck's law) can be determined by laws analogous to the displacement Wien's law. Thus, a pocket calculator is sufficient to determine the optimal wavelengths for the mono- or bi-spectral measurements. A more general methodology (based on the ordinary least squares method) to obtain the optimal wavelengths selection in a multi-spectral method for temperature measurement of surfaces exhibiting non-uniform emissivity, is also presented.

So, after a presentation of the laws analogous to the displacement Wien's law for "optimal" wavelengths selection for mono-spectral (Sections 2 and 4.1) and bi-spectral measurements (Section 4.1), the theoretical principle of the multi-spectral methods is presented (Sections 3.2 and 4.2). The Wien's approximation will be used to establish the existence of analytical relations whose validity will be extended numerically for Planck's law. Next, several (analytical) estimation models are validated numerically through Monte-Carlo simulations (Section 5) for different (simulated) spectral emissivity (or global transfer function including the emissivity) variations (chosen according to experimental data [23]), and compared experimentally (Section 6.2). The facility is presented in Section 6, and the considered variations of emissivity used to validate the theoretical models for estimating temperature through an inverse technique based on an ordinary least squares method are shown in Section 5. Two different cost functions ((8) and (11)) will be used and compared to estimate the temperature by inverse method: the first uses fluxes ratio and the Wien's approximation (7), and the second uses the fluxes (9) (Planck's law without any fluxes ratio).

2. Analogous Wien's law for optimal wavelengths selection : mono-spectral method

Calling $f(\lambda)$ the global spectral transfer function including all unknowns (emissivity $\varepsilon(\lambda)$, sample area, quantum efficiency...), the flux emitted by an object is defined by the Planck's law (1) which can take a simpler form (named Wien's approximation) if $\lambda T \ll C_2 \approx 14{,}400\ \mu\mathrm{m\,K}$:

$$\varphi(\lambda, T) = f(\lambda) M^{o}(\lambda, T) = f(\lambda)\frac{C_1 \lambda^{-5}}{\exp\left(\frac{C_2}{\lambda T}\right) - 1} \underset{\text{Wien's approximation}}{\simeq} f(\lambda) C_1 \lambda^{-5} \times \exp\left(\frac{-C_2}{\lambda T}\right), \quad \forall \lambda T \ll C_2 \approx 14{,}400\ \mu\mathrm{m\,K} \tag{1}$$

Considering λ as a parameter, by differentiating the Planck's law (1) with respect to temperature and equating the differential terms to errors, it can be shown that the relative error on the temperature is:

$$\frac{e_T}{T} = \frac{e_{\varphi}}{\varphi}\frac{\lambda T}{C_2}\left(1 - \exp\left(\frac{-C_2}{\lambda T}\right)\right) \underset{\text{Wien's approximation}}{\simeq} \frac{e_{\varphi}}{\varphi}\frac{\lambda T}{C_2} \tag{2}$$

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