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Importance of the spectral emissivity measurements at working temperature to determine the efficiency of a solar selective coating

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ABSTRACT

The total emissivity of the absorbing surfaces is a critical parameter in the calculation of the radiative thermal losses in solar thermal collectors. This is because the radiative heat losses have a significant economic impact on the final cost of the electricity produced in a solar thermal plant. This paper demonstrates the need to calculate the total emissivity from spectral emissivity measurements at the working temperature of the solar thermal collector, instead of using extrapolated values from spectral emissivities measured at room temperature. Usual uncertainties produced by the estimation of the total emissivity, in which its temperature dependence is only introduced by the Planck function, are analyzed.
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1. Introduction

Solar thermal collectors (STC) are especially relevant in solar thermal devices for producing heat from the sunlight ($T < 150$ °C), or producing electricity in concentrated solar power (CSP) plants ($250 < T < 800$ °C). A critical component of solar thermal collectors is the surface where the conversion of solar radiation into useful heat occurs. These solar absorbing surfaces (SAS) require very high solar absorptivity $\alpha(T)$ in visible and near infrared (NIR) wavelengths and low total emissivity $\varepsilon_T(T)$ in the NIR–mid infrared (MIR) spectral region [1]. These physical requirements must be achieved at the SAS working temperature, which can be around 600 °C in common CSP plants. There is a wide literature, including several reviews, see for example Refs. [1–5], studying SAS. At this point it is important to outline some of the early works on this subject where the basis of the main properties of the selective coatings was set [6–10]. However, the analysis of the SAS characterization literature demonstrates that, in most cases, the total emissivity is obtained by making use of two approximate methods. Both of them make use of experimental data between room temperature and 100 °C, and assume that the spectral emissivity $\varepsilon_\lambda(\lambda,T)$ of the SAS is constant with temperature. In one of these methods the total emissivity is measured at a fixed temperature, usually at $T < 100$ °C using a commercial emissometer. In the other method, the $\varepsilon_T(T)$ is obtained by using the reflectivity spectrum measured at room temperature, $R(\lambda)$, and extrapolating to working temperature T using the following integral:

$$\epsilon_T(T) = \frac{\int_0^\infty [1 - R(\lambda)]L(\lambda, T)d\lambda}{\int_0^\infty L(\lambda, T)d\lambda} \tag{1}$$

where $L(\lambda,T)$ is the Planck function for the emission of a blackbody. Both methods, the emissometer and reflectivity one, can give $\varepsilon_T(T)$ values that significantly differ from the real sample emissivity at working temperature because the coating spectral emissivity has usually a temperature dependence in the range of wavelengths where radiative transfer occurs. In addition, as it can be observed in other materials [11] the coating can even show an atypical temperature spectral emissivity behavior. Therefore, Eq. (1) should be replaced by

$$\epsilon_T(T) = \frac{\int_0^\infty \epsilon_\lambda(\lambda, T)L(, \lambda T)d\lambda}{\int_0^\infty L(\lambda, T)d\lambda} \tag{2}$$

which requires the measurement of the spectral emissivity $\varepsilon_\lambda(\lambda,T)$ at the working temperature [12].

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A simple calculation shows that small differences between the $\varepsilon_T(T)$ values calculated by using Eqs. (1) and (2) may be important in defining the efficiency of a solar selective coating. An effective coating requires $\alpha(T) > 0.95$ and $\varepsilon_T(T) < 0.05$ at working temperature (i.e. 600 °C). Therefore, certain difference between the values of the total emissivity obtained by Eqs. (1) and (2) produces an equivalent difference in the radiative thermal losses. These energy losses in the SAS increase proportionally to T^4 [4]. As a consequence, the differences between using Eqs. (1) or (2) may have significant economic impact on the final cost of the electricity produced in a solar thermal plant.

This paper is focused on demonstrating, from an experimental point of view, that the analysis of the efficiency of a solar coating at its working temperature requires the calculation of $\varepsilon_T(T)$ from emissivity spectrum measured at that temperature. A stack with two cermet layers of silicon nitride with different amounts of molybdenum over a silver infrared mirror layer is used as solar coating. The experimental measurements were carried out between 250 and 600 °C and the experimental results obtained are compared with those calculated by the usual approximate methods.

2. Experimental results

Fig. 1 shows a schematic representation of the solar selective coating used in this paper. Experimental details about the coating preparation as well as the physical and chemical characterization have been given elsewhere. See Ref. [13] and references cited therein.

Spectral emissivity measurements were carried out with a homemade IR-radiometer [14] at moderate vacuum ($\approx 10^{-3}$ mbar) during five heating cycles between room temperature and 600 °C. This moderate vacuum is used in a large number of industrial applications of solar collectors. Normal spectral emissivity is measured in each heating cycle at 15 different temperatures following the sequence shown in Ref. [12].

The radiometer allows an accurate detection of the spectral thermal radiation as well as its fast processing. The sample holder permits directional measurements and the sample chamber ensures a controlled atmosphere and moderate vacuum. The radiometer calibration was carried out using a modified two-temperature method [15] and the emissivity spectra were obtained applying the blacksur method described in Ref. [16]. The maximum combined standard uncertainty varies between 1% and 10% depending on wavelength and temperature [17]. The average uncertainty value is around 4%. The sample temperature was measured by means of two spot-welded thermocouples on the sample surface.

In Fig. 2 we plot the emissivity versus the heating cycle number for two temperatures and four wavelengths. Similar plots were found at other temperatures and wavelengths. It should be noted that after the third heating cycle changes in the emissivity value are smaller than the uncertainty in its measurement. It can be stated that thermal stability of the coating emissivity is ensured after a few initial cycles. It is an essential property if one wants to use a coating in a STC.

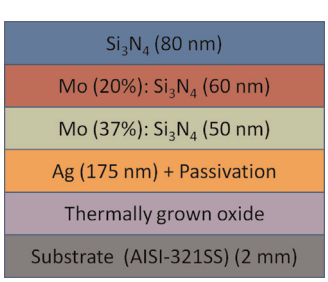

Fig. 1. Schematic representation of the solar selective coating.

In Fig. 3, the coating normal spectral emissivity at eight temperatures, between 250 and 600 °C, during the fifth heating cycle is plotted. Temperature dependence can hardly be detected and therefore a closer look has to be taken. In Fig. 4 the emissivity dependence on temperature at four different wavelengths is shown. Even though the emissivity usually increases with temperature [18,19], at short wavelengths such as 2 μm the emissivity decreases, whereas at longer wavelengths little or no evolution is appreciated. This behavior is crucial, since even small variations may be sufficient to give appreciable difference between calculated total emissivities from Eqs. (1) and (2). It is precisely the value of $\varepsilon_T(T)$ which indicates if a coating shows good performance for high temperature solar harvesting.

The comparison between the coating and substrate spectral emissivity values is an interesting feature when characterizing the coating efficiency. Fig. 5 shows the normal spectral emissivity of the coating and the substrate at 600 °C. It is observed that the coating spectral emissivity is appreciably lower than that of the substrate only for $\lambda > 5$ μm.

The interest of the results is that they can be used to calculate and analyze one of the fundamental physical parameters in a thermal solar coating: the radiation energy losses at the working temperature. For this calculation the knowledge of $\varepsilon_T(T)$ at this temperature is necessary. What follows the differences that may exist between the calculation performed by Eq. (1) and those made with Eq. (2) is analyzed for the coating shown in Fig. 1. Here it should be noted that the integral calculation in Eqs. (1) and (2) is only accurate in the

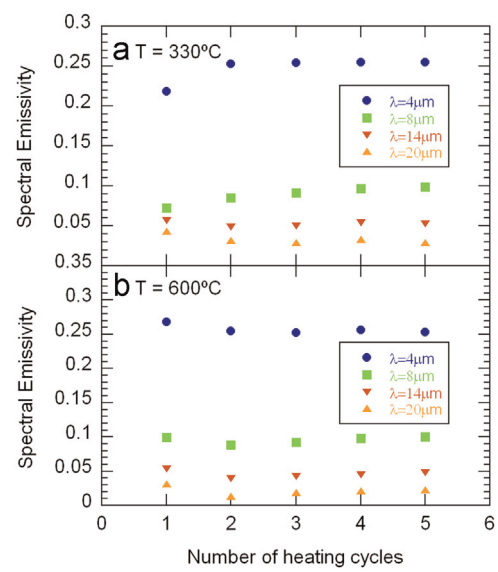

Fig. 2. Coating emissivity $\varepsilon(\lambda,T)$ as a function of heating cycle for 4, 8, 14 and 20 μm at (a) T=330 °C and (b) T=600 °C.

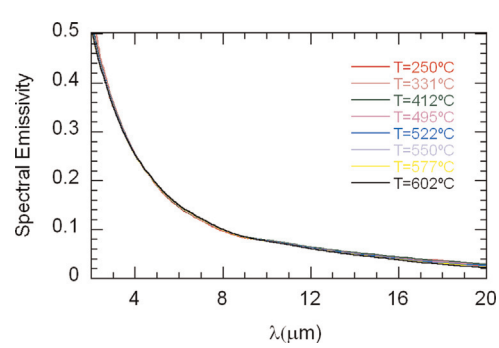

Fig. 3. Normal spectral emissivity $\varepsilon(\lambda,T)$ of the selective coating for eight different temperatures measured during the fifth heating cycle.

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