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Equipment and methods for measuring reflectance of concentrating solar reflector materials

Aránzazu Fernández-García[a,*], Florian Sutter[b], Lucía Martínez-Arcos[a], Christopher Sansom[c], Fabian Wolfertstetter[b], Christine Delord[d]

[a] CIEMAT-PSA, Senés Road, km. 4.5 B.O. Box 22, E04250, Tabernas, Almería, Spain
[b] DLR German Aerospace Center, Institute of Solar Research, PSA, Senés Road, Km. 4.5, P.O. Box 39, E04200, Tabernas, Almería, Spain
[c] Global CSP Laboratory, Cranfield University, Bedfordshire MK43 0AL, United Kingdom
[d] CEA LITEN, National Institute of Solar Energy INES, 73377 Le Bourget-du-Lac, France

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ABSTRACT

The proper optical characterization of solar reflector materials is a challenging task. Although several commercial instruments exist to measure reflectance, they have been developed for other applications and often do not meet all the specific requirements demanded by the solar thermal industry. In particular, the characterization of solar reflectors involve the complete solar spectral wavelength range, an incidence angle range from near normal to 70° and most importantly a very narrow acceptance angle range from near specular to 20 mrad. The accurate measurement of reflectance as a function of all the previously mentioned parameters has not been commercially implemented. This paper reviews the different alternatives to measure reflector materials, describes reflectance models used to approximate the missing information and presents current research work on prototype reflectometers to fill the gap.

1. Introduction

The development of renewable energy has increased over the past few years due to the high environmental cost of fossil fuels and our great dependence on them [1]. Solar energy is considered one of the most promising alternative sources of energy for avoiding the dependency on fossil energy resources [2]. In the last 30 years, 26% of the global research effort has been related to the use of solar energy [3]. Among solar technologies, solar thermal electricity (STE) from concentrating solar power (CSP) plants is set to play a decisive role in the renewable energy mix [4]. The two main systems of concentrating solar collectors, line-focusing (parabolic-trough collectors and Fresnel collectors) and point-focusing (solar towers, parabolic dishes and solar furnaces), have in common that the sunlight is focused onto a receiver by mirrored reflectors to increase the enthalpy of the heat transfer fluid flowing inside that receiver. Parabolic-trough technology is the most proven large-scale solar thermal power technology that is available today [4–6].

The reflectance of the concentrating reflectors (interchangeably called mirrors) has a direct impact on the overall efficiency of these solar thermal systems [7]. Its accurate assessment requires appropriate testing methods and measurement tools. This makes the measurement of the solar-weighted specular reflectance (which is the parameter that correctly quantifies the reflective quality of a solar reflector [8]) an important concern for solar reflector evaluation. However, currently there is no commercial instrument available to directly measure this optical parameter effectively [9], accomplishing all of the features required by a hypothetical ideal instrument. These requirements have been specified in [10] and include -among others- the following points:

– The measurement over the complete solar spectral wavelength range, but at least between $\lambda = 280$ and $\lambda = 2500$ nm. The remaining contribution to the direct irradiance in the spectral range of 2500–4000 nm can be calculated from the standard spectrum [11]

Abbreviations: $(SR)^2$, Space Resolved Specular Reflectometer; ARTA, Absolute Reflectance and Transmittance Analyzer; BRDF, bidirectional reflectance distribution function; CMOS, complementary metal–oxide–semiconductor; CPV, concentrating photovoltaics; CSP, concentrating solar power; D & S, Devices & Services; DNI, direct normal irradiance; EMA, Equivalent Model Algorithm; IEA, International Energy Agency; ISE, Institute for Solar Energy Systems; LED, light-emitting diodes; MIRA, Mirror Reflectance Function Analyzer; MWR, Multiple Wavelength Reflectometer; NIR, near infrared; OPAC, Optical & Aging Characterization; Pab, Pab advanced technologies Ltd (pab); PE, Perkin Elmer; PMT, photomultiplier; PSA, *Plataforma Solar de Almería*; S2R, Spectral Specular Reflectometer; SMQ, Solar Mirror Qualification; SMS, Schmitt Measurement Systems; STE, solar thermal electricity; TIS, Total Integrated Scatter; TraCS, Tracking Cleanliness Sensor; URA, universal reflectance accessory; UV, ultraviolet; Vis, visible; VLABS, Very-low-angle beam spread

* Corresponding author.
E-mail address: arantxa.fernandez@psa.es (A. Fernández-García).

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Nomenclature

Greek symbols

σ	standard deviation
σ_φ	equivalent roughness
α	absorptance
β	incident angle from the laser beam to the reference mirror (University of Malaysia set-up)
$\Delta\rho$	reflectance difference
θ	reflected angle from the reference mirror to the photo detector (University of Malaysia set-up)
θ_i	direction of the incident radiation
λ	wavelength
ξ	cleanliness
ρ	reflectance or amplitude of a reflectance Gaussian distribution
τ	transmittance
φ	acceptance angle
χ	parameter for the observed exponential decrease of the wide scattering angle

Roman symbols

a	major half axis of the ellipse
A_1, A_2	amplitude coefficients
a_1, a_2, a_3	amplitude coefficients
b	offset between reflection terms
c	minor half axis of the ellipse
C_{clean}	calibration constant for TraCS system
f	focal length
$F1$, $F2$	focal points of the ellipse
K	relative weight of two Gaussians
t	time
T_{clean}	time span
T_s	surface temperature

Subscripts

h	hemispherical
s	solar
λ	spectral

to be around 2.5%.

- Precise, selectable acceptance apertures or a range of acceptance angles appropriate to measure the specular reflectance as a function of φ.
- Measurement at various incidence angles ranging from near normal to at least 50° or an innovative approach to obtain the specular reflectance as a function of θ.
- Adjustment options to account for different mirror thicknesses and surface curvatures.
- Measurement spot size as large as possible.
- Non-contact measurement.
- High precision and repeatability.
- No influence by external stray light.

Reflectance measurements serve to qualify reflectors in mint condition, to evaluate their cleanliness due to soiling, or to quantify their vulnerability to ageing effects during exposure to the environment.

An evaluation formula presented by Pettit [12] has been widely used in the past. Although this approximation is appropriate for reflectors with high specularity in the whole solar spectrum, new research has demonstrated that for some innovative reflector materials a valid and adequate procedure is still missing. Research work of the last few years regarding the reflectance measurement procedure [13–15] and instruments [16–18] to assess solar reflector materials has advanced significantly.

It deserves to be mentioned the activities ongoing in several working groups during the last decade to stablish a proper protocol to measure the reflectance of concentrating solar reflector materials. A group of experts in the field of optical characterization of solar reflectors has been working since 2009 as members of the SolarPACES Organization (which belongs to the International Energy Agency, IEA) to create a reflectance measurement guideline [9,15]. Several versions of the guideline have been already published [10]. Under the framework of the Spanish standardization body AENOR, the sub-committee AEN/CTN 206/SC “Thermoelectric solar energy systems” is working on topics related to the concentrating solar thermal power plants since 2010 [19–21]. Several standards have been published or are in preparation, including one for the reflectors characterization and durability assessment. At international level, within the IEC TC 117 committee “Solar thermal electric plants” created in 2012, a project team is also focus on this subject [19–21]. The three working groups are linked among them to avoid duplicating the efforts and obtaining contradictory results.

Besides the characterization of reflector materials, research activities on the fluctuating reflectance losses due to soiling, i.e. the accumulation of dust and dirt on mirror surfaces when exposed to the environment, have increased significantly [22]. As soiling is quantified by monitoring the reflectance of mirrors over time, the here presented methods play an important role in this field of research. Applications of soiling research can be found in resource assessment studies and the optimization of cleaning cycles in running power plants. As CSP projects are located more closely to dusty environments like sand deserts [23], growing attention is given to the issue of soiling and thus reflectance measurement methods.

This paper presents a review of the techniques employed to assess the optical properties of solar reflectors, as a contribution to define the correct characterization protocol. In the first part, the models developed to calculate the representative optical parameters related to reflectance (both based on theoretical statements or experimental parameters) are presented. Secondly, commercial instruments used to optically characterize solar reflectors in laboratory and outdoors are reviewed. Finally, the known prototypes currently under development are described. Glossmeters use the specular reflection as a photometric value (the radiometric reflectance value weighted with the visual sensitivity function of the human eye) for the evaluation of gloss in relation to a black polished reference at defined incidence angles. As their capabilities are not suitable for evaluating the specular reflectance of solar mirror materials, they are not included in this work. Nomenclature and reflectance definitions used in this paper are in accordance with existing standards [25,26], with some slight improvements which will be fed into the standardization committees.

2. Reflectance models

Measuring the solar-weighted specular reflectance of a mirror requires instruments capable of measuring cumulative specular reflectance values over the whole solar spectrum. While some laboratory devices have been developed for this objective, no portable equipment to be used in the solar fields is available with the appropriate features. Over the years, models have been proposed to approach the solar-weighted specular reflectance by a combination of measurements with portable and laboratory de-