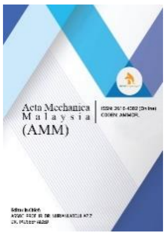
ZIBELINE INTERNATIONAL™ PUBLISHING

ISSN: 2616-4302 (Online)
CODEN: AMMCFL

Acta Mechanica Malaysia (AMM)

DOI: http://doi.org/10.26480/amm.02.2024.183.186



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RESEARCH ARTICLE

TRUNCATION EFFECTS OF OPTICAL PERFORMANCE FOR DIFFERENT SOLAR GEOMETRICAL- CONCENTRATORS

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ARTICLE DETAILS

Article History:

Received 23 September 2024
Revised 18 October 2024
Accepted 28 November 2024
Available online 02 December 2024

ABSTRACT

The height of a solar concentrator significantly influences the performance of a 3-D solar concentrator. Truncated concentrators offer a higher acceptance angle, making them suitable for capturing sunlight from varying sun inclinations. To improve understanding of the geometrical-optical performance of six different concentrators, this paper examines truncation of the aperture may affect optical performance for the top 20% of ideal concentrators. Although using truncated concentrators may result in lower concentration ratios, they compensate with high optical efficiency and exceptional performance across a wide range of solar angle. These configurations include the Elliptical Parabolic Concentrator (EPC), Circular Parabolic Concentrator (CCPC), Square Parabolic Concentrator (SPC), Elliptical Hyperboloid Concentrator (EHC), Circular Hyperboloid Concentrator (CHC), and Square Hyperboloid Concentrator (SHC). This study compares commonly used optical elements with newer concentrator designs based on their optical performance. A detailed analysis utilizing ray tracing techniques identifies key parameters that influence the overall performance of these concentrators. For instance, the CCPC achieves 92% acceptance at ±10º, while the Square Parabolic Concentrator (SPC) accepts approximately 77% at ±15º. The Elliptical Parabolic Concentrator (EPC) reaches about 29% at ±30º. Similarly, for hyperboloid profiles, some light ray's incident on the aperture area of each Circular Hyperboloid Concentrator (CHC) also reach the receiver for incidence angles between ±15º. However, the angular acceptance varies above ±15º due to differences in the reflector surface geometry. For example, the CHC attains 27% acceptance at ±15º, while the Square Hyperboloid Concentrator (SHC) achieves about 39% at the same angle. The Elliptical Hyperboloid Concentrator (EHC) reaches approximately 30% at ±30º.

KEYWORDS

Ray Tracing, hyperboloid concentrator; acceptance angle; optical efficiency.

1. INTRODUCTION

The economic development of countries hinges on the essential need for energy resources to meet the demands of the productive sector. Solar radiation stands out as a promising renewable energy source due to its cleanliness, abundance, and potential for large-scale application. It can effectively address global energy needs while maintaining a low environmental impact (Carter, 2014; Spacek et al., 2016; Chou et al., 2013). The emissions from fossil fuel usage, and rising costs of conventional fuels have prompted the scientific and engineering community to renew its focus on renewable energy options, particularly solar energy. For medium temperature applications (90–300°C), concentrating collectors are more suitable and are currently under investigation. The compound parabolic concentrator (CPC) offers a moderate concentration ratio and requires only occasional intermediate tracking. Notably, 3D CPCs do not necessitate advanced continuous tracking systems. Despite these advantages, research on 3D CPCs remains limited.

2. INTRODUCTION

Obviously, solar trough concentrators are widely utilized in solar energy applications due to their advantageous design, which allows for ease of manufacturing, transportation, and high efficiency. The previous mentioned concentrators come in various shapes tailored to specific purposes, including rectangular troughs, collectors with conical cross-sections (such as parabolic or hyperbolic designs), and dish configurations (Saleh et al., 2013). The hyperbolic concentrator is a significant design that has garnered considerable attention from researchers and designers. The focused on evaluating the optical performance of a 3-D Elliptical Hyperboloid Concentrator (EHC) using the ray-tracing tool Optics-Works. An extensive ray tracing technique was employed to calculate the optical efficiency of this novel 3-D EHC, assessing performance parameters such as optical concentration factor, optical efficiency, and geometric concentration ratio across various aspect ratios of the elliptical profile (Saleh et al., 2014).

The develop, and experimentally analyze a desalination unit utilizing a hyperboloid concentrator paired with a helical copper coil receiver. The elliptic hyperboloid concentrator is specifically designed to capture radiation over a wide range of incident angles, eliminating the need for tracking. Additionally, a CFD analysis was conducted to optimize the dimensions of the helical coil receiver, which was subsequently fabricated (Chittalakkotte et al., 2020). An employed an elliptic hyperboloid concentrator and a helical receiver in conjunction with a multi-tray desalination unit to enhance water purification efficiency. The proposed helical receiver leverages the Dean Flow effect to improve heat transfer in laminar flow. The effectiveness of this approach was analyzed concerning various physical parameters, leading to the suggestion of an optimized

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design based on the findings (Imhamed et al., 2010). Additionally, a hybrid sample with an angular truncation at the front was developed to enhance solar radiation absorption and improve efficiency.

Results indicated only slight changes in optical efficiency with variations in the truncation angle. However, the optical efficiency values were superior to those of designs with smaller concentration ratios, and efficiency increased with the length of the concentrator (Hamza and Hassan, 2022). The study examines the impact of truncation on the solar flux entering the solar receiver of a 30 kWe solar tower power plant, utilizing a three-dimensional compound parabolic concentrator (3D-CPC). The design and sizing of the 3D-CPC were initially carried out using SolidWorks software (Faye et al., 2022). A comprehensive ray tracing simulation was conducted to analyze and compare the ray trace diagrams, angular acceptance, optical efficiency, and energy flux distribution of three types of Compound Parabolic Concentrators (CPCs). The findings revealed that both the angular acceptance and optical efficiency of the three CPCs were identical (100%) for incidence angles between 0º and 15º, but showed significant variations beyond 15º (Paul, 2021).

3. Research Aims and Objectives

This research aims to provide a thorough understanding of the geometrical-optical performance of six distinct concentrator configurations with truncation. By conducting a comparative analysis of these various optical designs, the paper enhances the knowledge of concentrator technology and offers insights for optimizing performance in specific thermal applications. The findings have important implications for the development and enhancement of solar thermal systems that utilize concentrators. Additionally, the paper includes a comprehensive parametric study focused on further improving the overall performance of the truncation concentrators examined.

4. Research Methodology and Techniques

4.1 Research Methodology

Ray tracing techniques used to simulate light behavior as it interacts with different concentrator geometries. Identifies key parameters influencing performance, such as angles of incidence, efficiency and geometrical configurations. Each design has unique strengths in different thermal applications. The analysis reveals which configurations are optimal under various conditions, such as fixed vs. tracking installations implement a ray-tracing algorithm to simulate the interaction of sunlight with the concentrator. This involves calculating reflections based on the angle of incidence and the surface geometry. The analysis will determine how many rays reach the receiver area and the distribution of their intensity. Comparison of designs to Truncated Concentrator of typically has good efficiency due to a wider acceptance angle, however may have slightly lower concentration ratios.

Generally, CCPC profile offers high optical efficiency and concentration ratios due to its dual-axis design, effectively capturing sunlight Parabolic troughs and solar towers also achieve high concentration but may have lower ratios compared to hyperboloids Generally good conversion efficiency for thermal energy to electricity, but efficiency can drop at higher temperatures due to thermal losses. Truncated Hyperboloid Concentrators: The SHE profile provides uniform light distribution and can achieve high optical efficiency. They exhibit excellent thermal efficiency due to effective sunlight focusing, resulting in elevated operating temperatures and improved heat transfer. These concentrators are especially effective in compact designs and can reach very high temperatures (above 400°C), making them ideal for industrial processes. While they may have higher initial costs, their efficiency in suitable locations can lead to lower operational costs over time.

4.2 Research Techniques

Ray tracing techniques has been utilized as well as geometrical optical performance comparisons among the six concentrator-configurations has been under the investigation. Ray tracing analyses have performed for all configurations, maintaining a fixed concentration ratio of 18×. The significance of different cross-sections in ray tracing analysis lies in their impact on the optical performance and efficiency of solar concentrators. In each cross-section type influences the analysis: Light Collection: Elliptic cross-sections are effective at capturing sunlight from a wide range of angles, making them suitable for varying solar positions. Focusing Ability: They can focus light more uniformly at the receiver, which enhances thermal performance. Simplicity in Design: Circular cross-sections are easier to manufacture and align, which can reduce costs. Consistent Performance: They provide consistent optical efficiency across different sun angles but may not capture light as effectively as some other shapes. Efficiency: Square cross-sections can be more space-efficient in certain designs, allowing for compact installations. Uniform Distribution: They can offer a more uniform distribution of concentrated light at the receiver, improving the thermal collection efficiency. The shape influences how light reflects off the surfaces, affecting the overall optical efficiency. Each design can have distinct thermal characteristics that impact heat transfer and operational efficiency. The choice of cross-section is critical in optimizing the design of solar concentrators. By analyzing different geometries through ray tracing, researchers can identify which shapes provide the best performance for specific applications, ultimately leading to more efficient solar energy systems.

5. Geometric Configurations and Module Set-up

5.1 Geometric of Parabolic Profiles

A comparative analysis was performed on two geometric profiles: parabolic and hyperbolic, both of which exhibit symmetry along the vertical axis. Each profile incorporates circular, elliptical, and square apertures, as well as receiver cross-sections. To maintain uniformity in the evaluation of optical performance, the heights of the concentrators, areas of the receivers, and concentration ratios were standardized across all four configurations. The orientation of the incidence angle examined in this study is depicted in Figures 1 and 2. When the radiation source originates from the east (sunrise), the angle is designated as +90°. At noon, when the source radiation is perpendicular to the receiver and the sun reaches its zenith, the incident angle is recorded as 0°. As the source moves westward, the incidence angle varies to ±90. Geometries and Configurations of CCPC, EPC, and SPC are different in theoretical study, in methods of data generation, and in semantic scope.The geometry of the Parabolic Concentrator is illustrated in Figure. 1, which is symmetric with respect to the y-axis.

The interactions of sunlight with the parabolic surfaces of each collector (CCPC, EPC, and SPC) at an incidence angle of 0º are also depicted in Figure 1. However, as the angle of sunlight incidence increases away from perpendicular to the aperture, the effects of the parabolic reflector's geometry become more pronounced. It is evident that the amount of solar radiation energy collected by the receiver depends on the parabolic reflector's design, particularly when the incidence angle exceeds the collector's acceptance angle after sunlight reflections. In practical terms, this indicates that the parabolic profile will generate less electrical energy compared to other hyperboloid profiles. Additionally, the amount of solar radiation energy collected by the receiver is influenced by these geometric factors. It also shows the amount of solar radiation energy collected by the receiver along the major and minor axes, respectively.

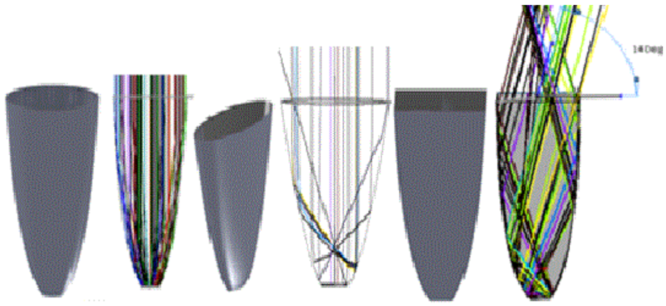

Figure 1: Parabolic profile geometry Concentrator with different cross-sections such as (CCPC, EPC, and SPC) and ray trance at an incidence angle of 0º

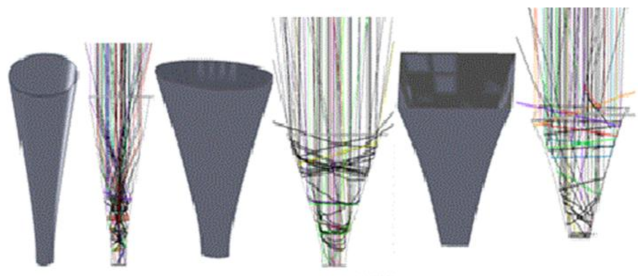

Figure 2: Hyperboloid profile geometry Concentrator with different cross-sections such as (CCHC, EHC, and SHC) and ray trance at Zero Incidence Angle.

6. Analysis of Flux Distribution Across Various Geometric Configurations

6.1 Flux Distribution at the Receiver of Parabolic Profile Concentrators

In figure **3** illustrates the comparison of solar energy concentration across the solar receiver for different cross-sections at the selected incidence angle of 0°. It is clear from these figures that the distribution of solar energy for each cross-section is non-uniform, and the degree of uniformity varies with the reflector surface geometry of the parabolic design and the incidence angle. At each incidence angle, the energy flux concentration across the major and minor axes of the receiver is more uniform for the Square Parabolic Concentrator (SPC) compared to the Elliptical Parabolic Concentrator (EPC) and Circular Parabolic Concentrator (CCPC), as shown in Figure 1. Practically, this suggests that at each incidence angle, the SPC will generate more heat than the EPC or CCPC. Conversely, the CCPC will produce more heat than the EPC only for incidence angles between 0° and 10°, as its energy concentration distribution is lower than that of the EPC. However, beyond 10°, the CCPC loses its advantage over the standard CPC due to high non-uniform energy concentration.

Therefore, if solar radiation uniformity across the solar concentrator's surface is the primary criterion for selecting the best SPC for solar heat generation, the SPC is preferable to both the EPC and CCPC. The analysis of flux distributions on the receiver area has been conducted for different geometric shapes and cross-sections. In figure 3, the flux distribution for parabolic profile concentrators with circular, elliptical, and square cross-sections is presented. The parabolic concentrators produce significantly high flux values concentrated over a small area, whereas the elliptical concentrators exhibit lower flux values spread over a larger area. Additionally, the minor axes at a concentrator height of 0.8 m for the three parabolic surfaces of each collector at an incidence angle of 0º are also shown in Figure 3. As the EPC increases irradiance from 907 to 5290 (W/m^2) at the receiver is observed.

However, beyond an CCPC and SPC, there are a noted increase in irradiance at the receiver a bout 16600 (W/m^2). In addition, Figure 3 presents 3-D flux distributions, the flux distribution across one plane, and the results of ray tracing for the three receivers associated with the connector. In figure 4 illustrates that the flux distribution for SPC, CCPC, and EPC is more dispersed throughout the elliptical receiver area, with the highest concentration occurring at the intersection of the major and minor axes.

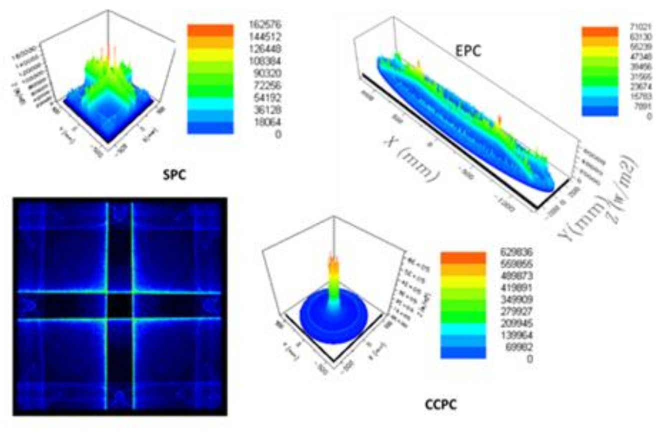

Figure 3: Flux Distribution of Parabolic Profile Concentrator for (SPC, EPC, CCPC)

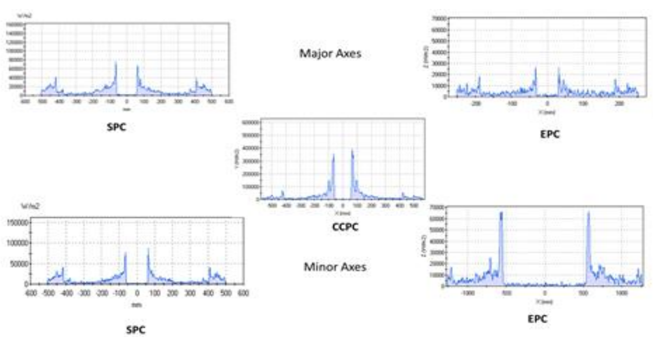

Figure 4: The Flux Distribution for SPC, CCPC & EPC

6.2 Receiver Flux Distribution for Hyperboloid Profile Concentrators

The ray tracing analysis involved an examination of energy flux distributions along both the major and minor axes of the receiver, focusing on three distinct geometrical configurations: CHC, EHC, and SHC. A normal flux value of 1000 W/m^2 was used for the simulation. The variations in flux distributions along the receiver's major. The flux distribution for hyperboloid profile concentrators with circular and elliptical cross-sections is shown in Figure 5. The circular hyperboloid concentrator (CHC) achieved a maximum flux value of 4840 W/m^2, while the elliptical hyperboloid concentrator (EHC) recorded a maximum of 5350 W/m^2. and square hyperboloid concentrator (EHC) recorded a maximum of 1950 W/m^2. As seen in figure 5, the peak flux is concentrated at the center of the CHC receiver area. In figure 6 shows that the flux distribution for the EHC and SHC are more scattered across the elliptical and square receivers' area, with the peak occurring at the intersection of the major and minor axes.

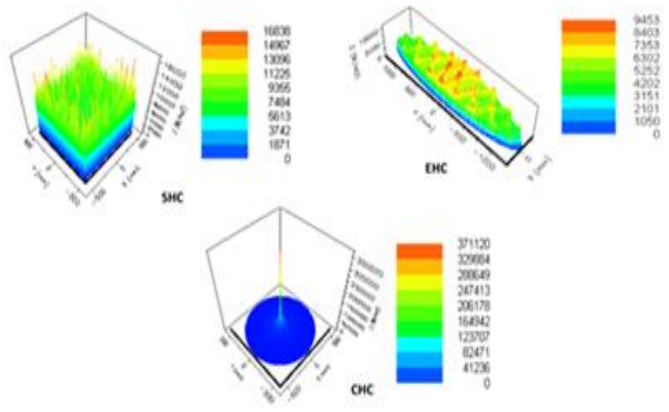

Figure 5: Flux Distribution of Hyperboloid Profile Concentrator for (SHC, EHC & CHC)

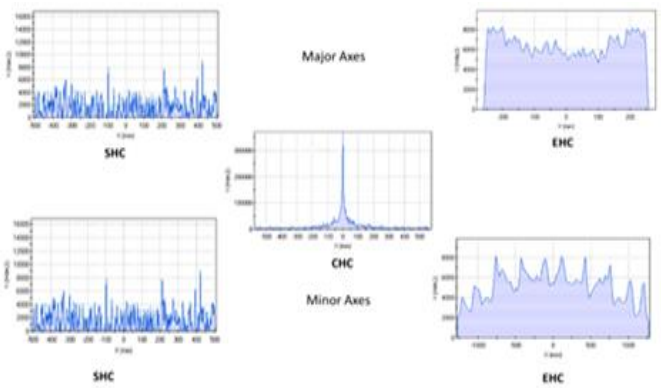

Figure 6: Variation of Flux Distribution for (CHC, SHC & EPC) Along the Receiver

6.3 Effect of Truncation on Optical Efficiency

To determine the influence of truncation on optical efficiency, the height of both the parabolic and hyperboloid concentrators was reduced by 20% of their original dimensions. This reduction in height resulted in a concentration ratio of 18×. Details the effect of this truncation on the optical efficiency and acceptance angle for both types of concentrators Truncation can help reduce the amount of concentrator material while maintaining desired output levels.

6.3.1 Optical efficiency for profile is parabolic

In figure 7 illustrates the variation in optical efficiency different cross-sections when the profile is parabolic. The configurations examined include the Elliptical Parabolic Concentrator (EPC), Circular Parabolic Concentrator (CCPC), and Square Parabolic Concentrator (SPC). Each figure compares the optical efficiency for various acceptance angles. For incidence angles between ±15º, the Circular Parabolic Concentrator (CCPC) achieves an optical efficiency of approximately 92%. In contrast, the Elliptical Parabolic Concentrator (EPC) demonstrates a wider range of solar angles, from 0º to 30º, with an efficiency of about 26%. The Square Parabolic Concentrator (SPC) has an optical efficiency of around 80% for angles between ±15º, with a total length of only about 800 mm.

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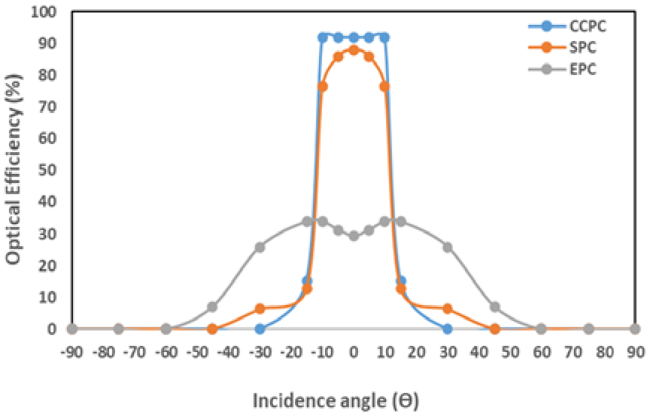

Figure 7: Efficiency of Optical Performance in the Parabolic Concentrator with Circular, Square, and Elliptical Cross Sections

The variation in optical efficiency with solar incidence angle as the source moves along the major axe of the aperture for 20 percentages of concentrator height truncation. As the truncation percentage increases, optical efficiency improves, while the concentration ratio declines. The corresponding decrease in concentration ratio is also depicted in the figure. At a 20% truncation of the concentrator height. Figure 8 illustrates the variation in optical efficiency for different cross-sections with a hyperboloid profile. The configurations analysed include the Elliptical Hyperboloid Concentrator (EHC), Circular Hyperboloid Concentrator (CHC), and Square Hyperboloid Concentrator (SHC). To compares the optical efficiency across various acceptance angles. For incidence angles between ±15º, the Circular Hyperboloid Concentrator (CHC) achieves an optical efficiency of approximately 26%. In contrast, the Elliptical Hyperboloid Concentrator (EHC) offers a wider range of solar angles, from ± 30º, with an efficiency of about 30%. The Square Hyperboloid Concentrator (SHC) has an optical efficiency of around 39% for angles between ± 30º, with a total length of only about 800 mm.

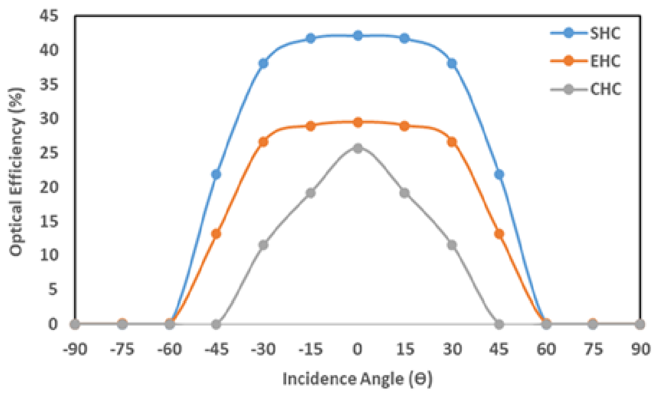

Figure 8: Efficiency of Optical Performance in the Hyperboloid Concentrator with Circular, Square and Elliptic Cross Section

7. Conclusion

The study found that the angular acceptance and optical efficiency of the CCPC and SPC concentrators were nearly the same (92%) and (80%) for incidence angles between ±10º and ±15º receptively, while the EPC accepted only about 26% at the angle ±30º. Additionally, beyond ±15º, the optical efficiency of both CCPC and SPC was lower than that of the EPC due to variations in reflector surface geometry, which resulted in the rejection of some light rays. In contrast, solar radiation intensity on the solar receiver was more uniform for the SPC compared to the CCPC and EPC. Regarding annual solar radiation accumulation, results indicated that both the CCPC and SPC collected approximately the same amount of energy (16,600 W/m^2). The EHC exhibited a higher optical efficiency of 30% for an acceptance angle of ±30°, in contrast to the CHC, which recorded a lower efficiency of 26% with a narrower acceptance angle of ±15° where Hyperboloid Concentrator (SHC) has an optical efficiency of around 39% for angles between ± 30º, with a total length of only about 800 mm It is evident that parabolic and hyperboloid concentrators have distinct advantages over other geometries. Parabolic concentrators show higher optical efficiencies at lower acceptance angles, making them suitable for use with tracking devices. On the other hand, hyperboloid concentrators, with their lower optical efficiency at wider acceptance angles, are more appropriate for non-tracking systems. Notably, the EHC and SHC, with its broader acceptance angle, demonstrated superior optical efficiency compared to the other configurations.

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