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Optical and thermal characterization of a variable geometry concentrator using ray-tracing tools and experimental data

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HIGHLIGHTS

- We optically modelled a variable geometry concentrator with ray-tracing tools.
- The solar thermal collector with a fixed mirror concentrator has been tested.
- The energy equation is determined using ray-tracing results and experimental data.
- It can be applied for in situ measurements of large-scale solar thermal collectors.

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ABSTRACT

Ray-tracing tools are commonly used to optically characterize solar concentrators, but the International Standards used to certify collectors for heating do not allow the use of these tools to analyse the optical behaviour of solar thermal systems. Solar concentrators for the medium temperature range often are of large dimensions and cannot be easily reoriented to the sun without an expensive rotating test platform suggested by the International Standards; therefore, some deficiencies can be detected if the standards procedures are applied to these types of concentrating collectors. In this paper, the use of ray-tracing tools combined with thermal experimental data is proposed to determine the energy balance coefficients by a Weighted Least Square adjustment (WLS). The main advantages of this methodology are that the measurement of the thermal efficiency at normal incidence and solar concentrator reorientation are not required, the optical behaviour of the system can be determined for any position of the sun, and it can be used for in situ measurements for large-scale solar thermal collectors.

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1. Introduction

Solar thermal concentrator devices focus sunlight into a receiver in order to obtain elevated efficiencies at high temperatures. In some cases, the geometry of these devices is modified in function of the position of the sun. For example, in the Linear Fresnel Reflector (LFR) [1] the mirrors are moved to redirect the sun rays into a fixed linear receiver; and in the case of the Fixed Mirror Solar Concentrator (FMSC) [2], or the Stationary Reflector with Tracking Absorber (SRTA) [3], the receiver moves within a circular path while the reflector remains static. Another typical example is the configuration of a central tower plant [4], where the reflectors (heliostats) are moved to reflect the sun rays towards a central point receiver. All these optical systems are examples of a variable geometry concentrator, and differ from the designs of the Parabolic Trough Collector (PTC), and parabolic dishes, where the relative position between the mirror and the receiver does not change during the day (the geometry remains constant).

New types of collectors in the medium temperature range (80–250 °C) [5] have emerged lately, such as the LFR from PSE AG [6] and the fixed-mirror CCStaR prototype (Concentrating Collector with Stationary Reflector) [7]. These solar concentrators are systems with variable geometry, and a testing procedure is needed in order to certify their behaviour in real working conditions; as is the case for the ISO standards used to certified conventional collectors for domestic hot water or space heating, i.e. Flat Plate Collectors (FPC), Evacuated Tube Collectors (ETC), and Compound Parabolic Collector (CPC).

There are standards that provide the testing procedure for the thermal performance of solar systems. The withdrawn European norm EN 12975-2 [8] and the new version of the International Standard ISO 9806:2013 [9] that replaced the European Standard [8] are applicable to the most typical collectors available in the

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Nomenclature

α	solar absorbance of the absorber tube (–)
η_{0b}^{opt}	optical efficiency of the collector relative to beam solar radiation (–)
η_{0d}^{opt}	optical efficiency of the collector relative to solar diffuse radiation (–)
θ_i	incidence angle (°)
θ_L	longitudinal incidence angle (°)
θ_T	transversal incidence angle (°)
ρ	reflectance of the reflector (–)
σ	standard deviation combining all optical errors (mrad)
A_a	aperture area of the collector (m^2)
b_i	fitting parameters
C_a	ratio of collector and receiver apertures (–)
c_1	heat loss coefficient respect to $(t_m - t_a)$=0 K ($W\,m^{-2}\,K^{-1}$)
c_2	dependence to the temperature of the heat loss coefficient ($W\,m^{-2}\,K^{-2}$)
c_5	effective thermal capacity ($J\,m^{-2}\,K^{-1}$)
F	focus distance (m)
F'	heat removal factor also called thermal efficiency (–)
G_{DNI}	direct normal irradiance ($W\,m^{-2}$)
G_T	global irradiance on collector plane ($W\,m^{-2}$)
G_{dT}	diffuse irradiance on collector plane ($W\,m^{-2}$)
G_{bT}	direct irradiance incident on collector plane = $G_{DNI} \times \cos\theta i$ ($W\,m^{-2}$)
K_b	incidence angle modifier relative to the direct incidence radiation (–)
K_d	incidence angle modifier relative to the diffuse radiation (–)
k	extinction coefficient (m^{-1})

N	total number of mirrors
$\dot{Q}$	output power (W)
t	time (s)
t_a	ambient temperature (°C)
t_e	output fluid temperature (°C)
t_{in}	inner fluid temperature (°C)
t_m	average fluid temperature $t_m = (t_e + t_{in})/2$ (°C)
W	aperture width
y	fitting dependent variable
z_i	fitting independent variable

Abbreviations

CPC	Compound Parabolic Collector
CSFMSC	Curved Slats Fixed Mirror Solar Concentrator
CCStaR	Concentrating Collector with Stationary Reflector
ETC	Evacuated Tube Collector
FMSC	Fixed Mirror Solar Concentrator
FPC	Flat Plate Collector
IAM	Incidence Angle Modifier
ISO	International Organization for Standardization
LFR	Linear Fresnel Reflector
MAE	mean absolute error
ME	mean error
MLR	multiple linear regression
PTC	Parabolic Trough Collector
RMSE	root mean square error
SRTA	Stationary Reflector with Tracking Absorber
WLS	Weighted Least Square

market (FPC, ETC, and CPC), where the quasi-dynamic thermal performance of glazed and unglazed liquid heating solar collectors is specified. Tracking concentrating collectors were more detailed in those standards [8,9] because of the separation between direct and diffuse efficiency gives a more accurate characterization of a tracking concentrating collector. Unfortunately, the standards cannot be applied to concentrators with complex Incidence Angle Modifiers (IAM), as is the case for variable geometry collectors, because they do not specify the procedure for experimentally determining the IAM when it is not feasible to obtain all the measuring angles. The American Standard ASTM 905 [10] applies the quasi-steady state conditions to a one- or a two-axis tracking reflecting concentrating collector. This testing method can be applied to collectors with a geometric concentration ratio of seven or greater, as the effects of diffuse irradiance on performance are negligible. However, this testing method is not intended for, and may not be applicable to fixed-mirror tracking-receiver collectors. On the other hand, the American Standard ASHRAE 93 [11] can be applied to a solar concentrator, even though only direct radiation is used for the steady-state model, and not much detail to particular testing processes for solar concentrators with variable geometry is mentioned.

In many studies, the thermal testing procedures stipulated in the standards have been applied to a solar concentrator. Jaramillo et al. [12] tested a PTC according to the ASHRAE 93 [11], as well as Nkwetta and Smyth [13] did for a low-concentrator evacuated system. Xu et al. [14] realized a comparison of three outdoor test methods for determining the thermal performance of PTC's: the steady-state method of the ASHRAE 93 [11], the quasi-dynamic method of the EN 12975-2 [8], and a new dynamic method developed by the authors. In addition, solar concentrators can be thermally characterized by energy balance equations, and as a result, there are many studies that have not implemented the standards but have instead applied their own models, with examples being, the latter study mentioned above [14], or the experimental validation for a LFR prototype by Pino et al. [15], or the newly proposed models to characterize solar thermal collectors [16,17].

The authors of this paper had tested in [18] a solar concentrator prototype with variable geometry called CCStaR V2 (a prototype similar to the one analysed in this paper called CCStaR V1). A new procedure to characterize the prototype optically and thermally, based on the quasi-dynamic model of the standard EN 12975-2 [8], was presented, of which “dummy variables” method [19] and the optical results of a ray-tracing simulation used as initial hypothesis for the energy balance equation were the main contributions. The study showed some deficiencies in the EN 12975-2 standard for variable geometry concentrators such as: the lack of definition for the requirements of the IAM in the testing procedure, the lack of the thermal efficiency procedure if the efficiency at normal incidence could not be acquired from testing due to the characteristics of the solar concentrator (collectors with large structures and with cumbersome orientation adjustments), and difficulties in obtaining the effective thermal capacity term for solar thermal concentrators. We proposed in [18] the use of ray-tracing software in order to assess the initial hypotheses for the collector thermal model, stipulating the condition that the simulation results must fall within a ±5% error from the experimental results. In this procedure, it was also found necessary to add the heat removal factor F' obtained from previous testing.

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