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Design and Characterization of a Roof-Mounted Compound Parabolic Concentrator with Phase Change Material

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Abstract

This paper presents the design, fabrication and performance of a roof mounted compound parabolic concentrators (CPC) with and without Phase Change Material (PCM) for electricity generation. A truncated Asymmetric Compound Parabolic Concentrator with concentration ratio of 1.83, acceptance-half angles of 60° and an absorber width of 125 mm was designed, constructed and experimentally characterised on the roof of the Simon Perry Building at Trinity College Dublin, Ireland (53.344295, -6.252416). A CPC and a reference PV system were tested under outdoor conditions with 4-cell PV strings. The first challenge of the project was to determine the power generation, efficiency and temperature of both systems and compare the results. The experimental results revealed that at solar incident radiation of 800W/m^2, the CPC system increased the power and efficiency by 34 % (power by factor 1.34) and 22 % (efficiency by factor 1.22) respectively, compared with the reference PV system. However, the solar cell temperature in the CPC system increased by 74 % (temperature by factor 1.74). In order to reduce the temperature, a convective cooling system was introduced. The results showed that when the temperature increased by 22% (temperature by factor 1.22) compared with the reference PV system, the power and efficiency improved by 84 % (power by factor 1.84) and 65 % (efficiency by factor 1.65) respectively.

The second challenge was to control the temperature by removing and storing the heat. In order to achieve this, an aluminium container with dimensions of 526 X 120 X 13 mm and thickness 2 mm was designed and manufactured. The container was filled with microencapsulated PCM (mPCM) powder and placed on the back of the solar cells in the CPC system. Experimental results showed that the CPC/PCM system increased the temperature of the solar cells by 2% (temperature by factor 1.02) and increased the power by 10 % (power by factor 1.10) compared with the reference PV system. In addition, the temperature in the PCM container was reduced by 17.1 ºC in 12 hrs, as it stored the heat.

Keywords:

Building integration; Compound parabolic concentrator; Phase change material; Photovoltaics.

1. Introduction

Photovoltaics convert solar radiation to electrical energy. The efficiency and power output depends on the solar radiation intensity which reaches the solar cell surface. The amount of solar radiation over the solar cell surface can be increased using a concentrator (Mallick, 2003). PV concentrators can be classified into four types: Lens concentrator, Mirror concentrator, Reflector concentrator and Static concentrator (McCormack, 2016). An example of a reflector concentrator is the compound parabolic concentrator. In this type of concentrator, a large portion of the reflector area can be eliminated without reducing the concentration ratio. Also they have the potential to reduce the electricity production cost by concentrating the incoming light onto a smaller area of PV (Rabl, 1979). However, the temperature in the compound parabolic concentrator become in an important factor which needs a consideration. In this study, an asymmetric compound parabolic concentrator has been designed, constructed and experimentally characterized for roof integration in Dublin, Ireland. In order to reduce the quantity of reflector material, the CPC was truncated by 70% leading to a geometrical concentration ratio of 1.83, as is shown in Fig. 1. The system was constructed based on an optical performance analysis using ray trace techniques (Ortega, 2017). The physical and geometrical characteristics are shown in Table 1.

Table 1.
Physical and geometrical properties of the cpc

Acceptance-half angle	60°
Absorber (mm)	125
Refl. 1 (mm)	155.34
Refl. 2 (mm)	128.54
Aperture (mm)	228.43
Geometrical Concentration ratio	1.83
Truncation Refl. 2 (%)	70.02

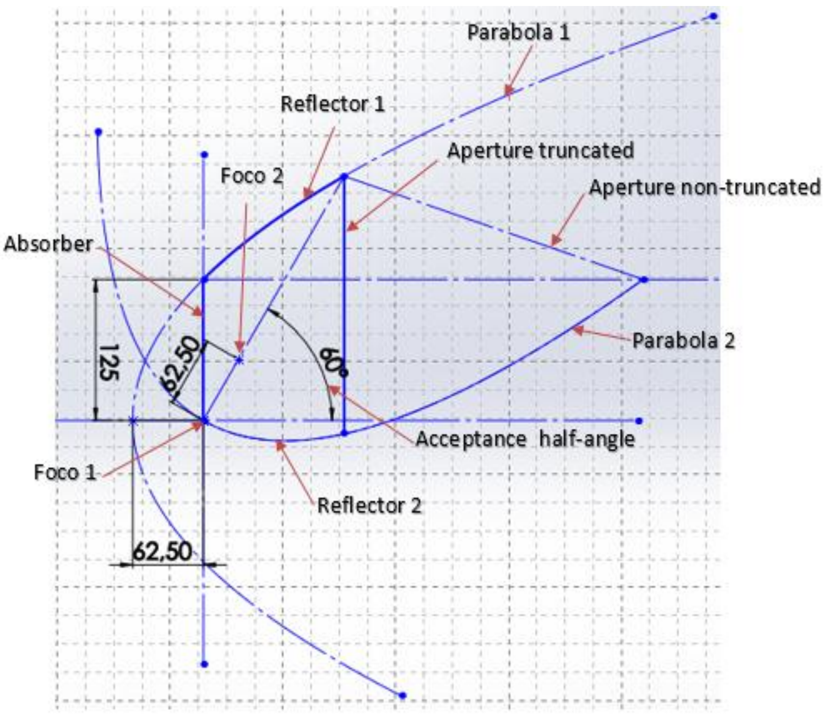

Fig. 1. Parabolas which form the CPC system with an acceptance half angle of 60° generated in SolidWorks.

2. Design, manufacture and assembly of the CPC

The CPC was composed of a PV absorber, reflector, reflector supports, thermocouples, aperture cover and frame. The materials selection, design and fabrication for each component of the CPC system are described in the following section.

2.1. Reflective material employed for CPC system

Aluminium Foil with a reflectivity average of 0.76 and 1mm thickness (Easygrow Co.) was chosen as the reflector of the CPC system due to its low cost and acceptable reflectivity properties. The reflectivity of the film is about 0.76 (76%).

2.2. Design and material selection for reflector support and back plate

The reflector supports and backplate were designed using aluminium due to their advantages such as low weight, good thermal conductivity and low cost. In order to provide strength to the bond and bending surface, two types of reflector support (north and south) were designed and manufactured from aluminium material with 25 mm thickness to provide strength to the bond and bending surface. For each reflector, six pieces were designed using Autocad and SolidWorks and those designs were transferred to a CNC machine. The details of both reflector designs are shown in Fig. 2.

To provide the base for the solar cell, a back plate was designed from aluminium with 6mm thickness. The dimensions of the back plate were 706 X 525 mm and forty-six holes of Ø11 mm were machined to fix the support reflectors, frame and foam. The detailed design of the aluminium back plate is shown in Fig. 3.

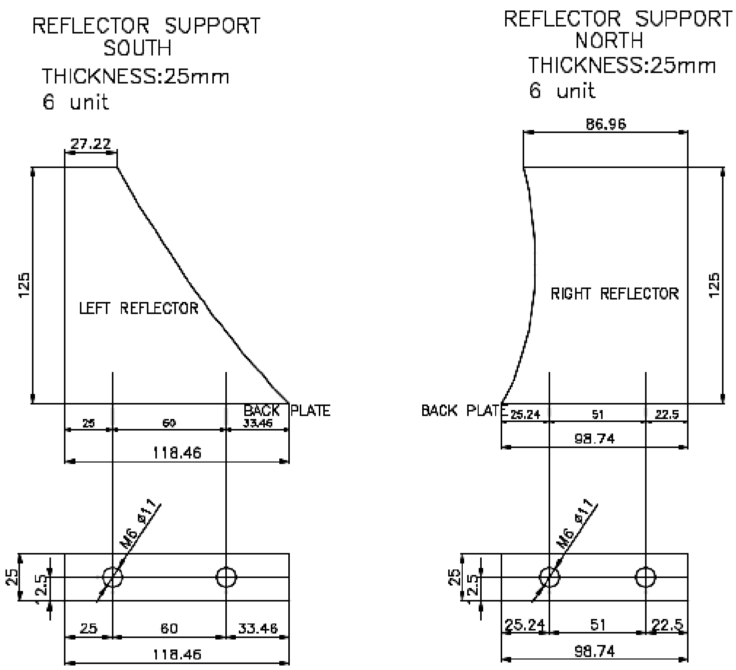

Fig. 2. Detail design of reflector support in Autocad.

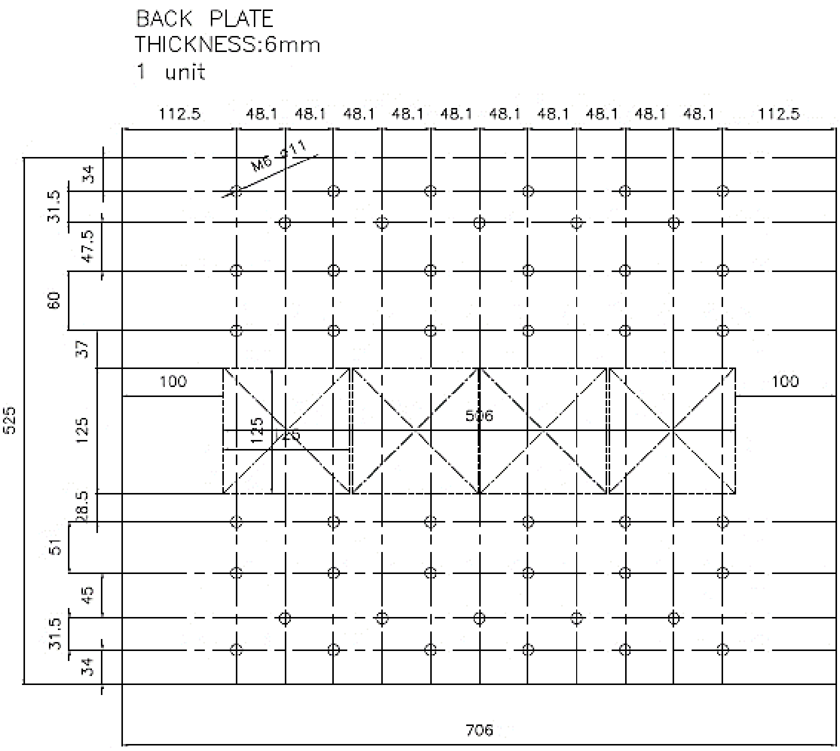

Fig. 3. Detail design of aluminium back plate in Autocad.

2.3. Solar cell selection and interconnection

Monocrystaline bare solettes solar cells, 125 mm squared manufactured by SunPower were selected for the CPC system and reference PV system. According to their technical specification the solar cells dimensions are 125 X 125 mm, with an efficiency of 17.5 %, Grade A, short circuit current of 5.15 A, open circuit voltage of 0.515 V and maximum power output of 2.941 W. Four solar cells in series were selected for the CPC system. The series connection provides a higher voltage and lower current in order to protect personnel and equipment from risk where the maximum voltage for the system was 2 V. For the solar cell interconnection, two copper PV ribbons with 2 mm and 5 mm width and 0.2 mm thickness were used. For the soldering process, a leaded solder wire with alloy metal Sn-43Pb-14Bi (Almil Serie: KR-15) of 0.65 mm diameter was used with the soldering iron heated to 260 °C.

2.4. Thermocouple selection and characterization

Twenty "K" type thermocouples (chromel-alumel) were used for thermal analysis of the CPC and PV systems. All thermocouples were previously tested at 21°C, 40°C, 50°C and 60°C using a 235 Column Heater Beckman. The results showed a maximum measured deviation of ±0.4°C compared with a Thermometer HD 2307.0 RTD. Thermocouple distribution in each system is presented in Table 2.

Table 2.
Thermocouples location

System	Solar Cell	Back plate	System Internal	Refl.	Glass Internal	Glass External	Total
CPC	4	3	1	2	1	1	12
PV	4	3	1	N/A	0	0	8

2.5. Electric circuit, solar sensor and data collection

Two electrical circuits with the same characteristics were used to collect current and voltage for the CPC system and reference PV system independently. A resistor of 0.2 ohms with maximum power of 15 W was used for each circuit. In order to avoid high current, a RS 257-408 shunt with a conversion factor of 20A-200 mV was connected in series and then connected to the data logger. The final circuit is represented in Fig.4.

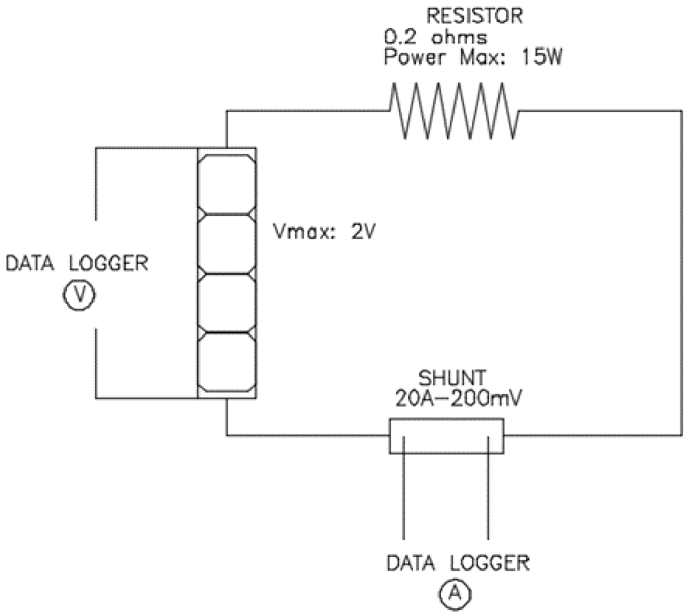

Fig. 4. Electric circuit forming the monitoring system.

The horizontal solar radiation was recorded using a Kipp and Zonen Sp Lite 2 pyranometer with a sensitivity of 10.2 μV/Wm. A data logger (Agilent 3472A LXI) was used for the electrical and thermal characterization of the CPC and reference PV systems. Twenty-five channels were programmed and used to measure voltage, current, temperature and solar radiation. The data were recorded every minute.

2.6. System assembly

Each individual reflector support and the frame structure were fixed to an aluminium back plate using M6 screws. A 1 mm thick aluminium sheet was bonded between the foil reflector and reflector supports surface in order to give the parabolic shape to the system. The two Perspex sheets and low iron glass were placed in the respective slots and the foam was located between the frame structure and the support reflectors. Araldite was used to secure each thermocouple to the required position in the system. Initially, four thermocouples were fixed in the centre back of each solar cell. Then, the solar cell string was placed on 2 mm glass of dimension 130 x 515 mm, providing easy access to the string. Two small pieces of wood for were fixed in the glass in order to give a gap between location of the thermocouples and the solar cell.

3. Phase Change Material selection and container design

3.1 Phase change material selection

Micronal DS 5040 X, dry powder paraffin wax mixture encapsulated in highly crosslinked polymethylmethacrylate with a melting temperature of 23 ºC was chosen for this study. The appropriate phase change material (PCM) should have a melting temperature of about 25 ºC for an appropriate performance of the solar cell. The characteristics of the PCM Micronal DS 5040 X are shown in table 3.

Table 3.
Characteristics of Micronal DS 5040 X (Micronal, 2017).

Physical form	Powder
Particle size	ca. 50 – 300 μm
Bulk density	ca. 300 – 400 kg/m^3
Melting point	ca. 23 ºC
Enthalpy of fusion	ca. 96 KJ/Kg
Thermal capacity (integral, 10 - 30 ºC)	ca. 136 KJ/Kg
Other features	Low - dusting

3.2 Container design

The PCM container was custom made from 2 mm stainless steel with dimensions of 526 X 120 X 13 mm and positioned on the back of the solar cells in the CPC system. This material was chosen as it does not readily corrode or stain which was a very important consideration in the temperate maritime climate of Ireland. It has a thermal conductivity of 19 W/m^2.

Full contact between the solar cell string and the PCM container was required to obtain good thermal contact, effective PV cooling and heat transfer to the PCM. Four "K" thermocouples were located in the middle of the PCM inside the container. The thermocouples were fixed to a piece of bamboo in order to provide a temperature measure in the centre of the container depth without heat loses. The required volume of the PCM and thus the PCM container dimensions depended on the solar cell string dimensions and the depth was designed as a function of the available space in the CPC system. A detailed design of the PCM container and the thermocouple distribution are shown in figures 5 and 6.

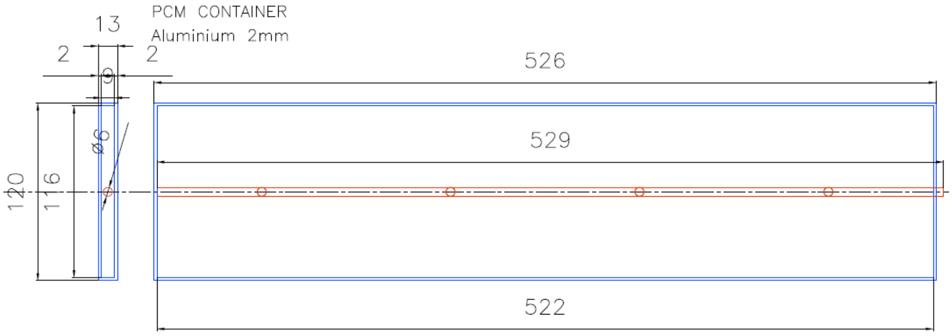

Fig. 5. Details of the PCM container design.

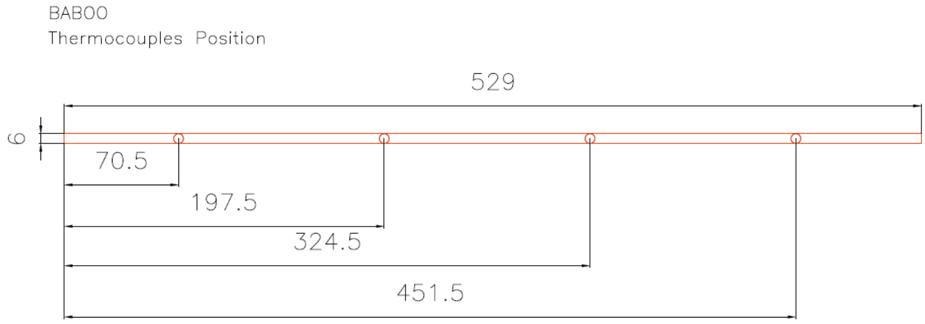

Fig. 6. Thermocouple locations fixed to bamboo.

4. Outdoor characterization CPC and PV system

4.1. Roof assembly

The experiment was conducted facing south on the roof Trinity college Dublin, mounted to sub frame rails and then secured with concrete slabs to eliminate the risk of movement in windy conditions. Twelve thermocouples were attached to the systems on the roof. A pyranometer was used to measure the solar radiation incident. Connection of the twenty-five channels in the data logger was carried out and programed to enable data acquisition from both systems. Silicone Acetate Standard Grade (from saBesto Company) was used and placed in the slots and frame in each system. The final location of CPC system and PV system are shown in Fig. 7.

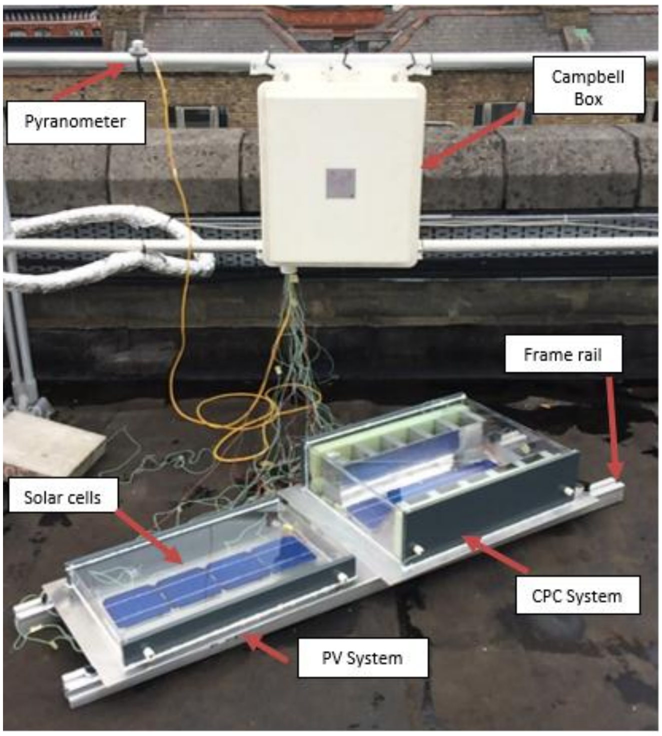

Fig. 7. Final location CPC and PV system on the roof at Trinity College Dublin, Ireland

4.2. Power, efficiency and temperature of CPC and PV system

The data were recorded on the 17th of July 2017 from 9:00 to 18:00. The weather during testing was generally sunny. The variation of solar radiation and power with the time are shown in Fig. 8. A combination graph shows the efficiency and temperature behaviour with solar radiation in Fig. 9. As it is expected the maximum power and efficiency values were reached between 12:00 and 14:00. However, by increasing average solar cell temperature, the efficiency of the system decreased at high solar radiation. From Fig. 9, it can be seen that the maximum radiation of 794 W/m² was achieved at 13:32 for this day, the power achieved for the CPC system and PV system were 8.6 W and 8.3 W respectively and the temperature for the solar cells were 82.6 °C for the CPC system and 71.4 °C for the PV system. A maximum CPC system efficiency of 18.6 % was achieved at 744 W/m² of solar incident radiation when the power generated by the system was 8.7 W and the maximum power of 8.9 W was achieved at 778 W/m² when the efficiency was 18.3 %. The test shows that the CPC system was 10 °C higher than the PV panel when both systems were characterized outside.

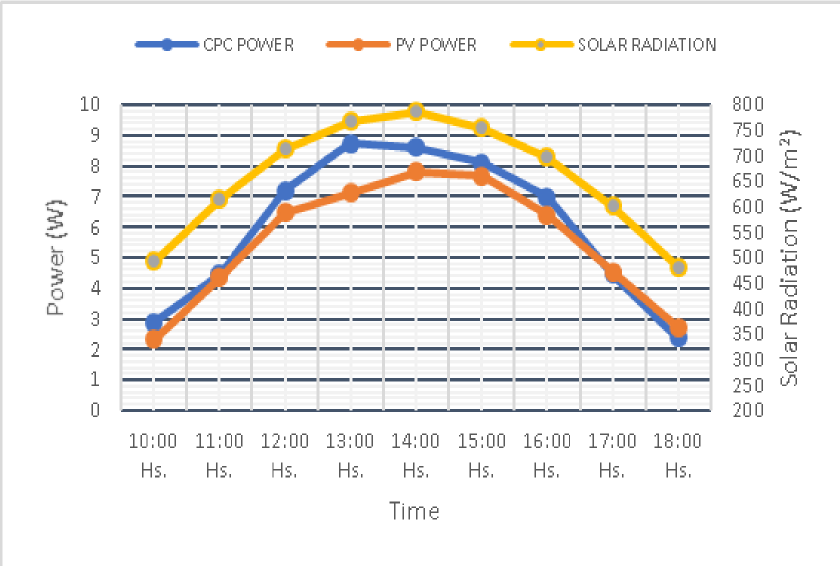

Fig. 8. Variation of solar radiation and power with time on the 17th July 2017.

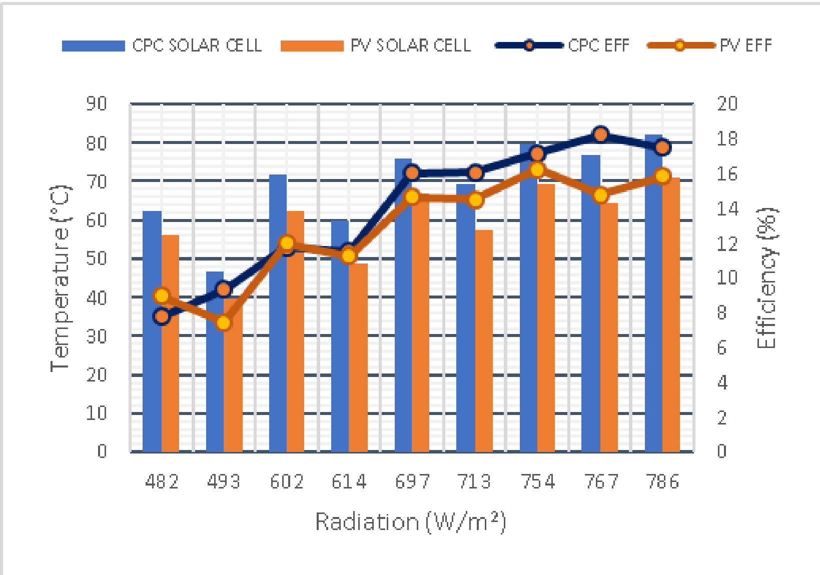

Fig. 9. Average temperature, efficiency with radiation for CPC and PV system.

4.3. Effect of temperature in the CPC system

A distribution of temperature in the CPC system is shown in Fig. 10. Measurement of the solar cell temperature was undertaken in the centre of each solar cell and the average temperature for each solar cell with time and the results are shown in Fig. 11. Due to the nature of the optics and heat transfer of the CPC system, solar cells temperatures were not the same and solar cell number 2 revealed the maximum value in the string between 11:00 and 16:00.

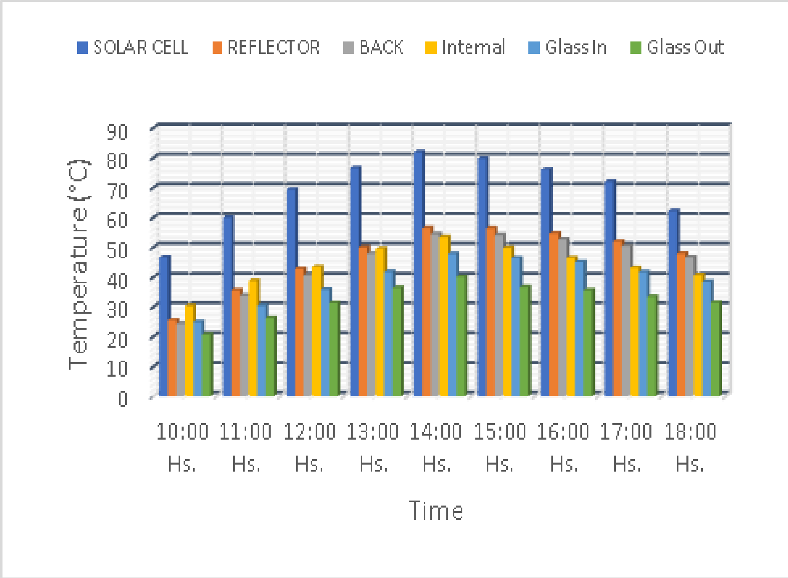

Fig. 10. Average temperature distribution in the CPC system on 17th July 2017.

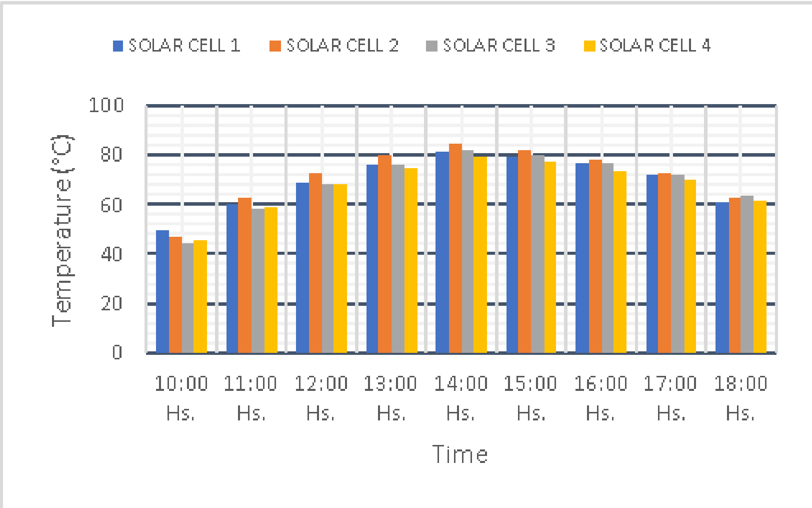

Fig. 11. Temperature in each solar cell in the CPC system on 17th July 2017.

4.4. Analysis with convective cooling

For this experiment the aperture cover glass and the two Perspex sheet were removed for the period of nine hours from 9:00 to 18:00 on 18th July 2017. The weather during testing was generally sunny with intermittent cloud cover. The average solar incident radiation, the wind speed velocity on the roof and its effect on the solar cell temperature with time can be found in Fig. 12. The average wind speed on the roof was 1.88 m/s and solar cell temperature was 48.5 °C in the cooler CPC system.

From Fig. 13 and Fig. 14, it can be observed that the efficiency and power improved when the CPC system was cooled by convection. Efficiency for the cooled CPC system and CPC system were 23 % and 17 % respectively at the solar radiation intensity of 800 W/m^2. At the same radiation the temperatures were 55 °C for the cooled CPC and 78 °C for CPC system. In addition, the power produced by the cooled CPC was 11 W and 8 W for CPC.

These results revealed an improvement in the cooled CPC system over the simple CPC system. At the solar incident radiation of 800 W/m^2 the improvements were of 6 % in terms of efficiency and 3 W in terms of power output when the temperatures in the solar cells were reduced by 23 °C with an average wind speed of 1.88 m/s.

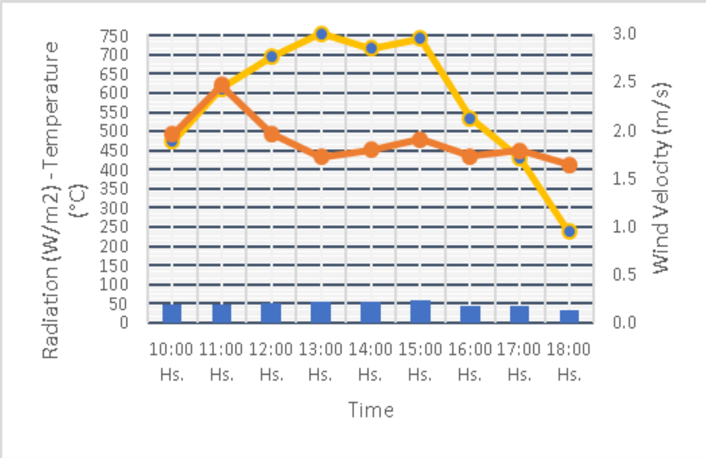

Fig. 12. Average solar radiation, wind speed and solar cells temperatures with time on 18th July 2017.

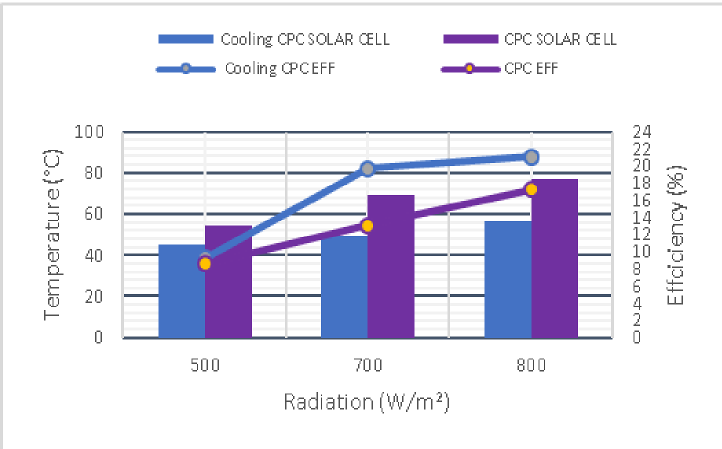

Fig. 13. Average temperature and efficiency with radiation for the Cooling CPC system and CPC system.

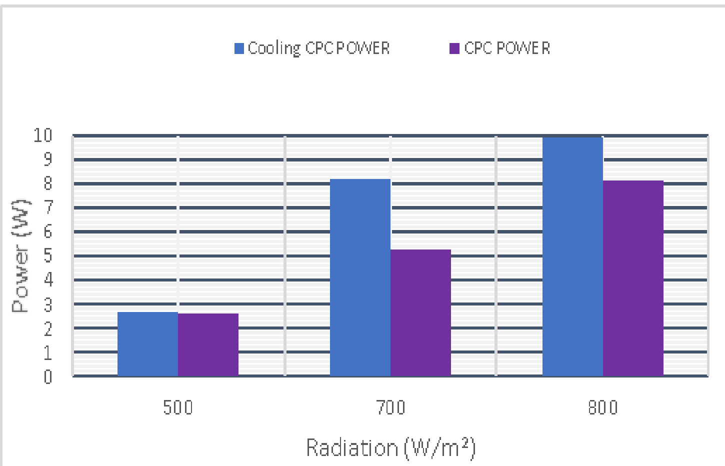

Fig. 14. Average power output with radiation for the cooling.

5. Outdoor characterization CPC/PCM and PV system

5.1. Assembly CPC/PCM system

It is very important to make sure there is no air gap between the container and the solar cells. The air gap can lead to heat loses between the solar cell and the PCM container, producing a reduction of heat to be transferred to the PCM container. However, full contact can lead to power losses due to a short circuit between the solar cell connection and the aluminium container (Mallick, 2007). Due to time constraints of the project, the container was placed in the back of the solar cell without being glued and the CPC/PCM system was electrically characterized. The final arrangement of CPC/PCM system is shown in Fig. 15.

Fig. 15. Final disposition for the CPC/PCM system.

5.2. Analysis of CPC/PCM system

The data were recorded on the 4th and 5th of November 2017 during the day and night. The weather during testing was generally sunny with intermittent cloud cover. The variation of solar radiation, power, temperature and efficiency with the time are shown in Fig. 16, 17, 18 and 19 respectively.

From figures 17 and 19, it can be seen that the efficiency and power for the CPC/PCM system were higher than the PV system in the afternoon specially on November 5th due to the highest radiation. An abrupt power reduction can be seen around 10:00 due to the shadow caused by another device on the roof. The maximum efficiency achieved for the CPC/PCM system and reference PV system were 4.3 % and 4.1 % respectively and the maximum power for the CPC/PCM system were 1.1 W and for the reference PV system 1 W, at solar incident radiation 400 W/m^2. At this radiation, the temperature for the solar cells were 27.4 °C for the CPC/PCM system and 26.2 °C for the PV system. Therefore, the CPC/PCM system had an increase of 0.2 % in efficiency and 0.1 W in power when the solar cell temperature was only 1.2 °C more than the PV system. From figure 18, it can be seen that the temperature of the PCM is always lower that the solar cell in the CPC system and the solar cell in the reference PV system. The maximum temperatures were 28.8 ºC for the CPC/PCM system, 29.7 ºC for the PV system and 20.1 ºC for the PCM. During the night, PCM temperature was on average about 3 ºC and it took up to 12 hours to reduce to 17.1 ºC.

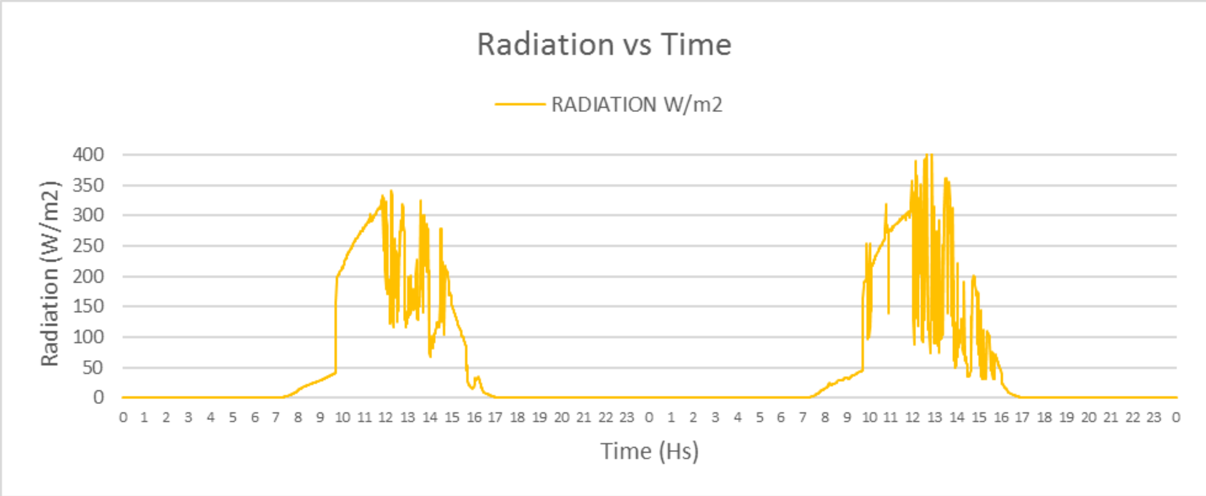

Fig. 16. Solar radiation with time at 4th and 5th November 2017.

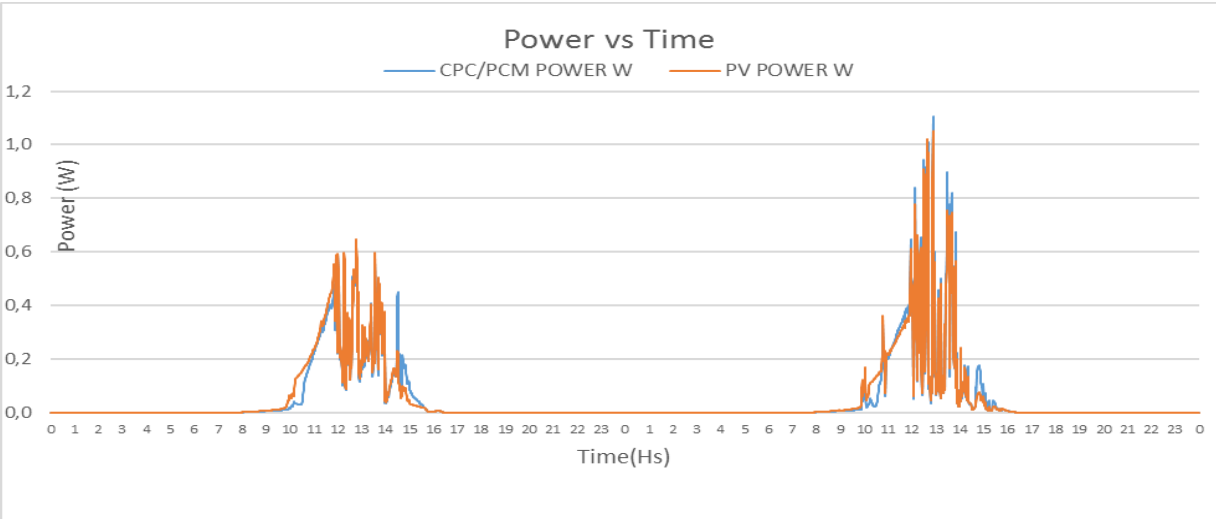

Fig. 17. Power with time for the CPC/PCM and PV system at 4th and 5th November 2017.

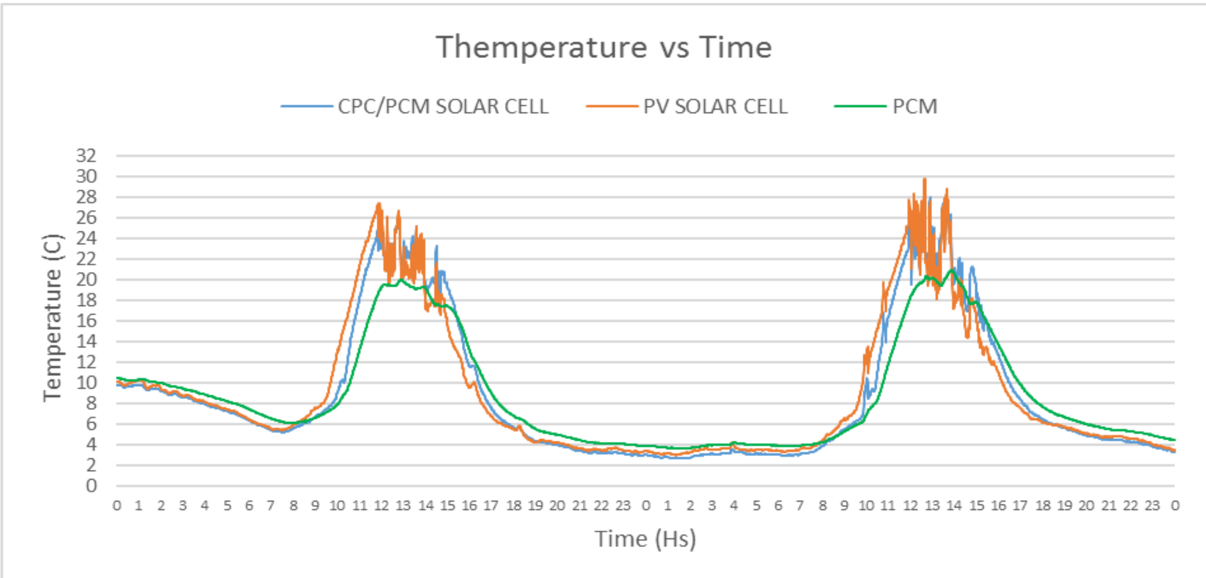

Fig. 18. Temperature with time for the CPC/PCM and PV system at 4th and 5th November 2017.

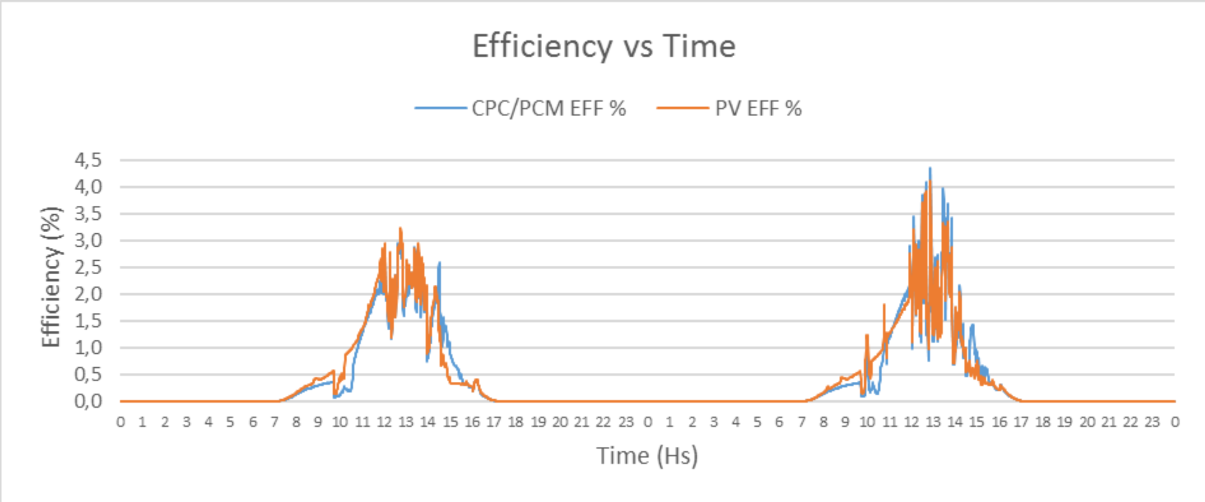

Fig. 19. Efficiency with time for the CPC/PCM and PV system at 4th and 5th November 2017.

6. Conclusion

Three different CPC system configurations were manufactured and tested in outdoor conditions and the results were compared with a reference PV system with the same solar cell area and characteristics. The experimental results showed that the efficiency, power and temperature from CPC system were higher than the PV system. The solar cell temperatures for the CPC system decreased when ambient convective cooling was added and as a consequence of this the efficiency and power generated improved. The power and efficiency for the CPC system increased when the PCM container was incorporated in the back of the solar cell string compared with the PV system due to heat absorption from the PCM. In addition, the heat is stored in the PCM container.

The maximum efficiency, power and temperature achieved by CPC system were 18.6 %, 8.9 W and 83.6 °C respectively. The values represented an increase by 35 % in efficiency, 12 % in power and 14 % in temperature compared with the PV system. The average efficiency, power and temperature achieved by the cooled CPC system at solar incident radiation of 800 W/m2 were 23 %, 11 W and 55 °C respectively. The values represented an increase by 65 % in efficiency, 84 % in power and 22 % in temperature compared with the PV system.

The average efficiency, power and temperature achieved by the CPC/PCM system at solar incident radiation of 400W/m^2 were 4.3 %, 1.1 W and 27.4 °C respectively. The values represented an increase by 4 % in efficiency and 10 % in power compared with the PV system. In addition, the temperature increased only by 2 % compared with the PV system.

7. Acknowledgment

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