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Design and prototyping of optical Compound Parabolic Concentrator (CPC) for concentrating solar cell.

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ABSTRACT

In this project work using Compound Parabolic Concentrators (CPC) as primary optical elements for concentrated photovoltaic cell are evaluated. The most outstanding physical obstacle in these systems is the area that must be exposed for obtaining the maximum use of the solar energy and also Scaling a single concentrator such that it covers a large solar panel has disadvantages in terms of height and cost of the concentrator. These disadvantages can be overcome by deploying an array of CPC as the top part of the solar cell. The objective of this project work is to design a non tracking non-imaging CPC solar collector for 1 cm^2 organic solar cell and to achieve maximum concentration and also to predict energy output, cost effectiveness for CPC's. A project work is carried out by building a prototype of 3D printed CPC followed by Optical design, Mechanical design, Software Modelling and optimization using commercial software. A 1 cm^2 organic solar cell is considered as a benchmarking and the CPC is design and fabricated for this cell. The system is non tracking and consists of arrays of a CPC which is mounted on the top of a solar cell. But here we will calculate the energy output considering single concentrator and single solar cell only. The Result analysis will be done by comparing it with experimentation result. The objective of this project is to provide guideline to model any type of solar concentrators or complex solar systems.

Keywords— **Compound parabolic concentrator (CPC) ,3D-printed,non-imaging,non-tracking,Organic solar cell.**

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I. INTRODUCTION

Concentrator photovoltaic (CPV) systems in use today can be divided, in first instance, into two main categories: Fresnel lens refractors and parabolic reflectors. Both can be either point focus (3D) or linear focus (2D) concentrators. The concept of the compound parabolic concentrator (CPC) as a primary concentrator has received some attention in the field of building integrated PV, but only for low concentration (<5x) non-tracking applications with few exceptions. For solar tracking applications, CPCs offer the possibility of high solar concentration ratios, in principle approaching the theoretical limits. However, one of the largest hurdles in the use of CPCs for primary optics in PV concentrators is their unwieldy character and the necessary high material usage. This can in part be offset by reducing the length of the CPCs with the so called truncated CPCs, or T-CPCs, which use far less material with only a minor reduction in concentration ratio and optical efficiency. Despite this improvement, the surface area of the primary optical component remains high compared to a lens or a parabolic mirror. Thin solar cells benefit from low bulk recombination of excited charge carriers. Hence the performance of a thick solar cell generally improves by reducing its thickness provided that the absorptance stays constant. Therefore, large efforts have been made to obtain high absorptance in thin solar cells by modifications of the solar cell surface to obtain internal light trapping. However, these internal cell modifications often have a negative impact on the material quality and the electrical performance of the solar cell .For example ,by texturing the surface of crystalline silicon(c-Si)solar cells the surface recombination velocity increases due to the enlarged surface area. For other cells like nanocrystalline silicon (nc-Si) the growth of a solar cell on top of a textured scattering surfaces is challenging while for organic solar cells texturing is less effective. It is thus challenging to realize the full theoretical potential of internal light trapping for most solar cells and there is a need for better light trapping methods.

In this work, some new possibilities for cheap and easily manufactured CPCs will be discussed, as alternative of the more diffused concentrators and also we demonstrate the energy output by applying one external light trap CPC on a 1 cm^2 solar cell.

II. CLASSIFICATION OF CONCENTRATING COLLECTOR

The different concentrating concentrators are generally classified as under:

1. Focusing and Non-Focusing type. Whether the Collector focuses the solar radiation on the absorber or just diverts it. Focusing type collectors are further classified in line focusing and point focusing collector.
2. Tracking and Non Tracking type: Whether the Collector is provided with Tracking Mechanism so that it can follow the sun or is of Fixed Orientation.
3. Tracking type is further classified as Single axis tracking and Double axis tracking. Tracking can be intermittent (daily or weekly tracking) or Continuous Tracking.
4. Concentrating Ratio achievable. Concentration ratio achievable can be between 1 (limiting value for Flat Plate Collector) to 10,000 (Parabolic Dish Collector). Concentration ratio also approximately determines the operating temperature of the collector.

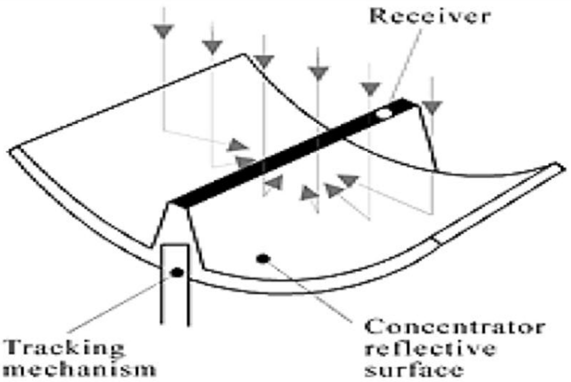


Fig.1 Cylindrical Parabolic Concentrator.

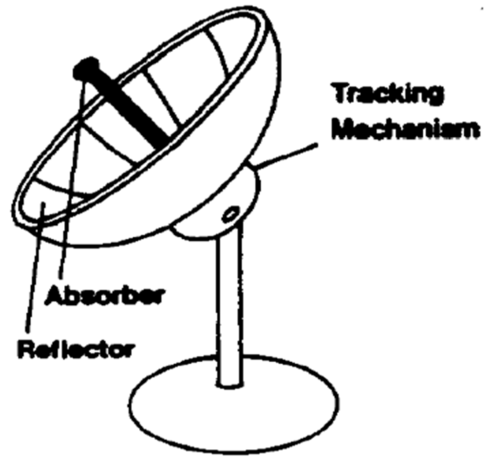


Fig.2 Parabolic Dish Collector.

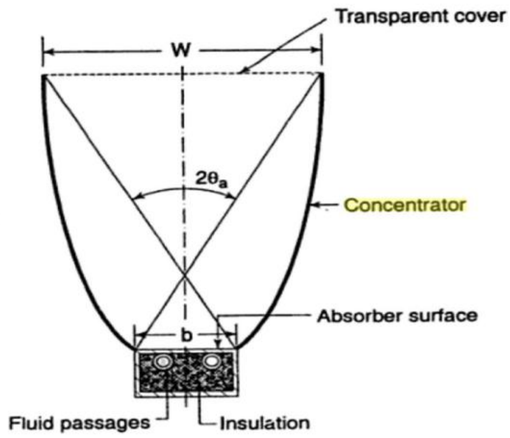


Fig.3 Compound Parabolic Concentrator

The collector that can be compared with Compound Parabolic Concentrator are discussed. They are

1. Cylindrical Parabolic Concentrator: it is conventional imaging collector. It focuses the solar energy on a line, through which water flows. The aperture areas vary from 1 – $6m^2$. The concentration ratio is in the range of 10 – 80. Temperature up to 400°C can be obtained. A simple working model is shown in figure-1.
2. Parabolic Dish Collector: This is similar to cylindrical parabolic concentrator except here the focusing is point focusing instead of line focusing. Hence a very high concentration ratio is achieved. The delivery temperature created by this collector is the highest among all the collectors around 600°C. Figure 2 describes the working of Parabolic Dish Collector.

A more sophisticated parabolic collector trough can be designed, that avoids the need to track the sun altogether, by combining two parabolas together, to form the "Compound Parabolic Trough Solar Collector." When this is done, the cofocal point then becomes a co-focal line. If a coolant filled pipe solar energy absorber pipe, or a tubular evacuated tube solar energy absorber tube is co-located at the co-focal line, there will then be a maximum of concentrated solar energy delivered and transferred to the energy absorber tube! Such solar collectors do not need tracking, and require only occasional season angle adjustments (several times a year) are required to keep the aperture perpendicular to the noonday sun, to the maintain maximum power output. By selecting non-imaging optics we can thus avoid the need to keep the collector aperture pointed at the sun. Instead, we can collect and concentrate Solar Energy from multiple directions separately or at once. So while the sun moves across the sky, we can still accept and concentrate the Solar Thermal Energy all day using a properly designed compound Parabolic Trough Concentrating Solar Collector coupled with Evacuated (vacuum) tube Solar energy Capture Tubes. Using this type of collector, the output energy of a Solar Energy Capture Tube can be increased by a factor of 4- 6 times using a stationary solar collector.

III. DEFINITION OF TERMS THAT CHARACTERIZE CONCENTRATING COLLECTORS

Underneath are some of the terms that are present when discussing Concentrating Collectors.

a) **Zenith angle (θ):** It is the angle between sun's ray and perpendicular line to the horizontal plane. It is shown in figure 4.

b) **Altitude angle (α):** It is defined as the angle between sun rays and a horizontal plane. It is shown in figure 4.

c) **Surface Azimuth angle (γ):** It is the angle in a horizontal plane, between the line due south and the projection of normal to the surface on the horizontal plane. It is also shown in figure 4.

d) **Latitude (ϕ):** The latitude of a location is the angle made by the radial line joining the given location to the centre of the earth with its projection on the equatorial plane.

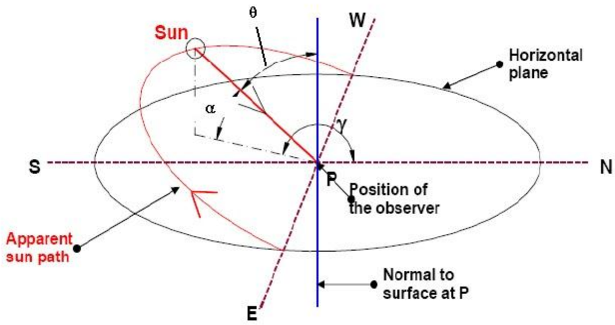


Fig.4 Sun and Earth angles

e) **Declination (δ):** The angle between the line joining the centres of the sun and earth and its projection on the equatorial plane is called as declination angle.

Declination is due to the rotation of earth about an axis which makes an angle 661/2º with the plane of its rotation around the sun.

f) **Hour angle (ω):** The angle through which the earth must be rotated to bring the meridian of the plane directly under the sun is called as hour angle.

g) **Angle of incidence (θ_i):** It is the angle between beam radiation on a surface and the normal to that surface. The angle of incidence is calculated by the following formulae:

h)**Acceptance Angle (2θc):** It is the limiting angle over which incident ray path may deviate from normal to the aperture plane and still reach the absorber.

Concentrators with large acceptance angle need to be moved on seasonally while concentrators with smaller acceptance angle need to be moved continuously to track the sun.

IV. COMPOUND PARABOLIC CONCENTRATOR

The Compound Parabolic Concentrating Collector is non-imaging like a flat plate collector. The collector concept was originated by Winston in 1978. The concentration ratio up to 10 can be achieved in the non-tracking mode easily. Thus it leads to cost savings. A lot of work has been done in the field of compound parabolic concentrator by Rabl and Kreith.

It is one of the collectors which has the highest possible concentration permissible by thermodynamic limit for a given acceptance angle. Its **large acceptance angle** results in intermittent tracking towards the sun.

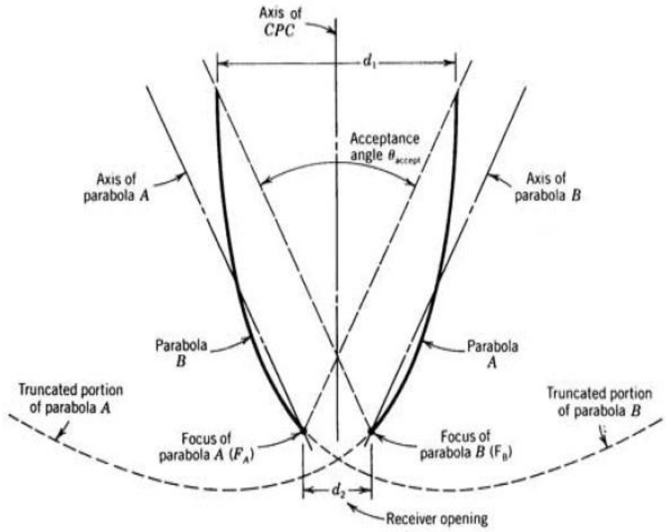


Fig. 5 Layout of Compound Parabolic Concentrator

The acceptance angle of the CPC is obtained by joining the focus to the opposite aperture edge. The concentration ratio is given by *w/b*. The height and aperture area for a CPC are calculated as per the desired operating temperature. To reduce the cost the height is generally truncated to half as it doesn't much affect the concentration ratio. Generally the CPC are of larger acceptance angle and are oriented in the east west direction. Hence only intermittent tracking every 15 days or even up to every 2 months (for concentration ratio 3 – 5) is needed. For good performances of parabolic trough and parabolic dish, a continuous tracking is required.

For a concentrating collector the amount of diffused radiation that can be collected is given by 1 /CR. The general Concentration Ratio for a CPC is around 3 – 10, while that for PTC and Parabolic Dish Collector is more than 1000. Thus the advantage of a CPC is that it can collect diffuse radiation too. Thus its performance is satisfactory in cloudy atmosphere too.

The CPC was used for many different applications, ranging from high-energy physics to solar energy collection. In the field of solar energy, CPCs have mainly been used in solar thermal applications, most commonly as static linear collectors focusing light onto evacuated tubes at low concentration (~1.5x). There are applications where CPCs are used as the primary concentrator with photovoltaic cells, and other where they have been considered as secondary, non-imaging concentrator stage for some PV concentrator systems. Some projects have looked at the use of CPC troughs for combined PV-thermal (PV/T) applications. In Sweden, Brogren firstly explored the use of CPCs for PV/T applications that require water for space heating, then further investigated. One of the advantages that CPCs offer with respect to conventional imaging systems (parabolic mirrors and some Fresnel lenses) is their higher tolerance to misalignments with respect to the sun disk direction. Since

CPCs approach the behaviour of ideal concentrators, their optical efficiency can be kept closed to unity up to the acceptance angle with a reduction factor for the entrance flux of only the cosine of the misalignment angle. As a consequence, for a given optical concentration ratio, they show the largest acceptance angle. The requirement on tracking accuracy is therefore lower, compared to other concentrators with the same concentration ratio.

Different Absorber Shape

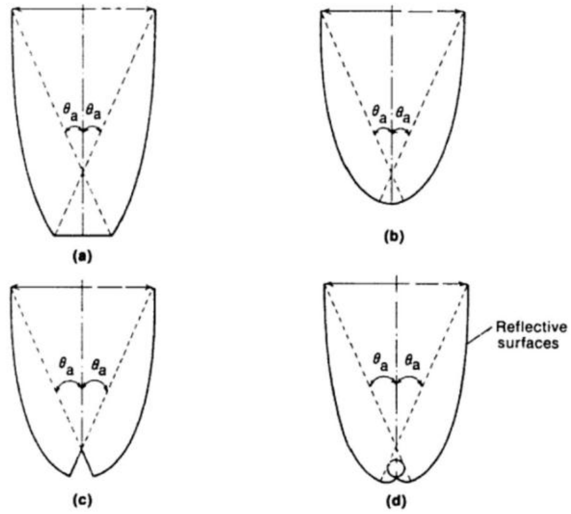


Fig. 6 Different absorber shape (a) basic CPC, (b) fin receiver, (c) bifurcated fin receiver, and (d) tubular receiver.

Now for a particular desired temperature, the height and aperture area of CPC are determined from the available equation. Now even if CPC is truncated to half of the size, the
collector efficiency won't suffer much, as the edge of the CPC
were nearly parallel to the axis of the collector. The different
absorber shapes that are presently used with a CPC are shown
in the figure.

V.DESIGN & EXPERIMENTAL STUDY

Compound Parabolic Concentrator design

The design of compound parabolic concentrator is structurally simpler than other types of concentrated collectors. The dimensional parameters of the ideal 3D-CPC, length L, input aperture diameter a_{in} and output aperture diameter a_{out} ,acceptance angle θ_{in} are expressed as:-

$$L = \frac{a_{out}.(1+sin\theta_{in}^{m}).cos\theta_{in}^{m}}{sin^2\theta_{in}^{m}} \qquad 1$$

$$a_{in} = \frac{a_{out}}{sin\theta_{in}^{m}} \qquad 2$$

Calculating for $a_{out} = 12mm$, $\theta_{in} = 12°$ we get $a_{in} = 60mm$ and L=328.179mm.

The major disadvantage of the 3D CPC is its length L, In practice the CPC length is halved, without significant loss of optical efficiency. Thus the length of the parabola is taken approximately half i.e. 160mm.

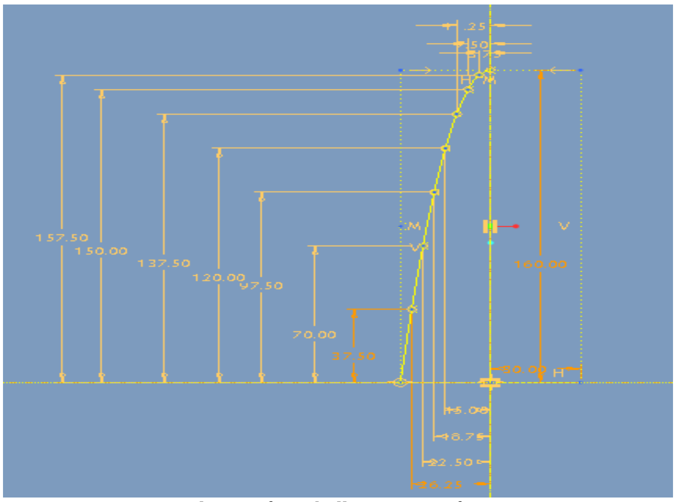


Fig.7 Ploting of Parabolla in Creo Software

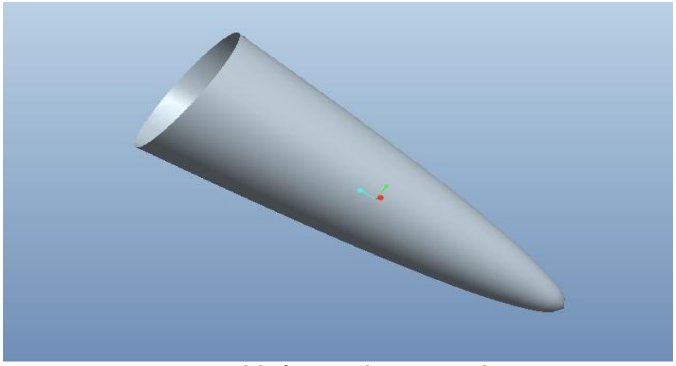
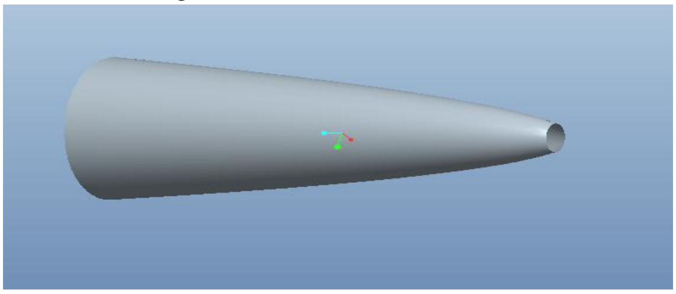


Fig.8 Model of CPC without truncated



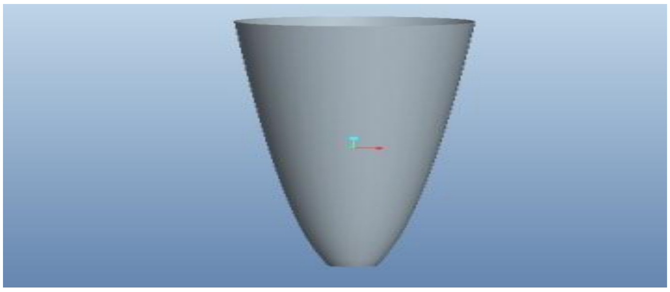
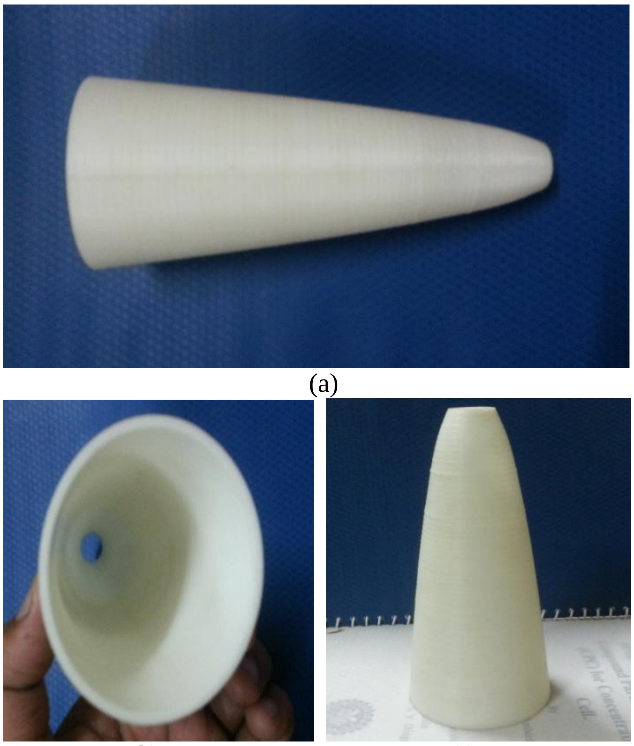


Fig.9 Model of truncated CPC by taking input aperture diameter as 12mm.



(a)

(b) (c)

Fig. 10 (a),(b),(c) 3D printed model of CPC

Figure 10 show the fabricated concentrators with a concentration factor of C=5x. They were 3D-printed,chemically polished with acetone vapor and metalized. The cage and the concentrators will coated with silver, which is also used in optical telescopes because of its high reflectance. The flat reflective bottom side of the concentrator forms the top of the cage which reflects the light back to the solar cell. The light traps were placed on top of an organic solar cell which is illustrated in Fig..

Cell Dimension

The Photovoltaic solar cell of dimension 10×10 mm is the benchmarking of the study. The CPC is designed for this cell and will be mounted on the cell.

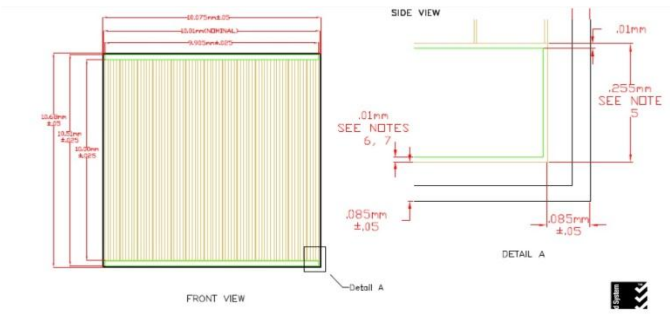


Fig.11 Photovoltaic Cell Layout

1. Initially as seen in the above section design and fabrication of the Prototype of non-tracking compound Parabolic concentrator (CPC) Solar Collector system is done .
2. To achieve maximum concentration and also to predict energy output, cost effectiveness and reliability for non tracking CPC's.

This will be done by mounting the CPC on to the solar cell and at an fixed angle depending upon the latitude as the CPC is non-tracking and the readings will be taken during the day time. The electricity generation is impeded by high temperatures, and cooling the cells actively with water is one efficient way to increase the yield.

VII.CONCLUSION

We demonstrated that external light trapping is of interest for all solar cells as its effectiveness does not depend on the refractive index or texture of the solar cell and it is easy to apply. As the device is an add-on it guarantees that there is no negative impact on the electrical properties of the solar cell. The use of some CPC designs as primary concentrators for CPV has been described. 3D CPC structures have been evaluated for solar cell of $\mathbf{1}\ cm^{2}$ and some particular solutions have been selected for possible photovoltaic applications. Historically, the large reflective area required for CPCs has limited their use to being secondary collectors or concentrators for low level of concentration, but, considering the very low price of currently available, high efficiency film reflectors, or the possibility of industrially coating small size structures with high reflective metals, this family of optical objects can be considered as a competitive choice for CPV applications.

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