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Optical and thermal performance of double receiver compound parabolic concentrator

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HIGHLIGHTS

- A geometric characterisation and optical models were developed.
- The optical efficiency of a static symmetric CPC has been determined for thermal application.
- The effects of the receiver size and shape on optical efficiency of CPC was investigated.
- The potentials of using double receiver in one concentrator has been elaborated.
- The thermal performance of the double and single receiver CPC was compared experimentally.

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ABSTRACT

Conventional solar compound parabolic concentrators are normally fitted with one tubular receiver positioned along the axis of the two parabolas. This work investigates the potential of using either two tubular receivers in one compound parabolic concentrator or an elliptical single receiver. Using advanced ray tracing technique, the optical efficiency of a compound parabolic concentrator with two tubular receivers aligned horizontally and vertically was predicted. Results showed that the horizontal configuration outperforms both the single and the vertical configurations by up to 15%. Also, a horizontally aligned elliptical single tube showed an increase in the average daily optical efficiency by 17% compared to the single tube configuration. The thermal performance of the single and double horizontally aligned tubular receivers was determined using a thermosyphon heat pipe experimentally tested utilising the heat flux obtained from the optical simulation at different acceptance angles. Results show that double tube configuration thermally outperforms the single one in terms of heat transferred to the cooling water by 21%, 19.8% and 18.3% for acceptance angles of 30°, 40° and 60° respectively. This work highlights the potential of using either two tubular receivers or single elliptical one aligned horizontally in one concentrator to improve the optical and thermal efficiencies of compound parabolic collectors.

1. Introduction

Interest in renewable energy technologies is increasing due to the problems associated with the use of conventional fuel such as global warming and the cost of the fuel. Solar technology is one of the most promising renewable energy sources due to the availability of solar radiation in many parts of the world and the range of its applications. But the cost of the solar systems especially photovoltaic is still a hindrance to its development due to the low efficiency and the huge initial investments. Concentrating solar system is one of the steps taken to reduce the total cost of the system by decreasing the number of the PV modules or thermal receivers by increasing the outputs through the use of optical material to concentrate the solar radiation on a small area. The cost of concentrating system is generally lower than that of the flat plate with additional advantages of saving space and other logistics. Among such concentrators is compound parabolic concentrator (CPC) which was invented independently by Hinterberger and Winston (in 1966) and in USSR by Baranov and Melnocov) in the same year [1]. Since then, its potentials as concentrator for solar collectors was investigated by many researchers for wide range of applications [2–5].

Compound Parabolic Concentrators (CPC) are non-imaging concentrators which have properties of both concentrating and flat plate collectors with low errors of alignment for reflective and receiving surfaces and high optical and quantum efficiency [3]. CPC solar collector consists of two halves of parabolas with a

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Nomenclature

Abbreviation

- E (***a***:***b***) elliptical receiver with ***a*** and ***b*** major and minor axes respectively
- HPCPC***x***R***y*** heat pipe based compound parabolic concentrator with ***x*** acceptance angle and ***y*** receiver radius
- HA horizontally aligned double tube
- VA vertically aligned double tube

Symbols

- θ_a acceptance angle, °
- r receiver radius, m
- C geometric concentration ratio
- A area, m^2
- P power, W
- Q rate of heat transfer, W
- C_p specific heat capacity of water, kJ/kg K
- $\dot{m}$ mass flow rate of water, kg/s

Subscripts

- *ap* aperture of the concentrator
- *re* receiver
- *in* inlet
- *out* outlet

receiver fitted along the axis of symmetry of those parabolas. Various works were reported in literature on CPC ranging from using different receiver types, different working fluids to different geometric configurations to improve its optical and thermal performance. Rabl [6,7] are among the earlier works on the general characteristics of CPC solar collectors in terms of concentration ratio, acceptance angle, average number of reflections, sensitivity to mirror error, operating temperature and heat transfer. With the increase of the understanding of CPC's operations, more attention is given to the ways of reducing heat losses especially from the receiver side and this led to various modifications applied to the receiver and reflectors.

Farouk et al. [8] presented an asymmetric CPC with inverted absorber. They used ray tracing to analyse the optical performance and investigated the effects of the gap height on the optical efficiency and the convection heat losses and concluded that the optical efficiency decreases with increasing the gap height. The potentials of using various receiver shapes (like tubes, wedge, and fins) for different applications was analysed by Rabl [9].

Fraidenraich et al. [10] studied analytically the geometric and optical properties of fully illuminated inverted V shape receiver with vertex angle greater or equal to the CPC acceptance half angle by predicting the maximum energy that can be collected and the cost benefits for different collector orientations and various vertex and acceptance angles. The results of this study produced the best collector design with a concentration ratio between 1.0 and 1.2, East–West orientation, acceptance and absorber vertex angles of 30° and 65° respectively for the Recife – PE, Brazil. Design, construction and testing of two water solar heaters utilising stationary asymmetric CPC was presented by Tripanagnostopoulos [11] with two different receiver configurations; two separated tubular receivers (CPC 1) and separated flat absorbers (CPC 2). Although the results showed that the CPC 2 configuration outperformed the CPC 1 but the superiority of CPC 2 cannot be attributed to the geometry since the authors used different surface finish for the two receivers. Norton et al. [12] studied the performance of three different designs of CPC; conventional tubular (design A), small tube attached to a U-shaped fin (design B) and glass plate inserted perpendicular to the cover (design C). The three designs were tested out door and the results reported showed 0.68 and 0.77 optical efficiency for design A and B respectively while C showed comparable performance with design B. Although new designs show improvement from conventional, but design B have higher overall heat loss coefficient than the conventional.

Modification to the tubular absorber of the CPC is one of the approaches employed by some authors for improving the performance of the collector. This is done by introducing cavities (with or without baffles) on the receiver especially around the area with high flux concentration to reduce heat losses and increase the efficiency [13–15]. Although considerable improvement has been reported by using this approach, but the process has to be done with greater care so that the flow of the working fluid should not be affected. When the cavities are large or not well positioned, the shape of the receiver can be distorted and the flow of the working fluid inside the tube will be affected. It has been shown that the non-uniformity of solar radiation on the flat absorber surface during certain period of operations can be used to improve the efficiency of the collector as reported by Tripanagnostopoulos [16]. Studies were made on the design of asymmetric and symmetric CPC with flat absorbers which were divided into four sections as channels for the fluid flow. The absorber was divided into segments and the working fluid is passed through the channels with high concentration of radiation while other channels were kept at stagnation temperature. It is shown that temperature range of 100–200 °C can be achieved with simple concentrating collector [16].

Other approaches involve the use of special coating materials or different configurations of receiver [17–19]. The issue with this approach is the cost of the coating materials to be used, which has to be compared with the performance enhancement achieved.

Apart from the modifications made to the receiver to improve the performance, heat pipe with or without wick materials (thermosyphon) are sometimes used to enhance the heat transfer and hence reduces losses and increases the overall efficiency [20–23]. All the works reported utilise one receiver in each concentrator even in applications which require several number of tubes. This work investigates the performance of a CPC collector fitted with two tubes. Using advanced ray tracing techniques, the solar radiation received by two cylindrical tubes aligned horizontally and vertically in one CPC was predicted and compared with that received by single cylindrical and single elliptical tubes with different configurations. The flux concentrated on the receivers obtained from optical simulation was used as input in the experimental thermal performance testing of a thermosyphon heat pipe.

2. The CPC geometry

The shape of the concentrator in CPC can be symmetric or asymmetric which can be fitted with the receiver of different configurations such as flat, tubular, wedge, and bifacial. The type and shape of the tube may influence the overall performance of the collector. Heat pipe has been found to be effective in transferring the heat gain from the evaporator to the condenser sections where it is transferred to the cooling fluid. Also certain factors need to be considered in designing solar thermal CPC concentrator such as the height, aperture width and the concentration ratio. In this paper, a heat pipe based compound parabolic collector (HPCPC) will be developed.