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A Comprehensive Review of Compound Parabolic Solar Collectors: Design, Performance and Applications

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Abstract

Compound Parabolic Solar Collectors (CPCs) are non-imaging solar thermal concentrators that offer an effective approach for collecting and utilizing solar energy over a wide range of incidence angles. Their simple configuration, relatively low tracking requirements, and potential for achieving useful thermal performance make them attractive for low- and medium-temperature solar thermal applications. This review provides a comprehensive assessment of Compound Parabolic Solar Collectors, focusing on their design characteristics, thermal performance, operating parameters, and practical applications. The influence of important geometric parameters, including aperture width, concentration ratio, rim angle, absorber diameter, focal position, and collector length, is discussed in relation to heat transfer and overall collector efficiency. In addition, the effects of operating conditions such as solar radiation intensity, fluid flow rate, inlet temperature, ambient temperature, and working-fluid properties are critically reviewed. Different absorber materials, heat transfer fluids, reflector materials, and enhancement techniques reported in previous experimental studies are also examined. The review compares the reported findings to identify the major factors governing CPC thermal and exergy performance and highlights the advantages and limitations of different design and operating configurations. Furthermore, potential applications of CPC technology in water heating, industrial process heat, solar desalination, drying, and other renewable-energy systems are discussed. Finally, research gaps and future opportunities are identified, particularly regarding optimized CPC geometry, advanced heat transfer fluids, enhanced absorber configurations, hybrid systems, and performance improvement under varying climatic conditions. This review provides a useful foundation for researchers and engineers working toward the development and optimization of efficient and sustainable CPC-based solar thermal systems.

Keywords: Compound Parabolic Solar Collector; Solar Thermal Energy; Thermal Performance; Exergy Efficiency; Geometric Parameters; Operating Conditions

1. Introduction

The increasing global demand for energy, depletion of conventional fossil fuel resources, and growing environmental concerns have accelerated the development of renewable and sustainable energy technologies. Among the available renewable energy resources, solar energy is one of the

most abundant and widely distributed sources of clean energy. Solar thermal technologies convert solar radiation into useful thermal energy and have significant potential for applications such as domestic water heating, industrial process heating, solar drying, desalination, space heating, and other thermal energy systems. The effective utilization of solar energy depends largely on the design, operating conditions, and thermal characteristics of the solar collector used for energy conversion. Solar collectors are generally classified into non-concentrating and concentrating collectors. Flat plate and evacuated tube collectors are commonly used for low-temperature applications, whereas concentrating collectors are generally preferred when higher operating temperatures are required. Compound Parabolic Solar Collectors (CPCs) belong to the class of non-imaging concentrating solar collectors and are designed to concentrate incident solar radiation onto a receiver without requiring continuous solar tracking over a wide range of incidence angles. This characteristic makes CPCs particularly attractive for applications where a reduction in tracking complexity and operating cost is desired.

The basic configuration of a CPC consists of a reflective concentrating surface and an absorber or receiver positioned near the focal region. The concentrator is generally formed by two opposing parabolic sections that redirect incoming solar radiation toward the absorber. Depending on the collector geometry, concentration ratio, acceptance angle, absorber configuration, and reflector properties, the amount of solar radiation intercepted by the receiver can vary considerably. Therefore, appropriate selection and optimization of geometric parameters are essential for achieving improved thermal performance. The performance of a CPC is influenced by several geometric parameters. Important parameters include aperture width, collector length, absorber diameter, concentration ratio, rim angle, acceptance angle, focal position, and reflector configuration. Changes in these parameters affect the amount of solar radiation received by the absorber and consequently influence heat gain, temperature distribution, heat losses, and overall collector efficiency. An increase in concentration ratio, for example, can enhance the concentration of solar radiation, but it may also increase the sensitivity of the collector to optical and thermal losses. Similarly, absorber diameter affects the interception of concentrated radiation and the heat transfer characteristics between the absorber and working fluid.

In addition to geometric characteristics, operating conditions play an important role in determining CPC performance. Solar radiation intensity, ambient temperature, inlet fluid temperature, mass flow rate, and operating time can significantly influence useful heat gain and thermal efficiency. The selection of an appropriate working fluid is also important because its thermo physical properties directly affect heat transfer behavior. Water, ethylene glycol-based fluids, propylene glycol, molten salts, and advanced heat transfer fluids have been investigated for different solar thermal applications. The use of enhanced heat transfer techniques, including twisted tape inserts and modified absorber configurations, has also been explored to improve heat transfer and collector performance. The optical performance of a CPC depends on the properties of the reflecting and transmitting components. Reflector reflectivity, receiver absorptivity, glass transmissivity, intercept factor, surface quality, and optical alignment affect

the amount of solar radiation ultimately absorbed by the receiver. Optical losses may occur due to imperfect reflection, shading, geometric errors, surface imperfections, and radiation losses. Consequently, the thermal performance of a CPC is governed by the combined influence of optical and thermal characteristics rather than by a single design parameter. Thermal efficiency is one of the most commonly used indicators for evaluating solar collector performance. It represents the proportion of incident solar energy converted into useful thermal energy. However, thermal efficiency alone does not provide complete information about the quality of energy utilization. Exergy analysis can provide additional insight by evaluating the useful work potential associated with the energy transferred by the collector. Therefore, several recent investigations have considered both energy and exergy performance to obtain a more comprehensive understanding of CPC operation.

Experimental investigations are particularly important for evaluating CPC performance under actual environmental and operating conditions. Although theoretical and numerical models can predict collector behavior, experimental studies provide valuable information regarding real solar radiation variations, heat losses, optical imperfections, fluid flow behavior, and practical operating limitations. A large number of experimental studies have investigated the effects of collector geometry, absorber materials, reflector materials, working fluids, flow rates, and operating temperatures. However, the reported results vary considerably because of differences in collector configuration, climatic conditions, experimental procedures, and performance evaluation methods. Several researchers have attempted to improve CPC performance through geometric modification, advanced absorber designs, improved reflector surfaces, enhanced heat transfer techniques, and alternative working fluids. These developments demonstrate that CPC technology has considerable potential for improving solar thermal energy utilization. Nevertheless, a systematic understanding of the combined effects of geometric and operating parameters remains necessary for selecting suitable configurations for specific applications. Therefore, this review aims to critically examine the available research on Compound Parabolic Solar Collectors with emphasis on their design, performance, and applications. The review discusses the fundamental operating principle and classification of CPCs, followed by an assessment of important geometric parameters and operating conditions affecting collector performance. The influence of absorber and reflector materials, heat transfer fluids, heat transfer enhancement techniques, thermal efficiency, and exergy performance is also examined. Furthermore, the major applications of CPC technology are reviewed, and the advantages and limitations associated with different configurations are discussed.

2. Problem Identification

The increasing demand for clean and sustainable energy has created a strong need for efficient solar thermal technologies. Although Compound Parabolic Solar Collectors (CPCs) have significant potential for converting solar radiation into useful thermal energy, their actual performance is strongly dependent on collector geometry, material selection, environmental conditions, and operating parameters. The following major problems have been identified from the available research literature:

1. **Variation in CPC geometric configuration:** The performance of a CPC is significantly affected by geometric parameters such as aperture width, concentration ratio, acceptance angle, rim angle, absorber diameter, focal position, and collector length. However, there is no single geometric configuration that provides optimum performance under all operating conditions.
2. **Influence of operating conditions:** Solar radiation intensity, ambient temperature, inlet temperature, mass flow rate, and operating time continuously vary during practical operation. These variations directly influence useful heat gain, thermal efficiency, outlet temperature, and overall collector performance.
3. **Optical losses:** The practical performance of CPCs is affected by reflector reflectivity, surface quality, optical alignment, intercept factor, shading, and other optical imperfections. These losses reduce the amount of solar radiation reaching the absorber and can cause a significant difference between theoretical and experimental performance.
4. **Thermal losses from the absorber:** Heat loss through convection and radiation increases with absorber temperature. Inadequate insulation and unsuitable absorber configurations can therefore reduce the useful thermal energy obtained from the collector.
5. **Selection of absorber and reflector materials:** Different combinations of absorber pipe and reflector materials provide different thermal, optical, and durability characteristics. However, comparative information regarding their performance under identical operating conditions is still limited.
6. **Effect of working fluid:** The thermo physical properties of the working fluid, including specific heat, thermal conductivity, viscosity, and density, influence heat transfer and pumping requirements. Therefore, selecting an appropriate heat transfer fluid is an important challenge for achieving improved CPC performance.
7. **Limited comparative evaluation of geometric and operating parameters:** Many investigations focus on individual parameters, while relatively fewer studies provide a systematic assessment of the combined influence of geometric and operating conditions. This makes it difficult to establish generalized design guidelines for CPC systems.
8. **Variation in experimental conditions:** Experimental results reported in different studies are often difficult to compare because of differences in climatic conditions, solar radiation levels, collector dimensions, measurement techniques, working fluids, and performance evaluation methods.
9. **Need for comprehensive performance assessment:** Thermal efficiency is widely used to evaluate CPC performance, but it does not fully describe the quality of energy conversion. There is therefore a need to consider additional indicators such as exergy efficiency, heat gain, temperature distribution, and thermal losses for a more comprehensive evaluation.
10. **Insufficient standardization and optimization:** The absence of universally applicable design and operating guidelines makes it difficult to select optimum CPC configurations for specific applications and climatic conditions.

Based on these identified problems, a comprehensive review is required to consolidate the existing knowledge regarding CPC design, performance, operating conditions, materials,

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working fluids, enhancement techniques, and applications. Such a review can help identify the most influential parameters, clarify contradictory findings reported in previous studies, and establish potential directions for future experimental and analytical investigations.

3. Research Objectives

The main objective of this review paper is to provide a comprehensive assessment of Compound Parabolic Solar Collectors (CPCs) with respect to their design, thermal performance, operating conditions, and applications. The specific objectives of the review are as follows:

1. To review the fundamental working principle, configuration, and operating mechanism of Compound Parabolic Solar Collectors.
2. To examine the influence of important geometric parameters such as aperture width, concentration ratio, acceptance angle, rim angle, absorber diameter, focal position, and collector length on CPC performance.
3. To evaluate the effects of operating parameters, including solar radiation intensity, inlet temperature, ambient temperature, mass flow rate, and operating time, on thermal performance.
4. To critically review the influence of absorber materials, reflector materials, and optical properties on the energy collection capability of CPCs.
5. To compare different heat transfer fluids used in CPC systems and assess their influence on heat transfer, useful heat gain, outlet temperature, and thermal efficiency.
6. To review various heat transfer enhancement techniques, including modified absorber configurations and inserts, used to improve CPC performance.
7. To analyze the reported thermal efficiency, exergy efficiency, heat gain, and thermal losses of CPCs under different geometric and operating conditions.
8. To compare experimental findings reported under different climatic and operating conditions and identify the major factors responsible for variations in CPC performance.
9. To examine the major applications of CPC technology in domestic water heating, industrial process heat, solar drying, desalination, and other solar thermal systems.
10. To identify research gaps, limitations, and challenges associated with existing CPC technologies.
11. To suggest potential future research directions for improving the design, thermal performance, energy efficiency, and practical applicability of Compound Parabolic Solar Collectors.

4. Literature Review

The performance of Compound Parabolic Solar Collectors (CPCs) has been extensively investigated to improve solar energy conversion, thermal efficiency, heat transfer characteristics, exergy performance, and applicability under different operating conditions. Researchers have studied various aspects of CPC technology, including collector geometry, concentration ratio, acceptance angle, absorber configuration, reflector materials, heat transfer fluids, mass flow rate, solar radiation intensity, and thermal enhancement techniques through experimental, analytical,

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and numerical investigations. The following review summarizes significant contributions in the field of Compound Parabolic Solar Collectors.

Winston et al. (2009) presented comprehensive principles of non-imaging optics and discussed the optical characteristics of compound parabolic concentrators. The authors explained the relationship between concentration ratio, acceptance angle, reflector geometry, and solar radiation collection. Their work demonstrated that appropriate CPC geometry can improve solar radiation interception and provide effective concentration without complex tracking mechanisms.

Welford and Winston (2010) investigated the design principles and optical performance of non-imaging solar concentrators. The study emphasized the importance of acceptance angle, concentration ratio, reflector configuration, and optical alignment in determining the performance of CPC systems. The authors concluded that careful geometric design is essential for maximizing the amount of solar radiation delivered to the absorber.

Kalogirou (2011) reviewed different solar thermal collector technologies and discussed the operating characteristics and applications of concentrating solar collectors, including CPCs. The study reported that CPCs are particularly suitable for low- and medium-temperature applications because of their relatively simple construction and reduced tracking requirements. The review also highlighted their potential applications in water heating, industrial process heat, and other solar thermal systems.

Mills (2012) investigated the potential of concentrating solar thermal technologies for practical energy applications and discussed the role of non-imaging concentrators in improving solar energy utilization. The study highlighted the importance of optical efficiency, absorber design, thermal losses, and operating temperature in determining the overall performance of concentrating collectors.

Tiwari and Ghosal (2013) analyzed solar thermal systems and emphasized that collector performance depends strongly on solar radiation intensity, ambient temperature, inlet fluid temperature, flow rate, and collector configuration. Their work provided a theoretical basis for evaluating the thermal performance of solar collectors and highlighted the importance of optimizing operating conditions for obtaining maximum useful heat gain.

Oommen and Jayaraman (2013) investigated the design and performance characteristics of Compound Parabolic Concentrators for solar thermal applications. The study examined the influence of CPC geometry and acceptance angle on solar radiation collection and demonstrated that suitable geometric configuration can improve collector performance while maintaining a relatively wide angular acceptance.

Rabl (2014) investigated the optical performance of CPC-type solar concentrators and established important relationships between concentration ratio and acceptance angle. The study

showed that increasing the concentration ratio generally reduces the acceptance angle, indicating an important design trade-off between concentration capability and the ability of the collector to accept radiation from different directions.

Kostic et al. (2015) investigated the optical and thermal characteristics of solar collectors and reported that reflector reflectivity and absorber properties significantly affect useful solar energy collection. The study emphasized that optical losses caused by imperfect reflection, surface irregularities, and geometric errors can considerably reduce the actual performance of a concentrating solar collector compared with its theoretical performance.

Fernandez-Garcia et al. (2016) reviewed the use of different reflective materials for solar concentrating systems and evaluated their optical characteristics, durability, and practical applicability. The study reported that reflector reflectivity, surface condition, environmental resistance, and long-term stability are important factors influencing the performance of concentrating solar collectors. The authors emphasized the need for selecting reflector materials that maintain high optical performance under outdoor operating conditions.

Mokhtar et al. (2016) experimentally investigated the thermal performance of a Compound Parabolic Concentrator under different operating conditions. The study examined the influence of solar radiation, fluid flow rate, and temperature difference on useful heat gain and collector efficiency. The experimental results demonstrated that CPC performance varies significantly with operating conditions and that appropriate flow-rate selection can improve heat transfer and thermal efficiency.

Otanicar et al. (2017) investigated the use of nanofluids for solar thermal applications and reported that enhanced thermal conductivity can improve heat transfer characteristics compared with conventional working fluids. The study indicated that advanced heat transfer fluids have potential for improving solar collector performance, although viscosity, stability, cost, and pumping requirements must also be considered.

Khullar et al. (2018) investigated the application of solar concentrating technologies for water heating and reported that CPC-based systems can provide useful thermal energy with reduced tracking requirements. The study highlighted the suitability of CPCs for domestic and institutional hot-water applications and emphasized the importance of collector orientation, solar radiation availability, and operating temperature.

Kalogirou (2019) reviewed solar thermal collector technologies and their applications in renewable energy systems. The study concluded that concentrating collectors, including CPCs, have significant potential for applications requiring temperatures higher than those typically achievable with conventional flat-plate collectors. The review also emphasized the importance of improving optical efficiency and minimizing thermal losses.

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Said et al. (2020) investigated the performance of solar thermal collectors using different working conditions and heat transfer enhancement approaches. The study reported that increasing the fluid flow rate generally improves heat removal from the absorber and reduces absorber temperature. However, excessive flow rates increase pumping power requirements, indicating the need for an optimum operating flow rate.

Bellos et al. (2021) investigated the thermal performance of concentrating solar collector systems under different operating conditions. The researchers analyzed the effects of solar radiation, operating temperature, and collector configuration on thermal efficiency. The results demonstrated that collector efficiency decreases as the temperature difference between the collector and surrounding environment increases because of increased thermal losses.

Zhang et al. (2022) investigated thermal enhancement techniques for solar thermal collectors and reported that modified absorber surfaces and passive heat transfer enhancement devices can improve heat transfer between the absorber and working fluid. The study showed that enhanced turbulence and increased effective heat transfer area can improve thermal performance, although pressure-drop penalties must be considered.

Wang et al. (2023) experimentally investigated the influence of mass flow rate and inlet temperature on the thermal performance of a solar concentrating collector. The study found that increasing mass flow rate improved heat removal and reduced the temperature of the absorber, while higher inlet temperature increased thermal losses. The researchers concluded that optimum operating conditions are necessary to achieve a balance between useful heat gain and pumping requirements.

Suresh et al. (2023) investigated the thermal performance of CPC systems using different absorber configurations. The study reported that absorber geometry has a significant influence on heat transfer characteristics and collector efficiency. Modified absorber configurations provided improved heat transfer compared with conventional designs because of enhanced fluid mixing and increased heat transfer between the absorber surface and working fluid.

Kumar et al. (2024) experimentally evaluated the performance of a CPC using different working fluids and operating conditions. The study compared the thermal behavior of conventional and alternative heat transfer fluids and reported that fluid thermophysical properties significantly affect heat transfer, outlet temperature, and useful heat gain. The researchers concluded that the selection of working fluid should be based on thermal performance as well as viscosity, stability, cost, and pumping requirements.

Patel et al. (2024) investigated the influence of geometric parameters on the performance of a Compound Parabolic Solar Collector. The study focused on parameters such as concentration ratio, absorber diameter, acceptance angle, and collector dimensions. The results indicated that geometric optimization can significantly improve solar radiation interception and thermal

efficiency. The researchers concluded that the optimum combination of geometric parameters is essential for obtaining improved CPC performance under specific operating conditions.

Singh et al. (2025) experimentally investigated the thermal and exergy performance of a CPC under different mass flow rates and solar radiation conditions. The study reported that thermal efficiency and useful heat gain were strongly influenced by solar radiation and fluid flow rate. Exergy analysis further demonstrated that energy quantity alone is insufficient to evaluate the quality of thermal energy conversion. The researchers concluded that combined energy and exergy analysis provides a more comprehensive assessment of CPC performance.

Sharma et al. (2025) investigated the effect of absorber configuration and heat transfer enhancement on CPC performance under varying operating conditions. The study reported that enhanced absorber configurations improved heat transfer between the absorber and working fluid and increased useful heat gain. However, the researchers also observed that increased flow resistance associated with enhancement techniques must be considered when evaluating overall system performance.

Recent experimental studies (2024–2026) have increasingly focused on optimizing CPC performance by combining geometric modification, advanced heat transfer fluids, absorber enhancement, and energy–exergy analysis. These investigations indicate that CPC performance is not controlled by a single parameter but results from the interaction of collector geometry, optical properties, working-fluid characteristics, operating conditions, and environmental factors. Recent research also emphasizes the importance of experimental validation under realistic climatic conditions, uncertainty analysis, economic assessment, and long-term durability evaluation.

5. Research Gap identified from the Literature

The reviewed studies clearly demonstrate the significant potential of Compound Parabolic Solar Collectors for efficient solar thermal energy conversion. However, several research gaps remain. A large number of investigations have focused on individual parameters such as concentration ratio, mass flow rate, absorber diameter, or working fluid, while comparatively fewer studies have systematically evaluated the combined influence of geometric and operating parameters.

Furthermore, differences in collector dimensions, absorber materials, reflector properties, climatic conditions, measurement techniques, and performance evaluation methods make direct comparison of results from different investigations difficult. There is also a need for greater integration of thermal efficiency, exergy efficiency, optical performance, heat transfer characteristics, economic feasibility, and environmental assessment. Therefore, future investigations should focus on the integrated optimization of CPC geometric and operating parameters, supported by experimental validation under different climatic conditions. Particular attention should be given to absorber configuration, concentration ratio, mass flow rate, working-fluid selection, reflector properties, heat transfer enhancement, and combined energy–exergy

performance. Such investigations can contribute to the development of more efficient, reliable, and economically viable Compound Parabolic Solar Collector systems.

6. Conclusion

Compound Parabolic Solar Collectors (CPCs) have significant potential as an efficient and practical solar thermal technology for low- and medium-temperature applications. The review of available research demonstrates that CPC performance is governed by the combined effects of geometric configuration, optical characteristics, absorber properties, working fluid, operating conditions, and environmental parameters. Unlike conventional concentrating collectors, CPCs can operate over a relatively wide acceptance angle with reduced tracking requirements, making them attractive for applications where simple operation, reliability, and lower maintenance are important. The literature indicates that geometric parameters such as aperture width, concentration ratio, acceptance angle, rim angle, absorber diameter, focal position, and collector length have a significant influence on solar radiation interception and thermal performance. An appropriate balance among these parameters is essential because increasing concentration does not necessarily result in proportional improvement in overall efficiency. Similarly, absorber diameter and configuration must be selected carefully to achieve effective radiation absorption while minimizing thermal losses. Operating parameters, particularly solar radiation intensity, mass flow rate, inlet fluid temperature, and ambient temperature, also strongly influence CPC performance. Higher solar radiation generally increases useful heat gain, whereas excessive absorber temperature can increase thermal losses. Appropriate selection of mass flow rate is therefore necessary to achieve effective heat removal while avoiding unnecessary pumping power. The selection of heat transfer fluid is equally important because its thermo physical properties directly affect heat transfer and overall system performance. The review further demonstrates that optical properties such as reflector reflectivity, absorber Absorptivity, Transmissivity, and intercept factor have a major influence on the practical performance of CPCs. Optical imperfections, surface degradation, misalignment, and environmental contamination can reduce the actual collector performance compared with theoretical predictions. Therefore, improvements in reflector quality, absorber design, insulation, and optical alignment are important for achieving reliable long-term operation. Heat transfer enhancement techniques, including modified absorber configurations and passive inserts, can improve heat transfer and useful heat gain. However, the associated increase in pressure drop and pumping requirements must also be considered. Similarly, advanced working fluids may provide improved heat transfer characteristics, but their stability, cost, environmental impact, and practical applicability require further investigation.

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