Renewable Energy 101 (2017) 804–815

Contents lists available at ScienceDirect

Renewable Energy

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

Full analytical formulation for Dielectric Totally Internally Reflecting Concentrators designs and solar applications

O.H. Cruz-Silva [a], O.A. Jaramillo [a, *], Mónica Borunda [b, c]

[a] Instituto de Energías Renovables, Universidad Nacional Autónoma de México, Priv. Xochicalco s/n, Temixco, Morelos, 62580, Mexico
[b] CONACYT Research Fellow-IIE, Consejo Nacional de Ciencia y Tecnología, Av. Insurgentes Sur 1582, Col. Crédito Constructor, D.F., 03940, Mexico
[c] Instituto Nacional de Electricidad y Energías Limpias, Reforma 113, Col. Palmira, Morelos, 62490, Mexico

ARTICLE INFO

Article history:
Received 22 January 2016
Received in revised form
1 September 2016
Accepted 17 September 2016

Keywords:
Solar concentrators
Concentrated solar energy
Nonimaging optics
Dielectric solar concentrators
Secondary concentrators

ABSTRACT

Over the last years many efforts have been focused to develop concentrated solar energy technologies. On the other hand, nonimaging optical devices such as Dielectric Totally Internally Reflecting Concentrators (DTIRCs) stand out for their high concentration and homogeneous radiant flux on the spot of the receiver of the concentrator. In this work we reformulate the original formulation of DTIRCs to obtain an analytical framework for feasible designs which are easily implemented for computer numerical control (CNC) manufacturing. Additionally we extend the formulation to aspherical front surfaces, such as Parabolic Dielectric Totally Internally Reflecting Concentrators (PDTIRC) and Elliptic Dielectric Totally Internally Reflecting Concentrators (EDTIRCs), and discuss their most relevant features for concentrated solar applications. It turns out that DTIRC devices are attractive candidates for solar concentration technology since they provide high concentration without solar tracking. In particular, we present two case studies of two stage concentrator devices. We analyse the solar flux distribution in a linear Fresnel reflector and a parabolic trough collector with a DTIRC as secondary concentrator.

1. Introduction

Nonimaging optical devices are optimal optical systems to transfer the radiative energy from a source to a target instead of forming an image as usual optical devices [1–3]. The main applications of nonimaging optical devices are: a) in solar energy concentration to maximise the amount of energy applied to a receiver, b) in illumination to control the distribution of light [4]. Nonimaging optical devices used for concentration have the following advantages over the conventional imaging concentrator devices [5]:

- wider acceptance angles resulting in higher tolerances and therefore higher efficiencies for: less precise tracking, imperfectly manufactured optics, imperfectly assembled components, movements of the system due to wind, finite stiffness of the supporting structure, deformation due to aging, capture of circumsolar radiation and other imperfections in the system;
- higher solar concentrations leading to: smaller solar cells, higher temperatures and lower thermal losses;
- possibility of a uniform illumination of the receiver to: improve reliability and efficiency of the solar cells and improve heat transfer;
- design flexibility such that different kinds of optics with different geometries can be tailored for different applications.

Nonimaging concentrators are used in applications involving high radiation concentrations, and when there is the need for uniform fluxes and the requirement of compact devices. DTIRCs are also used as secondary concentrators for the pumping of power laser systems (Nd:YAG and GaAs) through concentrated radiation [6,7]. Additionally DTIRCs have recently attracted the interest in infrared detection [8] and optical antennas with wireless communication [9,10]. DTIRCs are also used in optical collimators and beam shapers where the exit aperture is located in the front surface and the entrance aperture is located in the narrowest part of the device [11,12]. Additionally DTRICs are applied in interior lightening with optic fiber [13–15] and for transportation of radiative energy [16,17].

In addition to the previous applications, DTIRCs have been used for solar applications and photovoltaic concentration in a variety of

---

* Corresponding author.
E-mail address: ojs@ier.unam.mx (O.A. Jaramillo).

http://dx.doi.org/10.1016/j.renene.2016.09.037
0960-1481/© 2016 Elsevier Ltd. All rights reserved.

Nomenclature

$\bar{a}$	Semi-major axis of elliptical front surface
C	Optical path (cm)
C_{3D}	3D Geometrical concentration ratio
C_{max}	3D Maximum concentration (thermodynamic limit)
d_0	Exit aperture (cm)
e	Chord
H	Concentrator height (cm)
H	Front surface height (cm)
$l_k k_{th}$	ray path portion for $k = 1,2,3,4$ (cm)
n	Refractive index
p	Focus of the parabolic front surface
q	Minor axis to major axis ratio
R	Front surface radius (cm)
(r,ϕ)	Polar coordinates of incident point
(x_0,y_0)	Coordinates of the incident point
(x,y)	Profile coordinates
α	Angle between chord and wavefront (deg)
ε	Eccentricity
θ_a	Acceptance angle (deg)
θ	Incident angle (deg)
θ'	Angle of refraction (deg)
Θ	Maximum angle of refraction (deg)
θ_0	Exit angle (deg)
θ_c	Critical angle (deg)
φ	Front surface arc angle (deg)

devices [18]. One of the first applications was in a two-stage photovoltaic concentrator with Fresnel lenses as primaries and DTIRC as secondaries [19]. They found that the two-stage concentrator offers a higher concentration and a more uniform flux distribution on the photovoltaic cell than the point focusing Fresnel lens alone. In the following we present a brief review of some of the reported work.

In 1997, DTIRCs were introduced in space applications. In Ref. [20] DTIRCs are considered as refractive secondary concentrators for solar high temperature heat receivers operating at temperatures up to 2500° K for space applications. They found that solid single crystal refractive devices have more advantages than conventional hollow reflective compound parabolic concentrators, such as higher concentration ratio and efficiency. Moreover, when the refractive concentrator is combined with a flux extractor rod provides a flux tailoring within the heat receiver cavity. Years later, a DTIRC is used as the secondary concentrator for the solar thermal application in space in the NASA flight demonstration program [21].

In 2006, Dominguez et al. [22] considered a two stage concentrator consisting of an aspheric bulk lens, and a dielectric secondary lens with total internal reflection. They used a GaAs cell as receiver. They proposed a method for the spectral characterization of the system through the measurement of its optical efficiency as a function of the wavelength.

In 2011, Muhammad-Sukki et al. [23,24] presented an optimised design for an optical concentrator for a Building Integrated Photovoltaic system is proposed. The device is a Solar Photonic Optoelectronic Transformer that uses a DTIRC concentrator to improve its performance and provide higher optical gain.

In 2013, Bitterli et al. [25] proposed an array of parabolic concentrators to direct the incoming light into a cell. They applied the device to collimate radiation and to micro highly concentrated photovoltaic solar cells. In the same year, Cooper et al. [26] introduced a two-stage line-to-point focus solar concentrator with tracking secondary optics. They proposed a one-axis tracking trough as the primary concentrator and a tracking system for the secondary stage concentrator. Another reported work in the same year was done by Muhammad et al. [27]. In this work they investigated the electric and optical performances of their mirror symmetrical dielectric totally internally reflecting concentrator. Their aim is to increase the electrical output of a solar photovoltaic system and reduce the size of the PV cell needed.

In 2014, Muhammad et al. [28] continued their research and utilized DTIRCs in Building Integrated Photovoltaic Systems (BIPVS) to concentrate energy in two-dimensions with a wide field of view in order to minimize the photovoltaic field and dispense the use of solar tracking.

In 2015, Thomsen et al. [29] proposed a DTIRC for use with bifacial photovoltaic cells. They considered the bifacial cell immersed in a dielectric. They considered two types of DTIRC structures: CPC-like structures and vertical structures. The vertical structure gives a lower concentration than the CPC structure, but it is also a shorter structure with more uniform flux distribution over the receiver. In the same year Abu-Bakar et al. [30] considered a rotationally asymmetrical dielectric totally internally reflecting concentrator. They optimised the device by looking at the best material and fabrication technique. They achieved an increase in the electrical output of the solar PV system.

DTIRCs offers advantages and disadvantages compared to compound parabolic concentrators (CPCs) [31]. DTIRCs exhibit higher geometrical concentration gain, higher efficiency, flux tailoring and smaller sizes. In addition DTIRCs work without any needs of cooling features. The disadvantage of DTIRCs over CPCs is that they cannot efficiently transfer all of the solar energy that it collects into a lower index media [21].

The main objective of this work is to restructure the Ning's formulation [32] to define the spherical profile of a DTIRC. We introduce an innovative formulation to completely define the DTIRC profile and present its applications to concentrated solar energy. We present a complete validated analytical formulation for the Phase Conserving Method for a DTIRC on basis of imposing the conservation of the etendue. We extend the formulation to parabolic, PDTIRC, and elliptical, EDTIRC, profiles. We carried out two case studies for applications in concentrated solar energy since these devices are excellent candidates for concentrated photovoltaic due to the homogeneous distribution of the solar flux in the receiver.

The paper is organized as follows. In Section 2 we present the original formulation for the DTIRCs developed by Ning [32]. In Section 3 we highlight the problems around the original formulation and we present our procedure to define a viable DTIRC profile. In Section 4 we generalize the formulation to parabolic and elliptical profiles. In Section 5 we validate our model by comparing our results with some results previously reported in literature. Additionally we present more designs with different parameters. Solar applications are presented in Section 6. First we consider a linear Fresnel reflector coupled to a DTIRC as a secondary concentrator and study the solar flux distribution on the target of the system. We then consider a parabolic trough collector with a DTIRC as a secondary concentrator and perform the same