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Optical and thermal characterization procedure for a variable geometry concentrator: A standard approach

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ABSTRACT

Concentrating solar collectors are mentioned in the International Standards, but the general testing methods for solar collectors mentioned cannot easily be applied to such unusual collector designs. In this study, the best optical and thermal model for a variable geometry solar concentrator has been investigated. In the particular case of a collector with a fixed mirror concentrator, the relative position of the receiver with respect to the reflector is not constant during the day, and this variable geometry is not taken into account in the current testing Standards. An optical characterization of the prototype using a ray-tracing program has been performed, and the results have been used as an initial hypothesis to define two thermal models adapted from the European Standard. Those two different models have been compared. The optical results obtained from experiments have been compared to ray-tracing simulation results, and they have been found to be quite similar, considering the measurement uncertainties. This validation procedure of the optical simulation could be an important point to be taken into account in a future Standard revision for variable geometry collector types for which the normal incidence is not easy to obtain.

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1. Introduction

For an operating temperature range of 80–250 °C, referred to as medium temperature [1], a variety of collector designs are available with different optical concentrations and different kinds of solar tracker. These include parabolic troughs, linear Fresnel reflectors (LFR), and concentrators with fixed reflectors and mobile focus. As is the case with conventional solar collectors, the medium-temperature collectors must be tested by Standard procedure before being introduced to the market.

Various Standards have been existed for decades for conventional solar thermal collector efficiency testing. The European Standard EN 12975-1 [2] (for collector requirements) is clearly not applicable to tracking concentrating solar collectors. However, the International Standard ISO 9806 [3] which is the new version in 2013 of the European Standard for testing method EN 12975-2 [4] and in particular, the quasi-dynamic test, is applicable for concentrators ranging from compound parabolic collectors (CPCs) to high concentrating tracking designs.

Recent studies to test concentrating solar collectors, adapting the collector model to a parabolic trough, are based on this European Standard [5–7].

The American Standard ASHRAE 93 [8] is applicable for all collector designs and mentions to concentrators with a biaxial incidence angle modifier (IAM) and a single-axis linear concentrator, but there is not much detail regarding particular testing processes for solar concentrators. A study of parabolic troughs based on this American Standard can be seen in Ref. [9].

The American Standard ASTM 905 [10] is especially applicable to one- or two-axis tracking reflecting concentrating collectors. In this testing method, the effects of diffuse irradiance on the performance are insignificant, and the efficiency curve is referred to direct irradiance incident on collector plane G_{bT}. However, this Standard does not mention variable geometry collectors such as the Fresnel reflector or fixed reflectors and their mobile focus for which requirements still need to be drawn up for testing procedures.

The Incidence Angle Modifier (IAM) is defined as the ratio between the optical efficiency at a specific angle and the optical efficiency at normal incidence. This ratio provides a means of determining the optical performance when the sun's direction is not perpendicular to the collector plane. The IAM is essential to determine the long-term optical performance of a solar collector.

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For a conventional flat-plate collector, the IAM value depends on the incidence angle, and is determined by a well-known model, first mentioned by Souka and Safwat [11] and then referred to in the Standards ASHRAE 93 [8], EN 12975-2 [4], and ISO 9806 [3]. The measure of thermal efficiency, at zero thermal losses, for normal incidence is mandatory in those Standards.

According to the Standards [3,4] in order to characterize the IAM along the whole range from 0 to 90° for a conventional flat-plate collector only one value of IAM must be measured, normally at incidence angle $\theta_i = 50°$.

For asymmetrical collectors, such as evacuated tubes and CPC collectors, the commonly accepted model for determining the IAM is a biaxial model [12,13], where the IAM is given by the product of the components that are transversal and longitudinal to the planes of the receiver, according to the angles defined in Fig. 1 (θ_T transversal incidence angle and θ_L longitudinal angle).

In this case, different values at various incidence angles (20°, 40°, 60°, etc) are required. From those measured values, the rest of the transversal and longitudinal IAM curves are extrapolated to all the incidence angles in order to calculate the collector power output at any solar incidence direction.

While the testing procedure for the determination of IAM in flat plate and evacuated tube collectors is adequately explained in the Standard ASHRAE 93 [8], EN 12975-2 [4], and ISO 9806 [3], that is not the case concerning solar concentrators with variable geometry, nor does a normalized model exist. Moreover, in some cases, such as the LFR and concentrators with fixed reflectors and mobile focus [14–16], the measurement of thermal efficiency at normal incidence is not possible when the outdoor testing bench is located in a latitude away from Equator (if the solar concentrator is on a horizontal surface), as the sun never crosses the zenith point in its annual trajectory. In Standards, the normal incidence efficiency is mandatory because it is used as a reference value to obtain the IAM, so this testing procedure cannot be applied for those concentrators. Although in our case it was possible to measure the efficiency at normal incidence, an easy way to avoid this problem, as proposed in this paper, would be to first use a simulation to characterize the collector's optical behavior and to then validate the simulation results, using the experimental data from a testing campaign. In a previous study [17], the minimum incidence angles that should be characterized experimentally on the variable geometry collector have been analyzed in order to calculate its long-term output. This analysis was based on the energy impact on the receiver depending on the location and its simulated IAM.

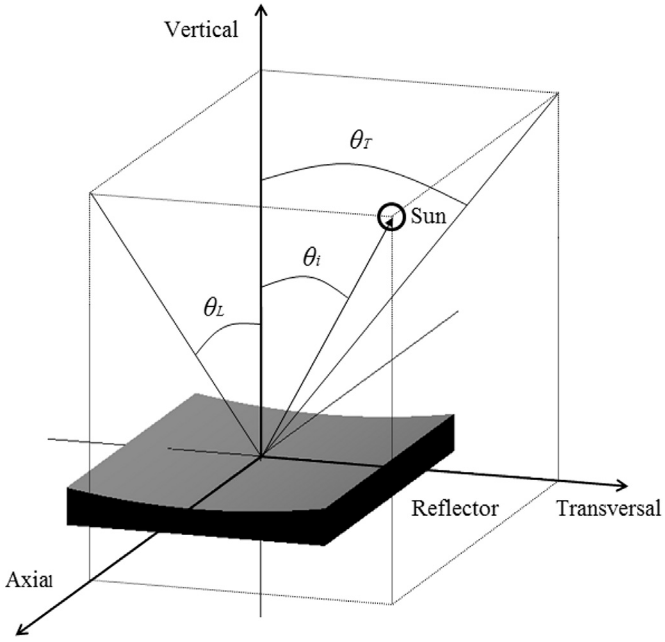

Fig. 1. Incidence angles definition.

In this paper, the purely optical behavior of a fixed mirror and tracking absorber prototype (with variable geometry) – for instance, the optical efficiency and the IAM for all possible angle ranges – has first been simulated by a ray-tracing program. Then, the optical results have been used as an initial hypothesis to formulate the efficiency model of the system. Later, the thermal and optical behaviors have been characterized, using a testing campaign under quasi-dynamic conditions according to the European Standard [4]. Finally, those experimental results have been compared to the simulation results in order to validate the ray-tracing program and the considered hypotheses. The aim of this study has been to present a procedure with which to characterize the optical and thermal behavior of a variable geometry collector, using optical simulation.

2. Materials – the fixed mirror prototype

The Concentrating Collector with Stationary Reflector (CCStaR) prototype, developed by the company Tecnologia Solar Concentradora S.L. (http://www.tsc-concentra.com) in close collaboration with the University of the Balearic Islands, is a solar concentrator with a static reflector and moving receiver. The geometry is based on the so-called Curved Slats Fixed Mirror Solar Concentrator (CSFMSC) [15,18] with only one parabolic mirror. The CSFMSC consists of a static reflector formed by curved mirrors segments and a mobile receiver that tracks the sun in a circular path. In the case when the number of segments is equal to one, the concentrator is simpler, and the reflector is composed of only one parabolic mirror.

A parabola only has one focus point for normal incidence. Nevertheless, given a high enough F/W ratio (where F is the focus distance and W the aperture width), the dispersion of the radiation can be kept in a reduced area for all of the significant sun angles (from the energy point of view). Furthermore, the path described by the area where the radiation is concentrated is a circular path which can be easily tracked with a rotating arm on a tube receiver – see Fig. 2(a) and (b). Therefore, the solar rays are for most part reflected toward the receiver without the need of moving the whole system, only the receiver. This particularity makes it easier to integrate it on a building roof because the reflector, which is the heaviest part of the system, is fixed.

The receiver angle position θ_r is the angle between the axis that links the receiver to its rotational axis and the parabola axis - see θ_r in Fig. 2(b). The receiver is positioned at an angle $\theta_r = 2\theta_T$, where θ_T is the incidence angle on the reflector in the transversal plane (see Fig. 1).

The CSFMSC geometry was first analyzed by Balasubramanian and Sankarasubramanian in 1993, using analytical geometric tools [18]. A more detailed optical study, using a ray-tracing procedure was presented recently in Refs. [15,19] and a thermal analysis in Ref. [20].

The CCStaR project started in 2006 with the aim to develop a solar thermal collector with a working temperature range between 100 °C and 200 °C that could, at the same time, be easily integrated into light building roofs. The two main applications for the development were industrial process heat applications, and double stage solar cooling. In the project, three prototypes have been tested. This study presents the results of the newest prototype, called CCStaR V2.

The reflector of the CCstaR V2 prototype consists of 32 parabolic mirrors, distributed in 8 rows of 4 mirrors each (see Fig. 3). The

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