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A simple method to achieve a uniform flux distribution in a multi-faceted point focus concentrator

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ABSTRACT

A method to achieve a uniform flux distribution with a multi-faceted point focus concentrator for laboratory tests is proposed in this work. The method can be applied to different types of receiver - thermal or photovoltaic - and no additional device is required to homogenize the flux. The technique consists in moving the receiver from the focal plane and enlarging the solar spot impinging on it. At the same time, each mirror aim-point is adjusted in order to superimpose the images that have been generated by every facet. To evaluate the method, a real multi-faceted concentrator composed of eighteen spherical mirrors was modeled in a ray-tracing software. The procedure was validated through the comparison of an image of the real solar spot on the receiver generated by three mirrors, and the simulated flux obtained the same way. This way a mean concentrator global optical error of 2.8 mrad was estimated. This value was used then for further analyses. Results show that the concentration factor can be varied in a range of 150–900 suns over a receiver diameter of up to 7 cm. Hence, according to the receiver requirements, it is possible to expand the distribution and to alter the intensity of the flux. Finally, optical parametrical analyses were carried out, from which it is inferred that good quality optics give rise to a more homogeneous solar flux on the receiver.

1. Introduction

Compared with other energy sources, one of the main disadvantages of solar energy is the low power density. A concentrating solar system with sun tracking allows to increase the radiation density on a receiver/absorber by the use of reflective or refractive surfaces. However, temporal and spatial flux control on the receiver is still one of the main challenges that have to be faced. Over the last few years, several concentrating solar systems have been proposed to produce different flux distributions depending on the application, scale and receiver shape.

For instance, for central receiver Gallo et al. [1] studied the flux produced by a heliostat field onto a fluidized bed receiver placed at the top of a tower in a concentrated solar power plant. In that work, one of the goals was to limit the solar flux in order to avoid temperature higher than material limit resistance. In the same field, Salomé et al. [2] proposed an algorithm to control the flux distribution on a solar central receiver by the use of an optimized aiming point strategy for the heliostats. Results were later validated at Themis solar tower.

Numerous studies are related to the adjustment and control of flux distribution in solar furnaces [3–8]: Riveros-Rosas et al. [5] studied the optical design of a solar furnace located at the Renewable Energy Institute of the National Autonomous University of Mexico (IER-UNAM). The final design was determined by several analyses and optimizations in terms of maximum peak concentration, economical and practical considerations. For the same solar furnace, Perez-Enciso et al. [6] investigated the sunlight spot's drift.

Solar simulators are often used as a radiation source for thermochemical studies in the laboratory. In that area, the importance of a homogeneous flux distribution has been pointed out too. For example, Alonso and Romero [9] concluded that radial temperature gradients, due to non-uniform distribution, penalize

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thermochemical processes in solar reactors.

Achieving specific flux distribution is a central matter for point focus concentrators. Riveros-Rosas et al. [10] investigated the proper size of the facets to optimize the performance of multi-faceted point focus concentrators and they also determined their optical errors. For that, they developed a novel ray-tracing program based on the convolution technique. Li et al. [11] studied a system in which the parabolic dish is coupled with a Stirling engine. They realized ray-tracing simulations to obtain different flux distributions on the engine surface, which they then coupled with computational fluid dynamics (CFD) simulations. The objectives were to define an optimized shape for a solar receiver-Stirling heater and to achieve a considerably uniform temperature distribution on heater head tubes. The analyses were then validated by experimental tests using a 4-lamp solar simulator. Shuai et al. [12] studied the radiation performance in a cavity receiver integrated within a dish solar concentrator. In particular, they determined the sunshape and surface slope errors. In addition, five different cavity geometries were analyzed with the aim to achieve a uniform wall radiation flux. Riveros-Rosas et al. [13] described a numerical procedure to obtain three dimensional surfaces with uniform irradiation generated by a parabolic concentrator.

The above mentioned ones are different examples showing how significant it is to control the flux distribution in thermal applications. Although concentrating photovoltaics (CPV) represents the field where more efforts have been done to study the flux distribution effects on the receiver. Achieving uniform temperature profiles in the photovoltaic (PV) cells has been pointed out as a primary issue to improve their performance [14,15]. Baig et al. [16] summarized the causes and consequences (mainly electrical and thermal) of a non-uniform illumination on PV cells. A non-uniform flux distribution in the receiver reduces the efficiency and it can generate a non-homogenous temperature distribution, provoking undesired peaks that can damage the PV cells. Moreover, hot spots in PV cells are not desirable since electric production decreases with the temperature. Chenlo and Cid [17] proposed two models to study cell performances under conditions of non-uniform illumination and temperature. Their conclusion was that system losses were higher from the combined effects of non-uniform illumination and temperature, than from the sum of both effects taken independently.

When the receiver is composed of several PV cells, some of the cells are connected in series to form a string and some strings are connected in parallel to compose an array. Cell efficiency decreases when the temperature increases and, for each string, the cell with the lowest output limits the current. Therefore, the cell with the highest temperature limits the efficiency of the whole string. This problem does not persist under a uniform temperature across each series connection [18].

Due to these reasons, several concentrator shapes have been investigated to achieve a uniform flux distribution on PV receivers. Khamooshi et al. [19] classified those concentrators into three categories, according to their flux intensity: low (<40 suns), medium (40–300 suns), and high (300–2000 suns) where the suns are calculated as the ratio of the mean radiant flux density on a receiver area (G_x) and the average normal global irradiance (G) (see eq. (1)):

$$X\,[suns] = G_x/G. \quad (1)$$

Chong et al. [20] listed several kind of CPV systems according to the concentration element and analyzed their optical performances. They defined five categories: linear focusing lens, two dimensional focusing lens, linear focusing reflector, two-dimensional focusing reflector, and central receiver system.

The use of Fresnel lenses or other refractive elements reduces the optical efficiency to an 80% because of the absorptivity of the lens and the reflection on its surface [21]. In the case of mirrors, reflectivity can reach 0.95 for second surfaces [22] and higher values for first surface mirrors.

Most of the concentration systems presented secondary and even tertiary reflectors and/or refractors. In some cases, the second reflecting element was a homogenizer kaleidoscope, consisting of a light pipe with inner reflecting walls [23–27]. Typically, this component does not concentrate but changes the flux distribution by multiple reflections [25]. In other cases, the secondary element is based on Köhler optics [28,29] or non-imaging concentrator as compound parabolic collectors (CPC) [30,31].

The use of secondary components (kaleidoscopes, CPC, Köhler optics) to control the flux distribution increases the cost of the system, in particular for Köhler optics, as well as adding optical losses. Another drawback related to the use of the kaleidoscope is the shading effects, as reported by Kreske et al. and Meller and Kribus [23,25].

In the case of parabolic or spherical concentrators, the flux distribution at the focal plane presents a Gaussian profile. Typically, to obtain a more uniform distribution, attempts were made to defocus the concentrated light by moving the target plane. However, such an approach did not provide adequate uniformity [32]. Hence, new kinds of two-dimensional focusing reflectors were proposed to get a more homogenous irradiation. Jorgensen and Wendelin [32] designed a multistep molded dish capable of reaching a uniform flux distribution of almost 200 suns over a circular area of approximately 8 cm in diameter. Tan et al. [21] designed a non-imaging dish concentrator and obtained the best results for a concentration ratio of approximately 400 suns.

In the present work, what is proposed is a method to achieve a uniform flux distribution, in a range of medium concentration, for different kinds of receivers by the use of a multi-faceted point focus concentrator. No additional device is needed to homogenize the flux. The receiver can be moved from the focal plane enlarging its spot and each mirror can be re-oriented individually to adjust its aim-point and to superimpose the images that have been generated by every facet. By changing the number of used facets, one can vary the concentration intensity. Hence, according to the receiver requirements, it is possible to expand the flux distribution and to alter the intensity on it. To evaluate the method, a real multi-faceted concentrator was simulated. Global optical error for the simulated mirrors was determined by means of an experimental validation. Finally, optical parametrical analyses were conducted and the influence of global optical error on the flux shape was investigated, too.

2. Methodology

2.1. Description of solar concentrator

The proposed method to achieve a uniform flux distribution is based on the solar concentrator DEFRAC (Device for the study of high concentrated radiative flux, from Spanish: Dispositivo para el Estudio de Flujos Radiativos Altamente Concentrados), which is located at the IER-UNAM in the city of Temixco, Morelos. DEFRAC is a point focus solar concentrator composed by eighteen spherical mirrors and it is mounted on an equatorial solar tracker (see Fig. 1a). Each mirror presents a 30 cm diameter and 1.9 cm thickness. The focal lengths of the mirrors are grouped in three sets according to their disposition: A, B and C (see Fig. 1b). The focal length is 2.098 m for A mirrors, 2.074 m for B mirrors, 2.025 m for C mirrors, obtaining a total focal length for the DEFRAC of 2.0 m along its axis. Each facet has to be manually oriented by means of three