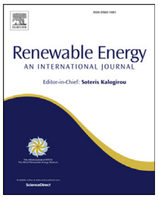
Renewable Energy xxx (2016) 1–11

Contents lists available at ScienceDirect

Renewable Energy

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



A model-based approach for optical performance assessment and optimization of a solar dish

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ARTICLE INFO

Article history:
Received 31 January 2016
Received in revised form
18 May 2016
Accepted 21 May 2016
Available online xxx

Keywords:
Solar dish
Laser 3D scanning
Photogrammetry
Monte-Carlo ray-tracing
Flux density distribution
Optimization

ABSTRACT

The solar dish is a point-focusing concentrator with a very high concentration ratio ranging from hundreds to thousands. Practical assessment and optimization methods are necessary to assemble solar dishes with satisfying concentration ratios and flux density distributions, which is very important for the overall solar thermal systems to achieve high efficiency. A solar dish usually consists of many mirror facets installed on a supporting structure with a dual-axis tracking system. Small mirror facets are easy to manufacture, but the alignment of many mirror facets is very challenging. A model-based approach for optical performance assessment and optimization of a solar dish was proposed, and flux density measurements were carried out to validate the approach. The simulation and experimental results showed very good consistency and suggested that the concentration ratio and the intercept factor could be increased from ~500 to ~1500 and 0.66 to 0.9 respectively after assembly optimization.

1. Introduction

Solar dishes can provide very high concentrated flux, whose average geometric concentration ratio could be up to 3000 suns [1]. It is very suitable for high-temperature solar receivers, such as Stirling engine heater, gas receiver for Brayton cycle, thermochemical reactor, etc. Higher temperature typically enables higher efficiency, e.g., the recent world record of 31.25% net conversion from solar power to grid electricity had been demonstrated by the Stirling Energy Systems (SES) [1]. It is noted that high-temperature solar receivers always have small receiver apertures to reduce heat losses through radiation and convection, while excessively high concentrated flux at unexpected locations, or hot point, is likely leading to failure [2] or lifetime shortening.

A variety of factors can influence flux density distribution of solar dishes, including specular error, small waviness error (also called local slope error), alignment error, structural deflection and track error. These errors can be classified as random errors or systematic errors. Andraka et al. [2] reported that various kinds of errors shall not be regarded as root-mean-square (RMS) overall errors, which would mislead the designer and lead to system component damage or poor system performance. While RMS method is more suitable for random errors, the systematic errors should be estimated separately.

The specular error is used to describe an imperfect-smooth reflective surface where the reflected rays are slightly scattered. A typical reflector, e.g., a glass mirror, has very good flatness and its specularity, which can be represented by Gaussian Bell curve, is small ($\sigma_{specular} < 0.2$ milliradian (mrad)) [3]; and for poly film and aluminum, the specular errors are often greater than 1 mrad [4]. Small waviness of a real reflector in the order of several milliradians is referred to as the slope error; it makes the reflected rays different from the ideal ones. According to the reflection law, the slope error has a double effect on the reflected rays, i.e. the deviation angle of reflected ray is double of that of slope error. This means the slope error is a very important property of the mirror facet.

Big dish concentrators usually consist of tens of mirror facets installed on a supporting structure with a dual-axis tracking system. Each facet with inappropriate position leads to diffused flux distribution or dangerously high peak flux at unexpected locations. The alignment of mirror facets is very important but highly time-consuming due to the lack of systematic way to assess the alignment quality as feedback and the complexity of the many-mirror assembly.

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http://dx.doi.org/10.1016/j.renene.2016.05.076
0960-1481/

Please cite this article in press as: G. Xiao, et al., A model-based approach for optical performance assessment and optimization of a solar dish, Renewable Energy (2016), http://dx.doi.org/10.1016/j.renene.2016.05.076

Nomenclature

DNI	direct normal irradiance, W/m^2
D_{stud}	distance between inner stud and outer stud
$\overrightarrow{dN}$	slop error vector
dS	mirror surface element
F	focal length
$f(x)$	probability density function of x-axis
$f(y)$	probability density function of y-axis
$f(r)$	probability density function of polar radius
$\vec{I}$	incident ray unit vector
M	measured coordinates
MCRT	Monte-Carlo ray-tracing
N	ideal unit normal vector
N'	measured unit normal vector
P_X	cumulative distribution function of x-axis
P_Y	cumulative distribution function of y-axis
P_r	cumulative distribution function of polar radius
R	direction cosine matrix
RMS	root-mean-square
$\vec{R}$	ideal reflected ray unit vector
$\vec{R'}$	real reflected ray unit vector
r	polar radius
r_{es}	the earth-sun distance
r_s	radius of the sun
T	theoretical coordinates
$\overrightarrow{\|\|}$	the length of a vector
$[\ ]'$	the transpose of a matrix
Greek symbols	
ΔT	translation matrix
θ	slope error
θ_s	solar half angle
Λ	diagonal matrix of $diag[1,1,0]$
σ	standard deviation
σ_{al}	realignment error
σ_{ad1}	adjustment error of outer stud 1
σ_{ad2}	adjustment error of outer stud 2
σ_{ph}	photogrammetry error
σ_{sl}	slope error of mirror facet
σ_{tot}	total error
φ	polar angle

In the past decades, there are mainly three kinds of methods to measure the slope error of solar reflector, which are VSHOT, photogrammetry and deflectometry respectively [5]. The VSHOT (Video Scanning Hartmann Optical Test) is a laser trace device to measure the slope of the reflector directly at many positions on its surface and can get an accuracy of±0.25 mrad in RMS slope error [6,7]. The photogrammetry is essentially the science of quantitative analysis of measurements from photographs, and it is used in maps of Earth, archaeological and architectural recording, biological measurement, industrial metrology, and engineering surveillance [8]. In 1996, the so called “Big Dish” of 400 m^2 at the Australian National University (ANU) was measured using the photogrammetry method and the slope error uncertainties of approximately 0.2 mrad or less could be reached if the surface ripple deviations of the reflector are below ±2 mm and frequencies below 2 m^{-1} [9]. Pottler et al. [10] measured the 3D coordinates of solar concentrators and their components to determine the slope error, deflection due to thermal expansion and gravity by photogrammetry method. Deflectometry or fringe reflection uses a camera to get the fringe patterns reflected by the mirror and the patterns viewed by camera shows distortions compared to the original pattern, based on which the curvature of the specular mirror is measured [11]. A deflectometry technology named SOFAST (Sandia Optical Fringe Analysis Slope Tool) was developed for dish mirrors [12] with uncertainty of ±0.05 mrad [13]. SOFAST used a computer-connected camera to view the LCD screen. A series of fringe patterns were displayed on the screen while the images were captured, and thus through an analytical transformation, the surface normal map could be shown. A color-coded targets method based on “distant observer” was developed by Ulmer et al. [14]. A flat target with colored stripes is adopted instead of LCD or project screen placed close to the focal plane of the concentrator. A digital camera is located at an observation point on the optical axis at some distance from it. The maximum measurement uncertainty for slope error is ±0.5 mrad. However this method needs hundreds meters observe distance without barrier, which may be unpractical for on-site measurement.

These three types of solar concentrator surface measurement have been successfully developed in the past three decades. The VSHOT is suitable for dish or trough concentrator measurements, but it takes a lot of time to set up and to scan large surface. Photogrammetry can be used for any type of solar concentrators. However, photogrammetry needs a lot of special retro-reflective targets pasted on the concentrator surface to get enough coordinate data to calculated the surface slope error, which is a time-consuming work. The deflectometry is suitable for measuring large surface with high resolution and less time-consuming. However, the images processing procedure seems not that easy, and the calibration problem is a trouble encountered in the practical measurement [5].

As for the alignment methods for solar dishes, Diver et al. [15,16] developed an alignment method for stretched-membrane dish. In this method, an artificial light source was reflected by the concentrator’s facets to a target, and alignment was completed by adjusting the facet aim to the predetermined aim location at the target. A color look back alignment was successfully tested in laboratory field, where a target mounted near the focus point with a distant observer or light source [17,18]. This alignment method needs the dish to be oriented horizontally, making the adjustment difficult and time consuming, typically taking 4–6 h per dish with 40–80 facets on the dish. However, the look back method had been less successful for production quality mirror facets due to distortions of the reflected images [19]. The Alignment Implementation for Manufacturing using Fringe Analysis Slope technique (AIMFAST) was proposed by Sandia National Laboratories [19], using fringe reflection techniques to characterize facets, which could reduce the alignment time to about 2 h per dish. However, this AIMFAST could not determine the real Cartesian coordinates of facets and needs relative accurate pre-alignment to reduce the iterative realignment times using specially designed automated tooling. As mentioned above, the calibration also may be a trouble encountered.

Although quite a few methods were developed to measure slope error and align mirror facets, there is no general or standard method to assess the optical performance of solar dishes. Fast and reliable methods are still needed to establish manufacturing and installation requirements to improve the dish performance and

Please cite this article in press as: G. Xiao, et al., A model-based approach for optical performance assessment and optimization of a solar dish, Renewable Energy (2016), http://dx.doi.org/10.1016/j.renene.2016.05.076