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Quantitative temperature field measurements on a non-gray multi-materials scene by thermoreflectometry

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HIGHLIGHTS

- We evaluate experimentally a non-contact camera based temperature measurement method called thermoreflectometry.
- This method is based on a continuous evaluation of emissivity by reflectometry.
- A heterogeneous multi-materials scene composed of dielectrics and metals is elaborated and characterized by spectrometry.
- True temperature fields are retrieved on this complex scene and compared to reference methods.

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ABSTRACT

This article addresses the problem of measuring an accurate temperature field on a multi-materials scene composed of two dielectric and one metallic materials. The measurements of thermo-radiative properties demonstrate that the scene exhibit very different emissivity spectra and thermal conductivities inducing high thermal gradients. From these radiative properties, the calculation of the theoretical temperature error of conventional passive methods highlights that a method may be suitable for measuring only one material but no method provides satisfactory measurements of the sets of materials. The proposed method, called thermoreflectometry, performs a simultaneous measurement on all materials thanks to an on-line indirect determination of emissivity based on a bidirectional reflectivity measurement. Its temperature error is compared to that of the selected passive method for each material through an experimental validation on the multi-materials scene. These results highlight the accuracy of thermoreflectometry and shows opening prospects for the on-line temperature control of dynamical processes.

1. Introduction

For numerous scientific or industrial projects in aeronautical [1], nuclear [2] or space [3] domains, thermal diagnosis is a major issue. The measured hot surfaces under process are often composed of different opaque materials, metallic or dielectric, and are submitted to spatially variable high heat flux. These surfaces also exhibit some strong surface-state variations (localized oxidations, delaminations) and some possibly steep temperature gradients (convection effects, localized heating, multimaterial objects). In our laboratory, a multi-material scene representing such measurement case has been developed and is displayed in Fig. 1. The scene exhibits different materials (metallic and dielectric), with different emissivity spectra (increasing and decreasing with wavelength) and thermal conductivities (low and high), and these properties may vary with time. This scene regroups all the major problems of a thermal diagnosis based on temperature measurements with non-contact and non-invasive methods. These methods involve an analysis of the flux emitted by the scene. Unfortunately, this flux is a complex function of mainly two parameters: temperature and emissivity. The major problem for non-invasive methods is then to separate in the signal obtained S^r the temperature and emissivity influence, as shown by Eq. (1).

$$S^r(\lambda, T) = \varepsilon^r(\lambda, T) S_0(\lambda, T) \quad (1)$$

For a scene involved in dynamical processes, the emissivity is always unknown, but, in addition, varies during the measurement with temperature and surface's roughness. To provide a

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Nomenclature

λ	wavelength, μm
Λ	bichromatic effective wavelength, μm
i, r, x	incidence, reflexion and any direction, –
ε^r	directional emissivity, –
ε^r_r	emissivity ratio, –
$f^{i,x,r}$	reflexion indicator, –
$\rho^{i,\cap}$	directional hemispheric reflectivity, –
$\rho^{i,r}$	bidirectional reflectivity, sr^{-1}
$\eta^{r,i}$	diffusion factor, sr
S	camera signal, DL
C_2	second planck constant = $1.44 \cdot 10^4$ K μm
T	thermodynamical temperature, °C
T^r_R	radiance temperature, °C
$T_{1\lambda}$	monochromatic thermography temperature, °C
$T_{2\lambda}$	bichromatic thermography temperature, °C
$T_{2\lambda,\rho}$	thermoreflectometry temperature, °C
a_i	parameters fitting the emissivity variation, –
X_A	quantity X expressed on the Erbium oxide part, –
X_B	quantity X expressed on the Dysprosium oxide part, –
X_C	quantity X expressed on the Steel Oxide part, –
$\overline{X}$	spatial mean value of quantity X, –
σ_X	spatial standard deviation of quantity X, –
ΔX	error commited on quantity X, –
X^i	directional quantity X expressed in incidence direction i
X^r	directional quantity X expressed in reception direction r, –
$X^{i,r}$	bidirectional quantity X expressed in directions i and r, –

quantitative temperature measurement, non-invasive techniques have to take into account these emissivity variations which are specific to each material of the measured scene. This article then addresses the problem of an accurate, in situ and on-line measurement of the true temperature field on a multi-material scene under real dynamical conditions with both emissivity and temperature gradients.

The non-intrusive methods based on the definition of emissivity [4] (comparison of the object's radiance to the black body's radiance at the same temperature) are not considered here because they are not suitable for dynamic processes. However, for dielectric materials, monochromatic thermography at Christiansen's wavelength (around 10 μm, see[5]), where emissivity is equal to unity, can be an elegant approach. Performing thermography at these wavelengths is possible with a specific filter for each material. Although the Christiansen's wavelength depends slightly on temperature and surface, the filter would be effective on a restricted temperature range and a relatively homogeneous surface to minimize the uncertainty of temperature measurement. For metallic materials, bichromatic thermography [6–8], can perform a real time temperature field measurement. Bichromatic thermography assumes that the emissivity ratio at two wavelengths is known and constant. Unfortunately, emissivity ratio of metallic material usually decreases with temperature and oxidations. Multiwavelength thermography [9] then infers that the emissivity variation versus wavelength follows a particular law (linear, polynomial or exponential). For a multi-materials scene with dielectric and metallic materials, designing a law suitable for all variations of emissivity materials can be tricky. These passive methods are suitable for temperature field measurement on some specific materials but their application to a multi-materials scene is difficult. In addition, they are often very limited for dynamical conditions, when in situ properties quickly go off initial hypothesis. Without making assumptions on the emissivity behavior, the best approach would be to perform an emissivity measurement online and in situ with an active thermography method which require an external excitation of the material. This excitation creates a heat increase on the material surface, which is detected by the camera. This excitation can be optical (lock-in [10], pulsed or stimulated thermography [11]), mechanical (vibrothermography [12]), acoustic (thermosonics [13]), or magnetic (Eddy-current thermography [14]). These techniques all exhibit the same drawback: the difficulty of extrapolating the excitation source size to a surface-like measurement. Thanks to Kirchhoff's laws, active methods enabling the determination of emissivity via a reflection factor require less energy. Methods involving reflectance measurement are usually realized by an integrating sphere [15]. Flash assisted multiwavelength pyrometry (FAMP) [16] is more complete and take into account external radiations. Unfortunately, these methods require laboratory equipment (integrating sphere, parabolic mirrors, a spectrometer and an in situ reference) with a low ability to be integrated into embedded systems. On the other hand, pyroreflectometry or thermoreflectometry [17,18] performs an on-line evaluation of the reflection factor with only two low-power lasers. For opaque materials, the true temperature field measurement is computed from a measurement of bidirectional reflectivity and radiance temperature achieved with a specific near infrared radiometric model [19]. An extensive sensitivity simulation study of this method is provided in [20], and leads to the dimensioning of a prototype.

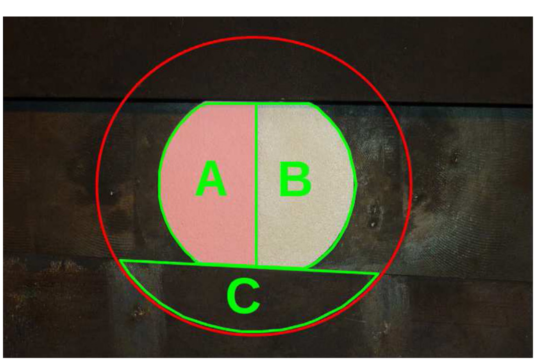

Fig. 1. Photograph of the complex scene mounted on the heating element. Item A: Erbium oxide part ($Zr0_2 + Er_2O_3$). Item B: Dysprosium oxide part ($Zr0_2 + Dy_2O_3$). Item C: Steel Oxide flange.

The novelty aspect presented in this paper is the challenging case of retrieving an accurate temperature field on a scene composed of different materials (dielectric and metallic) heated to different temperatures. After a description of radiative properties of the multi-materials scene, the conventional passive methods, such as monochromatic, bichromatic and multiwavelengths thermography, are evaluated in a simulation study. This comparison is also continuing in the experimental section. Christiansen's monochromatic thermography is carried out on the dielectric materials, and bichromatic thermography on the oxide metal part, and these temperatures constitute the reference temperature for each part. The errors of thermoreflectometry are then calculated and used to evaluate the accuracy of the method. This method also provides the emissivity field of the scene, which is a relevant parameter to evaluate the physical consistency of the overall results.