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Research Paper

Non-destructive testing method to quantify aging of materials by its apparent emissivity: Case of glass-based reflectors

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HIGHLIGHTS

- Aging of glass-based reflectors used in concentrated solar plants.
- Effects of damp heat protocol on infrared spectral emissivity of glass-based reflectors.
- Effects of damp heat protocol on normal LWIR apparent emissivity of glass-based reflectors.
- In-situ mapping of the aging of glass-based reflectors by utilizing apparent emissivity.

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ABSTRACT

In this paper, the measurement capabilities of apparent emissivity are tested by means of a generic LWIR system to quantify the aging of materials. A theoretical frame permitted to elaborate abacuses and to correlate a scaling law to identify the relevant parameters, and to foretell performance in terms of absolute aging time interval resolution as well. The predictions are done for both indoor and outdoor situations. They are compared with measurements performed on glass-based mirrors of a heliostat of the solar furnace of Odeillo after having undergone a Damp Heat accelerated aging test. Apparent emissivity measurements implement an indoor home-made device which had already been characterized. The performances are in accordance with the predictions and allow to discriminate initial natural aging of glass mirror combined with accelerated aging with an interval resolution from 4 to 10 years keeping in mind that we are in quest of differentiating two mirror glasses or of quantifying the absolute aging of each mirror. Limitations of indoor measurements come mainly from the accuracy of Non-Uniformity Correction and from the internal drift compensation inherent to any IR system. Outdoor performances are foreseen to be as efficient by optimizing the contrast $t_{app.} - t_{env.}$. If we consider an uncertainty of emitting temperature of 0.25 °C and the one of apparent temperature of 0.1 °C, a standard outdoor thermography would enable to discriminate absolute aging produced by Damp Heat test with a 10 standard year resolution.

1. Introduction

All the research on renewable energy systems is mainly bound to demonstrate the energy efficiency of such alternative systems in order to interest potential investors. The performance race turns out to be more expensive, the systems are physically limited and the natural aging remains difficult to quantify.

In a conventional approach to quantify the durability of solar thermal power plants, one is mainly interested in the aging of the absorber. However, it must be borne in mind that reflectors play an important role in the solar concentration. Regarding reflector types, glass-based reflectors still prove to be the most durable ones in solar applications. Climatic stress factors are responsible for their degradations resulting in a decrease of the global efficiency of the plant. Contemporaneous studies on silvered-glass reflectors for solar applications report solar-weighted hemispherical reflectance degradation up to 6% for thin glass reflector and less than 3% for the thick glass after more than 36 months in a climatic

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Nomenclature

t	temperature, °C
T	temperature, K
$\Delta\lambda$	spectral bandwidth $\Delta\lambda$ of the IR system
$L^0_{\Delta\lambda}$	thermosignal of blackbody within the spectral bandwidth, OS
$L_{\Delta\lambda}$	thermosignal provided by the IR system, OS
$s(t)$	sensitivity of the IR system, OS/°C
$r(\lambda)$	spectral response of the IR system
$\varepsilon(\lambda, T)$	hemispherical spectral emissivity
$\delta\lambda$	width of the Gaussian anomaly, μm
$\delta\varepsilon$	amplitude of the Gaussian anomaly
$\delta\varepsilon_{rect}$	amplitude of the Gaussian anomaly distributed over $\Delta\lambda$
λ_c	spectral barycenter of the anomaly, μm
$\varepsilon_{\Delta\lambda}$	normal apparent emissivity
$\Delta\varepsilon_{\Delta\lambda}$	gap of normal LWIR apparent emissivity
OS	output signal
SWIR	Short Wavelength Infrared
MWIR	Medium Wavelength Infrared
LWIR	Long-Wavelength Infrared
DH	Damp Heat

Subscripts

app.	apparent temperature
env.	reflected temperature

chamber (60 °C/60–75% of relative humidity) and over 6 years of outdoor conditions at various sites worldwide [1]. Sandstorms are among climatic parameters that cause a significant diminution of the mirror optical performance by generating surface erosion: Karim et al. [2] report irreversible losses in relative specular reflectivity of 0.2% and 0.4% respectively in two different sites (ocean and desert sites in Morocco) during a period of 240 days (0.66 years) of natural exposure. The morphological study of impacts highlights typical diameters 30–50 μm with a depth of 6–10 μm. It is noticeable that the impacted surface ratio in the order of 1.1–1.6% makes difficult to detect the incipient degradation by non-intrusive means. The effect of the combination of wind speed and aerosol concentration is also tested in controlled environment: Lopez-Martin et al. [3] found significant losses of specular reflectance up to 26% for the least favorable conditions. They pointed out that the effect of wind speed on optical degradation is more important than the effect of aerosol concentration. The connection of accelerated sandstorm tests under natural conditions has not been established yet and to date it is impossible to predict the durability of the mirror as it is dependent on a combination of climatic parameters (wind speed and dominant direction) and of aerosol properties.

The challenge in the in-situ quantification of the aging of reflectors is then the definition of the associated indicators and their measuring means. Numerous aging mechanisms induce modification of the spectral emissivity of the materials due to significant changes of surface morphology (owing to corrosion, recrystallization, cracking, etc.) or in volume (moisture ingress and chemical alteration). In a previous work, we demonstrated the connection of the apparent emissivity of common materials with their spectral emissivity obtained by IR reflectometry [4]. The apparent emissivity allows to quantify the aging only if the degradations produce spectral emissivity anomalies within the spectral band of the IR system.

The apparent emissivity measurement implements non-contact temperature measurements and benefits from imaging techniques developed for infrared thermography. This non-destructive and non-intrusive approach should then be effective to quantify the material aging by mapping their apparent emissivities or reflectivities [5].

In this paper, in the theoretical part the sensitivity of the apparent emissivity to spectral anomalies and its measurement capabilities will be itemized. The theoretical and experimental performances will be compared thanks to a home-made device which was already characterized in a previous work [6]. The method is applied on some samples of glass mirrors of heliostats of the solar furnace of Odeillo after having undergone an IEC standard damp heat accelerated aging test [7]. The possibility of quantifying the aging of mirrors is concluded at the scale of a solar power plant.

2. Apparent emissivity

Apparent emissivity appears in the radiometric equation used by infrared cameras. This parameter measures the emission thermosignal of the target compared to a blackbody at the same temperature. It is designed by $\varepsilon_{\Delta\lambda}(t)$. The expression of the radiometric equation is given by:

$$L_{\Delta\lambda}(t_{app.}) = \varepsilon_{\Delta\lambda}(t) \times L^0_{\Delta\lambda}(t) + (1 - \varepsilon_{\Delta\lambda}(t)) \times L^0_{\Delta\lambda}(t_{env.}) \tag{1}$$

where $L^0_{\Delta\lambda}(t)$ and $L^0_{\Delta\lambda}(t_{env.})$ are the blackbody thermosignals respectively associated to the emission temperature t of the sample and to the environment temperature $t_{env.}$. $L_{\Delta\lambda}(t_{app.})$ is the raw thermosignal given by the camera and is associated to the apparent temperature $t_{app.}$. These thermosignals are reported to the spectral band of detection of the camera and to its spectral response. Once the validity of the model of the transmitter is admitted, the expression of apparent emissivity becomes trivial:

$$\varepsilon_{\Delta\lambda}(t) = \frac{L_{\Delta\lambda}(t_{app.}) - L^0_{\Delta\lambda}(t_{env.})}{L^0_{\Delta\lambda}(t) - L^0_{\Delta\lambda}(t_{env.})} \tag{2}$$

Its determination can be made possible with the measurement of three temperatures (apparent, environment and emission ones) and the calibration curve of the system. The calibration of the infrared system is more precisely explained by Riou et al. [8]. This indicator is specific to the detection technique implemented in the camera, the spectral band of detection and the spectral emissivity of the target.

A model of apparent emissivity was submitted by Chrzanowski in 1996 [9]:

$$\varepsilon_{\Delta\lambda}(T) = \frac{\int_{\lambda_1}^{\lambda_2} \varepsilon(\lambda, T) R^0(\lambda, T) r(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} R^0(\lambda, T) r(\lambda) d\lambda} \tag{3}$$

where $\varepsilon(\lambda, T)$ is the spectral emissivity of the target, $r(\lambda)$ is the spectral response of the infrared system and $R^0(\lambda, T)$ is the blackbody radiance. All the parameters are integrated over the spectral band of the camera $\Delta\lambda$ which can be found with the aid of the method developed by Riou et al. [8]. The connection of normal LWIR apparent emissivity to the spectral emissivity ranging within [0.1–0.95] is fully verified for emitter temperatures varying in the range [20–120 °C].