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A note on design of linear dielectric compound parabolic concentrators

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ABSTRACT

In this communication, three-dimensional radiation transfer within linear dielectric compound parabolic concentrators (DCPC) is investigated based on vector algebra and solar geometry, and the design of DCPC oriented in east-west direction is addressed. The analysis shows that, the projected incident and refractive angles of solar rays on the cross-section of DCPC are not subjected to the correlation as Snell law except for incident rays on the cross-section, hence, the acceptance half-angle (θ_a) of DCPC should be determined based on time variations of projected refractive angle and minimum time ($2t_c$) required to concentrate direct sunlight in all days of a year. It is also found that, to make all refractive radiation within θ_a are totally internally reflected onto the absorber, DCPC with a restricted exit angle (DCPC-θ_a/θ_e should be employed, and solar leakage from walls of DCPC-θ_a/90 can be avoided or reduced by increasing θ_a and number of periodical tilt-angle adjustment in a year. Calculations show that, the minimum θ_a of DCPC depends on t_c and strategy of tilt-angle adjustment; and for a given t_c, the ratio (R_c) of maximum geometric concentration of DCPC to that of reflective CPC ($n = 1$) is dependent on number of periodical tilt-angle adjustment in a year, but always larger than refractive index (n) of dielectric. Calculations also indicate that, for DCPCs with $n > 1.4$, when solar rays incident towards onto right/left wall, the radiation incident on its opposite wall (left/right) will be totally internally reflected, and multiple reflections of solar rays on way to the absorber will also be total internal reflection for radiation within its acceptance angle.

Nomenclature

C_g	geometric concentration of full DCPCs (dimensionless)
N	Day number counting from equinoxes
n	refractive index of dielectric (dimensionless)
n_M	unit vector of the normal to parabolic wall at point M
n_s	unit vector from the earth to the sun
n_r	unit vector from the earth to the "virtual sun" seen within dielectric
R_c	ratio of maximum geometric concentration of DCPC to that of similar reflective CPC (n = 1) with identical minimum daily time ($2t_c$) as DCPC to collect direct sunlight (dimensionless)
t_c	cutoff solar time measuring from solar-noon to collect direct radiation for minimum hours of $2t_c$ per day (hour)

Greek letters

*α	tilt angle adjustment of DCPCs' aperture from site latitude
β	tilt-angle of DCPVs' aperture from the horizon
δ	declination of the Sun
δ_{N+1}	declination of the sun in N + 1 day counting from equinoxes
φ_s	azimuth angle of the sun measuring from south to west
ϕ	polar angle of any point on parabolic walls
γ	tilt-angle of any line relative to x-axis
λ	site latitude
θ_a	acceptance half-angle of DCPCs
$\theta_{a,0}$	acceptance half-angle of similar reflective CPC
θ_e	maximum exit angle of DCPC-θ_a/θ_e for refractive radiation within its acceptance angle
θ_{ap}	incident angle of solar rays on the aperture of DCPVs
θ_c	critical incident angle for total internal reflection
$\theta_{i,M}$	incident angle of solar ray at point M of parabolic walls of DCPVs
$\theta_{i,pl}$	incident angle of solar ray on the plane wall of DCPCs
θ_r	refractive angle of incident solar ray on the dielectric side of air-dielectric aperture
$\theta_{r,0}$	refractive angle of incident solar rays at solar-noon
$\theta_{p,i}$	projected angle of incident solar rays on the cross-section of DCPC
$\theta_{p,r}$	projected angle of refractive solar rays on the cross-section of DCPC
ω	solar hour angle
ω_c	cutoff solar hour angle to collect direct sunlight in all days of a year

*The unit of all angles is radiant in mathematical expressions and

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degree in text.

1. Introduction

Concentrating solar radiation onto solar cells enables the cost of a photovoltaic system to be reduced per unit of energy delivered, and the compound parabolic concentrators (CPC) were widely tested in recent years due to advantages of simple in the structure, easy in manufacture and combination with facades of buildings, and no need for sun-tracking (Mallick and Eames, 2007). Experimental studies performed by Mallick et al. (2004, 2006) showed that, compared with similar non-concentrating PV panel, the use of an asymmetric CPC (2.1×) increased the maximum power point of photovoltaic modules by 62%, but the temperature of solar cells was only 12 °C higher. Brogren et al. (2003) tested a CPC (3×) based Cu(In, Ga)Se_2 PV module, and 1.9 times of maximum power output as that of identical modules without using CPCs was experimentally observed. An experiment study by Yousef et al. (2016) in the hot and arid climatic conditions showed that, in comparison with similar solar panels, the electricity from CPV (2.4×) with and without cooling of solar cells was 52% and 33% higher, respectively. These studies showed that, the use of reflective CPC could increase the power output of PV systems, but the power increase was much less than it's geometric concentration, a result of optical loss due to imperfect reflections of solar rays on way to solar cells (Tang and Wang, 2013), electrical loss due to rising cell temperature, uneven irradiation and increased incident angle. To make solar irradiation on solar cells of reflective CPCs more uniform, Hatwaambo et al. (2008, 2009) test a CPC with rolling marks on reflectors and found that the such effort can but not significantly improve the photovoltaic performance of CPVs, in turn it results in a great decrease in collectible radiation (Yu and Tang, 2015). Recent experimental investigation by Yu et al. (2015) and Baig et al. (2014) indicated that, solar flux distribution on solar cells of CPC based PV systems had an insignificant effect on the power output, but the incident angle of solar rays have a considerable effect, especially as the incident angle > 60°. Bahaidarah et al. (2016) experimentally investigated effects of thermal environment on the performance of CPC based PV/T systems, and found that, the glazed PV/T system reduced the power output due to higher cell temperature thus suitable for higher thermal gain, and the unglazed system was suitable for greater electricity output. Another comparative experiment performed by Bahaidarah et al. (2014) showed that, as compared to similar flat PV strings, the use of CPC (2.3×) increased the power output by 39% and 23% with and without cooling, respectively. To reduce optical loss due to imperfect reflections, Su et al. (2012) and Li et al. (2013) proposed a lens-walled CPC and results obtained by ray-tracing analysis showed that such CPC is more favorable in terms of solar flux distribution, optical efficiency and acceptance angle as compared to reflective CPCs. To enhance solar absorption, CPC-θ_a/θ_e, a CPC with a maximum exit angle (θ_e) for radiation within its acceptance angle (θ_a), was suggested by Rabl and Winston (1976), and indicated that the use of such CPC can improve the photovoltaic performance.

As compared to reflective CPCs, dielectric internally reflecting compound parabolic concentrators (DCPCs) share advantages of wide solar acceptance angles thanks to the refraction of solar rays, and higher optical efficiency thanks to total internal reflection. The absorption losses can be minimized by employing a dielectric material with a low extinction coefficient and by minimizing the path length of solar rays. The earlier works of Winston (1976) and Rabl (1976) stated that, given θ_a of a source at infinity, the use of dielectric with a refractive index n increases the geometric concentration of linear CPCs by a factor of n. Acrylic panels employing two-dimensional and three-dimensional CPCs for use with photovoltaic solar cells were first proposed by Welford and Winston (1978). The early work of Rabl (1976) indicated that, given minimum time of 7 h required to collect direct sunlight in all day of a year, for a truly stationary solar concentrator, the limit of useful concentration is about 2, and this can be increased to about 4 by means of a dielectric medium with $n = 1.5$. Muhammad-Sukki et al. (2013) developed a mirror symmetrical dielectric totally internally reflecting CPC (4.9×) based photovoltaic system for building applications, and measurements showed that the use of DCPC increased the maximum power output point by a factor of 4.2. Ray trace analysis by Sellami and Mallick (2013) showed that, the crossed compound parabolic concentrator (3.6×) has a maximum of optical efficiency of 95%. A three dimensional ray trace analysis by Zacharopoulos et al (2000) indicated that the DCPCs, made of low-iron glass, had the optical efficiency over 90% for a wide range of incident angle and over 40% even for incident angle outside its acceptance angle. The incident angle of solar rays on internal walls of DCPCs gradually decreases from the upper tip to lower end (Tang et al., 2018), thus, solar rays incident on the lower part of parabolic walls are likely not totally internally reflected onto the absorber. Therefore, to avoid radiation leakage, it is necessary either to metalize lower part of external walls or employ DCPC with a restricted exit angle (DCPC-θ_a/θ_e). However, metalizing external walls of DCPCs would result in an extra loss due to imperfect reflections on the metalizing walls. Ray tracing and experimental investigation by Pei et al. (2012) revealed that part of radiation incident on walls of DCPC can't undergo internal reflection, even within the acceptance angle. A study by Baig et al. (2014) indicated that metalizing external walls of a linear asymmetric DCPC (2.8×) based PV system resulted in an increase of 16% in the average power output, implying that > 16% of incident radiation was leaked through walls where there is no reflective film.

Stationary linear CPCs are usually oriented in the east-west direction for efficient radiation collection, and periodical tilt-angle adjustment in a year is required to ensure direct sunlight within its acceptance angle for specified minimum hours in all days of a year (Rabl, 1976; 1985). The optical performance of reflective CPCs is uniquely determined by projected incident angle of solar rays ($\theta_{p,i}$) on the cross-section (Rabl, 1985; Yu and Su, 2015; Tang et al, 2018), and solar rays incident at $\theta_{p,i}$ less than its acceptance angle ($\theta_{a,0}$) will be accepted. Therefore, acceptance half-angle ($\theta_{a,0}$) of linear reflective CPCs oriented in east–west direction is commonly determined based on time variations of $\theta_{p,i}$ and minimum hours ($2t_c$) required to collect direct sunlight in all days of a year (Rabl, 1976; Tang et al, 2010). Similarly, the acceptance angle ($2\theta_a$) of linear DCPCs should be determined based on time variations of projected angle ($\theta_{p,r}$) of refractive rays in all days of a year as DCPCs are designed to concentrate refracted sunlight, and θ_e should be determined in such way making incident angle of refracted solar rays on plane walls larger than critical incident angle for total internal reflection.

Analysis in above indicates that, to perform design of a linear DCPC-θ_a/θ_e, it is essential to investigate three-dimensional radiation transfer within a linear DCPC. However, similar works were rarely found in the literature, and the design of linear DCPCs in the past was commonly conducted based on two-dimensional radiation transfer model where radiation transfer on the cross-section of DCPCs is considered. In this communication, three-dimensional radiation transfer within linear DCPCs are investigated based on vector algebra and solar geometry, and design of DCPCs oriented in the east-west direction with the aperture being yearly fixed, yearly adjusted two and four times is addressed.

2. Three-dimensional radiation transfer within linear DCPCs

2.1. Equation of linear DCPC's profile

For sake of simplicity, the width of absorber of DCPCs is set to be 1, hence, in the coordinate system as shown in Figs. 1 and 2, the right parabola of DCPC-θ_a/θ_e is expressed by (Rabl, 1985; Yu et al., 2016):