Renewable and Sustainable Energy Reviews 69 (2017) 673–684

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

A survey of methods for the evaluation of reflective solar concentrator optics

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ARTICLE INFO

Keywords:
Optical characterization
Solar concentrator
Concentrating mirrors
Parabolic trough
Heliostats

ABSTRACT

The optical quality of concentrators has a direct impact on the thermal efficiency of concentrating solar power plants. There is a need to evaluate the quality of the mirrors before installation and during operation. A review of the optical characterization techniques that have been developed for solar concentrators is presented. A brief description of the operation and methodology of each technique is done. The strengths and possible vulnerabilities of the techniques are also discussed. A classification of the different techniques in families according to their underlying principles of operation is proposed. Finally an analysis of the available information about the accuracy and precision of the different methods is carried out.

1. Introduction

The optical quality of reflective surfaces is a topic of major importance in Concentrating Solar Power (CSP) plants. All of the different technologies [1,2,86–88], parabolic trough, linear Fresnel, parabolic dish, and power towers, rely on the optical accuracy of the solar collector field in order to provide competitive power production [80]. While it is a constant goal to reduce collector field costs, because they constitute up to 60% of the overall plant investment costs, maintaining and improving the optical quality of the systems is equally important.

Deviation of the mirror shapes from their design geometry, as well as imperfections in the reflecting surfaces, can lead to important energy losses, in the form of radiation spillage. This is a particularly acute problem, due to the large dimensions of CSP plants; even if the solar modules can be properly manufactured, assembling the parts on site can lead to severe misalignment and deviations. Therefore, testing methods are required both at the factory floor and field levels.

To address the above need, a variety of optical testing methods have been proposed over the years. Advances in computational systems and image processing techniques have allowed for more robust measurements techniques and fast evaluation methodologies. Also, optical techniques from other fields have been adapted to the evaluation of solar concentrators with satisfactory results. These techniques provide details of the surface under test as a way of knowing their departure from ideal design.

The objective of the present paper is to carry out a review of the different techniques that have been developed for the optical characterization of solar concentrating mirrors. In order to facilitate the understanding of the literature and its evolution, a comprehensive classification of the techniques is attempted, based on their underlying principles and common features. The strengths and weaknesses of the methods are discussed and compared. In particular, a revision of the available information about the accuracy and precision of the different methods is presented. The paper closes with an overview of the techniques, and the challenges they face to contribute to the characterization of solar concentrators.

Some of the methods presented here have already been reviewed in a previous work [11], but here we include many additional works and emphasize the relationships between different techniques. A very important problem in the optics of solar concentrators is soiling of mirrors. This has bee reviewed elsewhere [89] and will not be discussed here.

2. Solar concentrator optics

Due to plant cost considerations, high precision optics is not affordable for solar concentrators, except in the case of high tempera-

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http://dx.doi.org/10.1016/j.rser.2016.11.048
Received 14 October 2015; Received in revised form 11 October 2016; Accepted 1 November 2016
1364-0321/

ture solar furnaces, conceived essentially for research purposes [3]. In general, there is a trade-off between performance and cost, which favours the use of mirrors with lower precision than those found in traditional optical instruments. In solar concentrators generally image formation is not an important concern. Thus, optical imperfection is a fact of life, which has to be considered in the design and evaluation of these systems.

The quality and shape of the reflecting surfaces of a solar concentrator determine the achieved concentration level and the irradiance distribution on the receiver. The deviations from ideal performance are referred as optical errors of the concentrator. There are different contributions to these optical errors [1,2]. In the first place, the shape of solar concentrating surfaces may deviate from the ideal curves. This departure from design geometry is referred as contouring or slope errors. A second contribution comes from canting errors, which are the deviations of the orientation of individual mirror facets from their nominal directions. Finally, the reflecting materials themselves may deviate from the specular reflection law. This is due to micro and meso-scale surface roughness, which produce surface scattering. These different contributions to imperfect reflection of solar radiation are illustrated in Fig. 1.

A complete knowledge of the optics of a particular solar concentrator would be attained if the detailed shape of each reflecting surface were known, together with the characteristic scattering function of the reflecting material. Then, the radiative flux (irradiance) distribution at the receiver could be predicted to any desired level of accuracy. This complete knowledge however, is an ideal situation that is generally not achieved. For mirror surface qualification, there is a trade-off between the level of detail and testing speed and cost requirements. Moreover, an excess of detail may be cumbersome when the flux distribution produced by a large number of reflecting facets is to be modelled. In practice, different levels of detail are required in the knowledge of the optical and shape characteristic of solar concentrators in different situations.

At the coarser level, two parameters suffice to describe the optical response of a solar concentrator: the average reflectance of the surface, and the standard deviation σ_{opt} of the global optical error function. The latter is a Gaussian function that describes the distribution of angular ray deviations $\Delta\theta$ (Fig. 1d), with respect to the ideal condition [4]. Usually σ_{opt} is referred as the optical error of the surface. Many ray tracing codes for solar concentrators carry out calculations based on these two parameters, as the optical simulation of a whole CSP plant with a more detailed input is both cumbersome and unnecessary in most cases. However, if qualification of concentrating mirror facets at the production level is the objective, a greater level of detail is necessary.

The optical error is a lumped parameter that results from different causes; thus, a second level of description of solar concentrator optics implies the determination of the different separate contributions to this error. In particular, σ_{opt} can be expressed as the addition of several errors in quadrature [1,2]:

$$\sigma_{opt}^2 = \sigma_{spec}^2 + \sigma_{shape}^2 + \sigma_{canting}^2 \quad (1)$$

The first contribution to Eq. (1) is the specularity error σ_{spec}, which is the standard deviation of the characteristic scattering function of the reflecting material, discussed above. This function expresses the scattering due to surface roughness, and is well described by a Gaussian function in some cases [5]. The second and third contributions are the shape error σ_{shape}, characterizing the curvature deviations of the facets from their ideal shapes, and the facet canting error $\sigma_{canting}$, describing the misalignment of those facets. These last two contributions sometimes are lumped together in a single parameter, known as the slope error σ_{slope}.

At a third level of description, the shape of the reflector is fit with a modified ideal curve, and the specularity error is also used. Finally, the highest information level is a detailed knowledge of the real concentrator shape, with a high resolution, as mentioned before. The different characterization techniques reviewed in this document, alone or in combination, can provide information at these different levels.

The different techniques that will be discussed provide information at these different levels. Some of them are appropriate for qualification of the concentrator shape at production levels, while others are more suitable for evaluation of the collectors in the field, to assess the effects of ageing. Others methods are suitable for alignment and canting of concentrator facets.

In particular, there are different techniques to characterize the reflectivity and specularity of the reflecting material itself [6–8]. However these are of different nature as those used to evaluate shape and canting errors, and will not be discussed here. It is necessary to point out that in glass mirrors the microscopic errors causing loss of

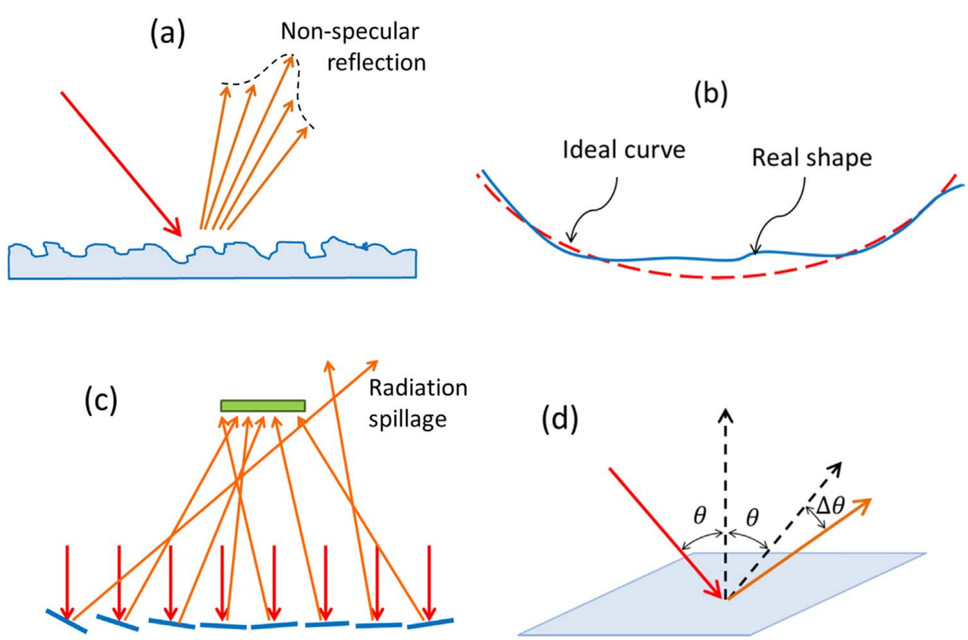

Fig. 1. Concentrating mirror features causing deviations from ideal reflection: (a) Surface roughness, (b) contouring errors, and (c) facet canting errors; resulting reflected ray deviation (d).