Solar Energy Materials and Solar Cells 176 (2018) 119–133

Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

journal homepage: www.elsevier.com/locate/solmat

The effect of incidence angle on the reflectance of solar mirrors

Florian Sutter[a,*], Marco Montecchi[b], Haymo von Dahlen[a], Aránzazu Fernández-García[c], Marc Röger[a]

[a] DLR German Aerospace Center, Institute of Solar Research, Plataforma Solar de Almeria, Ctra. Senés Km. 4, P.O.Box 44, 04200 Tabernas, Almería, Spain
[b] ENEA C.R. Casaccia, Departmet of Energy Technologies, Via Anguillarese, 301, 00123 S. Maria di Galeria, Roma, Italy
[c] CIEMAT, Plataforma Solar de Almeria, Ctra. Senés Km. 4, P.O.Box 22, 04200 Tabernas, Almería, Spain

ARTICLE INFO

Keywords:
Reflectance
Incidence angle
Solar reflector
Solar weighting
Spectral reflectometer

ABSTRACT

Solar reflectors for Concentrating Solar Technologies require a high reflectance in the terrestrial solar spectrum (280–4000 nm). Besides the wavelength, the reflectance of solar mirror materials is also dependent on the incidence angle of the incoming sunlight. The commonly used measurement equipment measures the reflectance at fixed near-normal incidence angles, typically between 8° and 15°. In this work, the annual incidence angle frequency distribution has been calculated for a LS3/Eurotrough-type parabolic-trough collector located at different sites, and for the heliostat field of the solar tower system CESA-1 located at the Plataforma Solar de Almería in Tabernas, southern Spain. It was found that the most frequent incidence angles registered in the solar field are quite higher than the ones at which reflectance is measured with state of the art instruments, obtaining mean incidence angles in the range of 28–35° depending on the type and location of the solar field.

A methodology to predict the off-normal reflectance of silvered-glass mirrors based on near-normal reflectance and transmittance measurements of the uncoated glass is presented. The complex refractive index of 2, 4 and 5 mm thick solar glass and the deposited silver was determined and used to model the solar weighted reflectance of silvered-glass mirrors at different incidence angles. The model was compared to experimental measurements. For this purpose, the Spectral Specular Reflectometer (S2R) has been improved and updated with a polarizer crystal to measure reflectance at perpendicular (s-pol) and parallel (p-pol) polarizations up to incidence angles of $\theta = 70°$.

Eight solar mirror materials (three silvered-glass mirrors of different glass thicknesses, two anti-soiling coated glass mirrors, two enhanced aluminum reflectors and a silvered polymer film) have been measured over a broad range of incidence angles and the results have been weighted with the annual incidence angle frequency distribution. The obtained incidence angle-weighted reflectance is a suited parameter to compare the efficiency of solar mirror materials taking into account their use in a specific collector type and location.

1. Introduction

In Concentrating Solar Technologies (CST), solar light is concentrated on a focal point or a focal line by using 2-axis or 1-axis tracking mirrors. A receiver, located in the focal point or line transforms the collected solar radiation either directly to electricity with concentrating photovoltaic (CPV) systems [1], to heat which can be used in a heat engine to produce electricity with concentrating solar power (CSP) systems [2] or for chemical [3] or thermal processes in industrial applications [4].

The reflectance, ρ, is defined as the ratio of the radiant flux reflected from a surface to that of the incident radiation [5]. The reflectance of tracking solar mirrors, $\rho_{\lambda,\varphi}(\lambda,\theta,\varphi,T_s)$, is dependent on the following four parameters: the wavelength λ and the incidence angle θ of the incident light, the acceptance angle φ of the receiver, which defines the admissible angular area around the perfect specular reflection, and the surface temperature T_s [6,7].

The relevant wavelength range for solar reflectors is the terrestrial solar spectrum $\lambda = [280, 4000]$ nm. A representative mean value of all ρ in this range is obtained by performing a solar weighting with a standard solar spectrum (e.g. according to [8] (direct irradiance) for air mass AM 1.5 or [9]). Because the far-NIR and UV ranges have a low impact and it is practically more convenient for the measurement equipment, the relevant measurement range for reflectance evaluation can be resized to $\lambda = [320, 2500]$ nm. The absolute weight of solar radiation in the wavelength intervals [280, 320] and [2500, 4000] nm is less than 1% in total.

For the temperature range achieved during normal operation of

---

[*] Corresponding author.
E-mail address: Florian.Sutter@dlr.de (F. Sutter).

https://doi.org/10.1016/j.solmat.2017.11.029
Received 25 September 2017; Received in revised form 14 November 2017; Accepted 16 November 2017

Nomenclature

CESA-1	central receiver power tower at PSA
CPV	Concentrating Photovoltaics
CSP	Concentrating Solar Power
CST	Concentrating Solar Technologies
DNI	Direct Normal Irradiance
EMA	Equivalent Model Algorithm
ENEA	Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile
NIR	Near infrared
NIST	National Institute of Standards and Technology
PSA	Plataforma Solar de Almería, located in Tabernas, Spain
PTC	parabolic–trough collector
S2R	Spectral Specular Reflectance Accessory
ST	solar tower
TIS	Total Integrated Scattering
URA	Universal Reflectance Accessory
B_1	constant of Sellmeier's equation [-]
B_2	constant of Sellmeier's equation [-]
B_3	constant of Sellmeier's equation [-]
C_1	constant of Sellmeier's equation [μm^2]
C_2	constant of Sellmeier's equation [μm^2]
C_3	constant of Sellmeier's equation [μm^2]
E_λ	Spectral irradiance of standard solar spectrum [W/m^3]
f	Focal length of PTC [m]
h	thickness of glass slab [mm]
k_g	extinction coefficient of glass [-]
$k_{g,s}$	solar weighted extinction coefficient of glass in the range [320,2500]nm [-]
k_s	extinction coefficient of silver [-]
$\bar{n}_s$	complex refractive index of silver [-]
n_1	refractive index of air [-]
n_2	refractive index of medium 2 [-]
n_g	refractive index of glass [-]
$n_{g,s}$	solar-weighted refractive index of glass in the range 320-2500 nm [-]
n_s	refractive index of silver [-]
Θ_θ	relative annual incidence angle distribution (whole year) [-]
R	reflectance $\rho_{s,h}([320, 2500]nm, 8°, h)$ of glass slab [-]
R_f	reflectance $\rho_{s,h}([320, 2500]nm, 8°, h)$ of front face of glass slab [-]
T_s	surface temperature [°C]
w_{col}	aperture width of PTC [m]
$y(x)$	parabolic mirror shape [m]
α	absorption coefficient of the solar glass [nm^{-1}]
α_S	elevation angle of the sun [−90°; 90°] [°]
β	incidence angle after refraction [°]
$\gamma_{S,geo}$	azimut angle of the sun [0°; 360°] [°]
ε_1, ε_2	dielectric constants to describe the refractive index and extinction coefficient [-]
θ	incidence angle [°]
θ_{geom}	incidence angle of a PTC due to parabolic 2D-geometry [°]
θ_{sun}	incidence angle between collector normal and sun [°]
λ	wavelength [nm]
ρ	reflectance [-]
$\rho_{air\|glass}$	reflectance at the interface between air and glass [-]
$\rho_{air\|glass\|silver}$	reflectance of the Air|Glass|Silver model [-]
$\rho_{glass\|air}$	reflectance at the interface between glass and air [-]
$\rho_{glass\|silver}$	reflectance at the interface between glass and silver [-]
ρ_i	see $\rho_i(\lambda, T, L, \varphi)$ [-]
$\rho_i(\lambda, T, L, \varphi)$	incidence angle weighted specular reflectance for collector type T at a given location L [-]
$\rho_{non\text{-}pol}$	reflectance of non-polarized light [-]
$\rho_{p\text{-}pol}$	reflectance of parallel polarized light [-]
$\rho_{s,h}$	solar-weighted hemispherical reflectance at θ = 8° and [320,2500]nm [-]
$\rho_{s,h}([\lambda_1, \lambda_2], \theta, h)$	solar-weighted hemispherical reflectance [-]
$\rho_{s,\varphi}$	solar-weighted specular reflectance at θ = 8° and [320,2500]nm [-]
$\rho_{s,\varphi}([\lambda_1, \lambda_2], \theta, \varphi)$	solar-weighted specular reflectance [-]
$\rho_{s\text{-}pol}$	reflectance of perpendicular polarized light [-]
ρ_λ	spectral reflectance [-]
$\rho_{\lambda,h}(\lambda, \theta, h)$	spectral hemispherical reflectance [-]
τ	see $\tau_{s,h}$ [-]
$\tau(\lambda, \theta, h)$	spectral hemispherical transmittance [-]
τ_f	transmittance $\tau([320, 2500]nm, 8°, h)$ of front face of glass slab [-]
$\tau_{s,h}$	solar-weighted hemispherical transmittance at θ = 8° and [320,2500 nm] [-]
φ	acceptance angle [mrad]

primary solar mirrors in the field, the influence of T_s on ρ is not significant and may be neglected. Therefore, in the rest of this work, this parameter is omitted and the nomenclature used for reflectance is $\rho_{\lambda,\varphi}(\lambda, \theta, \varphi)$. The indices λ,φ denote specular monochromatic reflectance. The indices *s,h* denote solar weighted hemispherical reflectance in the wavelength range [320, 2500]nm.

For CST the specular reflectance plays a significant role, since scattered light outside the acceptance angle cone is lost to the energy

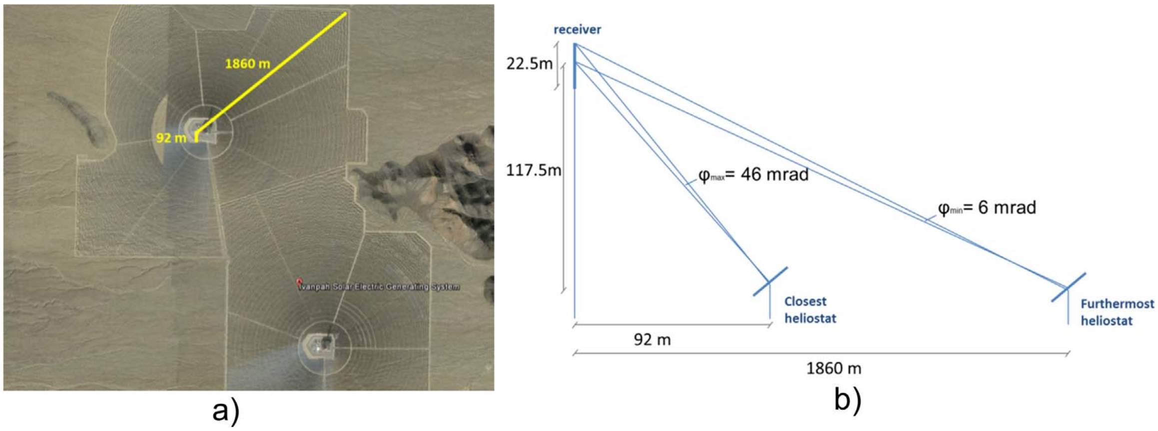

Fig. 1. a) Distance of closest and furthermost heliostat from the receiver in the ST plant of Ivanpah, b) dimensions used to compute the acceptance angle φ.