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 ℃ temperature and parabolic trough collectors are used for 700-900 ℃ temperature ranges. It is needed to develop and analyse solar collector, such as compound parabolic collectors (CPC) which can operate for intermediate temperature range from 50-300 ℃ 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 (4.58) and variable (4.58 to 5.87) concentration ratio by using model-based transient simulation approach. Two profiles of compound parabolic collector are analysed with fixed and variable concentration ratio for the subtropical climate of Taxila, Pakistan. 2D profiles of both collectors are modelled and designed in MATLAB and are then analysed optically by using Monte Carlo ray tracing technique through TracePro. In addition, thermal analysis of both profiles is also performed through ANSYS. The resulted optical efficiency with fixed and variable concentration is 91 % and 96 %, respectively at a given tilt angle. Whereas maximum temperature achieved with both profiles is 5°C and 7°C, 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.

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 ℃ temperature. Compound parabolic collectors lie in the range of medium temperature generation that is 50-300 ℃. These collectors are made up of two parabolas and absorber 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 (A. Rabl et al., 1980). 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 (Ari Rabl, 1976). Imaging type of concentrators require sun tracking for high efficiency and are 15% more efficient than stationary collectors (Y. Kim et al., 2008). Compound parabolic concentrator is the type of non-imaging concentrator (Guiqiang et al., 2013), and its concentration ratio is low as 2–5 and are used for intermediate temperature ranges as 30–350ºC. . Due to low concentration ratio, both beam and diffuse radiations are captured by CPC without tracking the sun (Y. S. Kim et al., 2013). Concentration ratio is inverse of acceptance angle of collector in case of compound parabolic collector (Bellos et al., 2016). Beam rays having incidence angle within the acceptance angle of collector will reflect towards absorber tube other having incidence angle greater than acceptance angle will reflect back into the atmosphere (Hsieh, 1981). 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 (Tay & Wijeysundera, 2016). As CPC is used for intermediate temperature ranges, it does not require proper tracking but only requires seasonal tilt (Terrón-Hernández et al., 2018). As it is characteristic of CPC to capture diffuse radiation, so it is advantageous to use CPC in tropical region where percentage of diffuse radiation is relatively high (Ratismith et al., 2014). Micintire in 1979 analysed effect of truncation on CPC which he concluded that by truncation the effect on efficiency of system is very minute in comparison to material saving of the collector (McIntire, 1979). Application of glass envelop around absorber tube was also done by R. Rabl to minimize convection losses but there was air trapped between absorber tube and glass envelop (A. Rabl et al., 1979). Argonne National Laboratory first used evacuated glass tubes in 1980 (Devanarayanan & Kalidasa Murugavel, 2014). Due to benefits of compound parabolic collector many researchers applied this collector for wider applications as solar heating and cooling (Tian et al., 2018) industrial process heat, methanol reforming and hydrogen production etc. Derrick et al. inspected different types of concentrators with integration of non-evacuated tube as absorber for E-W and N-S orientations (Derrick et al., 2006). Heat exchanger integrated with CPC was analysed by Tchinda et al with axial heat flux (Tchinda & Ngos, 2006). Sanil et al. first did application of evacuated glass tube in CPC (Snail et al., 1984). Xu et al. analysed CPC integrated with capillary tube instead of evacuated tube and found out that CPC integrated with evacuated tube is 12% more efficient than with capillary tube (Xu et al., 2020). Li Zheng et al. gave a review on CPC working with different absorbers with and without tracking the sun (Jiang et al., 2020). Wang et al. analyzed six different shapes of compound parabolic collector integrated with evacuated glass tube absorber and optimized their efficiency (Wang et al., 2016). Best way to measure optical efficiency of compound parabolic collector is use of Monte Carlo ray tracing method. Javed et al. optimized efficiency of collector by using single flow through evacuated tube and concentric tube as receiver in collector and he analysed that the CPC with concentric evacuated tub and oriented in E-W direction is most efficient system (Akhter et al., 2019). Orientation of CPC was analysed by Jimenez in his research and analysed that the CPC with concentric evacuated tube oriented in E-W direction was more efficient than the one oriented in N-S direction (Aguilar-Jiménez et al., 2018). To introduce effect of thermosiphoning in collector, Javed et al. analysed collector with variable concentration ratio along the length of collector by varying aperture area of collector (Akhter et al., 2020). Baum et al. analysed wedge type receiver which reduces material used in collector leading to minute loss of energy obtained from receiver. This design can be significant in designing of monofacial photovoltaic devices to determine concentrator configurations which are economically optimal (Baum & Gordon, n.d.).

In view of above literature, it is analysed that compound parabolic collector with variable concentration ratio has been rarely designed and developed in terms of its optical and thermal efficiency. Therefore, in this study, simulation and experimental comparative analysis between solar trough collector with variable concentration ratio (VCR) and fixed concentration ratio (FCR) is performed. The analysis is presented in terms of optical and thermal efficiencies.

SYSTEM DESIGN AND ANALYSIS

To design solar trough 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 designing of 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.

It is determined that sun zenith angle lies between 10.97^o and 57.21^o during summer and winter solstice, respectively for the considered location of University of Engineering and Technology Taxila, Pakistan. Acceptance angle is selected in this range that is 45° 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 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. FCR and VCR profiles of collector are modelled in MATLAB by using string method as in equations 1-3.

$$\begin{cases} x = r sin\varphi - \rho cos\varphi \\ y = -r cos\varphi - \rho sin\varphi \end{cases} \quad \textbf{(1)}$$

$$\frac{\rho}{r} = \begin{cases} \varphi + \gamma & \emptyset \leq \varphi \leq 0.5\pi + \theta_a \\ \frac{0.5\pi + \theta_a + \varphi + 2\gamma - cos(\varphi - \theta_a)}{1 + \sin(\varphi - \theta_a)} & 0.5\pi + \theta_a < \varphi \leq 1.5\pi - \theta_a \end{cases} \quad \textbf{(2)}$$

$$\gamma = \sqrt{R^2 + r^2} / r - \emptyset \quad \textbf{(3)}$$

r = Radius of Absorber

Profiles and acceptance angle of collectors with FCR and VCR are shown in Figure 1.

The developed models of both profiles are then optically and thermally analysed in TracePro and ANSYS Fluent respectively. In thermal analysis, fluid used is water and linear mesh is used in ANSYS meshing module. Grid independence analysis is performed to check the quality of mesh and collector performance at different number of nodes. K-epsilon turbulent model is selected, and collector is analysed at multiple fluid velocities. For incompressible flow outflow outlet is selected. Optical and thermal analysis is performed at different solar radiations measured experimentally throughout the day by using pyranometer. Both optical and thermal analyses are coupled by using optically obtained flux value in ANSYS thermal analysis.

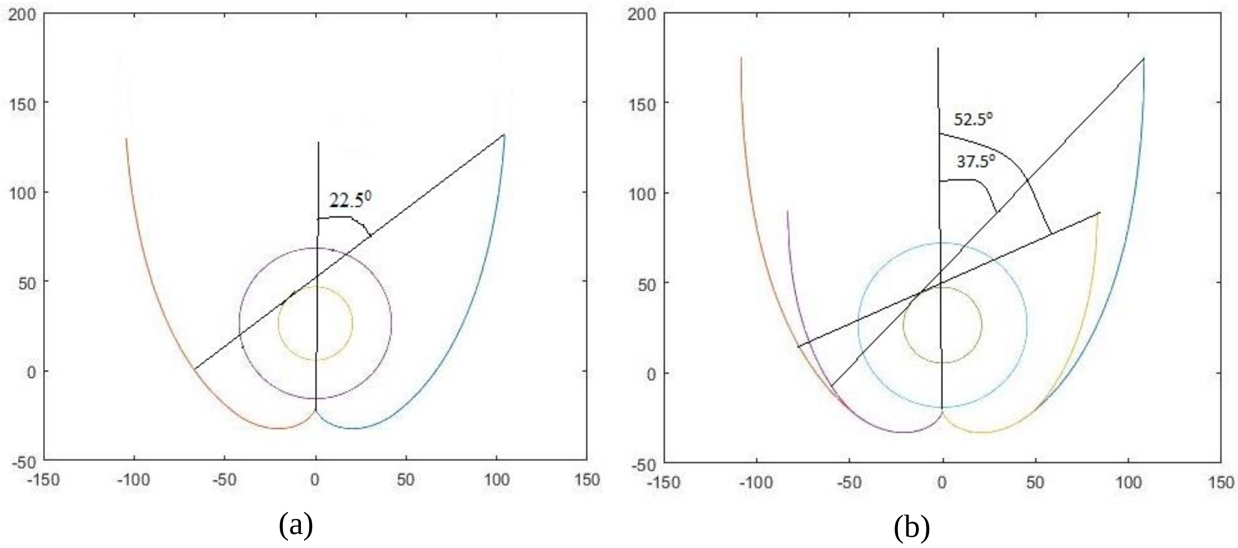


Figure 1: MATLAB generated 2D profiles of CPC (a) FCR, (b) VCR

Experimentally obtained solar radiations and ambient temperature for months of August to October are shown in Figure 2. These radiation values are used for optical and thermal analysis of CPC profiles.

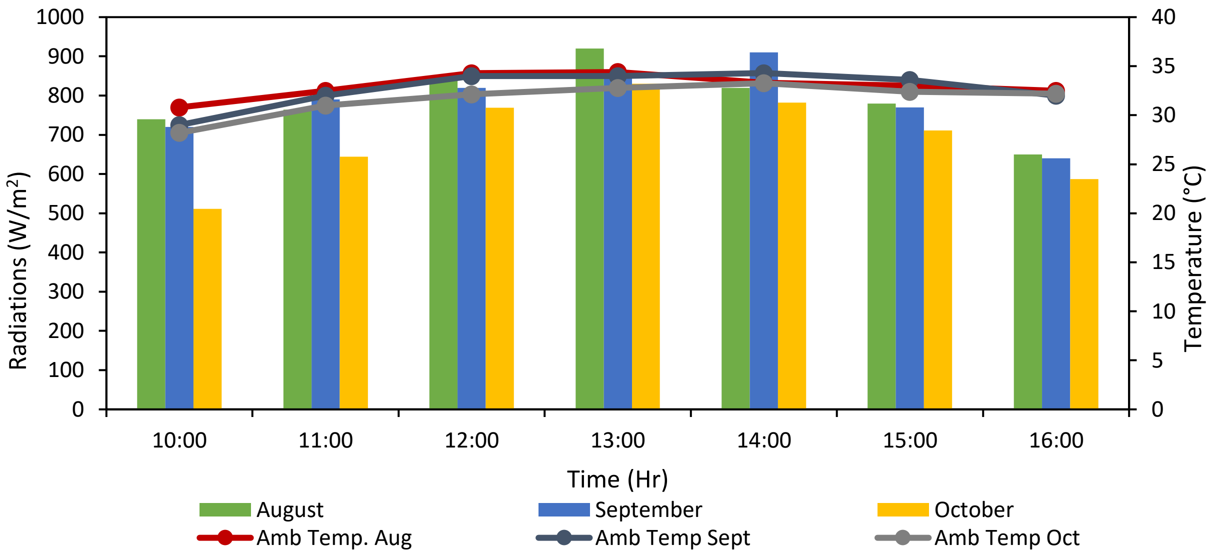
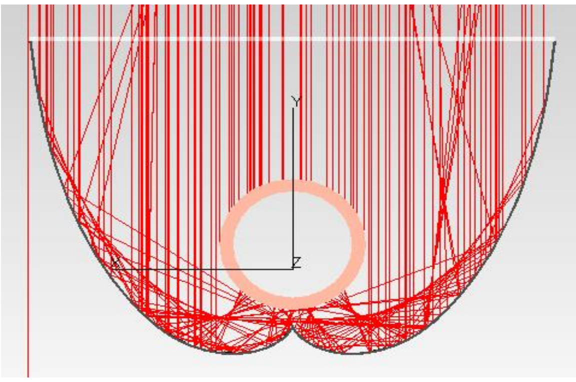


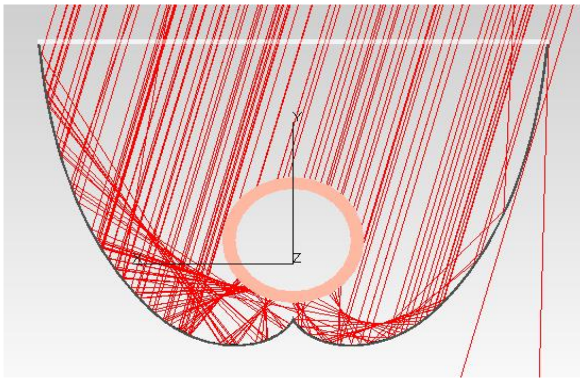
Figure 2: Real time data of solar radiations and ambient temperature

It can be seen from the figure that maximum radiation values and maximum ambient temperature are obtained during the month of August at peak time of 13:00. During the month of August as sun is high compared to September and October so in August maximum solar rays are obtained.

Optical analysis is performed at tilt angles of 0°, 15°, 25°, 35° and 45° in view of the zenith angle of sun throughout the year for Taxila. Generated flux from optical analysis is calculated throughout the length of collector for both profiles. Tracepro optical analysis of both profiles of CPC is shown in Figure 3.



(a)



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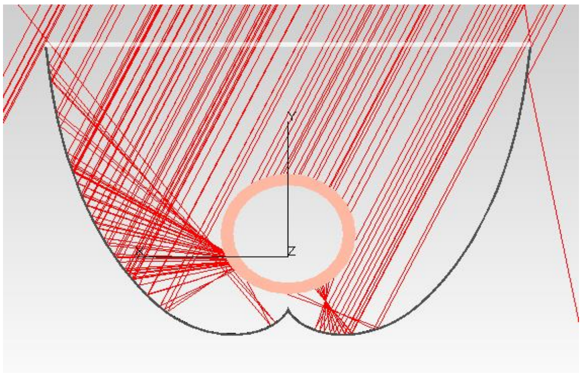

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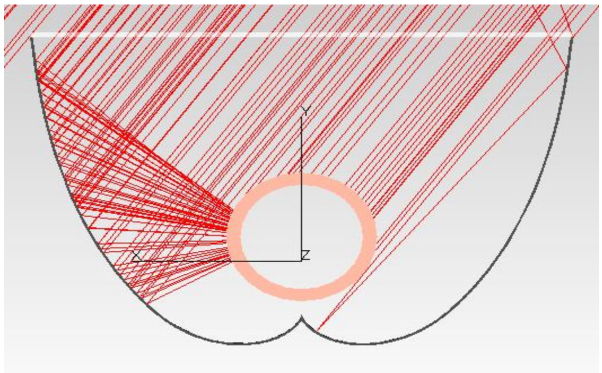

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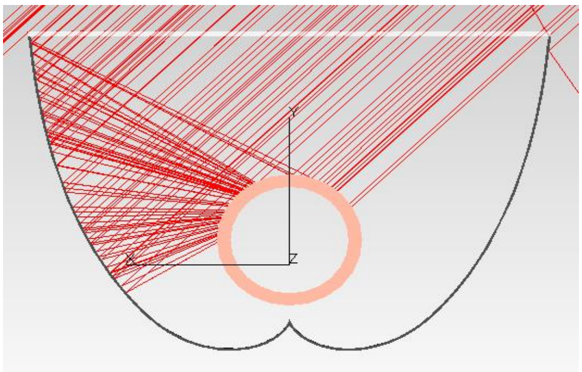

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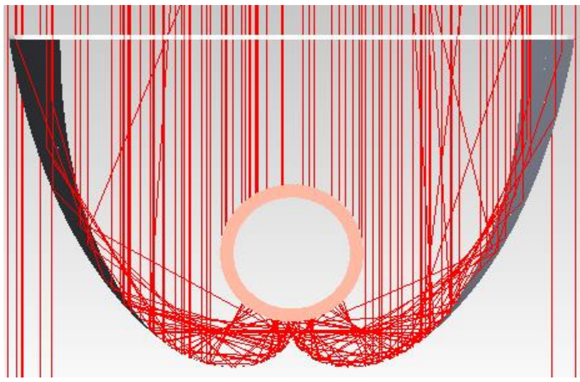

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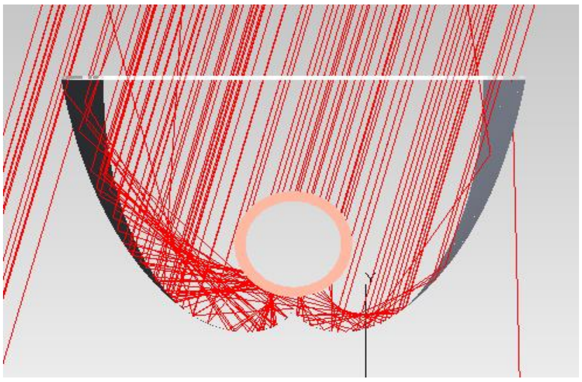

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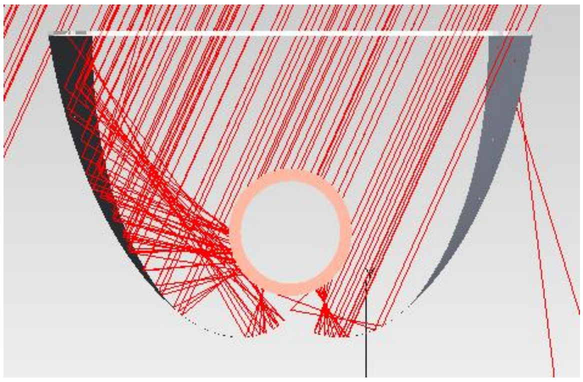

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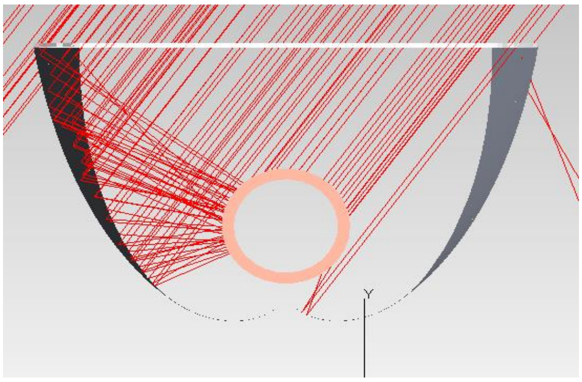
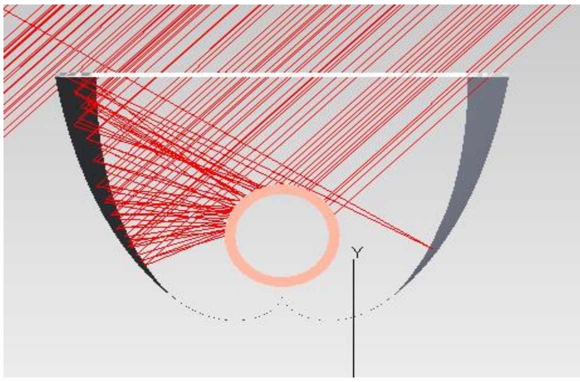


(i)



(j)

Figure 3: Ray tracing in TracePro (a) FCR at 0° (b) FCR at 15° (c) FCR at 25° (d) FCR at 35° (e) FCR at 45° (f) VCR at 0° (g) VCR at 15° (h) VCR at 25° (i) VCR at 35° (j) VCR at 45°

From Figure 3 it is illustrated that angle of the source is being changed from 0° to 45° which is in accordance with the movement of sun throughout the year for different days of the year. This can be considered as the tilt angle of the solar trough collector. mentioned tilt angles are within the acceptance angle of the collector and as angle change focus of the rays slightly shifts upward. As angle increases from the acceptance angle of collector focus abruptly shifts towards top. From the figure 3 it is evident that more rays are being entered in the collector aperture and more rays are being converged on the absorber tube in case of VCR profile compared to FCR profile.

Optical efficiency for FCR and VCR profile is calculated by using the value of flux obtained at the absorber after geometry is analysed optically. In case of FCR profile flux value remained same along the length at one tilt angle but for VCR profile value of flux kept on increasing and so does optical efficiency for the collector. As aperture area increased with the decrease of acceptance angle high number of rays entered the collector and more flux is obtained at absorber tube. Optical efficiency for both profiles is shown in Figure 4.

Theoretical formula to calculate the optical efficiency is given in Equation 4.

$$\eta_o = \rho\alpha\tau\gamma \quad \textbf{(4)}$$

Where, α= absorptivity of absorber tube, ρ= reflectivity of collector, τ= transmissivity of glass cover, and γ= intercept factor.

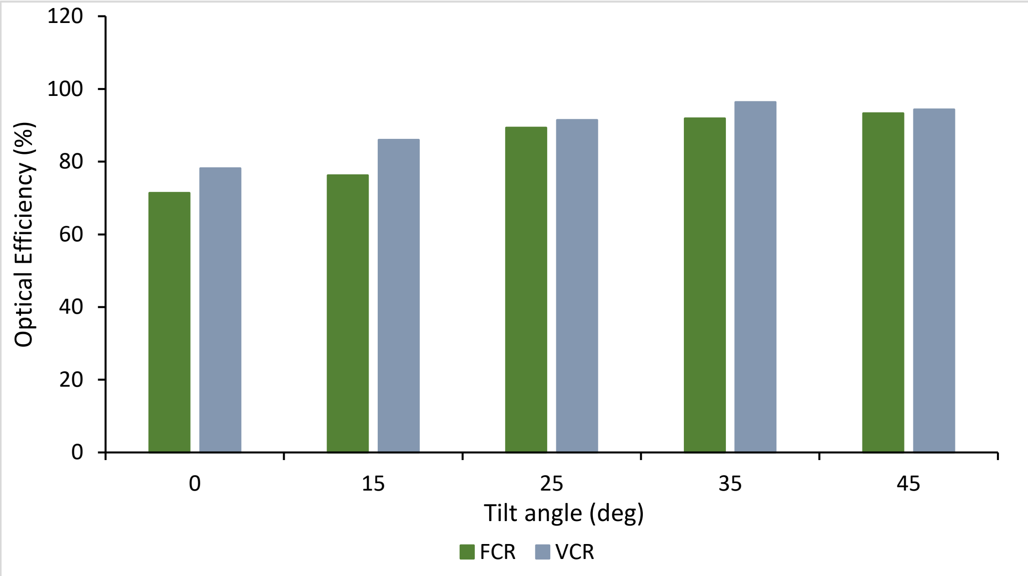


Figure 4: Optical efficiency of FCR and VCR profiles of CPC

It can be seen that as tilt angle increases and approaches to the designed acceptance angle of collector optical efficiency go on increasing. At 45° tilt angle FCR profile performed maximum as this is the design acceptance angle of this profile and at 35° tilt angle VCR profile performed maximum as this is closer to the design acceptance of large end of this profile which is 37.5°. Overall, VCR profile generated better optical results compared to FCR pro file at a given tilt angle and irradiation. At 35° tilt angle VCR profile generated 5% better results as compared to FCR profile.

Thermal analysis of CPC profiles is performed in ANSYS Fluent and linear mesh is generated. In thermal analysis only absorber tube is working domain. Boundary conditions are applied on the absorber tube and working fluid. Generated mesh for both FCR and VCR profiles is shown in Figure 5.

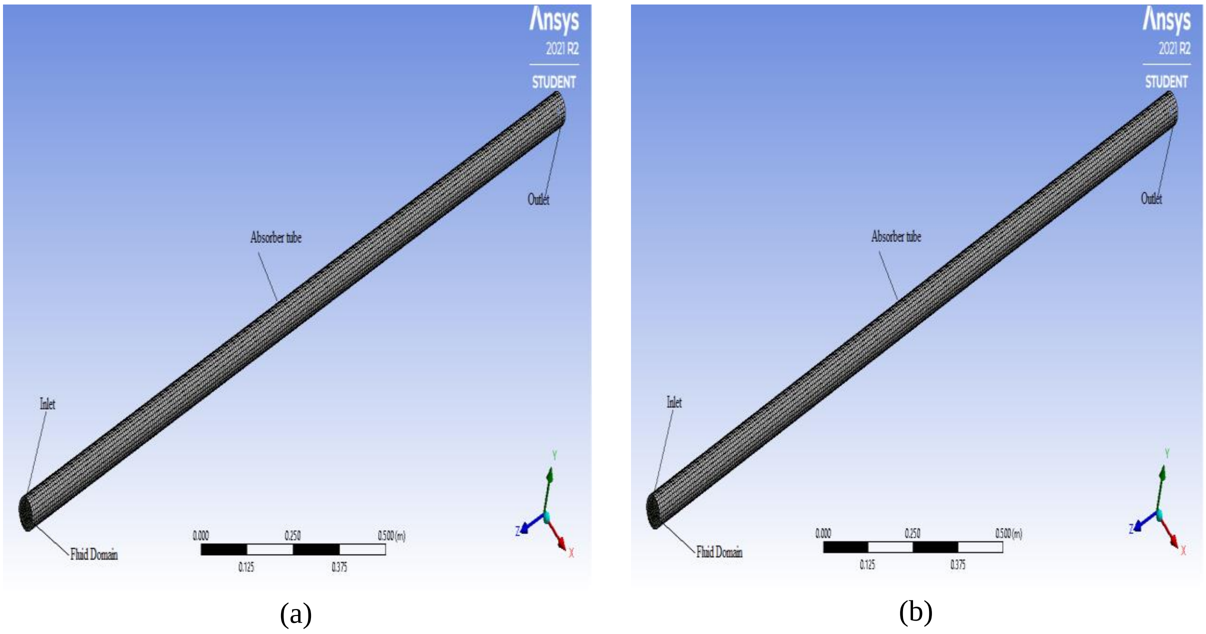


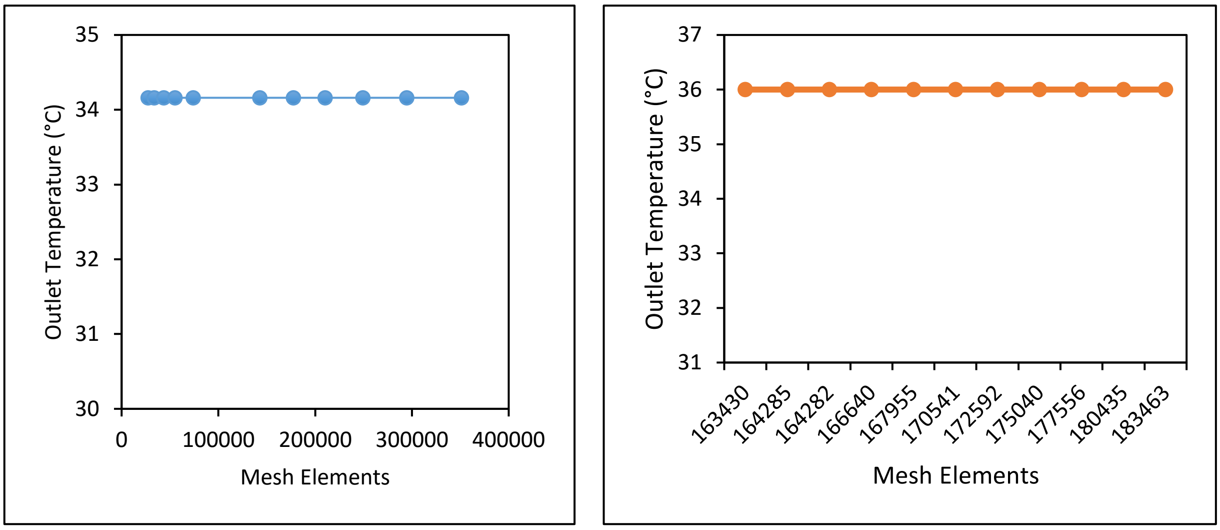
Figure 5: Mesh generation on absorber tube of collector

Inlet is on the left side of absorber tube and outlet is on right side. Fluid domain is created inside the absorber tube for the flow of fluid. Linear mesh in generated on the absorber tube and fluid domain. Applied boundary conditions are listed in Table 1.

Table 1: Applied Boundary Conditions

Viscous model	K-epsilon
Inlet	Velocity Inlet
Outlet	Outflow outlet
Absorber tube material	Copper
Fluid used	Water
Applied flux on FCR	600 W/m^2, 700 W/m^2, 850 W/m^2
Applied flux on VCR	Variable flux along the length + basic value of FCR flux

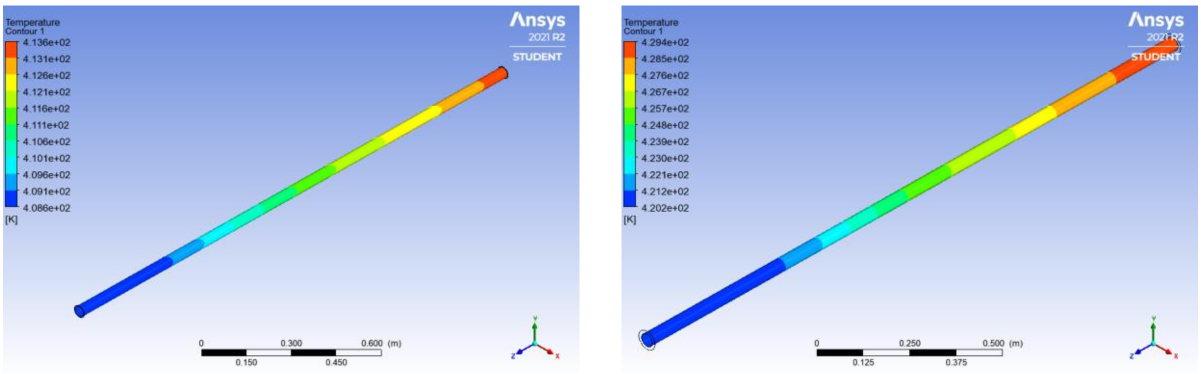
Mesh independence analysis is performed to know about the accuracy of the simulation. Mesh independence analysis is performed for both FCR and VCR profiles and a very minute change in values of outlet temperature of fluid are observed at different number of elements. Mesh independence analysis is shown in Figure 6.



(a) (b)

Figure 6: Mesh independence analysis of (a) FCR and (b) VCR profiles of CPC

Thermal analysis is performed on both collector profiles at three different fluid flow rate of 0.02 kg/s, 0.03 kg/s and 0.04 kg/s for three different irradiation values 600 W/m^2, 700 W/m^2 and 850 W/m^2 for three different time intervals of the day. In thermal analysis, after applying mesh and boundary conditions for fluid and absorber tube simulations are performed for 250 iterations and solution is converged. Temperature contours are generated for each performed simulation. Maximum temperature difference of 10° is achieved in case of VCR profile at 850 W/m^2 and 0.02 kg/s and in case of FCR profile at 850 W/m^2 and 0.02 kg/s. As flow rate is increased temperature difference is reduced but efficiency is increased. Generated temperature contours are shown in Figure 7.



(a) (b)

Figure 7: ANSYS generated temperature contours for (a) FCR profile and (b) VCR profile

Obtained temperature gain in result of the thermal simulations for FCR and VCR profiles at all three solar radiations and flow rates is shown in Figure 8.

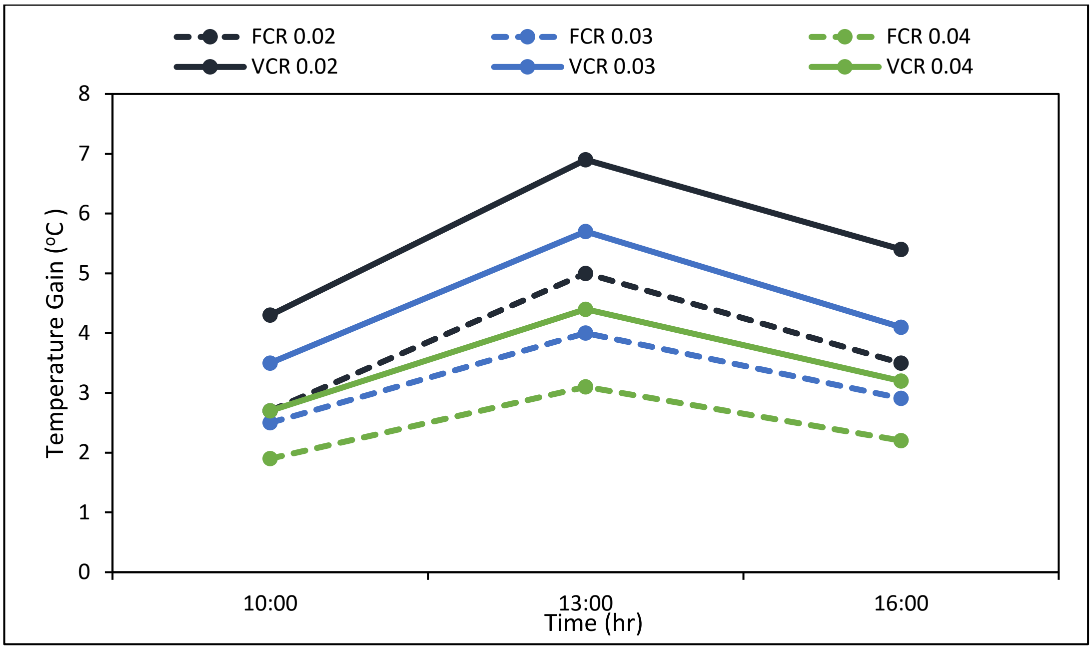


Figure 8: Temperature gain for FCR and VCR profiles

It is evident from the figure 8 that maximum temperature gain is obtained at 13:00 and at flow rate of 0.02 kg/s for VCR profile. In thermal analysis VCR profile performed 28.9% better compared to FCR profile. As in case of VCR profile heat flux is increasing along the length and is high from FCR profile because of the shape of the collector therefore, VCR profile showed better results.

Input flux value is applied that was generated from optical analysis in TracePro. In case of FCR profile flux value remained same but in VCR profile analysis variable flux is applied on absorber tube throughout the length of tube. Thermal efficiency for profiles of collector is calculated from the generated temperature difference. Efficiency of both profiles at different flow rates is shown in Figure 9. Theoretical formula to calculate thermal efficiency of solar collector is given in Equation 5-7.

$$\eta = \frac{Q_u}{Q_s} \quad \textbf{(5)}$$

$$Q_u = \omega\, C_p\, \Delta T \quad \textbf{(6)}$$

$$Q_s = A_a * G_e \quad \textbf{(7)}$$

Where, ω= fluid flow rate, C_p= specific heat of fluid at constant pressure, ΔT= Temperature difference between inlet and outlet, A_a =Aperture area of collector, G_e = Solar Radiations

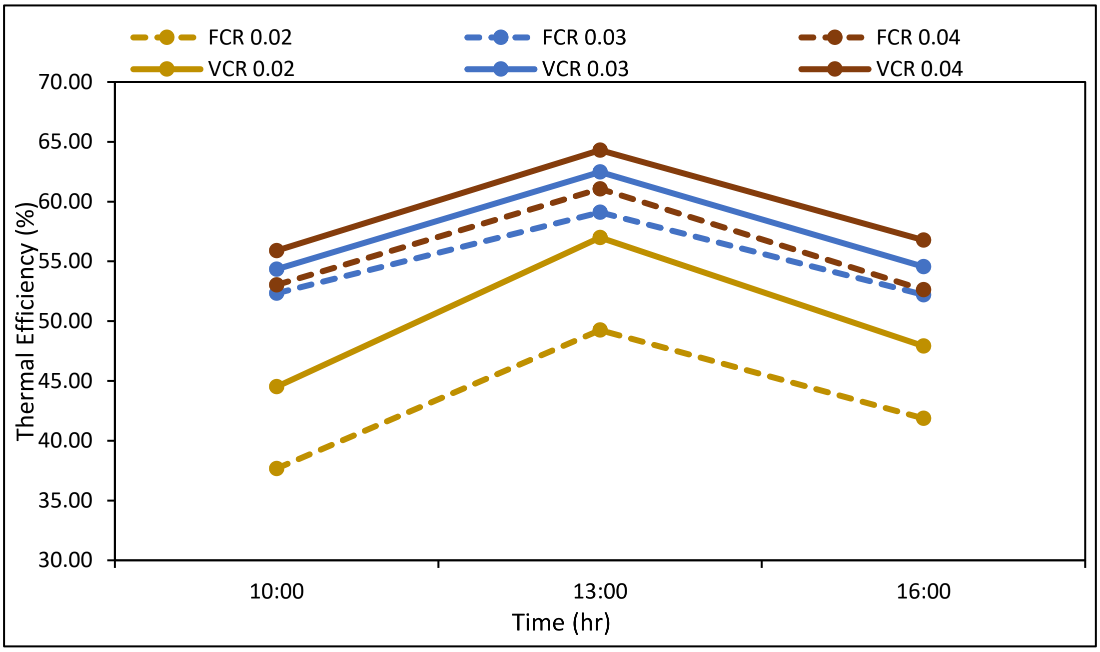


Figure 9: Thermal efficiency of FCR and VCR profiles

Maximum efficiency is obtained for VCR profile at maximum flow rate of 0.04 kg/s. VCR profile performed 28.9% better as compared to FCR profile because of the increase of flux along the length of tube.

CONCLUSION

In this paper, profiles of compound parabolic collector with fixed and variable concentration ratio have been developed and are then analysed thermally and optically. It has been determined that these profiles stand at better side as compared to non-concentrating collectors in respect to the temperature achievement. These two profiles are mutually compared, and analysis has been made that the profile of collector with variable concentration ratio performed 5% better during optical analysis than the profile with fixed concentration ratio and after the detailed thermal analysis on both the profiles it is concluded that profile with variable concentration ratio generated 28.9% better results compared to profile with fixed concentration ratio because of the increasing flux along the length in case of VCR profile. In future, it is recommended to perform thermosiphoning experimentation on compound parabolic collector to get rid of forced circulation of fluid in the collectors. With the application of flow circulation under capillary action efficiency of collector can be improved.

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