

Design and Optical Modeling of a Low-Profile Stationary Concentrating Solar Collector for Medium Temperature Heat Supply

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Abstract—Imaging type concentrating solar collectors need very accurate and continuous tracking mechanisms to efficiently collect and supply solar thermal energy in medium temperature range. Non-imaging nature of compound parabolic concentrators (CPC) enable these devices to concentrate incident radiation without the essential need of continuously tracking the source. CPC based solar collectors have great potential to supply solar thermal energy for numerous industrial applications especially operating in the medium temperature range. The choice of a CPC collector design varies depending on various aspects such as nature of intended application, operating temperature range, location and local environmental conditions. The present paper describes the design and optical modelling of a low concentration ($CR < 2$) symmetric 2-D CPC collector for medium temperature heat supply. Ray tracing technique was used to evaluate the optical performance of double parabolic concentrating trough and CPC trough with V-cavity at the bottom. The gap losses were significantly reduced by making V-shaped cavity at the bottom.

Index Terms—Acceptance Angle, Compound Parabolic Concentrator (CPC), Double Parabolic Concentrator (DPC), Concentration Ratio (CR)

I. INTRODUCTION

Prevailing energy scarcity coupled with increasing environmental challenges demand for the application of innovative renewable energy technologies especially solar thermal systems for sustainable and clean energy supply in cost-effective manner. Presently, major share of the industrial energy needs is being provided by limited conventional energy resources which are non-renewable and declining at rapid pace. The increased consumption of these conventional hydrocarbon-based fuels has also posed serious environmental threats. A major portion of the world total primary energy consumption is shared by industrial sector which is anticipated to further increase in the future as shown in Figure 1 [1]. Approximately, 40% of the total primary energy requirement of industrial sector is being met by natural gas while 41% by petroleum [2]. Prevailing energy scarcity scenario and increasing environmental concerns mandate for renewable and efficient energy garnering methods for energy security and sustainable development. In this perspective, solar thermal energy has got huge potential to meet future energy demand with minimum environmental

impact [3] because it is the most abundant and freely available source of renewable energy on the earth.

Flat plate collectors (FPCs) are the most commonly used solar thermal systems to exploit solar thermal energy but their applications are limited to low temperature range (usually below 90°C). Absorber area is almost equal to collector area in FPCs. To achieve medium or higher temperatures, solar radiations need to be concentrated on much smaller area of the absorber using various concentration techniques. Concentrating collectors such as parabolic troughs/dishes, Fresnel collectors and central tower systems, can be used to supply solar thermal energy in medium-to-high temperature range (above 100°C). However, these concentrating collectors essentially require precise and continuous tracking systems to achieve higher temperatures, efficiently collect solar energy and generally, very large-scale for efficient and cost effective heat supply [4].

CPC collectors are stationary non-imaging but concentrating type solar collectors which can efficiently collect and deliver solar thermal energy at medium temperatures ($90\text{-}250^{\circ}\text{C}$) without the essential need of accurate and continuous tracking mechanism [5]. Various designs of CPC based solar collectors have been presented and investigated by many researchers for various low- to medium-temperature solar thermal applications. The potential areas for application of CPC collectors include; industrial process heat, solar heating and cooling, water desalination and purification, hydrogen production by methanol reforming, solar hydrogen production, building integrated water heating systems and photovoltaic/thermal (PV/T) hybrid systems etc.

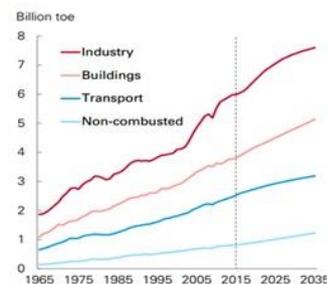


Figure 1: Sector-wise global primary energy consumption [1]

A. Compound Parabolic Concentrator

A CPC is the combination of two parabolas joined in such a manner that the the upper portions of parent parabolas almost become parallel to the common optical axis. In this way, all the incident solar radiations falling within the acceptance angle (angle between the two axis of parent parabolas) are directed towards the bottom of resulting CPC. Figure 2 shows the cross-section of a typical 2-D CPC construction. Incident solar radiations entering the inlet aperture of CPC at angles between $\pm \theta_a$ (called acceptance half angle) will be concentrated on a flat or tubular receiver positioned at the foot of both sides reflectors. The major advantages of a typical CPC collector include, but not limited to the following;

- i. No tracking mechanism is required for lower concentration range (below 3x) while for the medium concentration range (4x-10x) only intermittent seasonal adjustments is sufficient.
- ii. Both direct and diffuse radiations can be accepted for maximum possible acceptance angle for any given concentration ratio which give added advantage to these collectors.

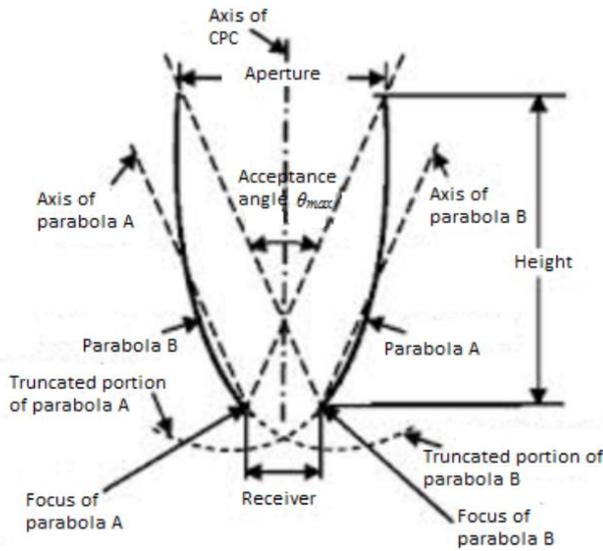


Figure 2: Cross-section of 2-D CPC collector

The initial concept of this non-imaging type concentrator was introduced by Winston [6] and Hinterberger [7] in 1965 while the idea of potential application of these ideal concentrators for the collection of solar energy was first presented by Roland Winston [8] in 1974. An ideal CPC collector can receive incoming radiations (including diffuse radiations) falling on entry aperture over maximum possible range of incident angles and direct the accepted radiations towards the bottom without continuous tracking the position of sun [9].

B. Geometric Construction of CPC

The design of a CPC can vary in many aspects depending on the intended application and geographical location. However, following basic components are generally part of every CPC;

Reflector: The primary function of a reflector or concentrator, as it is sometimes called, is to accept maximum amount of solar radiations falling on its aperture and concentrate onto the receiver with minimum losses. Material

of a good reflector should be selected such that it has maximum possible reflectance. Selective surface coatings can also be applied to increase the reflectivity of reflecting surfaces.

Absorber: Solar radiations fall on the receiver surface either directly or after reflecting from the concentrator. Absorbed solar heat is transferred to the heat transfer fluid (HTF) flowing inside the absorber. The material of absorber should have high absorptivity and low emmissivity to maximize the absorption of short wave solar radiations and minimize thermal losses as well as high-conductivity to transfer the absorbed heat to the HTF efficiently. Vacuum around the absorber can suppress convection losses while special surface coatings can help improve heat absorption and decrease radiation losses.

Outer Cover: A protective cover is sometimes used at the entry aperture which save the surface reflector from environmental damages. Such covers can also be helpful in reducing thermal losses from the internal cavities of concentrator. Therefore, an ideal cover should have maximum possible transmittivity towards the incoming short wave solar radiations and low transmittance for long wave thermal radiations emanating from the receiver to reduce thermal losses.

For an ideal CPC with tubular absorber as shown in Figure 3, any point M on the concentrator can be defined by considering angle φ (between lines from the origin O to K) and distance ρ (line MN between point M and tangent at point N on the periphery of absorber). Thus the right side of reflector of an ideal CPC with tubular absorber of radius 'r' can be generated using Equation (1) as given in [10];

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

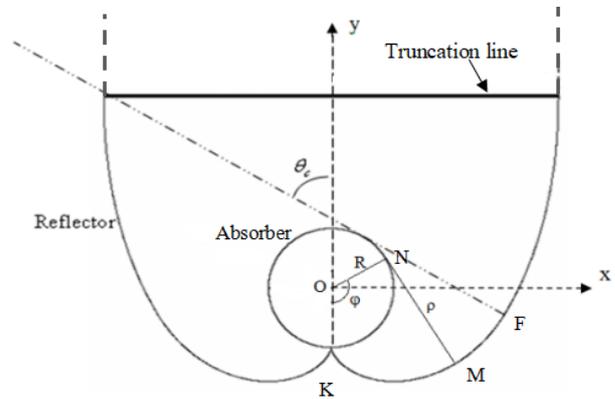


Figure 3: Geometric profile of a CPC with tubular absorber

The lower part in reflector profile ($0 \leq \varphi \leq \frac{1}{2}\pi + \theta_a$) is involute and upper part ($\frac{1}{2}\pi + \theta_a < \varphi \leq \frac{3}{2}\pi - \theta_a$) is parabolic. The distance 'ρ' can be determined by using string method as presented by [5] and expressed in Equation (2);

$$\frac{\rho}{r} = \begin{cases} \varphi, \dots, \text{for } 0 \leq \varphi \leq \frac{\pi}{2} + \theta_a \\ \frac{\pi + \theta_a + \varphi - \cos(\varphi - \theta_a)}{1 + \sin(\varphi - \theta_a)} \text{ for } \frac{\pi}{2} + \theta_a \leq \varphi \leq \frac{3\pi}{2} - \theta_a \end{cases} \quad (2)$$

Geometric concentration ratio (C_g) of a CPC is the ratio between area of entry aperture (A_{apr}) and area of the absorbing

surface (A_{abs}). For a trough-like CPC equipped with with a tubular receiver having length equal to that of the reflector, C_g can be defined as ratio between width of entry aperture and circumference of the tubular receiver [11] and is given in Equation (3);

$$C_g = \frac{A_{apr}}{A_{abs}} \quad (3)$$

As an exclusive type of non-imaging collectors, CPCs have widely been investigated by many researchers during the 1970s and 1980s. Winston et al. [12] and Rabl et al. [13, 14] carried out extensive calculations in the early 1970s which laid the foundation for future research in design, construction and modelling of CPCs [15]. Afterwards, numerous alternative designs of compound parabolic concentrating collectors have been presented and investigated by researchers. Performance of different designs of concentrating solar collectors in terms of concentration ratio, acceptance half angle, average number of reflections and reflector size was compared by [16]. He also analysed the relationship between CR, acceptance half angle, and operating temperature to design a CPC collector with high CR and maximum efficiency.

Numerous designs of CPCs for improved optical and thermal performance have been presented by many researchers. W. Winston and H. Hinterberger [12] proposed a general method for designing CPC reflector for the purpose of concentrating incident solar radiations onto a cylindrical receiver. Basic principles of optical design for some selected arrangements of non-imaging type evacuated and non-evacuated solar collectors were reviewed by [17]. Different designs of concentrators with cylindrical absorbers were compared by [18]. However, the research study only focused on comparison of annual energy collection for two configurations, i.e. north-south (NS) and east-west (EW) orientations and did not consider thermal losses in the performance evaluation.

C. Geometric Optics

Compound parabolic concentrating collectors have very good light focusing ability and performance of a CPC is significantly influenced by the material properties of reflectors, receivers, and covers (if used) as well as geometric design. Acceptance half angle and concentration ratio are among the most common parameters which describe the geometric characteristics of a CPC as shown in Figure 2. The maximum achievable optical concentration ratio (C_i) for an ideal trough-like CPC, as defined by [19], can be determined relation shown in (4);

$$C_i = \begin{cases} \frac{1}{\sin \theta_c} \dots\dots \text{for 2-D...CPC} \\ \frac{1}{\sin^2 \theta_c} \dots\dots \text{for 3-D...CPC} \end{cases} \quad (4)$$

re θ_c is the maximum acceptance half angle of a full-length CPC. Concentration ratio of a CPC is generally lower than other concentrating type collectors equipped with accurate tracking mechanisms [16] but have wide range of acceptance for any given acceptance half angle. CPC designs with lower concentration ratio (<3x) are mostly stationary while those

with higher CR (≤ 10) may involve a few intermittent tilt adjustments to ensure year-round performance.

D. Geometric Modifications

Various geometric modifications in reflectors and absorbers have been presented and studied by many researchers for performance enhancement and reduction in optical and thermal losses. Some of the modifications were based on geographic locations, intended applications and/or economic considerations for the manufacturing of collectors etc.

The reflector height of an ideal CPC with specific acceptance half angle is very large which leads to high material and manufacturing costs. However, this limitation can be overcome by exploiting the fact that the upper parts of reflectors are nearly perpendicular to the aperture and hence contribute very less in concentrating incident solar radiations. Therefore, top portions of an ideal CPC reflector can be removed with only small reduction in CR. Apart from reflector material saving, view field of a CPC is also increased as a result of truncation as shown in Figure 4 (a) and thus more radiations can reach the receiver, falling outside of the nominal acceptance half angle, which increase the overall energy gain and efficiency of the collector.

The effect of truncation on concentration ratio of CPC was quantified by [12] and [20]. Figure 4 (b) shows the variation of CR against height to aperture ratio for full length as well as for truncated 2-D CPC with flat bottom receiver. Solid lines show the variation of CR for different half acceptance angles for the truncated CPC while dashed line demonstrate the relationship for fully developed CPC. The solid lines become nearly steep near the dash line which indicate that the decrease in CR is reasonably small for useful truncation of upper parts of the reflector .

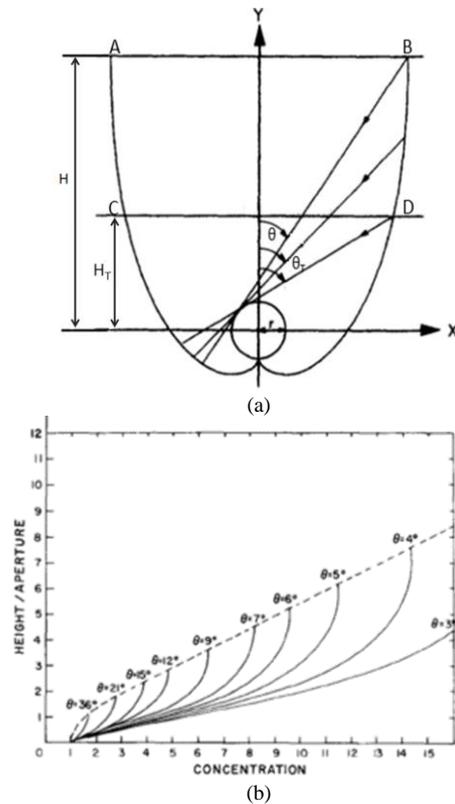


Figure 4: (a) Truncation of a 2-D CPC with tubular absorber, (b) Variation of CR against height/aperture ratio [12]

II. GEOMETRIC DESIGN OF THE PROPOSED CPC

The proposed CPC was constructed by joining two identical parabolic segments in such a way that the both were tilted inward by an angle of 30° where upper sides became almost vertical as shown in Figure 5 (b). The inner walls of the parent parabolic segments were truncated at intersection point and then fused together to form a profile of double parabolic trough. The bottom parts of both lower parabolic portions were replaced with corresponding circular portions to form a trough profile with a cusp at the center. A V-shaped cavity was provided at the bottom to lower the position of receiver in order to reduce gap losses occurring due to gap between the absorber tube and envelope glass tube. The initial position of the receiver is shown in dotted lines. The cross-section of resulting trough is shown in Figure 5 (c).

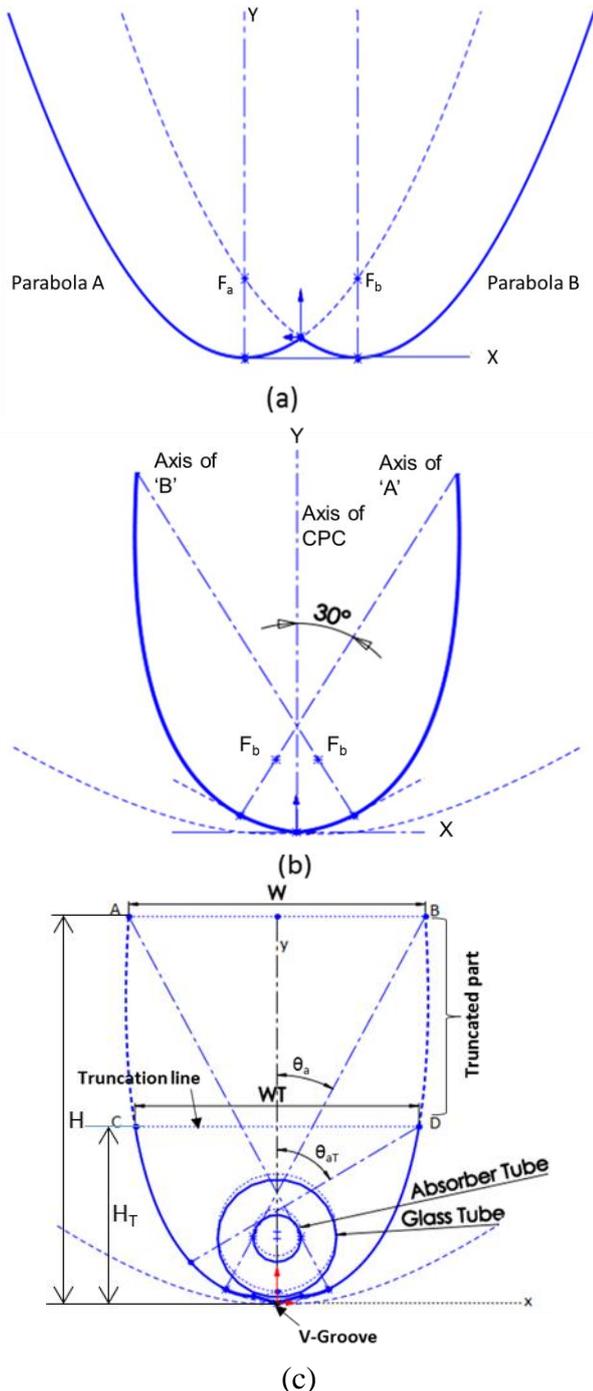


Figure 5: Construction of new CPC profile

A. Truncation Effect

The outer walls become almost normal to the entry aperture plane and thus contribute very little in the concentration of incident solar radiations. Therefore, upper vertical portion of reflector can be truncated with little decrease in aperture width and hence small corresponding loss in CR. Thus a significant amount of material was saved by removing upper halves of the reflector. As a result of truncation, view field of CPC was also increased from θ_a to θ_{aT} due to which effective period of incidence of direct solar radiations on the cylindrical absorber was almost doubled. Height of the CPC decreased linearly while width and CR first decreased slightly up to almost 50% truncation and then rapidly as the level of truncation increased as shown in Figure 6. Therefore, the upper portion of the original height was truncated by 50% with only about 8 % corresponding decrease in the CR. The vertical height of the truncated CPC was chosen 134 mm with 233 mm corresponding width while length of the reflector was 2000 mm. Construction parameters of the proposed CPC trough design are summarized in Table 1.

Table 1
Construction parameters of CPC

Parameter	Unit	Design Value	
		Original	Modified/truncated
Reflector size	mm	H=268 W=254	H _T = 134 W _T = 233
Aperture area	(m ²)	0.508	0.466
Concentration ratio (CR)	-	2.02	1.85
Acceptance half angle (θ_a)	degree	30	30+28
Absorber Tube	mm	L=2000 ϕ =40	-
Glass Tube	mm	L=2000 ϕ =100	-

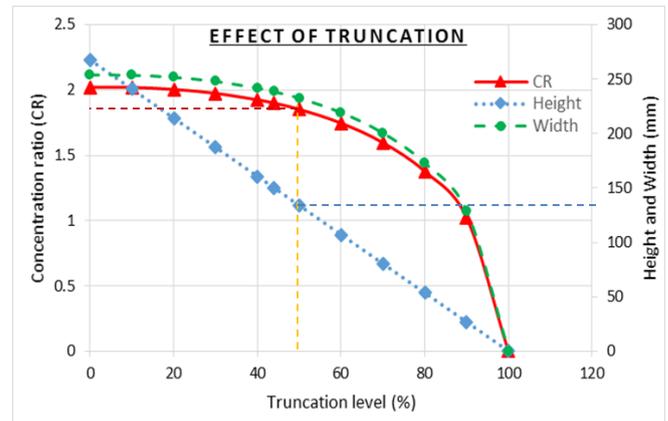


Figure 6: Effect of truncation on CR of the proposed CPC

A CPC module was constructed by assembling three similar troughs in such manner that the optical axis of outer troughs were tilted outward by an angle of 15° as shown in Figure 7. For north-south orientation of this configuration, more than one trough will be active for most of the time of a day. The central trough will capture maximum irradiance at noon while the outer troughs will capture more irradiance before and afternoon sessions when the incidence angle of solar radiations fall within the acceptance half angles of the outer troughs. This type of arrangement is anticipated to increase the effective time of operation and smooth out the

power output by maximizing the collection of solar energy in the first as well as second half of a day.

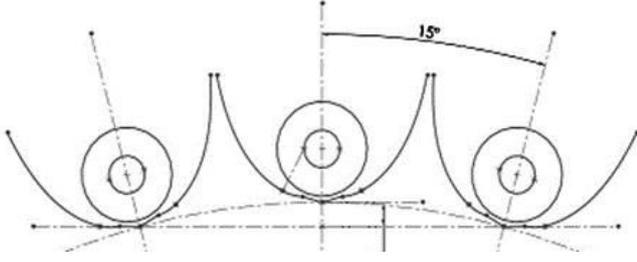


Figure 7: Front view of the proposed CPC module

III. OPTICAL MODELING

A considerable portion of solar radiations is reflected, absorbed or scattered by atmosphere depending upon the local weather conditions. The portion of solar energy that directly reach at the surface of earth on a clear sky, without any reflection, absorption, or scattering in the atmosphere, is approximately 1000 W/m^2 [21, 22]. Total radiations falling on a CPC collector consists of direct or beam radiations as well as diffuse radiations which must also be considered for accurate optical modelling. The total radiation intensity ' I_t ' for concentrating type collectors with concentration ratio ' C ', can be determined using (5), where ' I_b ' represent the direct or beam radiations and ' I_d ' is diffuse radiations as stated by [9];

$$I_t = I_b + \frac{I_d}{C} \quad (5)$$

A. Useful Optical Energy Gain

The useful optical energy of direct or beam radiations which is absorbed by the receiver of a CPC collector ' q_b ' can be determined using (6) by taking into account various optical losses;

$$q_b = I_b A_c \tau_c \tau_e \alpha_r p \quad (6)$$

where ' I_b ' indicate the intensity of beam radiations, ' A_c ' is area of entry aperture, ' τ_c ' and ' τ_e ' is transmissivity of cover (if any) and envelope (glass tube) respectively, ' α_r ' is absorptivity of absorber and ' p ' is the gap loss factor.

The open side of the receiver directly receives the diffuse radiations. Thus, area of absorber ' A_r ' is used in calculating the effective diffuse radiations. The amount of diffuse radiations can be calculated by (7) as given by [23] by neglecting specular and ground reflection of radiations;

$$q_d = I_d A_r \bar{\tau}_c \bar{\tau}_e \bar{\alpha}_r p \quad (7)$$

where $I_d, \bar{\tau}_c, \bar{\tau}_e, \bar{\alpha}_r$ are average values of the respective properties for diffuse solar radiations and can be determined on the basis of estimated value of effective incidence angle of diffuse radiations.

B. Optical Efficiency

The optical efficiency of a CPC can be defined as ratio of radiations energy absorbed by the absorber ' q_u ' to the total energy of radiations ' I_t ' incident on the entry aperture ' A_c '. Mathematically, optical efficiency can be described by (8);

$$\eta_o = \frac{q_u}{I_t A_c} \quad (8)$$

Considering beam and diffused radiations separately, equation (8) can be modified as given in (9);

$$\eta_o = \frac{q_b + q_d}{(I_b + I_d/C) A_c} \quad (9)$$

Since various different concentrators have been designed and developed by many researchers, the design parameters should be considered and selected according to the geometric characteristics of the specific concentrator. For example, a CPC with cylindrical receiver was developed by Hsieh [24]. He considered direct and diffuse components of incident light separately and assumed grey surfaces of the interacting components to derive an expression for the optical efficiency as given in (11);

$$\eta_o = \left(\frac{H_b + H_d/C}{H_b + H_d} \right) \rho_m^n \tau_c \tau_e \alpha_r f p \quad (10)$$

where ' H_b ' and ' H_d ' represent average values of beam and diffuse incident flux respectively; ' ρ ' is surface reflectivity of the concentrator, ' n ' is average number of reflections while ' τ_a and ' τ_e ' represent transmissivity of aperture cover (if used) and envelop of absorber tube respectively; ' α_r ' is absorptivity of absorber tube; ' f and ' p ' represent correction factors for multi-reflections of radiations and gap losses between reflector and absorber, respectively.

C. Ray Tracing

The CPC geometry was designed in SolidWorks and imported into TracePro-7.8.0 software. The material and surface properties were assigned to the collector components and optical paths of incident solar radiations (direct and reflected from the concentrator) were traced to evaluate the optical performance. Ray tracing diagrams for the double parabolic concentrating trough and CPC with V-groove at the bottom are shown in Figure 8 and Figure 9 respectively for three incident angles ($0^\circ, 25^\circ, 35^\circ$). Figure 8 (c) and Figure 9 (c) show that the CPC with V-cavity at the bottom can intercept more radiations than DPC at incident angles greater than nominal acceptance half angle. A considerable amount of incident radiations escape from the collector after reflecting from the concentrator and passing through the gap between absorber tube and evacuated glass tube which result in higher gap losses. Such gap losses can be reduced by using absorber tubes with extended fins to minimize the gap.

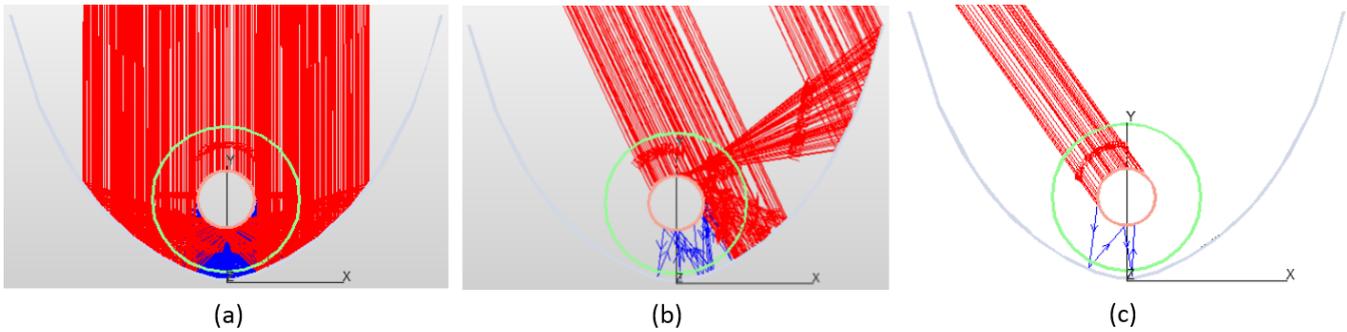


Figure 8: Ray paths for incident radiations on DPC at incidence angle (a) 0°, (b) 25°, (c) 35°

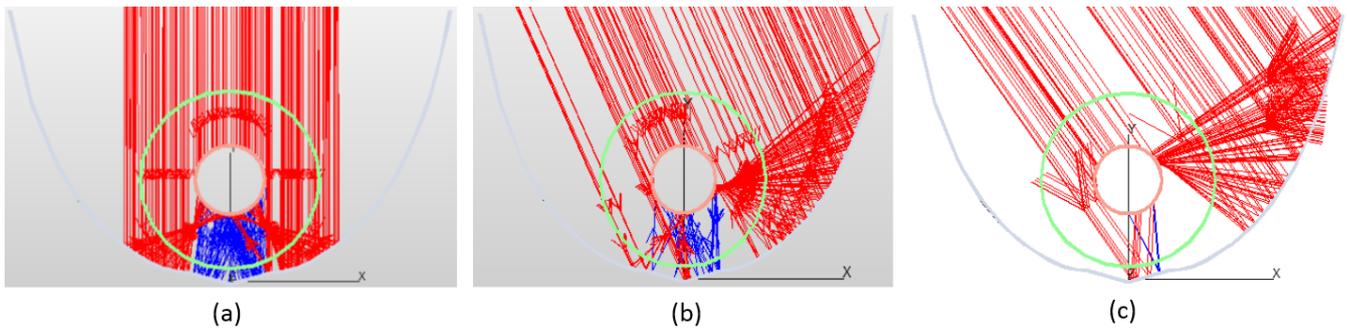


Figure 9: Ray paths for incident radiations on CPC with V-groove at incidence angle (a) 0°, (b) 25°, (c) 35°

IV. CONCLUSIONS

CPC collectors have great potential to provide solar thermal energy in the medium temperature range. Although concentration ratio is relatively low as compared to tracking solar collectors, CPC collectors have the advantage to collect both direct and diffuse radiations over relatively wide acceptance angle without the essential need of complex tracking mechanisms. In this paper, design of a low concentration CPC collector is presented which consists of three similarly constructed CPC troughs. Geometrical concentration ratio of the original CPC troughs was 2.02 and acceptance half angle 30°. Truncation level was selected to be 50% and thus upper halves of the reflectors were truncated to save significant cost of material and manufacturing of reflectors with only about 8% decrease in CR.

Monte Carlo ray tracing using TracePro 7.8.0 was applied to compare the optical performance of DPC and CPC with V-cavity. The ray tracing analysis showed that the CPC with V-cavity could intercept more radiations due to reduced gap losses. Gap losses can be further reduced by using absorber tube with extended fins.

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