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A review of nonimaging solar concentrators for stationary and passive tracking applications

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A R T I C L E I N F O

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Compound elliptical concentrators
Nonimaging Fresnel lenses
Dielectric compound parabolic concentrators
DCPC
Trumpet-shaped concentrators

A B S T R A C T

The solar energy research community has realized the redundancy of image-forming while collecting/concentrating solar energy with the discovery of the nonimaging type radiation collection mechanism in 1965. Since then, various nonimaging concentration mechanisms have proven their superior collection efficiency over their imaging counter-parts. The feasibility of using nonimaging concentrators successfully for stationary applications has rekindled interest in them. The economic benefits are appealing owing to the elimination of tracking costs (installation, operation & maintenance and auxiliary energy). This paper is an exhaustive review of the available nonimaging concentrating mechanisms with stationary applications in mind. This paper also explores the idea of coupling nonimaging concentrators with passive solar tracking mechanism.

1. Introduction

Amongst the total solar electric power worldwide today (as per 2015 data) [1], solar photovoltaics (PV) contribute about 227 GW, and concentrating solar power (CSP) technologies contribute about 4.8 GW in generation capacity. NREL's SolarPACES program constantly monitors and updates the global list of CSP projects that are either operational or currently under development [2]. The parabolic trough (an imaging-type solar concentrator technology) accounts for a vast majority of the CSP installations worldwide due to its cost advantage, although power tower systems are quickly catching up. United States and Spain being the front-runners, various other nations including the Middle East and North Africa (MENA) countries, South Africa, India, and China are fast adopting CSP [3].

No matter the type of CSP technology adopted, actively tracking the Sun in order to achieve meaningful concentration is a common trait in all of them. The concentration of solar radiation is typically achieved by using an active solar tracking mechanism coupled with a point- or line-focus imaging concentration system. However, even the best of the traditional imaging techniques of concentration fall short of the thermodynamic limit of maximum attainable concentration at least by a factor of four due to severe off-axis aberration and coma causing image blurring and broadening. Imaging is an inhibitive phenomenon as far as only energy concentration is concerned. The concentration of solar energy does not demand imaging qualities, but instead requires flexible concentrator designs coping with solar disk size, solar spectrum, and tracking errors while delivering a highly uniform flux [4]. Moreover, an active solar tracking mechanism, often accompanying an imaging concentrator, also adds to the capital and O & M costs while consuming a fraction of the power produced. Therefore, with all these disadvantages in view, nonimaging and stationary techniques of concentrating solar radiation are sought after.

Nonimaging concentrators have been used in solar energy collection systems ever since their discovery in 1965. In the decades that followed, various nonimaging concentrator designs were discovered and evaluated as stationary installations. The concentration ratios achieved were typical low (< 3X) or medium (3-10X). However, the application of these types of concentrators on a large scale or a utility

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Nomenclature

CPC	Compound Parabolic Concentrator
ACPC	Asymmetric Compound Parabolic Concentrator
BIPV	Building Integrated Photovoltaics
CCAC	Compound Circular Arc Concentrator
CEC	Compound Elliptical Concentrator
CHC	Compound Hyperbolic Concentrator
CPV	Concentrated Photovoltaics
CR	Concentration Ratio
CSP	Concentrated Solar Power
CSP	Concentrated Solar Power
d_1	Dimension of Entrance Aperture
d_2	Dimension of Exit Aperture
DACPC	Dielectric Asymmetric Parabolic Concentrator
DCPC	Dielectric Compound Parabolic Concentrator
ER	Energy Ratio
$F(\theta)$	Angular Acceptance Function
FDTD	Finite-Difference Time-Domain
GW	Giga Watt
H	Height of the CPC
h_c	Convective Heat Transfer Coefficient
h_{cd}	Conductive Heat Transfer Coefficient
h_R	Radiative Heat Transfer Coefficient
h_{tot}	Overall Heat Transfer Coefficient
H_{trunc}	Height of the truncated CPC
LVT	Lens-V Trough
MENA	Middle East and North Africa
n	Refractive Index of the Dielectric Media
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
PCCPC	Prism-coupled Compound Parabolic Concentrator
PV	Photovoltaics
R	Reflector-To-Aperture Ratio
SPC	Simple Parabolic Concentrator
α	Absorptivity
β	Prism Apex Angle
δ	Complete Acceptance Angle of V-trough
ε	Emissivity
θ	Angle of Incidence of an Arbitrary Light Ray
θ_a or θ_{max}	Acceptance Angle
θ_d	Truncated CPC's Edge Ray Angle
Φ	Half Angle Of The V-Shaped Cone

scale is yet to be materialized. This current paper is a review of the presently existing and upcoming nonimaging techniques for concentration of solar radiation in stationary or passive tracking applications. Novel applications, and modern techniques of raytracing analysis on nonimaging concentrators has also been discussed as a part of this review.

2. Stationary solar energy collectors

Stationary solar energy collector designs such as a flat plate and a concentric cylindrical tube have been prevalent in low temperature (< 200° F) applications such as solar domestic/pool water heating, dehydration of agricultural products, etc. since the beginning of the 20^{th} century [5]. As early as the mid-1970s, Falbel Energy System Corp. manufactured a stationary 'nonimaging' collector (called the FES delta solar collector) with a cylindrical cavity trough that achieved a net gain of 2.3X compared to a flat plate collector. Another company named Kaptron manufactured a modified stationary flat-plate solar collector by incorporating a window with optical ribs, an optical valve and a multi-reflection absorber enclosed in an insulated casing, thus making it more efficient over a conventional design [6]. In more recent times, a Stationary V-trough collector (cone angle=60°) was fabricated and tested in a solar water heating application for the geographical location of Kuala Lumpur (3.2°N and 101° 44′ E) [7]. The collector was oriented in the E-W direction with 0° tilt angle. With a surface area of 0.56 m^2, it achieved a diurnal power collection that varied between 0.154 and 0.261 kW. When compared with respect to a flat-plate absorber, the average relative solar concentration ratios of the V-trough varied between 1.19 and 1.85 throughout the year. Interestingly, the peak summer and winter months saw a decrement in the relative concentration ratio.

3. Nonimaging solar concentrators

Nonimaging concentrators are a classification of radiation collectors that direct the radiative energy passing the entry aperture (larger area, A_1) of the concentration system through to the exit aperture (smaller area, A_2) with minimum optical losses. The term 'nonimaging' or 'anidolic' (from Greek an: without, eidolon: image) refers to the virtue of the concentration system to focus the étendue or 'throughput' on a wider area rather than a single focal point and, thus, unable to form an image of the light source. Unlike the conventional imaging concentration systems, the quality of the image at the exit aperture is of least importance in these concentrators. An illustration of a hypothetical nonimaging concentration system is shown in Fig. 1. The concept of nonimaging collection of radiation came into the picture when the compound parabolic concentrator (CPC) was proposed by Hinterberg and Winston in 1965 as an efficient means of measuring Čerenkov radiation. The early 70 s saw a tremendous rise in the number of researchers experimenting on application of various CPC/modified CPC designs as solar concentrators. All these nonimaging collector designs obey a fundamental principle known as the edge-ray principle (used in the design of nonimaging optics) which can be summed up as: "if the edge or boundary rays from a source to an optical system (reflective or refractive) are able to be directed to the edges of a target area, then all the rays in between these edge rays will also be directed to the target area". Winston et al. [8] demonstrated the edge-ray principle using the string method. The same principle has also been refined by using a topological approach [9].

The properties of various nonimaging CPC-type concentrators including the compound elliptical concentrator (CEC), compound hyperbolic concentrator (CHC), trumpet-shaped concentrator and generalized involute reflectors were discussed by Gordon and Rabl [10]. A comparative review on various reflective type solar concentrators has been reported as well [11]. Collector characteristics such as geometric concentration ratio, acceptance angle, sensitivity to mirror

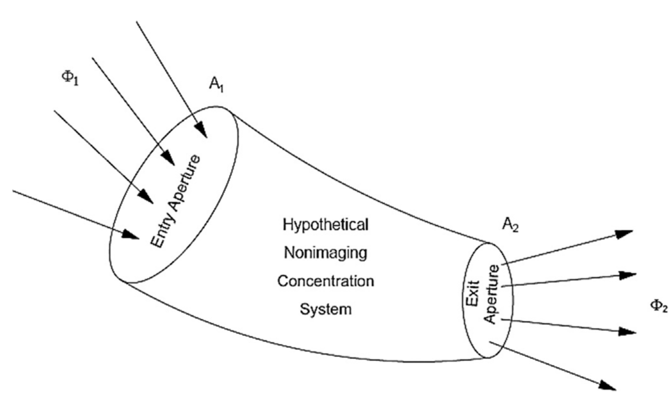

Fig. 1. Illustration of a nonimaging concentration system with entry flux (Φ_1) and exit flux (Φ_2).