Optical analysis of an evacuated tube collector with built-in compound parabolic concentrator for process heat applications

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Abstract. To date, insufficient attention has been paid to the potential of renewable energy resources in industrial applications. Up to 21% of final energy demand and feedstock-use in the manufacturing industry sector could be of renewable origin by 2050. Process temperatures found in industrial processes range from low (T<100ºC), medium (100ºC < T < 250ºC) to high (T > 250ºC) temperatures. Whereas low temperature applications are already addressed by well-established collector technologies, the medium temperature applications are still in an early development stage. The aim of this study is to evaluate the optical performance of an Evacuated Tube Collector with Compound Parabolic Concentrator (ETC-CPC) used for medium temperature industrial process heat. To this end, an optical simulation model is developed in Tonatiuh ray-tracing software and is validated towards the theoretical fully developed curve. The parametric analysis performed investigates the impact of the truncation origin, the reflectivity of the CPC mirror and the absorber radius on the optical efficiency and the power production of the solar collector. It is found that the collector with the biggest truncation origin (0.025m) performs better under small Sun angles (0°-20°), but worse under greater Sun angles (40°-90°). This happens because the collector with the greatest truncation origin has the biggest mirror area and under small Sun deviations this leads to more gains and higher efficiency. The quality of the mirror plays an important role in the optical efficiency of the collector, but mainly for incident angles less than 20°. Moreover, increasing the radius of the absorber, the power production per aperture area is increased. The variation of the absorber radius shows that the radius of the base scenario compensates most of the optical errors but without being big enough to have excess heat loss. The results of this study are valuable for the design, simulation and performance analysis of ETC-CPC for delivering medium temperature heat.

1. Introduction
To date, insufficient attention has been paid to the potential of renewable energy resources in industrial applications. An analysis suggests that up to 21% of final energy demand and feedstock-use in the manufacturing industry sector could be of renewable origin by 2050, a five-fold increase over current levels in absolute terms. In addition, if a 50% share of renewables in power generation is assumed, the share of direct and indirect renewable energy use rises to 31% in 2050 [1].

Currently he usage of for solar heat in industrial proceeded is limited. While low-temperature solar process heat can reach cost-effectiveness today in locations with good irradiation, in early 2014, there
were around 130 solar thermal plants for industrial process heating worldwide, comprising 93 MWth of total capacity [2].

Process temperatures found in industrial processes range from low (T<100°C), medium (100°C < T < 250°C) to high (T > 250°C) temperatures [3,4]. Whereas low temperature applications are already addressed by well-established collector technologies, the approach to medium temperature applications relies on a range of collector technologies [5].

The solar collector considered in the present study addresses the medium temperature applications and consists of a row of evacuated receiver tubes, in which an absorber with a special absorption layer is placed. A CPC is placed inside the evacuated tube and underneath the absorber tube in order to direct the solar radiation onto the absorber. The addition of the CPC component is expected to increase the optical efficiency of the evacuated tube collector.

2. State of the art

In the literature there are many studies discussing the optical and thermal properties of the evacuated tube collectors and the CPCs. Back in 1974, Winston [6] studied a novel collector with a trough-like reflecting wall light channel with a concentration factor of -10 without diurnal tracking of the sun. One year later, they further developed their study [7] by proposing the use of one tube receiver of general shape for maximizing the concentrating radiation. They provided the concentrator designs with different receiver cross sections; circular, oval and fin. Rabl [8] compared a variety of solar concentrators in terms of concentration ratio, acceptance angle, sensitivity to mirror errors, size of reflector area and average number of reflections. Discussing the connection between concentration, acceptance angle and operating temperature of a solar collector, he lead to a design method for maximum concentration. Rabl's following study [9] presented useful formulas for evaluating the convective and radiative heat transfers and the performance of a CPC solar collector. Calculation of optical losses was also implemented through the evaluation of the number of reflections and the effects of truncation were explicitly described. Rabl also developed [10] a simple analytic formula for calculating the average number of reflections, valid for many configurations, without any raytracing. Rabl studied the performance of various receivers [11], introduced an optimum method for calculating the gap between receiver and reflector and studied the effect of a glass envelope around the receiver. He also estimated the effect of mirror errors and receiver misalignment, as well as the effect of the temperature difference between fluid and absorber plate. Garisson [12] introduced valuable criteria for optimizing solar thermal energy collection and calculated the radiation, conduction and pumping losses. Garisson initial optimization steps lead to an all glass vacuum collector tube with an interior glass tube coated with a selective absorber. One of the first developments of evacuated CPC collectors was implemented by O’ Gallacher et al [13]. Design, development and testing of the collectors lead to the instantaneous performance curve development. The calculated efficiency was greater than 40% across the full operational range. Truncation of CPC solar collectors is extensively discussed in the study of Carvalho and Collares-Pereira [14]. They derived analytical expressions for the angular acceptance function of two-dimensional CPCs and specified the optical gains from truncation; increased acceptance of diffuse and beam radiation and reduced average number of reflections. Carvalho and Collares-Pereira experimentally tested [15] a CPC collector with an inverted “V” receiver, in different configurations. The calculation of the average yearly performance showed that up to 100°C, the CPC collector outperforms the flat plate and evacuated tubes and has a comparable cost. More recently, Kim et al. [16] developed and validated an one-dimensional numerical model for an all-glass evacuated tube solar collector. Kim et al showed that their model could be used in the design of all-glass solar collector tubes with different geometrical parameters. Kim et al. [17] continued their research by considering an evacuated CPC solar collector with a cylindrical absorber was discussed. Two types of evacuated CPC collectors, stationary and tracking, were designed and tested at outdoor conditions. The thermal performance was investigated numerically and experimentally and it was shown that the tracking CPC solar collector is more stable and has 14.9% higher thermal efficiency than the stationary one. All-glass vacuum tube collector was also the objective of the study of Li et al.
Li et al. developed and validated a heat transfer model considering a physical model and found reasonable deviations. Buttinger et al. [19] developed a new non-tracking, low concentrating collector that aimed specifically at delivering process heat at temperatures 120-150°C. Buttinger et al. study presented collector’s optical efficiency of about 50% at a temperature of 150°C with a radiation of 1000W/m². Glembin et al. [20] investigated the use of coaxial tubes for vacuum tube collectors and developed a model to calculate the temperatures. It was found that the collector efficiency highly depends on the flow rate and that the temperature difference is increased with decreasing flow rates. A mathematical procedure for the estimation of the annual radiation captured by fixed CPCs oriented in east-west direction was developed by Tang et al. [21]. Effects of tilt-angle and azimuth angle of CPCs on the annual solar gain were also presented. Ma et al. [22] studied the thermal performance of the individual glass evacuated tube solar collector through the development of an analytical model. The heat loss coefficient and heat efficiency factor were analyzed using one-dimensional analytical solutions. The thermal performance of a mini-channel based solar collector was investigated numerically by Sharma and Diaz [23]. The collector consisted of an evacuated-glass envelope with a U-shaped flat-tube absorber, in which there was an array of mini-channels located in the cross-section along its length. The authors developed a numerical model and prove an efficiency gain towards a similarly sized evacuated-tube solar collector. Pei et al. [24] set up an experimental rig of evacuated tube solar water heater systems with and without a mini-CPC reflector and compared their performance. They found that the evacuated tube collector without CPC has higher thermal and exergy efficiency than the collector with CPC. The evacuated tube collector without CPC found to be more suitable for low temperature applications, while the collector with CPC was found to be suitable for higher temperature applications. Nkwetta and Smyth analyzed two profiles of concentrated evacuated tube heat pipe solar collectors made of single-sided and double-sided absorber [25]. The concentrated double-sided absorber evacuated tube heat pipe proved better compared to the concentrated single-sided absorber evacuated tube heat pipe solar collector due to higher outlet temperature with greater temperature differential and improved thermal performance. Nkwetta and Smyth also evaluated the optical performance of an internal low-concentrating evacuated tube heat pipe solar collector for medium temperature applications [26]. Their raytracing analysis resulted in an optical efficiency of 79.13% for transverse angles 0-20°. A similar study on U-tube evacuated tubular collector with and without external CPC reflectors [27] developed an improved procedure to determine the transversal incidence angle modifier according to EN 12975-2. Badar et al. [28] dealt with a vacuum tube solar collector with coaxial piping (direct flow type) incorporating both single and two-phase flows. The analytical steady state model predicted the thermal performance of the collector and it was found that the collector efficiency is decreased with decreasing mass flow rate. Lauterbach et al. study focused on the calculation of the solar process heat potential of to specific industrial sectors in Germany [29]. Lauterbach et al. found that the theoretical potential of solar heat for industrial processes below 300°C in Germany accounts for 134 TWh per year and the technically applicable potential is 3.4% of the overall industrial heat demand. Antonelli, et al. research study [30] estimated the thermal heat losses inside CPC collectors, through CFD simulations on various CPC designs. The results were used to develop correlations for the Nusselt number on the receiver and to calculate the heat losses of the receiver. The influence of different parameters such as the shape of receiver, the tilt angle and the concentration ratio were also discussed. The relationship between the collector design, the optical efficiency and the size of the gap were also elaborated. Schmitt [31] studied the classification for the integration of solar process heat concepts for the majority of all industrial processes and operations. A new model with a V-shaped profile at the bottom of the CPC reflector was proposed [32]. The detailed optical model was built and design parameters were discussed, such as geometrical optics efficiency, transmittance, reflectance and absorption ratio. Kumar et al. [33] investigated theoretically the performance of heat pipe solar collectors and found that they are sensitive to the solar radiation, the ambient temperature as well as to the length of evaporator. Aguilar-Jiménez et al. [5] provided a comparative study of two compound parabolic concentrators with a concentric tube as absorber.
As shown it is limited research work performed considering the optical design aspects in ETC combined with built-in CPC reflector. This work aims at identifying the effect of main parameters, such as the truncation origin, the mirror reflectivity and the absorber radius to the optical efficiency of the ETC-CPC collector.

3. Optical Analysis

3.1. Description of the solar collector
Evacuated tube collectors differ in their design, in terms of materials and the shapes of the absorber [34]. The selected ETC-CPC type under investigation consists of an evacuated glass tube in which the absorber tube is placed (Figure 1) A truncated compound parabolic concentrator is placed inside the evacuated tube and underneath the absorber. The solar radiation that penetrates the glass tube it either hits directly the absorber or hits the surface of the CPC mirror and it is then reflected to the absorber. In the surface of the absorber tube, the solar energy is absorbed and converted into heat which is then transferred to the heat transfer medium that flows inside the absorber.

![Figure 1: Schematic diagram of the base-scenario for the ETC-CPC under investigation](image)

3.2. Methodology
The optical analysis is implemented through the development of an optical simulation model in Tonatiuh ray tracing software [35]. Tonatiuh is a Monte Carlo ray tracer for the optical simulation of solar concentrating systems and it was selected due to its high accuracy and adaptability to model modifications. Up to date, Tonatium has already been used in research work with similar subject [36, 37, 38].

Once the shape of the solar collector is developed, Tonatiuh simulates the system's optical behavior, under different solar conditions. These conditions are characterized by the Sun position in the sky, which define the main direction of the incoming direct solar radiation, and the direct solar irradiance, which defines the amount of radiant power per unit area normal to the main direction of the incoming solar radiation associated with that radiation.

Initially, a theoretical fully developed CPC curve was built and simulated in order to evaluate the accuracy of the results. CPC curve was aimed to have the same characteristics with the ETC-CPC solar collector under investigation. Table 1 shows the input variables, both for the base scenario of the ETC-CPC under investigation and the theoretical fully developed CPC curve. The solar conditions set
are: Sunshape, type: Pillbox, irradiance: 1000W/m², \( \theta_{\text{max}} \): 0.00465 rad. The simulation results for the fully developed curve showed intercept factor of 0.998 and therefore, the accuracy of the developed model is considered acceptable.

| Parameter | ETC-CPC | Fully developed curve | Unit |
|-----------|---------|-----------------------|------|
| \( D_{g,o} \) | 0.1     | not applicable        | m    |
| \( D_{g,i} \) | 0.093   | not applicable        | m    |
| \( D_{\text{abs},o} \) | 0.015   | 0.015                 | m    |
| \( R_{\text{cpc},i} \) | 0.0075  | 0.0105                | m    |
| \( R_{\text{cpc},o} \) | 0.0105  | 0.0105                | m    |
| \( \theta_{\text{acc}} \) | 20      | 20                    | deg  |
| \( \theta_{\text{trunc}} \) | 0       | 0                     | deg  |
| \( t_o \) | 0.025   | not applicable        | m    |
| \( \rho \) | 0.95    | 1                     | -    |
| \( L \) | 1       | 1                     | m    |
| \( A \) | 0.1     | 0.193                 | m²   |
| \( \text{DNI} \) | 1000    | 1000                  | W/m² |
| \( Q_{\text{abs}} \) | 84.8736 | 192.672               | W    |
| \( \eta_o \) | 84.87   | 99.83                 | %    |

Table 1: Technical characteristics of ETC-CPC under investigation and for the fully developed CPC curve.

Figure 2 depicts the path of the solar rays for the fully developed curve under various Sun deviations from the transversal plane. This was implemented via the "Sun Position" operation, by varying the Azimuth (Degrees North towards East) and the Elevation (Degrees from horizontal plane). With 500 rays selected to be showed, at 0° Sun deviation most of the sun rays actually hit the absorber and the concentrator produces 192.7W. At 20° deviation far less rays succeed to hit the absorber and the production becomes 113.5W. At Sun deviation 30°, most of the rays fail to hit the absorber and the power production has now become negligible.

Figure 2: Raytracing analysis in the fully developed curve. Sun at 0° deviation from the transversal plane (left), Sun at 20° (middle), Sun at 30° (right).

Figure 3 shows the raytracing analysis implemented for the base scenario of the ETC-CPC solar collector. The glass envelope is built as two concentric surfaces. In the figure this is not clearly shown due to the glass transparency. The intercept factor of this collector is 0.847, which is less than that of the fully developed curve. This can be attributed mainly to the truncation origin and the not ideal mirror reflectance value.
Figure 3: Raytracing analysis in the ETC-CPC solar collector. Sun at 0° (left), Sun at 20° (middle), Sun at 30° (right).

3.3. Base Scenario
The power produced by the ETC-CPC collector and the fully developed curve is shown in Figure 4. It can be seen that the power production of the ETC-CPC is evident under a greater range of Sun angles and that this production is minimised at 70° Sun deviation. On the other hand, the power production of the fully developed curve is greater for small Sun deviations up to 20°, but it is sharply eliminated for Sun deviations greater than 20°. As a whole, the truncated ETC-CPC solar collector performs better than the fully developed curve, due to the increase in acceptance angle.

Figure 4: Power per aperture area produced for fully developed curve and for ETC-CPC

The Incidence Angle Modifier (IAM) curve, both for the ETC-CPC collector and the fully developed curve follows the trends of the power production, as seen in Figure 5.
4. Parametric Analysis

Following the discussion of the performance of the base scenario, a parametric analysis is implemented to investigate the impact of variables on the optical efficiency and the power production of the ETC-CPC. The selected parameters are the truncation origin, the reflectivity of the CPC mirror and the absorber radius.

4.1. Truncation Origin

Truncation modifies the field of view of a CPC, allowing some rays beyond the nominal acceptance half angle to reach the absorber [14]. For this scope, the base scenario, 0.025m, was compared towards three additional truncation origins; namely, 0.01m, 0.015m and 0.02m. Figure 6 shows the power produced by each case. Indeed, the collector with the biggest truncation origin (0.025m) performs better under small Sun deviations (0°-20°), but worse under greater Sun deviations (40°-90°). This happens because the collector with the greatest truncation origin has the biggest mirror area and under small Sun deviations this leads to more gains and higher efficiency. However, the same collector has smaller acceptance angle and under greater Sun deviations this leads to less gains and lower efficiency. It can also be seen that there is a range of Sun deviations in which the power production of all cases is similar (20°-40°). The sharp angular cut-off between rays that do and rays that do not reach the absorber can be seen at the points where the curves cross the x-axis. This cut-off happens at around 70° Sun deviation for 0.025m truncation height and at 80° at 0.015m truncation height.
Figure 6: Power per aperture area produced for different truncation heights.

Regarding the IAM curve in Figure 7, for Sun deviations up to 20° all cases follow the same trend. However, under Sun deviations greater than 20°, there are greater deviations from the maximum optical efficiency which in turn result in greater differences in IAM curves. It is also evident that as the truncation origin of the solar collector increases, the IAM and the power produced are minimised at smaller Sun deviations.

Figure 7: IAM for different truncation heights
Figure 8: Maximum optical efficiency for different truncation origins

Figure 8 shows the maximum optical efficiency for the four truncation heights. As the truncation origin is increased, the mirror area is also increased, which leads to the increase in the optical efficiency.

4.2. Mirror Reflectivity

The quality of the mirror seems to play an important role in the optical efficiency of the collector, but mainly for incident angles less than 20°. Within this range, great variations in the power production can be seen (Figure 9) and subsequent variations are seen in the maximum optical efficiency (Figure 11). This happens because at small incident angles the solar rays are reflected many times before hitting the absorber and since there is a percentage of solar radiation lost in each reflection, the mirror reflectivity plays an important role on the optical efficiency and the produced power. On the other hand, under incident angles greater than 20°, the number of reflections is decreased and the impact of mirror reflectivity becomes less important.

Figure 9: Power produced for different values of mirror reflectivity, per aperture area

The reflectivity of the mirror does not have a significant impact on the IAM curve, as seen in Figure 10.
4.3. Absorber radius

The impact of varying the radius of the absorber is shown in Figure 12 - Figure 14. Increasing the radius of the absorber, the power production per aperture area is increased. This happens because increasing the radius, the absorber’s area is increased and therefore, more rays have the potential to hit the surface of the absorber. Specifically, for 30° incident angle, the 0.01m radius produces 451W/m², the 0.0075m produces 289W/m² whereas the 0.01m radius gives 215W/m². IAM curves follow the same trend. Moreover, a great difference in the maximum optical efficiency is seen (Figure 14) when the absorber radius is decreased, but this difference becomes negligible when the radius is increased further than the base scenario. This phenomenon indicates that the radius of the base scenario compensates most of the optical errors but without being big enough to have excess heat loss.
Figure 12: Power per aperture area produced for different values of absorber radius

Figure 13: IAM for various values of absorber radius

Figure 14: Maximum optical efficiency for various values of absorber radius
5. Discussion and Conclusions
In this study an analysis of an ETC-CPC was performed, through the development of an optical simulation model. The model was developed in Tonatiuh ray-tracing software and the model validation was implemented through the theoretical fully developed curve. A parametric analysis performed in order to investigate the impact of the truncation origin, the reflectivity of the CPC mirror and the absorber radius on the optical efficiency and the power production of the solar collector. It was found that the collector with the biggest truncation origin (0.025m) performed better under small Sun deviations thus 0°-20°, but worse under greater Sun deviations thus 40°-90°. This happens because the collector with the greatest truncation origin has the biggest mirror area and under small Sun deviations this leads to more gains and higher efficiency. The quality of the mirror played an important role in the optical efficiency of the collector, mainly for incident angles less than 20°. Moreover, increasing the radius of the absorber, the power production per aperture area was increased. The variation of the absorber radius showed that the base scenario is within reasonable dimensions, compensating most of the optical errors. The results of this study are useful for the design, simulation and performance analysis of the ETC-CPC.

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