Building Integrated Compound Parabolic Photovoltaic Concentrator: A review

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Abstract: This paper presents a review of design and performance of various compound parabolic concentrators (CPC) for electricity generation for integration in buildings. Performance of compound parabolic concentrator (CPC) in buildings is affected by various parameters such as reflector types, absorber position, glazing, temperature, materials and position of the system (facade or ceiling). However, due to a combination of optical, electrical resistance and temperature losses, the maximum output power of the system can be affected. This paper will outline recent developments and designs in CPC, illustrating CPC as a reliable source of electrical power for building integrated applications.

1. Introduction

Over the last decade, the use of photovoltaics (PV) as an integral part of the building e.g. façade, windows, walls, roofs, has significantly increased and is one of the fastest growing PV markets worldwide. Building integrated photovoltaic (BIPV) products differ from PV systems used for field applications and have potential to reduce the cost of the PV system (Mallick et al, 2006). Solar cells are the most expensive components of a photovoltaic (PV) system. Concentration of the light into a smaller area of PV, gives the potential to reduce the electricity production cost (Rabl et al, 1978).

2. Practical development of compound parabolic concentrator

Compound parabolic concentrators (CPC), concentrate radiation from the aperture to the receiver (Norton et al, 2011) and most of the incoming beam and diffuse radiation can be collected and/or reflected onto the absorber surface (Kessentini and Bouden, 2013). The performance of the solar cell can be improved significantly increasing the electric power yield for a unit area of PV (Norton et al, 2011).

The schematic diagram of a CPC is shown in Fig. 1. and it consists of two different parabolas (A and B), the axis of which are inclined at an angles $\pm\theta_c$ with respect to the optical axis. The angle $\pm\theta_c$ is defined as a collector half-acceptance angle (Devanayanan and Murugavel, 2014). The concentration ratio determines the increase in relative radiation at the surface of the exit aperture/absorber. The geometrical concentration ratio is defined as the ratio of the area of aperture to the area of the receiver (Duffie and Beckman, 1991). The optical concentration ratio indicates the proportion of incident rays within the collecting angle that emerge from the exit aperture (Rabl, 1976a). A CPC can be designed for different absorber shapes as shown in Fig. 2. and giving rise to a range of different reflector designs (Norton et al, 2011).

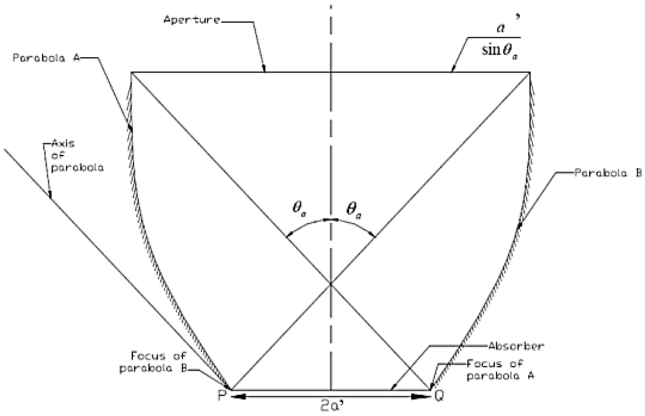

Fig. 1. Sectional view of the compound parabolic concentrator (CPC) (Welford and Winston, 1978).

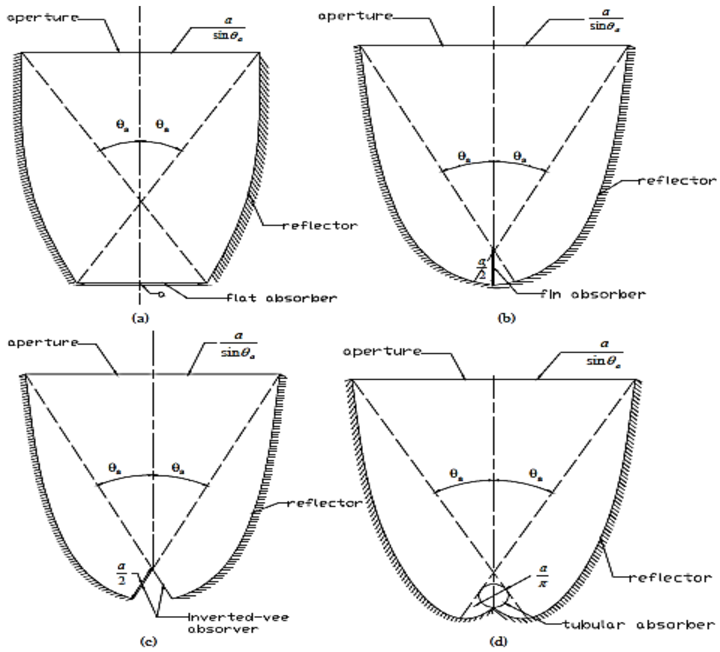

Fig. 2. Different CPC configurations: (a) CPC with flat absorber, (b) CPC with fin,
(c) CPC with "inverted vee" absorber, (d) CPC with tubular absorber (Mallick, 2003).

2.1. Development of CPCs

Over the past 50 years, researchers have worked with CPCs to improve the efficiencies (Winston, 1974; Rabl, 1976a; Zacharopoulos et al, 2000; Mallick et al, 2002; Othman et al, 2005; Wu, 2009). In 1960, Winston discovered CPC as a light collector for Čerenkov radiation counters and it was accepted for solar energy collection in the USA in 1974 (Devanayanan and Kalidasa, 2014). In 1976, Rabl calculated the convective and radioactive heat transfer through a CPC, and the equations for evaluating the performance of solar collectors based on the CPC principle were presented (Rabl, 1976b). For the first time a truncated CPC was used. The results show that a large portion of the reflector area can be eliminated without seriously reducing the concentration ratio. These results also indicate that the ideal concentrator CPC was different from conventional systems such as focusing parabolas and act as a radiation funnel with no focusing element. For a given acceptance angle, a CPC has a concentration ratio of two to four times compared to other solar concentrators, however it requires a larger reflector area (Wu, 2009). In 1976, Rabl also designed new concentrators, including the use of compound parabolic concentrators as second stage concentrators for the conventional parabolic or Fresnel mirrors. Such a combination approaches the performance of an ideal concentrator without demanding a large reflector (Rabl, 1976a).

In 1978, Winston et al proposed two CPCs collector with concentration ratios 3.0 (requiring two tilt adjustments per year) and 6.5 (requiring about one tilt adjustment per week). The results show that the optical efficiency of both collectors was 60%, the U-value is 3.0 W/m^2K and 1.6 W/m^2K respectively. Under full sunshine these numbers imply operating efficiencies of 45% at ΔT=50K and ΔT=100K, respectively (Winston et al, 1978b). Winston et al (1978a) confirmed that the conduction losses between absorber and reflector can be reduced by creating gaps between them.

In 1978, Mills and Giutronich examined both Parabolic and Non-Parabolic Asymmetrical Concentrators and compared with symmetrical designs. The results revealed that the focus and end points of the two parabolas of an asymmetric compound parabolic concentrator make different maximum acceptance-half angles with the absorber surface.

In 1986, Winston integrated evacuated CPCs for high temperature solar thermal systems (Winston et al, 1986a). In 1986, Winston also investigated the potential to maximize concentrating optics for solar electricity generation by using a secondary concentrator placed in the focal zone of a primary lens or paraboloidal mirror (Winston et al, 1986b). Two stage concentrators for both solar thermal and photovoltaic electricity generation have been tested. The first design used a Fresnel lens primary combined with totally internally reflecting Dielectric Compound Hyperbolic Concentrator secondaries. The second design was a facetted paraboloidal primary combined with a Compound Parabolic Concentrator (CPC). The results show that the solar flux concentration improved by a factor of 2 to 15 above that achievable by the primary alone (Winston et al, 1986b).

2.2. CPC design categorization

There have been variations in the CPC design to improve different aspects such as concentration ratio and irradiance distribution as illustrated in Fig. 3, (Mallick, 2015). The location, incident sun light conditions and tracker options decide which CPC type suits an application best (Mallick et al, 2015).

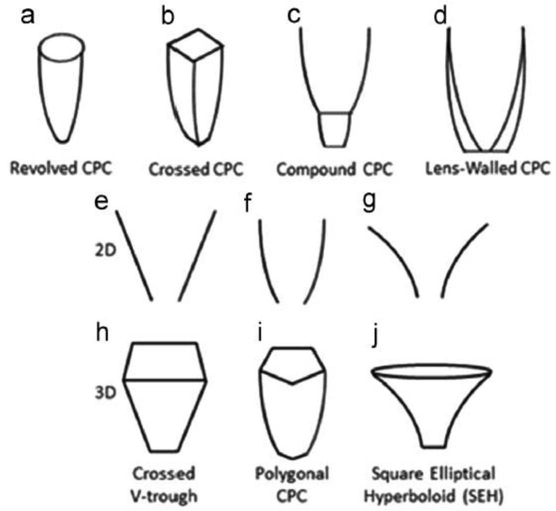

Fig. 3. Variations of CPC:(a) The revolved CPC. (b) The Crossed CPC. (c) The Compound CPC. (d) The Lens-Walled CPC. Examples of 2D profiles and possible 3D transformations: (e) V-trough. (f) CPC. (g) Compound Hyperbolic Concentrator. (h) 3D square aperture V-trough. (i) Polygonal aperture CPC. (j) Hyperboloid with an elliptical entry aperture and square exit aperture (Mallick et al, 2015).

3. Design, development and performance evaluation of various types of Building Integrates Compound Parabolic Concentrator

In 2000, Zacharopoulos et al showed that an asymmetric concentrator is more suitable for use on building facades. They proposed an optical analysis of three dimensional dielectric-field symmetric and asymmetric compound parabolic PV concentrator for building façade integration. The first concentrator was a symmetric CPC with a geometrical concentration ratio of 3.0 including a silvered circular section. A silvered dielectric circular reflector section is included between the lower reflector and the absorber to achieve the vertical orientation required for use on building facades. The second was an asymmetric CPC with a concentration ratio of 2.5. Both concentrators have an optical efficiency over 90%. The results revealed that the asymmetric design maintains optical efficiencies over 40% even for the incidence angles outside the two-dimensional angular acceptance range. For both concentrators angular acceptance was enhanced due to refraction and most solar energy collected by the photovoltaic material leaves concentrators at exit angles less than 40º. The performance of symmetric, asymmetric and flat plate devices with the same photovoltaic surface area was also compared. The results show that the symmetric cover collects the most energy at all aperture tilt angles over 40º.

Mallick et al (2002) used ray trace techniques to predict the optical characteristics of non-imaging asymmetric compound parabolic photovoltaic concentrators (ACPPVC) suitable for south facing façades in the UK (52° N) (Fig.4.). The truncated air filled ACPPVC had a geometric concentration ratio of 2.0 with acceptance angles of 0° and 50°. The results show that approximately 91% optical efficiency of the ACPPVC system was achieved for a wide range of solar incidence angles (Wu, 2009).

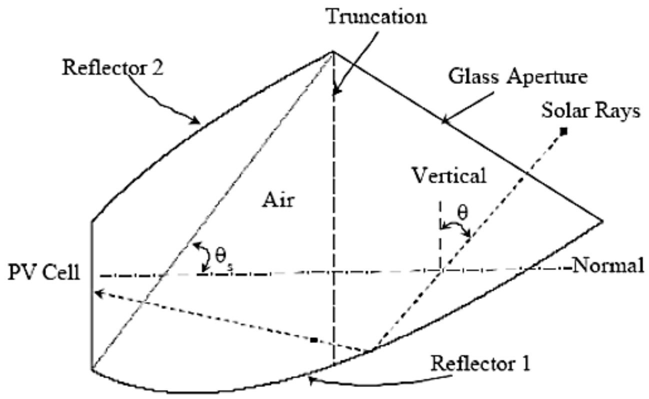

Fig. 4. Modelled photovoltaic concentrator for building façade integration in the UK (Mallick et al, 2002)

Mallick et al (2004) designed, constructed and experimentally characterized a novel non-imaging asymmetric compound parabolic photovoltaic concentrator (ACPPVC) (Fig.5.). An electrical and thermal analysis of the ACPPVC has been undertaken. The reflector system was removed from the PV panel to provide a non-concentrating PV panel for comparison against the concentrator panel. In both instances the active solar cell area was kept constant. The results revealed that the power produced by the ACPPVC was 1.62 times of the power generated by the flat PV panel. Although the power increased by a factor of 1.62, the aluminum back plate temperature of the concentrator panel was only 12 ºC higher than the flat panel. Approximately 8.5% electrical efficiency was achieved by the flat system compared to 6.8% for the ACPPVC with a fill factor of 65% (Mallick et al, 2004). A maximum system efficiency of 7.8% was obtained at a solar radiation level of 800W/m^2, and the maximum power generated by the system was 26W (Wu, 2009).

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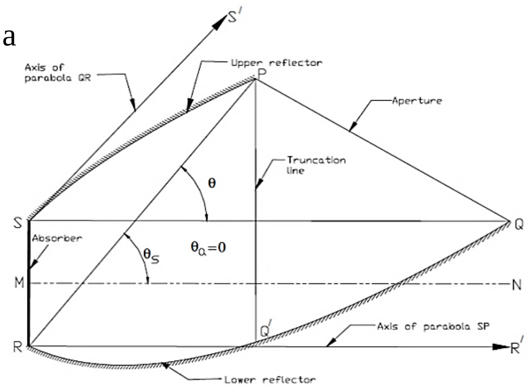

b

Acceptance-half angles	50° & 0°
Absorber width (mm)	50.0
Aperture width (mm)	100.0
Length of upper reflector (mm)	84.0
Length of lower reflector (mm)	71.0
Concentration ratio	2.0
Truncation (%)	54

Fig. 5. (a) Asymmetric compound parabolic concentrator for building integration in the UK with acceptance-half angles of 0ºand 50º (Mallick et al, 2004). (b) Physical and geometrical properties of a single trough ACPPVC (Mallick et al, 2004).

Mallick et al (2007a) undertook a detailed parametric analysis of the heat transfer in an experimentally characterized asymmetric compound parabolic photovoltaic concentrator suitable for building facade integration in the UK, using a comprehensive validated unified model for optics and heat transfer in line-axis solar energy systems. The results show that free and forced convection at the rear of the PV concentrator provides a significant temperature reduction in the PV. An inlet air velocity of 1.0 m/s in a 20 mm wide channel between the aperture cover and the reflector could decrease the PV cell temperature by 25.4 K. A maximum temperature reduction of 34.2 K is predicted for a front and rear air gap of 20 mm with an inlet air velocity of 1.0 m/s. (Mallick et al, 2007a).

Mallick et al (2007b) also analysed the power loss in an Asymmetric Compound Parabolic Photovoltaic Concentrator with a geometric concentration ratio of 2.0. The power loss of system is explained by a comparative analysis of the non-concentrating photovoltaic system for long-tabbed and short-tabbed solar cell strings. The results revealed an average of 3.4% electrical power loss due to resistance in the interconnections between each individual solar cell and 0.6% occurred due to the increased temperature of the PV cells in the ACPPVC system. The optical losses of the ACPPVC were 15% caused by the combined effect of the number of reflections at the reflectors and the misalignment of the imperfection in the reflector geometry. Due to a combination of optical and electrical resistance losses, the maximum output power achieved was only 1.62 times of non-concentrating counterpart (Mallick et al, 2007b).

In 2009, Wu designed, fabricated and experimentally characterised an Asymmetric Compound Parabolic Photovoltaic Concentrator (ACPPVC) for building façade integration (Fig. 6). Extensive indoor experiments were used to investigate the thermal behaviour and the I-V characterisation of a truncated Asymmetrical Compound Parabolic Photovoltaic Concentrator. Phase Change Material (PCM) was integrated to the rear of the PV panel to moderate the temperature rise of the PV and maintain good solar-electrical conversion efficiency. The result showed that the truncated ACPPVC system with a geometric concentration ratio of 2.0 was more suitable for the UK climate compared to the other ACPPVC systems simulated, due to the range of angular acceptance. For the ACPPVC with PCM system, it was observed that for an incident solar radiation intensity of 280W/m2, the average solar cell temperature of the system was reduced by 7°C and the electrical conversion efficiency increased by approximately 5%. For an incident solar radiation intensity of 672W/m^2, the average solar cell temperature of the system was reduced by 18°C and the electrical conversion efficiency increased by around 10% (Wu, 2009).

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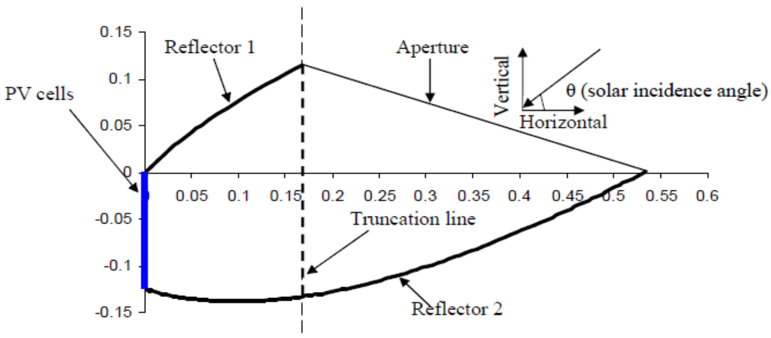

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Parameters		Values
Acceptance-half angles		38° & 55°
Absorber width(mm)		125
Aperture width(mm)		248.5
Length of reflector1(R1)(mm)		204.5
Length of reflector2(R2)(mm)		169.8
Concentration ratio		1.99
runcation (%)	Ref1	0
	Ref2	69.7

Fig. 6. (a) ACPPVC-55 system with acceptance-half angle of 0° and 55°, all dimensions in 'm'. (b) Geometrical characteristics of the truncated ACPPVC-55 (Wu, 2009).

4. Conclusions

This paper reviewed compound parabolic concentrators and their applications in building integration for electricity generation. A broad variety of practical realized design and performance of CPCs for building integrated has been presented. From this paper, it can be concluded that truncated Asymmetric Compound Parabolic Photovoltaic Concentrator (ACPPVC) is more suitable for use in building facades for the range of angular acceptance; however the power and the optical losses in ACPPVC system must be taken into account in order to improve the system efficiency. BICPC has been proven time and again to be an excellent option for electricity generation in buildings, however there is much cope for enhancement and improvement.

5. References

Devanayanan K., Murugavel K., Integrated collector storage solar water heater with compound parabolic concentrator-development and progress. Renewable and Sustainable Energy Reviews, 2014;39:51-64.

Duffie J., Beckman W., Solar engineering of thermal processes. Wiley y Sons Inc, Hoboken, 1991 New Jersey, USA.

Kessentini H., Bouden C., Numerical and experimental study of an integrated solar collector with CPC reflectors. Renew Energy, 2013;57:577-86.

Mallick T., Eames P., Norton B., Asymmetric compound parabolic photovoltaic concentrators for building integration in the UK: An optical analysis. World Renewable Energy Congress-VII, 29th June-5th July. Koln, Germany. 2002.

Mallick T., Optics and heat transfer for asymmetric compound parabolic photovoltaic concentrator for building integrated photovoltaics. PhD thesis. University of Ulster, Newtownabbey, N.I.U.K. 2003.

Mallick T., Eames P., Hyde T., Norton B., The design and experimental characterization of an asymmetric compound parabolic photovoltaic concentrator for building façade integration in the UK. Solar energy, 2004;77:319-327.

Mallick T., Eames P., Norton B., Non-concentrating and asymmetric compound parabolic concentrating building façade integrated photovoltaics: An experimental comparison. Solar Energy, 2006;80:834-849.

Mallick T., Eames P., Norton B., Using air flow to alleviate temperature elevation in solar cells within asymmetric compound parabolic concentrators. Solar Energy, 2007a;81:173-184.

Mallick T., Eames P., Norton B., Power losses in an asymmetric compound parabolic photovoltaic concentrator. Solar Energy Materials and Solar Cell, 2007b;91:1137-1146.

Mallick T., Shanks K., Senthilarasu S., Optics for concentrating photovoltaics: Trends limits and opportunities for materials and design. Renewable and Sustainable Energy Reviews, 2015;60:394-407.

Mills D., Giutronich J., Asymmetrical non-imaging cylindrical solar concentrators. Solar Energy, 1978;20:45-55.

Norton B., Eames P., Mallick T., Huang M., McCormack S., Mondol J., et al., Enhancing the performance of building integrated photovoltaics. Solar Energy, 2011;85:1629-1664.

Othman M., Yatim B., Sopian K., Bakar M., Performance analysis of a double-pass photovoltaic/thermal (PV/T) solar collector with CPC and fins. Renewable Energy, 2005;30:2005-2017.

Rabl A., Comparison of sola concentrators. Solar Energy, 1976a;18:93-111.

Rabl A., Optical and thermal proprieties of compound parabolic concentrators. Solar Energy, 1976b;18:497-511.

Rabl A., Collares-Pereira M., Simmons H., Googdman N., Greenman P., O'Gallagher, Simmons H., Wharton L., Winston R., Compound Parabolic Concentrators with non-evacuated receivers: Prototype performance and a larger scale demonstration in a school heating system. Mankind's Future Source of Energy, 1978;2:1227-1232.

Winston R., Principles of solar collectors of a novel design. Solar Energy, 1974;16:89-95.

Winston R. Ideal flux concentrators with reflector gaps. Appl Opt 1978a;17:1668–9.

Winston R., Goodman N., O'Gallagher J., Pereira M., Wharton L., Rabl A., Nonevacuated solar collectors with compound parabolic concentrators. Mankind's Future Source of Energy, 1978b; 2:1032.

Welford W., Winston R., The optics of non-imaging concentrators. Light and solar energy. London;Academic Press Inc;1978.

Winston R., O'Gallagher J., Scherts W., Integrated evacuated CPC's for high temperature solar thermal systems. Intersol Eighty Five, 1986a;1148-1152.

Winston R., O'Gallagher J., Maximally concentrating optics for solar electricity generation. Intersol Eighty Five, 1986b;1669-1673.

Wu Y., Thermal Management of Concentrator Photovoltaics. PhD Thesis. University of Warwick, U.K.; 2009.

Zacharopoulos A., Eames P., McLarno D., Norton B., Linear dielectric non-imaging concentrating covers for PV integrated building facades. Solar Energy, 2000;5:439-452.