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Towards Standardized Testing Methodologies for Optical Properties of Components in Concentrating Solar Thermal Power Plants

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Abstract. Precise knowledge of the optical properties of the components used in the solar field of concentrating solar thermal power plants is primordial to ensure their optimum power production. Those properties are measured and evaluated by different techniques and equipment, in laboratory conditions and/or in the field. Standards for such measurements and international consensus for the appropriate techniques are in preparation. The reference materials used as a standard for the calibration of the equipment are under discussion. This paper summarizes current testing methodologies and guidelines for the characterization of optical properties of solar mirrors and absorbers.

INTRODUCTION

Specific key components in the solar field of a solar thermal plant, or concentrating solar power (CSP) technology, are the mirrors and the receivers. Their optical properties are important for high production performance of the plant. Those properties are the solar specular reflectance of the mirrors, solar transmittance of the glass envelopes (in case of glass covers as in parabolic-trough and linear-Fresnel technology), and solar absorptance and solar emittance of the receivers.

In Spain, a standardization sub-committee AEN/CTN 206/SC "thermoelectric solar energy systems" deals with topics related to the concentrating solar thermal power plants since 2010. Several standards are advanced in preparation covering the components of the solar field, the reflectors and receiver tubes for trough collectors.

At international level, within the IEC TC 117 committee "Solar thermal electric plants" created in 2012, a project team works on the receiver tube for parabolic trough collectors, including the testing methods for obtaining its optical properties. Within Task III of the SolarPACES Organization (which belongs to the International Energy Agency, IEA), working groups are dealing specifically on the international guidelines for reflectance measurements [1], mirror shape, and durability assessment of reflectors and receiver tubes.

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In the photovoltaic (PV) sector, existing standards, including ISO and ASTM, are specifically applicable to optical properties measurements. Recently, an international IEC standard (IEC 62788-1-4) has been proposed by the Encapsulation Task Group within the Working Group 2 (WG2) of the IEC / TC 82 for the quantification of the optical performance of PV encapsulation materials.

In other sectors, such as glass in buildings, some standards are applicable to determine glass optical properties for solar radiation. The ISO 9050:2003 standard is devoted to the determination of light transmittance, solar direct transmittance, total solar energy transmittance, ultraviolet transmittance and related glazing factors [2], and the EN 410:2011 standard is dedicated to the determination of luminous and solar characteristics of glazing [3]. In this field, there are also some discrepancies due to the different calculation database used in both standards although the determination methods are the same.

Regarding the optical properties of plastics, the ISO 13468-2 standard [4] should be also mentioned for the determination of the total luminous transmittance of transparent materials and the ISO 17223:2014 standard [5] is devoted to the determination of yellowness index and change in yellowness index.

SOLAR REFLECTORS

Some standards are published for the solar reflectance measurement, such as standards ASTM E424 [6] and ASTM E 903 [7], but those testing methods are not specific to reflectors for CSP technologies.

For the measurement of the optical properties of reflectors, the group within SolarPACES task III has published a guideline specifically dealing with the hemispherical and specular reflectance (ρ) measurements of the reflectors for concentrating solar thermal applications [1]. According to this guideline, an UV-VIS-NIR spectrophotometer with an integrating sphere is used for the hemispherical spectral reflectance measurement of mirrors with high specularity (i.e. low beam spread, low scatter, low haze). The criteria under which a reflector can be considered of high specularity are defined in [1]. In addition, the group is working on specular reflectance measurements of materials which show scattering or haze effects (such as aluminum or polymer based reflectors). This topic involves research and setting up prototype reflectometers due to scarcity of commercial instruments to measure spectral specular reflectance at appropriate wavelengths (that is, in the solar range).

The measurement procedures applied in the AENOR standard draft to determine the ***reflectance*** and the ***shape*** (slope) of solar reflectors are referring to the guidelines developed and published under the framework of SolarPACES Task III [1]. The testing method in this standard draft is applicable to all reflector types. Hemispherical spectral reflectance is measured with a spectrophotometer with integrating sphere (diameter of at least 150 mm) at near normal incidence ($\theta_i \leq 15^\circ$). The solar hemispherical reflectance $\rho_{s,h}([\lambda_a,\lambda_b],\theta_i,h,T_s)$ shall be measured in the relevant solar spectrum (λ_a =280 nm and λ_b =2500 nm). It is recommended to use a wavelength interval of $\Delta\lambda$=5 nm or $\Delta\lambda$=10 nm and report it in the testing report. All measurements shall be carried out at ambient temperature of T_s =25±3°C. Before measuring, the sample should be cleaned carefully with demineralized water and a soft cloth and once the sample is dry, filtered pressurized air may be used to remove any remaining dust particles on the reflector surface. The reflectors surface may only be touched with gloves. The resulting hemispherical reflectance spectrum is weighted with the solar spectrum (direct normal and circumsolar) published in ASTM G173 [8].

According to the AENOR procedure, adopted from the methodology developed by SolarPACES Task III group [9], "*A solar mirror can be considered as highly specular and, consequently, the solar weighted hemispherical reflectance can be considered as the appropriate parameter to describe the reflector, only if the following experimental criterion, composed of two conditions, is passed:*

- *The difference between the experimental values of near-specular reflectance, $\rho_{s,\varphi}(\lambda,\theta_i,\varphi,T_s)$, at a λ in the range λ=[400, 700] nm and $\theta_i \leq 15^\circ$, measured for $\varphi \approx 7.5$ mrad and $\varphi \approx 23.0$ mrad must be less or equal than the experimental error (typically ±0.003). The two measurements must be accomplished in the same conditions (particularly with the same instrument and in the same point of the mirror surface), except for the φ angle. This test must be repeated at least at three different points of the mirror surface.*
- *The solar-weighted diffuse, ρ_d, reflectance at $\theta_i \leq 15^\circ$ and 7.5 mrad < φ < 120 mrad, $\rho_d([\lambda_a,\lambda_b],\theta_i \leq 15^\circ$, 7.5 mrad < φ < 120 mrad), measured with a high quality spectrophotometer equipped with an integrating sphere with diameter not less than 150 mm and configured to leave the specular beam escaping with a light-trap accessory, must be less or equal than the experimental error (typically ±0.003).*

If the criteria of high specularity previously defined are fulfilled, the solar near-specular reflectance, $\rho_{s,\varphi}([\lambda_a,\lambda_b],\theta_i,\varphi,T_s)$, can be assumed to be equal to the solar hemispherical reflectance, $\rho_{s,h}([\lambda_a,\lambda_b],\theta_i,h,T_s)$, in the same range and within the measurement uncertainty boundaries.

Otherwise:

- *The parameter $\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi,T_s)$ should preferably be measured at least at three wavelength bands in the solar wavelength range.*
- *As a minimum requirement, $\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi,T_s)$ must be measured at least at near normal incidence ($\theta_i <= 15°$) and at least at three φ in the range of $\varphi >= 0$ to $\varphi <= 25$ mrad.*

For the characterization of aged samples, the corresponding section of the SolarPACES guideline on measurement of aged samples applies. For the monitoring of the aging of samples (e.g. before and after an accelerated ageing test), measurement of the following parameter is sufficient:

- *Measurement of $\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi,T_s)$ is only necessary at one wavelength in the range λ=400 – 700 nm and one acceptance half-angle $\varphi \leq 25$mrad at an incidence angle near normal $\theta_i \leq 15°$".*

Examples of equipments used for hemispherical and specular reflectance, at DLR/CIEMAT and CENER, are presented in Figs. 1 and 2.

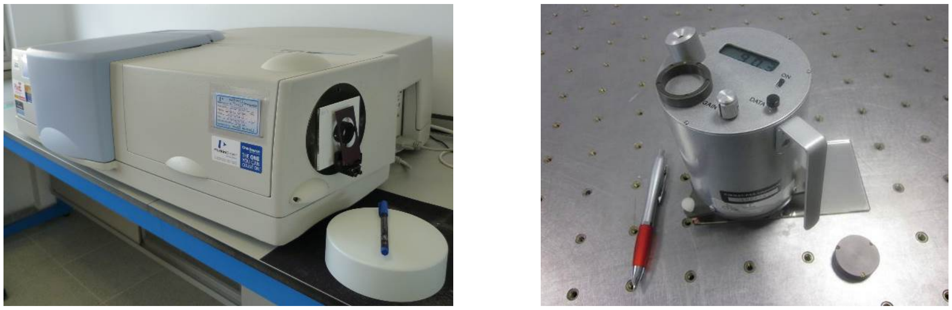

FIGURE 1. Perkin Elmer Lambda 1050 spectrophotometer (left) and D&S 15R-USB reflectometer (right) (source DLR/CIEMAT)

FIGURE 2. Optronics Laboratories OL 750 spectrophotometer (left) and Condor reflectometer (right) (source CENER)

For hemispherical measurement, different commercial spectrophotometer devices are available in the market, such as Perkin Elmer (models Lambda 950 and Lambda 1050) [10], Jasco (model V-670) [11], Gooch & Housego (model OL750) [12], Agilent [13], Shimadzu [14]...

For measuring specular reflectance different commercial devices have been applied and reported (Devices & Services model 15R [15], Abengoa model Condor [16], Surface Optics [17]). Further-on, new prototype devices are published (such as VLABS by Fraunhofer ISE [18], SQM by ENEA [19], a new instrument developed by the University of Zaragoza [20], MIRA, $(SR)^2$ and S2R by DLR [21, 22, 23], etc…).

For the measurement with both a spectrophotometer and a reflectometer, a reference sample is needed for data evaluation. Different types of calibration standards can be found, but the reference sample shall be a mirror of high specularity, and it is preferred to use a second surface mirror which does not degrade easily (scratches) [1]. The traceability of this reference mirror must be documented. The reference mirror ("secondary standard" or lab master reference) shall be handled with extreme care. It is recommended to use the secondary standard to calibrate additional working standards for daily use and carefully observe the problem of degradation due to scratching. The secondary standard can be used to check the working standards in regular intervals. In case of degradation, the working standards must be replaced.

Within the European project STAGE-STE [24] a round-robin test was organized in 2015-2016 for comparison of the durability test included in the AENOR standard draft, and other internal testing methodologies for aluminum mirrors. The participating institutions in this round-robin test are CEA (France), DLR/CIEMAT (Germany/Spain), LNEG (Portugal), CENER (Spain), and TECNALIA (Spain).

For the mirror shape different techniques could be used as the photogrammetry and deflectometry [25]

RECEIVER TUBES

For optical characterization of receivers tubes for parabolic through collector, two standard drafts are in progress: The first one in the Spanish committee AEN/CTN 206/SC 117 /WG2 [26] and the second one in the international committee IEC prIEC 62862-3-3, currently based on the Spanish standard. The IEC working group 62862-3-3 is led by the company RIOGLASS, and its publication is expected for 2017.

Two different testing methodologies are described in the drafts: destructive and non-destructive tests.

The destructive tests, aim at obtaining the solar absorptance α_S of the absorber tube and the solar transmittance τ_S of the glass envelope of the receiver, respectively, from spectrophotometric measurements. For these measurements, the UV-VIS-NIR spectrophotometer necessary is the same as the one used for the reflector characterization, see above. Hemispherical reflectance measurements of the absorber samples are used to calculate the solar absorptance α_s. Particular care in using holders for curved samples and adequate working reference calibrated periodically are advised. For transmittance measurements of antireflex-coated glass tube samples, the spectrophotometric measurement is a direct measurement with air as reference. Some existing standards are referred to obtaining the solar reflectance and solar transmittance values by using spectrophotometers, such as ASTM E424 [6] and ASTM E903 [7].

The thermal emittance, $\varepsilon_{t,}$ of the absorber tube can also be obtained by optical measurements by using a FTIR spectrophotometer equipped with a gold coated integrating sphere [27]. The hemispherical reflectance spectrum is obtained, and then the weighted hemispherical reflectance, $\rho_{IR,}$ at temperature T is calculated by weighting the spectrum measured with the black body spectrum at temperature T, according to Planck's law. The thermal emittance is found from the corresponding weighted hemispherical reflectance: $\varepsilon_t=1- \rho_{IR.}$.

With the non-destructive tests of the entire receiver tube, the objective is testing without destroying the protective vacuum insulation and possibly affecting coating properties. Some instruments and different configurations are possible and referred to in the AENOR and IEC standard drafts [28].

The optical testing bench used by CENER, developed in collaboration with the University of Zaragoza, measures spectrally resolved and simultaneously the solar absorptance α_S of the absorber tube and solar transmittance τ_S of the glass envelope of the receiver [29-31]. The optical test bench for PT receivers is able to perform spectral measurements of the glass envelope solar transmittance (τ_S) and absorber solar reflectance (ρ_S) in the wavelength range from 300 nm to 2500 nm, at different absorber tube temperatures. The test bench is comprised of a simultaneous transmittance (τ) and reflectance (ρ) measurement by using an optical sensor head (OSH) which moves along the PT receiver tube, and also through a rotation system allows measuring at different points around the tube section to test the uniformity of optical properties (see Fig. 3).

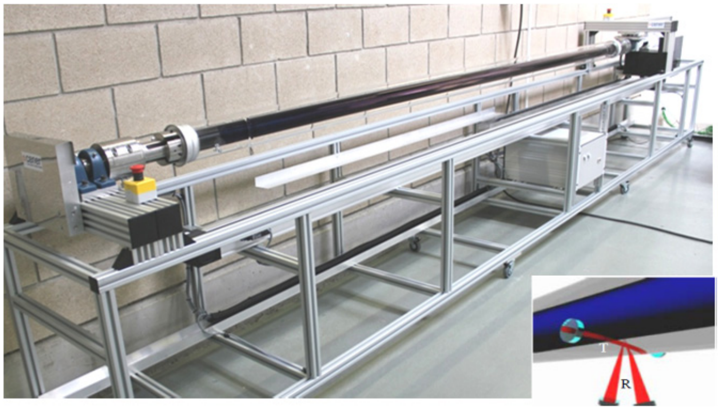

FIGURE 3. PT receiver optical characterization test bench PTR sample (source CENER)

For in-field measurement, the portable device Mini Incus by Abengoa, also developed with the University of Zaragoza, measures the optical properties of a receiver tube in field for 14 wavelengths, between 365 and 1950 nm [32] (see Fig. 4).

FIGURE 4. Portable device Mini Incus by Abengoa (source Abengoa)

The solar simulator optical testing bench (ElliRec, OptiRec, QRec) developed by DLR measures the overall optical efficiency, $\tau * \alpha$ product, using a reference receiver tube for comparison, achieving low uncertainty and highly reproducible results [33,34] (see Fig. 5).

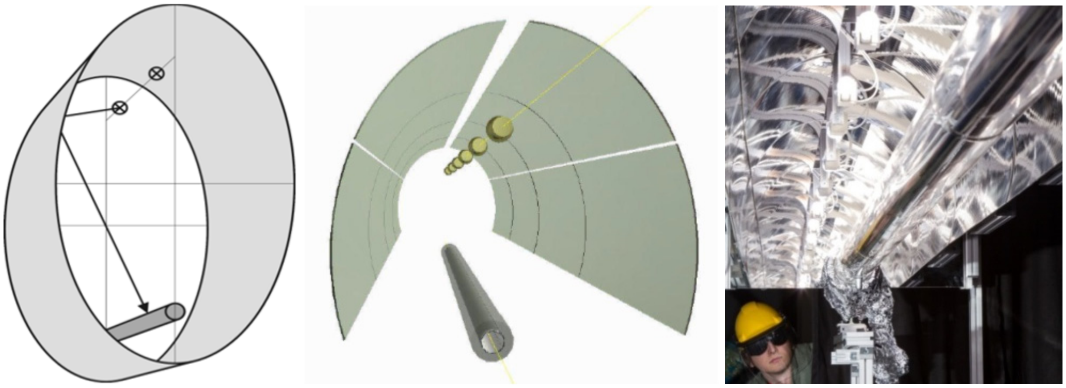

FIGURE 5. Schematic of the cylinder-elliptic linear focus solar simulator (left), realization in DLR (right) (source DLR)

Within the European project STAGE-STE [24] WP8.1 a round-robin test was organized in 2015-2016 for comparison of the optical measurement obtained by some equipments based on different configuration from different European laboratory using the AENOR and IEC standard drafts for no-destructive and destructive measurement (DLR (Germany), CENER (Spain), and Fraunhofer (Germany)) [35].

SOLAR SPECTRUM

For this data processing will be integrated, for the following expressions Eq. 1 and Eq. 2 shall be used.

$$\alpha_S = \frac{\sum_{\lambda_1}^{\lambda_2} (1 - \rho(\lambda_i)) E(\lambda_i) \Delta\lambda_i}{\sum_{\lambda_1}^{\lambda_2} E(\lambda_i) \Delta\lambda_i} \qquad (1)$$

$$\tau_S = \frac{\sum_{\lambda_1}^{\lambda_2} \tau(\lambda_i) E(\lambda_i) \Delta\lambda_i}{\sum_{\lambda_1}^{\lambda_2} E(\lambda_i) \Delta\lambda_i} \qquad (2)$$

where: $\rho(\lambda_i)$ is the measured spectral reflectance [-], $\tau(\lambda_i)$ is the measured spectral transmittance [-], λ_i is the wavelengths measured [nm], $\Delta\lambda i$ is the interval of the respective wavelengths [nm] and $E_{\lambda i}$ is the spectral distribution of the direct solar irradiance AM 1.5 D (i.e. ISO 9845-1 [36] or ASTM G173 [8] standards could be used). $E_{\lambda}i$ must be found by interpolation for the specific wavelengths measured and added up appropriately over the respective wavelength interval.

For the calculation of the solar properties, an integration calculation is used and different solar spectrum distribution from different references and standards could be used [27-30]. See Table 1 and Fig. 6 for a summary of the standard with solar spectrum. The more widely used spectrum in CSP sector is the direct normal distribution published in ASTM G173 [8].

TABLE 1. Comparison of standard solar spectra

Standard	Air mass	Measurement	Wavelength	Equipment	Precision
ISO 9845-1 [36]	AM 1,5 global	No	50 or 100 values selected with equal energy intervals between 305 nm and 4045 nm	--	--
ISO 9050 [2]	-- global	No test method, only requirement	From 300 nm to 2500 nm	Commercial spectrophotometer periodically calibrated with reference materials	± 0,01.
IEC 60904-3 [37]	--	No	uniform intervals (0.5 nm 280 to 400 nm, 1 nm 1700 nm 400 to 5 nm 4 000 1700 nm)	--	--
ASTM E 424 - 71 [6]	AM 2	Yes	20 values selected with equal energy intervals or weight values every 50 nm	Spectrophotometer with integrating sphere from 350 to 2500 nm	± 0.1 %
ASTM G173-03 [8]	AM 1,5 direct	No	0.5 nm intervals below 400 nm, 1 nm for 400 to 1700 nm, one intermediate value of 1702 nm, 5 nm intervals for 1705 to 4000 nm	--	--
EN 410 [3]	AM 1 global	Si	20 nm intervals for 300 to 800 nm, 50 nm intervals for 800 to 2100 nm, 100 nm intervals for 2100 to 2500 nm	quasi-normal incident radiation	--

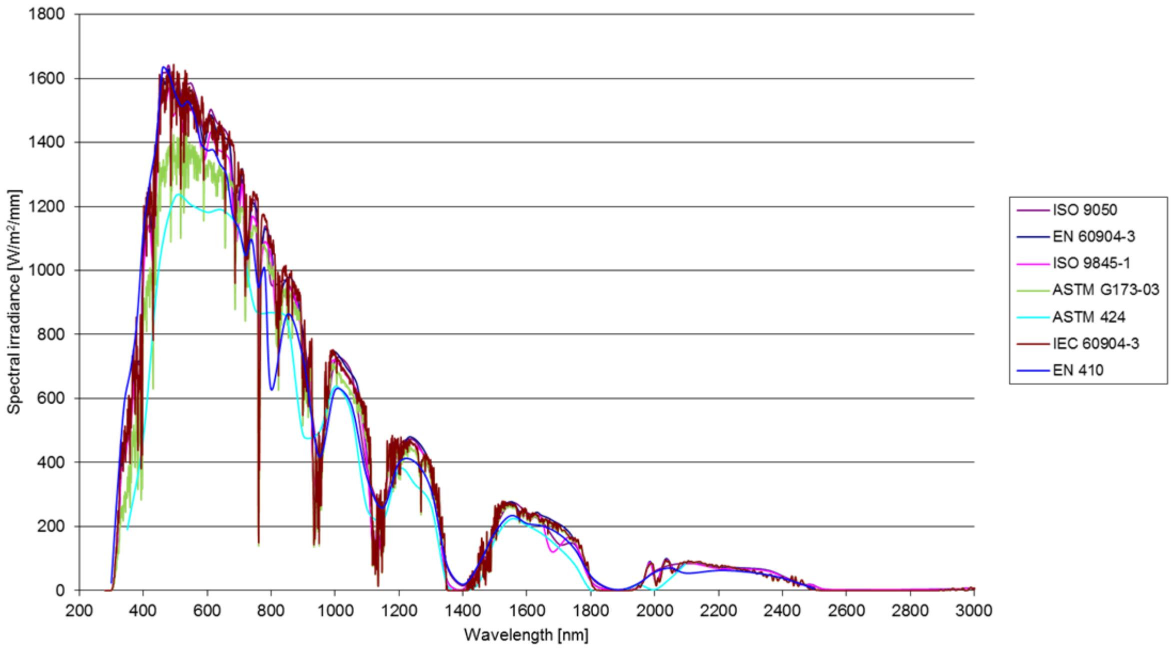

FIGURE 6. Comparison of the different solar spectra

CONCLUSION

Test methods for optical properties of mirrors and absorbers for CSP applications are defined based on existing standards and for a relevant direct solar spectrum. Different standardization committees (IEC) and experts groups (SolarPACES task III) are currently active on this topic at an international level. The reflectance measurements require reliable, durable and traceable reference samples. Measurement is straightforward with existing spectrometers for highly specular reflector materials (in particular for back silvered glass). Optical properties of receiver tubes for parabolic trough collectors are measured in the classic destructive manner with spectrophotometers, but with the challenge of the curved surface. Non-destructive measurement of the optical efficiency in a linear solar simulator by DLR has the advantage of high reproducibility of the results but requires definition of a reliable reference sample, usually a receiver tube of the same type. The reproducibility for this equipment has been measured to 0.04 [33]. Non-destructive measurement of the optical efficiency with a scanning device by CENER also has high reproducibility and use reference material for calibration The measurement precision for this equipment was measured below 1,31% [30]. The methods are already widely used and round robin tests aim at international agreements on the methods. Guidelines and standards are in advanced stage.

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