


Comparative Optical and Thermal Analysis of Compound Parabolic Solar Collector with Fixed and Variable Concentration Ratio [†]

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Abstract: Solar thermal collectors, such as flat plate and evacuated tube collectors, are used for maximum of 60–80 °C temperature and parabolic trough collectors are used for 700–900 °C temperature ranges. It is needed to develop and analyze solar collectors, such as compound parabolic collectors (CPC) which can operate in an intermediate temperature range from 50–300 °C for industrial and domestic applications. However, optical and thermal performance of CPC is strongly influenced by concentration ratio. The current study presents a comparative optical and thermal analysis of CPC with fixed (4) and variable (4.5 to 5.7) concentration ratio by using model-based transient simulation approach. Two profiles of compound parabolic collector are analyzed with fixed and variable concentration ratio for the subtropical climate of Taxila, Pakistan. 2D profiles of both collectors are modeled and designed in MATLAB and are then analyzed optically by using Monte Carlo ray tracing technique through TracePro. In addition, thermal analysis of both profiles is also performed through ANSYS. The resulting optical efficiencies with fixed and variable concentration are 72% and 79%, respectively. Whereas maximum temperature achieved with both profiles is 352 K and 367 K, respectively. Thus, it is concluded that performance of CPC with variable concentration ratio is much better compared to fixed value.

Keywords: compound parabolic collector; optical analysis; thermal analysis; ray tracing; solar collector



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1. Introduction

Among all renewable sources, solar is the widely available and the most reliable source of energy. To get maximum benefit out of solar, many researchers all around the world had participated in the development of solar assisted energy production devices. Among solar thermal collectors, flat plate and evacuated tube collector are not as efficient and can generate up to 60–80 °C temperature. Compound parabolic collectors lie in the range of medium temperature generation that is 50–300 °C. These collectors are made up of two parabolas and an absorber which is placed on the common foci of these two parabolas.

Compound parabolic collector was invented by Winston in 1960 and was presented later in 1974 which was used for the supply of hot water as end application [1]. These collectors are developed because efficiency of non-imaging collectors was low because of high convection losses. In 1976, Rabl made its optical analysis by deriving a mathematical model of the average number of rays reflected towards the absorber from the reflector [2]. Imaging type of concentrators require sun tracking for high efficiency and are 15% more

efficient than stationary collectors [3]. Compound parabolic concentrator is the type of non-imaging concentrator [4], and its concentration ratio is as low as 2–5 and used for intermediate temperature ranges as 30–350 °C. Due to a low concentration ratio, both beam and diffuse radiations are captured by CPC without tracking the sun [5]. Concentration ratio is inverse to the acceptance angle of the collector in case of compound parabolic collectors [6]. Beam rays, having incidence angle within the acceptance angle of the collector, will reflect towards the absorber tube, the other having an incidence angle greater than the acceptance angle will reflect beam rays back into the atmosphere [7]. Finite element method was developed in CPC absorber tube by Chew et al. but in this method glass cover and absorber tube were kept at constant temperature [8]. As CPC is used for intermediate temperature ranges, it does not require proper tracking but only requires seasonal tilt [9].

In view of above literature, it is analyzed that compound parabolic collector with variable concentration ratio has not been designed and studied earlier in terms of its optical and thermal efficiency. In this study, solar collector with variable concentration ratio (VCR) and fixed concentration ratio (FCR) are analyzed optically and thermally and results of both of the profiles are compared with each other.

2. Material and Methods

Design of Compound Parabolic Collector

To design solar collector, it is necessary to find sun path for the location at which solar collector is being installed. Acceptance angle is selected accordingly for the design of the collector. Collector is made up of stainless steel with reflectivity of almost 60%. Concentration ratio (CR) of the collector is key parameter which determines efficiency of the collector.

For University of Engineering and Technology Taxila sun movement lies between 10.97° and 57.21° zenith angle for summer and winter solstice respectively. The acceptance angle is selected in this range that is 60° for CPC with FCR. Collector with FCR is installed in E–W orientation while collector with VCR is designed with respect to working hours and is placed in a N–S orientation. Geometric CR for CPC with FCR is 4.58 and for CPC with VCR at small and large end are 4.58 and 5.87 respectively. Profiles and acceptance angle of collectors with FCR and VCR are shown in Figures 1 and 2.

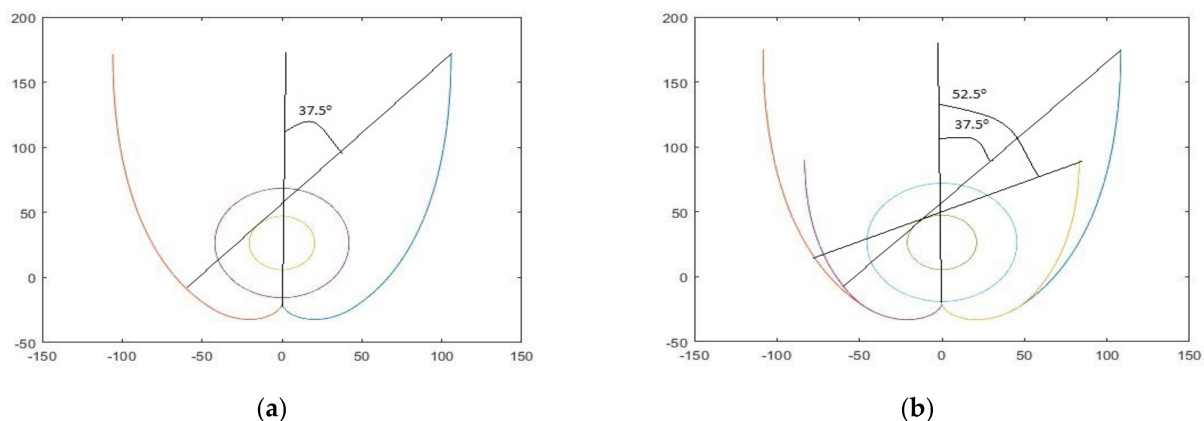


Figure 1. Profiles of collector. (a) FCR, (b) VCR.

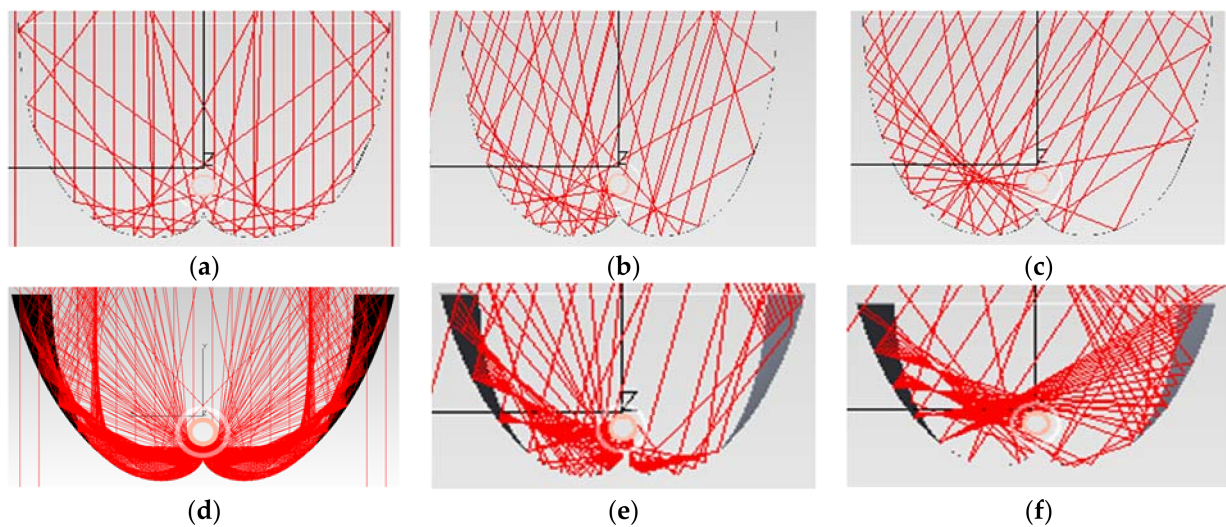


Figure 2. Ray Trace images for FCR (a) 0° , (b) 15° , and (c) 30° and for VCR (d) 0° , (e) 15° , and (f) 30° .

Non-tracking compound parabolic collectors are simulated optically and thermally by using TracePro and ANSYS as simulation tools for the efficient design of collectors.

Single flow through copper tubes is selected as an absorber tube for the collector in which fluid will be passed for the purpose of heat gain. The absorber tube is covered with borosilicate glass and a vacuum is created between the glass envelope and absorber tube to prevent convection heat losses. Tube is made up of copper and is coated with black chrome to increase the absorptivity of light. Bellows are provided on both ends of the tube to counter any kind of expansion in metal due to the increase in temperature.

3. Results and Discussion

Both profiles of collector having fixed, and variable concentration ratio are analyzed optically in TracePro to determine the optical efficiency of collector. Analysis is done by using Monte Carlo ray tracing method. Profiles of collectors are analyzed for rays coming at angle of 0° , 15° , and 30° into the aperture of collector. At these incident angles optical efficiency for FCR profile was 61%, 63% and 41% respectively while—for VCR profile—optical efficiency was 71.6% 72%, and 57% respectively. Ray tracing images of both profiles are shown in Figure 2.

Profiles are then numerically simulated for estimation of their thermal efficiency. For this purpose, ANSYS fluent is used as simulation tool for thermal simulation of collector profiles. In this method mesh was generated shown in Figure 3, boundary conditions were applied, and the collector was simulated for 250 iterations. In response to these iterations pressure, temperature, and velocity contours were generated which after detailed comparison for both profiles reveal that the profile with VCR managed to achieve higher temperature 367.028 K and profile with FCR achieved 355.81 K. In performed numerical simulations, pressure achieved in profile with FCR was 82.79 Pa and pressure achieved with VCR was 78.24 Pa. Generated temperature and pressure contours are shown in Figure 3.

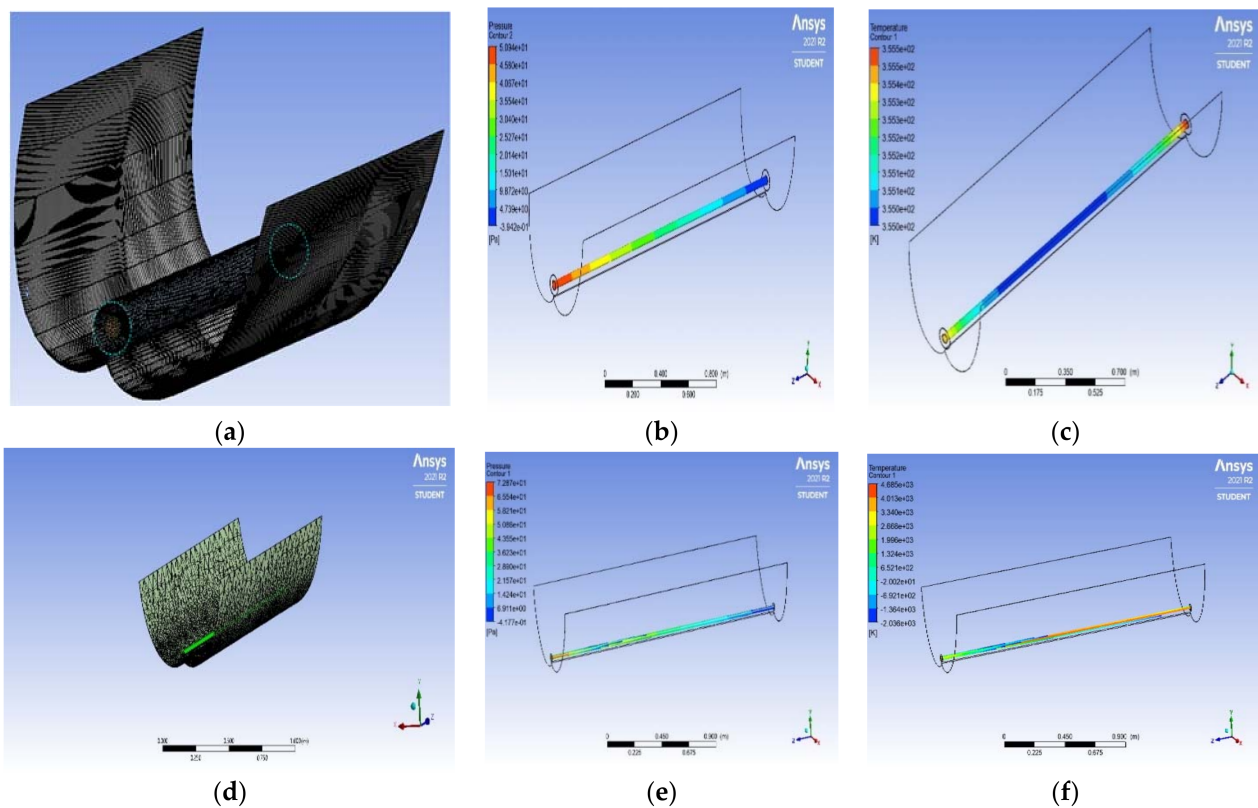


Figure 3. Thermal analysis mesh generation and results (a–c) for FCR (d–f) for VCR.

4. Conclusions

In this paper, profiles of compound parabolic collectors with fixed and variable concentration ratios were developed and then analyzed thermally and optically. It has been determined that these profiles perform better as compared to non-concentrating collectors with respect to the temperature achievement. These two profiles are mutually compared, and analysis has been made that the profile of collectors with variable concentration ratios are better than a profile with a fixed concentration ratio in terms of temperature and pressure during the analysis. In the future, it is recommended to perform thermosiphoning experimentation on compound parabolic collectors to get rid of forced circulation of fluid in the collectors. With the application of flow circulation under capillary action, efficiency of the collector can be improved.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

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