

Experimental Investigation of Compound Parabolic Solar Collector Performance under Different Geometric and Operating Conditions

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Abstract

The aim of this research is to experimentally investigate and optimize the performance of a Compound Parabolic Solar Collector (CPSC) under different geometric and operating conditions. An experimental CPSC setup was fabricated using three concentrator materials, namely mirror, aluminium sheet, and acrylic polymer sheet. Experiments were conducted at 12 PM, 1 PM, 2 PM, 3 PM, and 4 PM to evaluate their performance. Different receiver pipe materials, including copper, mild steel, and stainless steel, were also investigated using water, propylene glycol, and molten salt as working fluids. The analysis focused on important performance parameters such as exergy efficiency, instantaneous efficiency, heat transfer rate, and temperature difference. The experimental results showed that the aluminium collector with a copper pipe and water achieved the highest exergy efficiency of 61.89% at 2 PM. The highest instantaneous efficiency of 79.2% was obtained with the acrylic polymer collector using a copper pipe and propylene glycol at 12 PM. The highest heat transfer rate of 1144.07 W was recorded for the mirror collector with a copper-water combination ($D_i = 26$ mm, $D_o = 30$ mm) at 2 PM. The maximum temperature difference of 15°C was obtained with the acrylic polymer collector using a copper pipe and propylene glycol ($D_i = 24$ mm, $D_o = 28$ mm) at 3 PM. The results demonstrate that the selection of collector material, receiver pipe material, working fluid, and operating conditions significantly influences the performance of the CPSC.

Keywords: CPSC; 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 encouraged the development of renewable and sustainable energy technologies. Among the available renewable energy resources, solar energy is one of the most abundant and environmentally friendly sources of energy. Solar thermal systems provide an effective method of converting solar radiation into useful thermal energy for applications such as water heating, industrial process heating, solar drying, desalination, space heating, and other thermal energy requirements. The efficiency of solar thermal systems depends strongly on the collector configuration, operating conditions, heat transfer characteristics, and availability of solar radiation. Compound Parabolic Solar Collectors (CPCs) are non-imaging concentrating

solar collectors that have attracted considerable attention because of their ability to concentrate solar radiation over a relatively wide acceptance angle. Unlike conventional parabolic trough collectors, CPCs can operate with reduced or intermittent tracking requirements. Their relatively simple construction, compact configuration, and capability of collecting both direct and, to some extent, diffuse radiation make them suitable for low- and medium-temperature solar thermal applications.

A typical CPC consists of two opposing parabolic reflecting surfaces and an absorber located near the focal region. The reflecting surfaces redirect incident solar radiation toward the absorber, where the radiation is converted into thermal energy. The useful heat is then transferred to a working fluid flowing through the absorber. The performance of the collector is therefore dependent on the optical characteristics of the reflector, the geometry of the concentrator, absorber properties, heat transfer characteristics, and operating conditions.

The geometric configuration of a CPC plays an important role in determining its solar energy collection capability. Important geometric parameters include aperture width, collector length, absorber diameter, concentration ratio, acceptance angle, rim angle, focal position, and absorber-to-reflector arrangement. Any variation in these parameters can affect the amount of radiation intercepted by the absorber, heat transfer area, thermal losses, and overall collector efficiency. Therefore, appropriate selection of geometric parameters is essential for obtaining optimum performance. The concentration ratio is one of the most important parameters affecting CPC performance. It represents the ratio of the collector aperture area to the absorber area. A higher concentration ratio can increase the intensity of solar radiation incident on the absorber and potentially increase the useful heat gain. However, a high concentration ratio may also result in a smaller acceptance angle and increased sensitivity to optical alignment and manufacturing accuracy. Consequently, an optimum concentration ratio must be selected according to the intended operating conditions and application. The absorber diameter also has a significant influence on collector performance. A larger absorber diameter can intercept a greater proportion of concentrated radiation and provide a larger heat transfer surface. However, the larger absorber surface can also increase thermal losses to the surrounding environment. On the other hand, a smaller absorber may reduce thermal losses but can increase optical interception losses if the concentrated radiation does not completely fall on the absorber. Thus, the absorber diameter should be selected carefully to achieve a suitable balance between optical collection and thermal performance. In addition to geometric parameters, operating conditions significantly influence the performance of CPCs. Solar radiation intensity varies with time, weather conditions, atmospheric conditions, season, and geographical location. The useful heat gain and thermal efficiency of the collector are directly affected by the available solar radiation. Similarly, inlet fluid temperature, mass flow rate, ambient temperature, and operating duration influence the temperature difference between the absorber and surroundings and consequently affect thermal losses.

The mass flow rate of the working fluid is particularly important in experimental CPC investigations. Increasing the flow rate generally improves heat removal from the absorber and can reduce the absorber temperature. However, an excessive flow rate may increase pumping power requirements and may not provide a proportional increase in useful thermal energy. Therefore, an optimum mass flow rate is required for achieving an appropriate balance between heat transfer enhancement and energy consumption. The selection of the working fluid is another important factor affecting CPC performance. Water is widely used because of its high specific heat, availability, low cost, and favorable heat transfer properties. Other fluids such as ethylene glycol, propylene glycol, molten salts, and advanced heat transfer fluids may also be considered for specific temperature ranges and applications. The thermal conductivity, specific heat, viscosity, density, and thermal stability of the working fluid directly influence heat transfer characteristics and collector performance.

The optical performance of a CPC is determined by parameters such as reflector reflectivity, absorber Absorptivity, glass Transmissivity, intercept factor, and optical alignment. In practical systems, a portion of the incident solar radiation is lost because of imperfect reflection, surface irregularities, shading, misalignment, dust accumulation, and manufacturing imperfections. These optical losses reduce the actual energy delivered to the absorber. Therefore, proper reflector selection and accurate collector fabrication are essential for achieving improved experimental performance. Thermal losses are another important factor limiting CPC efficiency. Heat is lost from the absorber through convection, conduction, and radiation. As the absorber temperature increases, thermal losses generally increase, which can reduce the useful heat transferred to the working fluid. Proper insulation, suitable absorber materials, selective coatings, and optimized operating conditions can help minimize these losses and improve thermal performance.

Experimental investigation is essential for understanding the actual behavior of CPC systems under practical operating conditions. Although theoretical and numerical models can provide useful predictions, experimental studies account for real environmental variations, optical imperfections, heat losses, fluid-flow characteristics, and measurement uncertainties. Experimental evaluation also provides important information for validating theoretical models and determining suitable geometric and operating conditions. The evaluation of CPC performance is commonly based on useful heat gain and thermal efficiency. Useful heat gain represents the thermal energy transferred to the working fluid, while thermal efficiency indicates the fraction of incident solar energy converted into useful thermal energy. In addition to thermal efficiency, exergy efficiency can be used to evaluate the quality of energy conversion and identify thermodynamic losses within the system. A combined energy and exergy assessment provides a more comprehensive understanding of collector performance.

Although numerous studies have investigated CPCs, the combined effect of geometric and operating parameters remains an important area of research. Many experimental investigations have focused on individual parameters, while limited studies have systematically evaluated the

interaction between collector geometry, absorber characteristics, flow rate, working fluid, and environmental conditions under the same experimental setup. Differences in experimental procedures and climatic conditions also make direct comparison between published results difficult. Therefore, the present study focuses on the experimental investigation of Compound Parabolic Solar Collector performance under different geometric and operating conditions. The study aims to evaluate the influence of selected geometric parameters and operating conditions on useful heat gain, thermal efficiency, temperature characteristics, heat transfer behavior, and overall collector performance. The experimental results are expected to provide useful information for identifying suitable CPC configurations and operating conditions for improved solar thermal energy utilization.

2. Problem Identification

Compound Parabolic Solar Collectors (CPCs) have significant potential for converting solar radiation into useful thermal energy for low- and medium-temperature applications. However, achieving optimum CPC performance under varying environmental and operating conditions remains a major challenge. The thermal performance of a CPC depends on the combined influence of collector geometry, optical properties, absorber configuration, working fluid, solar radiation intensity, and operating parameters. Therefore, proper selection and optimization of these parameters are essential for obtaining maximum useful heat gain and thermal efficiency. The geometric configuration of a CPC strongly affects its solar radiation collection capability. Parameters such as aperture width, concentration ratio, absorber diameter, acceptance angle, rim angle, focal position, and collector length influence the amount of solar radiation intercepted by the absorber and the associated thermal losses. An inappropriate combination of these parameters can result in increased optical losses, inadequate concentration, or excessive heat loss. In particular, the concentration ratio and absorber diameter must be properly selected to achieve a suitable balance between solar energy concentration and thermal loss. The operating conditions also have a significant effect on CPC performance. Solar radiation intensity varies continuously with time and weather conditions, resulting in variations in absorber temperature, outlet fluid temperature, useful heat gain, and thermal efficiency. Similarly, mass flow rate, inlet fluid temperature, and ambient temperature influence heat transfer and thermal losses. A low flow rate may increase absorber temperature and heat losses, whereas a very high flow rate can increase pumping requirements and reduce the temperature rise of the working fluid. Therefore, identifying suitable operating conditions is necessary for optimum collector performance.

Optical and thermal losses further limit the practical performance of CPCs. Reflector reflectivity, absorber Absorptivity, intercept factor, surface quality, optical alignment, and manufacturing imperfections affect the amount of solar radiation reaching the absorber. At the same time, heat losses through convection, conduction, and radiation reduce the useful energy transferred to the working fluid. The selection of appropriate absorber and reflector materials, proper insulation, and accurate collector fabrication can help minimize these losses. Although several studies have investigated CPC performance, many investigations have focused on individual geometric or operating parameters. Limited experimental information is available regarding the combined

influence of geometric configuration and operating conditions under comparable experimental conditions. Differences in collector dimensions, absorber materials, working fluids, climatic conditions, and experimental procedures also make it difficult to compare results reported by different researchers. Therefore, a systematic experimental investigation is required to understand the interaction between geometric and operating parameters and their effect on CPC performance. The present study addresses these issues through an experimental investigation of Compound Parabolic Solar Collector performance under different geometric and operating conditions. The study focuses on evaluating the effects of selected collector geometry and operating parameters on useful heat gain, temperature characteristics, heat transfer, and thermal efficiency. The results are expected to provide useful information for identifying suitable geometric and operating conditions and for improving the overall performance and practical applicability of CPC-based solar thermal systems.

3. Research Objectives

The main objective of this research work is to conduct a comparative experimental investigation of a Compound Parabolic Solar Collector (CPC) under different geometric and operating conditions. The study aims to evaluate the influence of selected parameters on the thermal and exergy performance of the collector and to identify the conditions that provide optimum performance. The following objectives are addressed in this research work:

1. To determine the optimum geometric conditions for achieving the best performance of the Compound Parabolic Solar Collector.
2. To evaluate the exergy efficiency and instantaneous thermal efficiency of the collector using different receiver pipe diameters.
3. To determine the maximum instantaneous thermal efficiency of the Compound Parabolic Solar Collector under different operating conditions.
4. To determine the maximum exergy efficiency of the Compound Parabolic Solar Collector under different operating conditions.
5. To determine the maximum heat transfer rate of the Compound Parabolic Solar Collector under different geometric and operating conditions.

4. Research Methodology

The methodology adopted for the present research involves a systematic experimental investigation of a Compound Parabolic Solar Collector (CPC) under different geometric and operating conditions. The main objective of the methodology is to evaluate the influence of collector geometry, reflector material, receiver-pipe material and diameter, and working fluid on the thermal and exergy performance of the CPC. The research methodology is designed to provide a comparative assessment of different combinations of geometric and operating parameters and to identify the conditions that provide optimum collector performance. The methodology begins with the identification and selection of the major geometric and operating parameters affecting CPC performance. Important geometric parameters include aperture width, collector length, concentration ratio, receiver-pipe diameter, and receiver configuration.

Different reflector materials, including aluminium sheet, mirror, and acrylic polymer sheet, are considered to investigate their influence on the concentration and absorption of solar radiation. Receiver pipes made of different materials, including mild steel, copper, and stainless steel, are selected for the experimental investigation. Different receiver-pipe diameters are also considered to determine their effect on heat transfer, instantaneous thermal efficiency, and exergy efficiency. The selection of receiver materials is based on their thermal properties, availability, durability, and suitability for experimental operation.

Different working fluids, including water, propylene glycol, and molten salt, are considered to evaluate their influence on the heat transfer characteristics and overall performance of the CPC. The thermo physical properties of these fluids affect the rate of heat transfer, temperature rise, useful heat gain, and exergy performance of the collector. The experimental investigation therefore considers different combinations of receiver materials, receiver diameters, reflector materials, and working fluids. The CPC is designed and fabricated according to the selected geometric parameters. The reflector and receiver assembly are accurately positioned to ensure effective concentration of solar radiation onto the receiver pipe. Proper insulation is provided around the required components to minimize undesirable heat losses to the surroundings. The fabricated collector is then inspected and tested to ensure proper functioning of the experimental setup and accuracy of the measurement system. The experimental tests are conducted under different solar and operating conditions. During each experimental trial, important parameters such as solar radiation intensity, ambient temperature, inlet fluid temperature, outlet fluid temperature, receiver temperature, and mass flow rate are measured at specified time intervals. The experimental readings are recorded systematically for each combination of geometric and operating parameters to ensure reliable comparison of the results. The collected experimental data are used to calculate useful heat gain, temperature difference, heat-transfer rate, instantaneous thermal efficiency, and exergy efficiency of the CPC. The performance of the collector is evaluated for different receiver-pipe diameters, receiver materials, reflector materials, and working fluids. The obtained results are compared to determine the influence of each parameter on the overall thermal and exergy performance of the collector. The experimental results are subsequently analyzed to identify the geometric and operating conditions corresponding to maximum instantaneous thermal efficiency, maximum exergy efficiency, and maximum heat-transfer rate. Comparative analysis is performed to determine the most suitable combination of reflector material, receiver-pipe material, receiver-pipe diameter, and working fluid for achieving improved CPC performance.

For experimental work we fabricate compound parabolic solar collector. The important dimensions which we select in our research work are as follows:

- (a) Aperture width (W) of the collector is =1.2 m,
- (b) Length of collector and absorber pipe is = 2.4 m,
- (c) Inner diameter (Di) of hollow pipe is = 0.024m, 0.026 m, 0.028 m
- (d) Outer diameter (Do) of hollow pipe is = 0.028 m, 0.030 m, 0.032 m

- (e) Concentration ratio (C) is = 12.42
- (f) Specular reflectivity of glass = 0.38
- (g) Intercept factor for absorber pipe = 0.94
- (h) Transmissivity = 0.32
- (i) Absorptivity = 0.29

5. Fabrication and Result of CPSC

The physical structure of a Compound Parabolic Solar Collector is defined by various geometric parameters. These geometric parameters include the length of the solar collector, width of the solar collector, focal length of the collector, and rim angle of the collector. The shape and size of the receiver tube are defined by its length and diameter. The geometrical parameters of the Compound Parabolic Solar Collector are shown in Figure 5.1.

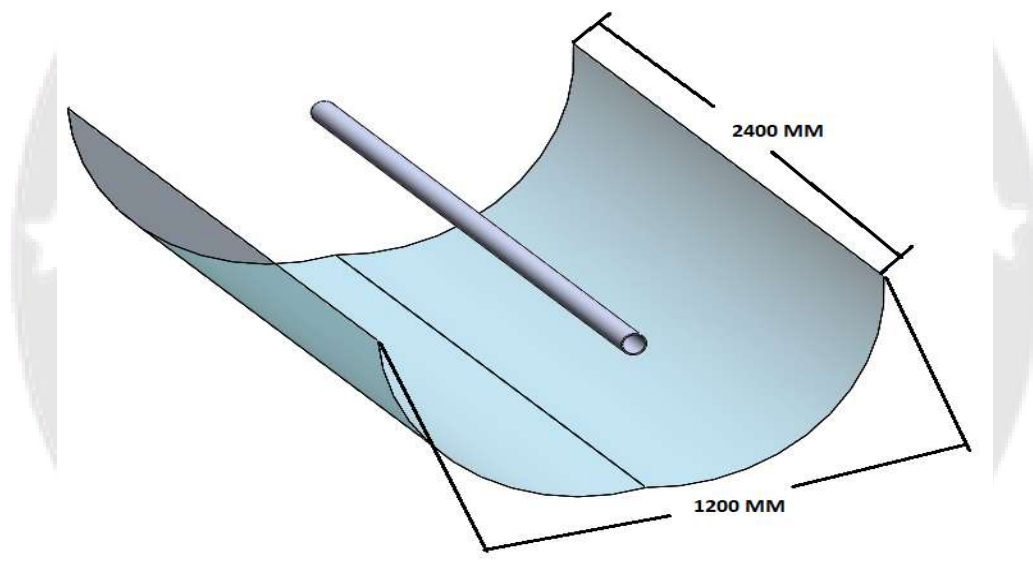


Figure 5.1: Geometrical characteristics of a CPSC

5.1 Concentration Ratio

It is defined as the ratio of the effective area of the aperture to the surface area of the absorber. This ratio is denoted by C. After deciding the diameter of the receiver tube, the concentration ratio is calculated using the following relation [17, 18, and 19]:

$$C = \{(W - DO) L\} / \{\pi DO L\} \quad (5.1)$$

$$C = \{(1200 - 30) \times 2400\} / \{3.14 \times 30 \times 2400\}$$

$$C = 12.42$$

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Table 5.1: Geometrical parameters of present work

S.No.	Parameters	Dimensions
1	Receiver tube Inner diameter D_i	24,26,28 mm
2	Receiver tube Outer diameter D_o	28,30,32 mm
3	Compound Parabolic solar collector, Length (L)	2400 mm
4	Compound Parabolic solar collector, Width (W)	1200 mm
5	Aperture Area (A)	2.88 m^2
6	Concentration ratio (C)	12.42, 11.62, 13.33



Figure 5.2: Compound parabolic solar collectors with receiver tube

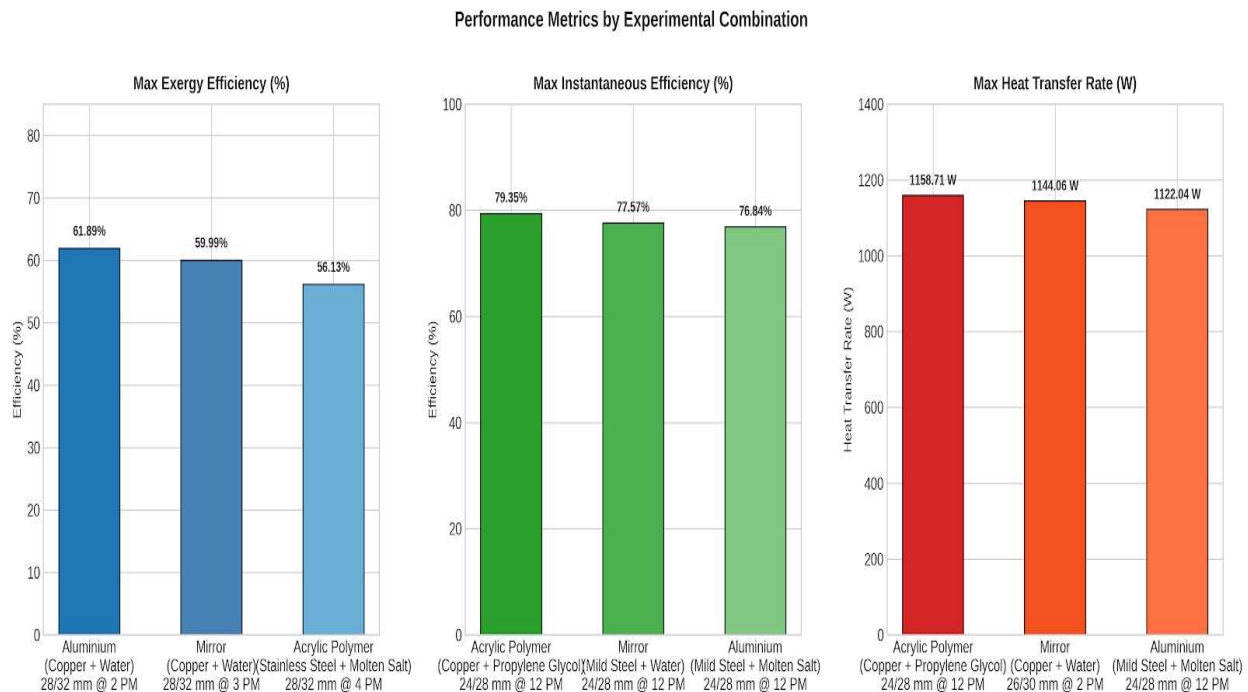


Figure 5.3: Comparison of result for different combinations

6. Conclusion

The major conclusions obtained from the experimental investigation are summarized below:

1. Exergy Efficiency

- The maximum exergy efficiency of 61.89% was obtained with the aluminium collector, copper receiver pipe, and water at 2 PM ($D_i = 28$ mm, $D_o = 32$ mm).
- The mirror collector with copper–water achieved a maximum exergy efficiency of 59.99% at 3 PM.
- The acrylic polymer collector with stainless steel–molten salt achieved a maximum exergy efficiency of 56.13% at 4 PM.

2. Instantaneous Efficiency

- The highest instantaneous efficiency of 79.35% was obtained with the acrylic polymer collector and copper–propylene glycol at 12 PM ($D_i = 24$ mm, $D_o = 28$ mm).
- The mirror collector with mild steel–water achieved 77.57% at 12 PM.
- The aluminium collector with mild steel–molten salt achieved 76.84% at 12 PM.

3. Rate of Heat Transfer

- The highest heat-transfer rate of 1158.71 W was obtained with the acrylic polymer collector and copper–propylene glycol at 12 PM ($D_i = 24$ mm, $D_o = 28$ mm).
- The mirror collector with copper–water achieved 1144.06 W at 2 PM ($D_i = 26$ mm, $D_o = 30$ mm).

- The aluminium collector with mild steel–molten salt achieved 1122.04 W at 12 PM ($D_i = 24$ mm, $D_o = 28$ mm).

Overall, the experimental results demonstrate that CPC performance is strongly influenced by the combined effects of reflector material, receiver-pipe material and diameter, working fluid, and operating time.

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