Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 125 (2016) 146–160

SOLAR ENERGY

www.elsevier.com/locate/solener

Optimized solar thermal concentrator system based on free-form trough reflector

Chung-Yu Tsai

Department of Mechanical and Computer-Aided Engineering, National Formosa University, 64 Wunhua Road, Huwei, Yunlin 632, Taiwan

Received 26 July 2015; received in revised form 29 November 2015; accepted 8 December 2015
Available online 2 January 2016

Communicated by: Associate Editor Antoine Bittar

Abstract

A solar thermal concentrator system is proposed comprising a free-form-trough (FFT) reflector and a cylindrical heat-pipe receiver. The profile of the reflector is designed using a free-form surface creation (FFSC) method such that each incident ray is directed to a certain user-specified point on the heat-pipe surface. The light ray paths within the concentrator system are analyzed using a skew-ray tracing approach. A method is then proposed for optimizing the geometry of the concentrator system in such a way as to achieve a uniform irradiance distribution on the heat-pipe surface. The validity of the proposed optimization approach is demonstrated by means of ZEMAX/SolidWorks-Flow simulations. The results show that the proposed FFT concentrator yields a significant improvement in both the irradiance uniformity and the heating efficiency compared to conventional cylindrical-trough and parabolic-trough concentrators.

Keywords: Solar concentrator; Trough concentrator; Free-form

1. Introduction

Solar thermal concentrator systems find use in an increasing number of applications nowadays, ranging from the heating of domestic hot water at one end of the scale to the generation of steam for large-scale power plant applications at the other (Price et al., 2002). Richter (1996) presented a solar concentrator consisting of a large stationary reflector with its focal point located on the surface of the heat-pipe receiver and a small mobile reflector designed to track the sun. Huang et al. (2010) developed a solar concentrator in the form of a circular prism array for use either as a standalone system or as a secondary concentrator in systems already containing a solar-energy focusing module. Kalogirou (2004) conducted an extensive survey of solar thermal collectors and their applications and concluded that such systems have significant environmental and economic benefits. Nilsson et al. (2007) presented three micro-structured reflectors for improving the illuminance uniformity and concentration ratio of stationary asymmetric parabolic concentrator systems. Garcia-Botella et al. (2006) showed that elliptical concentrators have many advantages compared to reflectors with symmetrical or free-form surfaces. Maruyama and Osako (2007) proposed a wedge-shaped concentrator in which the light was focused on the solar cell by means of specular reflection at the rear surface and refraction or total internal reflection at the front surface. McIntosh et al. (2007) showed that cylindrical luminescent solar concentrators (LSCs) achieve a higher optical concentration than square-planar LSCs. Leutz and Annen (2007) used a reverse ray-tracing model to evaluate the yearly energy collection efficiency of a

E-mail address: cyt@nfu.edu.tw

http://dx.doi.org/10.1016/j.solener.2015.12.011
0038-092X/

Nomenclature

$S\theta$	$\sin(\theta)$	α_i	rotation angle of generating curve ${}^i\mathbf{S}_i$ about y-axis
$C\theta$	$cos(\theta)$	β_i	argument of generating curve ${}^i\mathbf{S}_i$ in xy-plane
$(xyz)_0$	world coordinate frame	s_i	coefficient set as either +1 or −1 such that cosine of incidence angle is greater than zero
$(xyz)_i$	coordinate frame imbedded in ith boundary surface	λ_i	magnitude of vector $\overline{\mathbf{P}_{i-1}\mathbf{P}_i}$
i	boundary surface index, $i = 1, 2, \ldots, n$	θ_i	incidence angle of incoming ray on boundary surface $\mathbf{r}_i$
$\mathbf{r}_i$	ith boundary surface	D	entrance width of concentrator
$\mathbf{P}_i$	incidence point on $\mathbf{r}_i$	R	radius of heat-pipe
$\boldsymbol{\ell}_i$	unit directional vector of light ray reflected/refracted at ith boundary surface	I_{sun}	solar irradiance
$[\mathbf{P}_i \quad \boldsymbol{\ell}_i]^T$	reflected/refracted ray at ith boundary surface	W_{beam}	average power carried by each bundle of solar rays
${}^j\mathbf{A}_i$	pose of coordinate frame $(xyz)_i$ with respect to coordinate frame $(xyz)_j$	I_{ideal}	ideal irradiance distribution on heat-pipe
${}^i\mathbf{S}_i$	generating curve of ith axial symmetric boundary surface		

stationary solar concentrator. Sarmah et al. (2011) used a ray-tracing method to design and optimize three stationary dielectric asymmetric compound parabolic concentrators (DiACPCs) with acceptance half-angles of (0°/55°), (0°/66°) and (0°/77°), respectively. Tao et al. (2011) presented a solar concentrator system consisting of a compound-surface parabolic concentrator, a secondary reflection plane mirror, and a parabolic trough concentrator. Leutz et al. (1999) designed a convex-shaped non-imaging Fresnel lens for use as either a temperature generator in evacuated tube-type solar concentrators or a solar concentrator in PV applications. Timinger et al. (2000) proposed an optical measurement method for determining the geometry and surface reflectivity of non-imaging radiation concentrators.

The literature contains various proposals for improving the irradiance uniformity of solar concentrator systems. For example, Ryu et al. (2006) proposed a solar concentrator in which modularly faceted Fresnel lenses were used to achieve a uniform intensity on the absorber plane. Gonzalez-Garcia et al. (2009) designed solid lenses and mirrors based on a set of optimized concentric spherical rings to produce a desired energy distribution on the focal plane. Bergamin and Sammaraee (2010) proposed a method for improving the light distribution performance of solar cells by modifying the surface of the glass cover. Simon and Meyer (2010) observed the non-uniform surface temperature distribution of solar cells in the reverse bias mode and found a direct correlation between the locations of the hot-spot regions and the regions of high-impurity contaminants. Yu et al. (2014) flattened the solar flux distribution inside a cavity receiver using a multi-focal point model and a TABU meta-heuristic optimization method. Rabady and Andrawes (2014) designed a concentrator capable of achieving a uniform concentration of the incident light on the reflector surface by solving a second-order differential equation.

The present study proposes a novel free-form-trough (FFT) reflector, in which the reflector profile is designed using a free-form surface creation (FFSC) method such that each incident ray is directed to a particular user-specified point on the heat-pipe surface. Unlike most concentrators, in which the reflector surface comprises several discrete segments, the proposed FFT reflector has a continuous surface. A method is proposed for optimizing the geometry reflector profile in such a way as to maximize the irradiance uniformity on the surface of the heat-pipe receiver. The validity of the proposed optimization method is demonstrated by means of a simple illustrative example. Finally, ZEMAX/SolidWorks-Flow simulations are performed to compare the irradiance uniformity and heating efficiency of the optimized FFT concentrator with those of a cylindrical-trough (CT) concentrator and a standard-parabolic-trough (SPT) concentrator, respectively.

The remainder of this paper is organized as follows. Section 2 introduces the proposed free-form surface creation (FFSC) method. Section 3 analyzes the reflective behavior of the incident light rays at the FFT and heat-pipe boundary surfaces using an exact analytical model and a standard skew-ray tracing method (Lin and Lu, 2004). Section 4 derives the objective function used to optimize the irradiance uniformity of the FFT concentrator system. Section 5 presents a simple illustrative example to demonstrate the validity of the proposed optimization method. Section 6 presents and discusses the ZEMAX/SolidWorks-Flow simulation results for the FFT, CT and SPT concentrator systems. Finally, Section 7 provides some brief concluding remarks.

In accordance with the homogenous coordinate notation adopted in this study, the ith incidence point $P_{ix}\mathbf{i} + P_{iy}\mathbf{j} + P_{iz}\mathbf{k}$ is written in the form of the column matrix ${}^g\mathbf{P}_i = \begin{bmatrix} P_{ix} & P_{iy} & P_{iz} & 1 \end{bmatrix}^T$, where the pre-superscript "g"