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RESEARCH ARTICLE

COMPARISON OF OPTICAL PERFORMANCE OF CONCENTRATORS SUITABLE FOR THERMAL APPLICATIONS

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ABSTRACT

The paper focuses on six different concentrator configurations to provide better insight into the geometrical-optical performance of six different configurations are Elliptical Parabolic Concentrator (EPC), Circular Parabolic Concentrator (CCPC) and Square Parabolic Concentrator (SPC), Elliptical Hyperboloid Concentrator (EHC); Circular Hyperboloid Concentrator (CHC) and Square Hyperboloid Concentrator (SHC). In this study the most commonly used optical elements are compared with some newer designs of concentrators for their optical performance. Detailed analysis is performed using ray tracing technique to identify the important parameters affecting the overall performance of these concentrators. Finally, results are summarised showing the best practices to be employed for different thermal applications. The simulation analysis indicates that the parabolic geometry profiles (EPC, CCPC, SPC) achieve high optical efficiency values. The CCPC demonstrates the highest optical efficiency at 92% but has a narrow acceptance angle of ±15 degrees. The SPC achieves an optical efficiency of 85% with the same acceptance angle. In contrast, the EPC has a lower optical efficiency of 33% but offers a wider acceptance angle of ±30 degrees, twice that of the EPC. For the hyperboloid geometry profiles (EHC, CHC, SHC), the EHC achieves a maximum theoretical optical efficiency of 28% with an acceptance angle of ±30 degrees. The CHC exhibits a lower optical efficiency of 21% but with a narrower acceptance angle of ±15 degrees. The SHC attains an optical efficiency of 39% with an acceptance angle of ±30 degrees.

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1. INTRODUCTION

Research on optical characterization for different kinds of receivers used in solar concentrator systems is ongoing and is documented in the literature. A study by (1) examined the analysis of Compound Parabolic Concentrator (CPC) in conjunction with single and double elliptical pipe receivers. The study looked into several CPC configurations using these receivers. Researchers frequently use the simulation program OptisWorks 2012 to model the optical performance of different concentrator solar collectors. Ray-tracing techniques are used by this software to precisely simulate the behavior of light rays inside the collector shape. Optis-Works 2012 has been widely used by several academics in their studies (2–8). The study conducted by (9) has out a review with an emphasis on concentrating solar thermal collectors in order to look at current developments in solar concentrating collectors and highlight techniques for improving performance used with different concentrating technologies. The thermal and geometrical evaluation of a double evacuated new receiver tube system mounted on a parabolic trough collector (PTC) is the main subject of the study by (10) focuses performance analysis of an asymmetric compound parabolic concentrator (CPC) with a circular absorber. In order to investigate the optical and thermal performance of this specific configuration. (11) Enhancing the optical, electrical, and thermal performance of a concentrating photovoltaic/thermal system can be achieved using optimized polynomial compound parabolic concentrators. These concentrators are designed to maximize light capture and improve energy conversion efficiency (12) The study involved designing a conical solar collector and evaluating its performance based on ASHRAE standards to achieve higher efficiency. Due to experimental constraints, the optimal geometry of the collector was determined through numerical modeling (13) The study examines the optical performance of a 2-D hyperboloid solar concentrator. It builds on the fundamental equation for solar concentrators, adjusting parameters to assess optical efficiency. A 2-D MATLAB code is created to generate various concentrator shapes, with a focus on the 2-D hyperboloid concentrator (2-D-HC) (14). Ray tracing analysis is utilized to evaluate its optical efficiency.

2. RESEARCH SCOOPS AND OBJECTIVES

This research paper investigates the optical performance of a novel hyperboloid solar concentrator in both 2-D and 3-D configurations. Via comparing these two designs, they aim to understand how three-dimensionality affects the concentrator's effectiveness in concentrating sunlight and converting solar energy into usable forms (15). Study to evaluate the optical performance of a static 3-D Elliptical Hyperboloid Concentrator using ray tracing software. using ray tracing techniques to determine the optical efficiency of the static 3-D EHC including effective concentration ratio, optical efficiency, and geometric concentration ratio across different aspect ratios of the elliptical profile (16).

3. RESEARCH METHODS AND TECHNIQUES

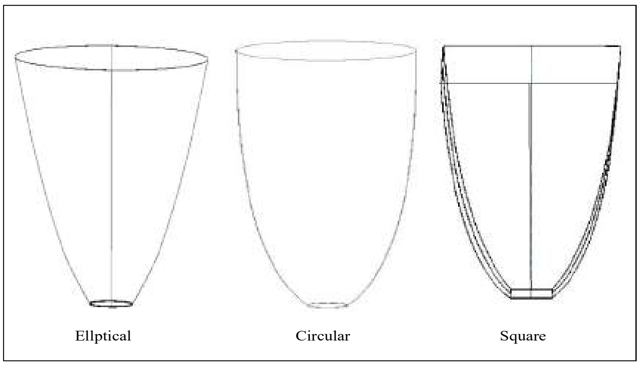
This study focuses on providing a comprehensive understanding of the geometrical-optical performance of six distinct concentrator configurations. Through a comparative analysis of these different optical designs, the paper contributes to knowledge of concentrator technology and offers insights to optimize performance for specific thermal applications. The findings presented in this study have significant implications for the development and improvement of solar thermal systems that employ concentrators. Furthermore, the paper conducts an extensive parametric study aimed at further enhancing the overall performance of the concentrators under investigation.

4. IMPORTANT PARAMETERS AFFECTING PERFORMANCE

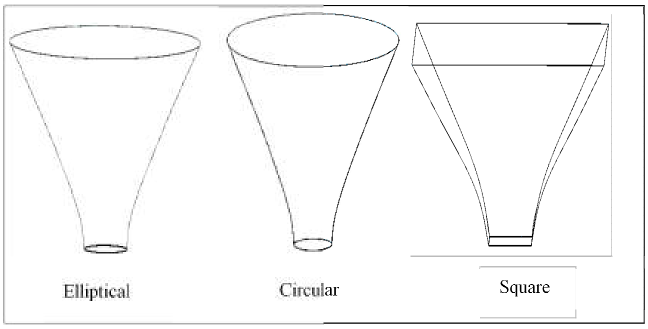
4.1. Concentrator Configurations: Concentrator configurations refer to the different designs and arrangements of concentrator systems used in solar energy applications. These configurations are designed to concentrate sunlight onto a smaller area, increasing its intensity and enabling more efficient energy conversion. Using ray tracing techniques to calculate the optical efficiency of the static 3-D concentrator for parabolic and hyperboloid profile with different shape of the cross section.

4.2. Different Geometrical Configurations Geometry Shapes Analysed for Different Shapes: A study was conducted to investigate the impact of different concentrator geometric profiles on the optical performance of solar systems. Six distinct geometries were examined: Elliptical Parabolic Concentrator (EPC), Circular Parabolic Concentrator (CPC), Square Parabolic Concentrator (SPC) as shown in figure (1a) and Circular Hyperboloid Concentrator (CHC), Elliptical Hyperboloid Concentrator (EHC), and Square Hyperboloid Concentrator (SHC). Figure (1b) illustrates the profiles of these geometries.

The study focused on comparing two symmetrical geometric profiles, namely the parabola and the hyperbola. In both profiles, the aperture and receiver cross sections were circular, elliptic, and square, as depicted in Figure 1. All six geometric concentrators shared the same height, receiver area, and concentration ratio to facilitate a fair evaluation of their optical performance. In this study, the orientation of the incidence angle is defined such that the radiation source originates from the east, corresponding to sunrise, where the angle is designated as +90˚. At noon, when the orientation of the source radiation is perpendicular to the receiver and the sun reaches its zenith, the incident angle is regarded as 0˚. As the source shifts towards the west, the incidence angle is represented as ±90˚.



A. Parabolic

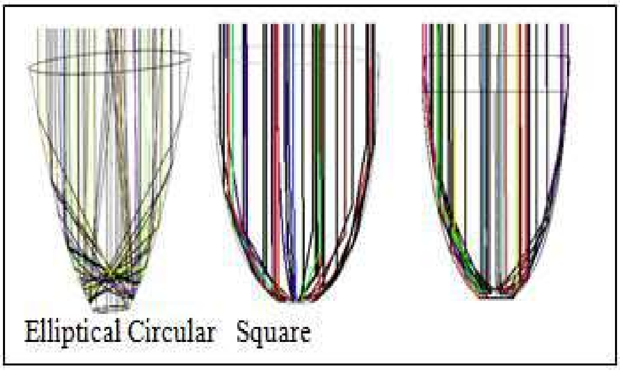


B. Hyperboloid

Figure 1. The profiles of the different geometries include (a) the Parabolic Geometry profile and (b) the Hyperboloid Geometry profile

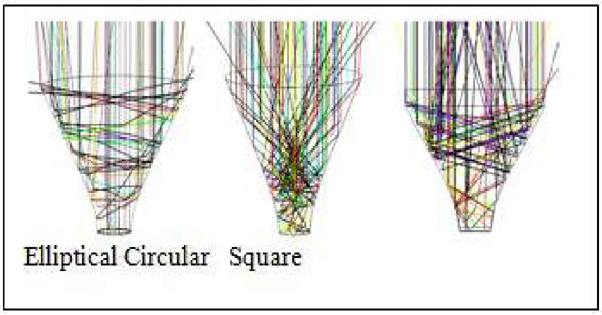
5. GEOMETRICAL-OPTICAL PERFORMANCE ANALYSIS

5.1. Analysis of Ray Tracing and Optical Efficiency Across Various Geometries: The analysis of ray tracing was conducted across six distinct geometries. The methodology and principles of ray tracing were elucidated in figure 2. The outcomes of the ray tracing analysis were derived from six static three-dimensional solar concentrators. In figure 2 (I and II), the ray tracing results for parabolic and hyperboloid geometric profiles featuring elliptical, circular, and square cross-sections were presented.



A. Parabolic

(i) Ray tracing of a parabolic geometric profile is conducted at an angle of 0 degrees



(ii) Ray tracing of hyperboloid geometry profile is conducted at an angle of 0 degrees.

Figure 2. Ray tracing of profiles characterized by parabolic and hyperboloid geometries Hyperboloid

Ray tracing of hyperboloid geometry profile is conducted at an angle of 0 degrees.

5.2. The Efficiency of Optical Performance Through the Use of Parabolic Geometric Profiles: Based on the ray tracing data, the optical efficiency was determined for parabolic and hyperboloid geometries at various angles of incidence. The optical efficiency variation of the parabolic concentrator, specifically the elliptic, square and circular cross-sections (EPC, CCPC, and SPC), was depicted in Figure 3. It was observed that the CCPC exhibited the highest optical efficiency, peaking at 92%, but with a narrow acceptance angle of ±15˚. On the other hand, the EPC confirmed lower optical efficiency, peaking at 33%, but had a wider acceptance angle of ±30˚, twice that of the CPC. The hight optical efficiency of square parabolic concentrator SPC is efficiency of 85%, but with a narrow acceptance angle of ±15˚.

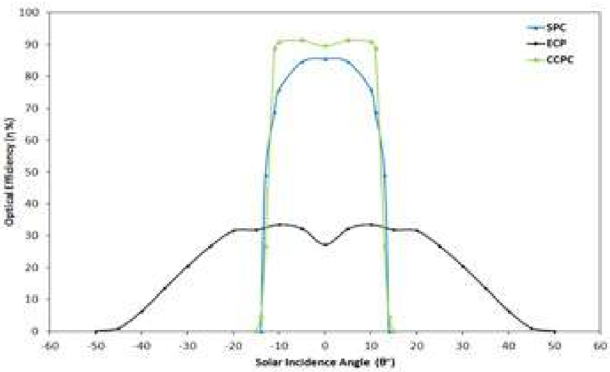


Figure 3. The optical efficiency of a parabolic profile with elliptical, circular, and square cross-sections

5.3. Optical Efficiency of Hyperboloid Geometry Profile: The hyperboloid concentrator's optical efficiency variation for elliptic, circular and square cross-sections (EHC, CHC, and SHC) at various incidence angles was shown in figure 4. a higher optical efficiency of 28% with an acceptance angle of ±30° was attained by the EHC. On the other hand, the CHC showed a narrower acceptance angle of ±15° and a lower optical efficiency of 24%. The optical efficiency of SHC was 39% with an acceptance angle of ±30°. The advantages of the parabolic and hyperbolic concentrator are widely known. Higher optical efficiency can be achieved using parabolic concentrators at lower acceptance angles, making them suitable for use in conjunction with tracking devices. Wider acceptance angles result in reduced optical efficiency for hyperboloid concentrators, which are useful for non-tracking systems.

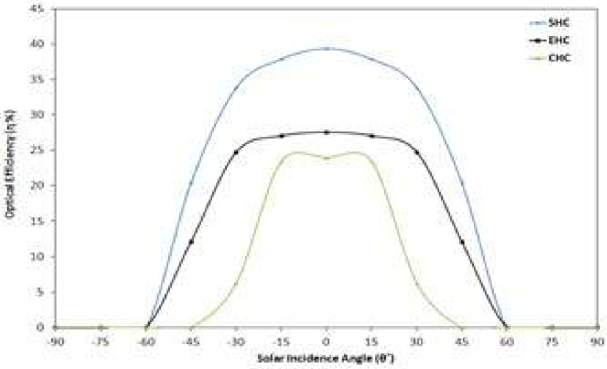


Figure 4. The effectiveness of optical performance in hyperboloid concentrators featuring elliptical, circular, and square cross-sectional shapes

6. ENERGY COLLECTED BY THE RECEIVE

6.1. Mean Energy Captured by a Receiver with a Parabolic Geometric Profile: The analysis was conducted to examine the mean energy captured by the receivers of Geometric Profile and hyperboloid Geometric Profile with circular, elliptic and square cross-sections at various incidence angles. The study focused on the circular cross-section parabolic concentrator (CCPC), elliptic cross-section parabolic concentrator (EPC) and square cross-section parabolic concentrator (SPC). Circular cross-section hyperboloid concentrator (CHC), and elliptic cross-section hyperboloid concentrator (EHC) and square cross-section hyperboloid concentrator (SHC). The outcomes revealed that the CCPC exhibits a higher absorbed energy flux compared to the EPC. The peak flux value for the CCPC reached 18,000 W/m2 at an acceptance angle of ±15 degrees, while the EPC achieved a peak flux value of 6,000 W/m2 at an acceptance angle of ±45 degrees. Whereas in the SPC achieved a peak flux value of 12,000 W/m2 at an acceptance angle of ±45 degrees. This indicates that the CCPC attains its peak flux at a lower acceptance angle than the EPC where SPC peak flux at with wider acceptance angle. The differences in absorbed energy flux and the influence of incidence angles on the performance of the studied concentrators. The results can aid in selecting the most suitable concentrator design based on the desired absorbed energy and acceptance angle requirements for a given application.

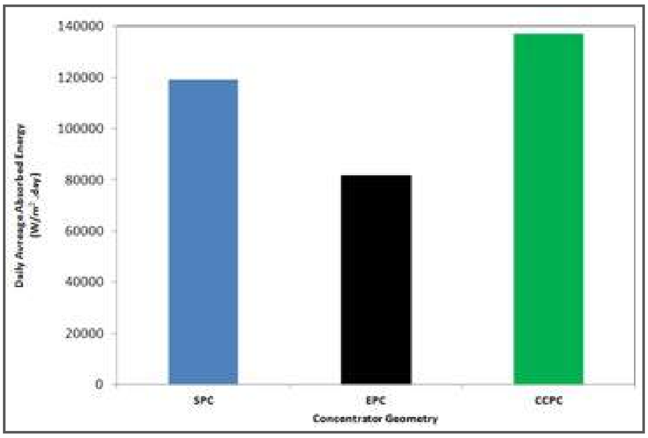


Figure 5. The regular daily energy received by the receiver of a parabolic concentrator

6.2. Average Daily Energy Absorption by The Receiver with a Hyperboloid Geometry Profile: An analysis utilizing ray tracing techniques was performed to assess the daily average energy captured by the receivers of parabolic and hyperboloid concentrators featuring circular, elliptic, and square cross-sections. The findings from this analysis are illustrated in figure 5. It was noted that the elliptic cross-section parabolic concentrator (EPC) captured a daily average energy of 8.3 kW/m2, whereas the circular cross-section parabolic concentrator (CCPC) captured a daily average energy of 13.7 kW/m2, and the square cross-section parabolic concentrator (SPC) captured a daily average energy of 12.0 kW/m2. These figures represent the energy absorption capacity of the receivers associated with these concentrators on a daily basis. The circular cross-section hyperboloid concentrator (CHC) absorbed a daily average energy of 16.1 kW/m2, while the elliptic cross-section hyperboloid concentrator (EHC) absorbed the highest daily average energy of 28.8 kW/m2

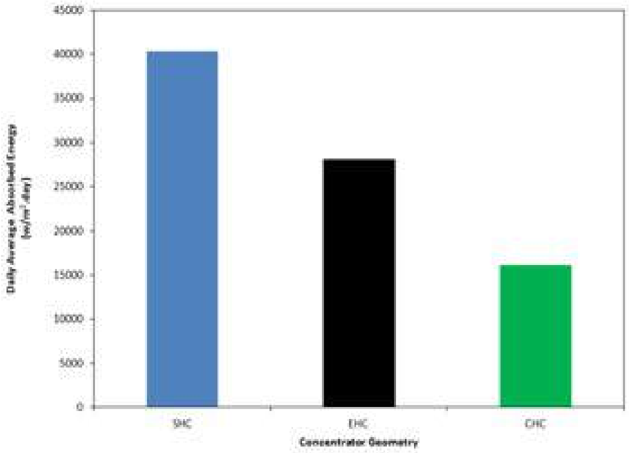


Figure 6. Illustrates the regular average energy captured by the receiver utilizing a hyperboloid geometry profile

Whereas the square cross-section hyperboloid concentrator (SHC) absorbed the highest daily average energy of 40.0 kW/m2. These results, as shown in figure 6, highlight the varying levels of daily energy absorption capability of the different concentrator designs. Furthermore, it provides information on the optical efficiency and acceptance angle for the different concentrators. The data provide valuable insights into the daily energy absorption capabilities and performance characteristics of the parabolic and hyperboloid concentrators with circular, elliptic and square cross-sections. They assist in understanding the comparative efficiency and efficacy of these concentrator designs for various solar energy applications.

7. CONCLUSION

In conclusion, this paper extensively investigated the optical performance of six distinct geometric profiles, namely CCPC, EPC, SPC, CHC, EHC, and SHC. The study revealed that CCPC achieved an optical efficiency of 92% with an acceptance angle of ± 15 degrees, ECPC reached 29% efficiency with an acceptance angle of ± 30 degrees, EHC attained 30% efficiency with an acceptance angle of ± 45 degrees, and CHC obtained 28% efficiency with an acceptance angle of ± 15 degrees. The SHC an optical efficiency of 39% with an acceptance angle of ±30 degrees. It was noted that the daily energy absorption capabilities of the receivers in these concentrators. The (EPC) absorbed an average daily energy of 8.3 kW/m2. In comparison, the (CCPC) absorbed 13.7 kW/m2 daily, and the (SPC) absorbed 12.0 kW/m2 daily. Also, the (CHC) absorbed 16.1 kW/m2 of energy per day, while the (EHC) absorbed the highest average daily energy of 28.8 kW/m2. and the (SHC) has the highest daily energy absorption rate of 40.0 kW/m2. Both studies concluded that Parabolic and hyperbolic concentrators are known for their advantages. Parabolic concentrators can achieve higher optical efficiency at lower acceptance angles non-tracking system due to its moderate optical efficiency with a ± 45-degree acceptance angle.

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