311: Performance Evaluation of Photovoltaic panel Integrated with Compound Parabolic Concentrator (CPC) Installed in Hot Arid Area

Mohamed S.YOUSEF [1], Ali K. ABDELRAHMAN[1], S A. NADA[2] AND S. OOKAWARA[3]

[1] Energy Resources Engineering Department, Egypt- Japan University of Science and Technology (E-JUST), Alexandria, Egypt, mohamed.mohamed@ejust.edu.eg

[2]Department of Mechanical Engineering, Benha Faculty of Engineering, Benha University, Benha, Egypt, samehnadar@yahoo.com

[3]Department of Chemical Engineering, Graduate School of Science and Engineering, Tokyo Institute of Technology, Tokyo, Japan, sokawara@chemeng.titech.ac.jp

Abstract: Egypt is facing energy crisis despite of the development in every consumption sector. Hence, a search for the efficient utilization of renewable energy, specially the solar energy is a must. The aim of the present work is experimentally and numerically investigating the performance of the photovoltaic (PV) panel integrated with truncated symmetric compound parabolic concentrator (CPC) in hot arid area. For the sake of the experimental work, symmetric CPC with geometrical concentration ratio of (2.4X) has been designed, fabricated and tested. Experiments have been conducted outdoors on the roof top of the Energy Resources Engineering (ERE) building at Egypt-Japan University of Science and Technology (E-JUST) in new Borg El-Arab city, Alexandria, Egypt (Longitude/Latitude: E 029º 42´ / N 30º 55´). A detailed thermal/electrical analytical model was developed and numerically solved using MATLAB software environment to calculate the thermal and electrical performance parameters of the (PV-CPC) system. The Numerical results were in a good agreement with the experimental results. Results showed that PV maximum power was enhanced by 18 % with CPC compared to the non-concentrating one. Although, the results indicate that concentration increases short circuit current (Isc) by 32%, it decreases open circuit voltage (Voc) by 5%. Finally, the proposed (PV-CPC) system yielded promising results in both increasing electrical power production with low cost and provide an advantage for building-integrated PV systems. The study recommends to use proper cooling system for further performance enhancement and effective operation of the (PV-CPC).

Keywords: Photovoltaic panel, Compound parabolic concentrator (CPC), Thermal-electrical model, Experimental, Numerical.

1. INTRODUCTION

In Egypt, Solar energy is currently considered the cleanest and the most abundant renewable energy source available to solve the problem of fossil fuel depletion and the dramatically increasing of electrical demand. Therefore, solar energy utilization has become more necessary. Electrical power can be generated from solar energy either by a direct conversion into electrical power by using photovoltaic (PV) technology or by converting it into thermal energy, then to electrical power. The direct conversion of solar radiation into electrical energy through PV technology is still the most suitable and economical way of utilizing solar energy in electric power generation. The widespread of using PV in electric power generation from solar energy is still relatively restricted due to its prohibitively high cost and the needed large areas. Using concentrating photovoltaic technology (CPV) technology has recently appeared to be the best approach to reduce the initial cost of solar PV cells by concentrating solar radiation into a smaller area with less- expensive reflectors. Many researchers have extensively investigated different types of solar concentrators used in CPV technology such as V-trough concentrator and compound parabolic concentrator (CPC). The CPC solar concentrators are considered the most suitable and efficient one for cost saving of electricity production by PV systems. In addition, the CPC concentrators can be utilized indifferent ways such as solar thermal applications, building integrated photovoltaic systems and advantage of the ability to collect solar radiation through large acceptance angle for stationary operation without need for tracking system is encouraging particularly for low concentration systems. Based on these concepts, (Mallick et al. 2004) performed experimental studies on photovoltaic modules equipped with designed an asymmetric compound parabolic photovoltaic concentrator. Although the theoretical geometric concentration ratio of CPC was 2 sun, the maximum output power increased only by 62%. This was attributed to a combination of optical and electrical resistance losses. (Hatwaambo et al. 2008) studied three different low-cost reflector materials, micro reflectors, rolled aluminum foil and anodized aluminum in a low concentrating (PV-CPC) system with a geometrical concentration ratio of 3.6 to concentrate solar radiation across a small module area and reduce the PV module cost. Nevertheless, the results revealed that the short-circuit current increased within a factor of 2.4, the fill factor decreased by 10% under the proposed concentration system due to non-uniform illumination that leads to increase in the resistive losses in the module. They concluded that the rolled aluminum reflector among other's reflector materials had a potential for the use as a PV – CPC reflector for cost reduction. The thermal performance of the evacuated CPC solar collector with a cylindrical receiver has been investigated by (Kim, Han, and Seo 2008) .They numerically presented a comparative study between stationary CPC solar collector and single axis tracking CPC solar collector. Results demonstrated that the thermal efficiency of the tracking CPC solar collector was 14.9% higher than that of the stationary CPC solar collector. (Hedayatizadeh et al. 2013) investigated numerically the thermal and electrical performances of a photovoltaic/thermal water collector integrated with a CPC system with a concentration ratio of 2 sun. They reported that the (PV/T-CPC) integrating system has a considerably positive impact on the thermal and electrical performance of the system. Simulation results were validated with previous experimental data from the literature and a good agreement was achieved. Finally, they presented parametric studies to study the effects of different factors on the thermal and electrical efficiency of the system such as solar radiation, mass flow rate, inlet water temperature and wind speed. (Sellami and Mallick 2013) studied experimentally and numerically the optical efficiency of a PV crossed compound parabolic concentrator (CCPC) system. Results demonstrated that the CCPC system with a concentration ratio of 3.6 provided promising results compared to a 3-D Compound Parabolic Concentrator (CPC) for the use as a static solar concentrator. Numerical results were validated against experimental measurements where a fair agreement was achieved. (Guiqiang et al. 2014) designed and investigated a stationary lens-walled compound parabolic concentrator (CPC) with air gap. They reported that the lens-walled CPC with air gap increases optical efficiency by more than 10% compared with the original lens-walled CPC. Recently, (H. M. Bahaidarah et al. 2014) investigated experimentally and numerically the performance of flat PV string and PV–CPC systems. They presented a comparative study of the two systems with and without cooling. Results revealed that cooling had a significant impact on the output maximum power for the two systems where the maximum power output of the PV–CPC system with cooling was about two times the power of PV module without cooling. Numerical results were compared with experimental data and a good agreement was obtained.

The above literature shows that few studies have investigated the effect of the different operating, design and geometric parameters on the performance of PV panel integrated with CPC collector, however studies for hot arid area are very limited. It is believed that the performance of the PV panel integrated with CPC collector strongly affected by the ambient conditions of the hot arid zones. Therefore, the present study aims to investigate, experimentally and numerically, the performance of the photovoltaic PV panel integrated with truncated symmetric compound parabolic concentrator (CPC) under the conditions of hot arid area. Symmetric CPC with geometrical concentration ratio of (2.4X) has been designed, fabricated and tested. Moreover, thermal and electrical models are developed using MATLAB software environment to validate the experimental measurements.

2. NUMERICAL MODEL

A schematic diagram and cross- sectional view of the PV-CPC system are shown in Fig. 1. Figure 1 also shows the dimension of the PV panel and the considered elemental length (dx) of the panel for modelling. The geometric and physical specifications of the PV-CPC collector as well as the climatic and operating parameters considered in this study are given in Table 1. The following assumptions have been considered during developing the proposed numerical model (H. M. Bahaidarah et al. 2014) : (1) the transmissivity of ethyl vinyl acetate (EVA) is 100%, (2) quasi-steady-state condition is considered for the system, (3) the mean temperature of each layer of PV panel is considered in the analysis, (4) temperatures variation along the thickness and width of the cell layers are negligible, (5) The CPC trough is free from fabrication errors.

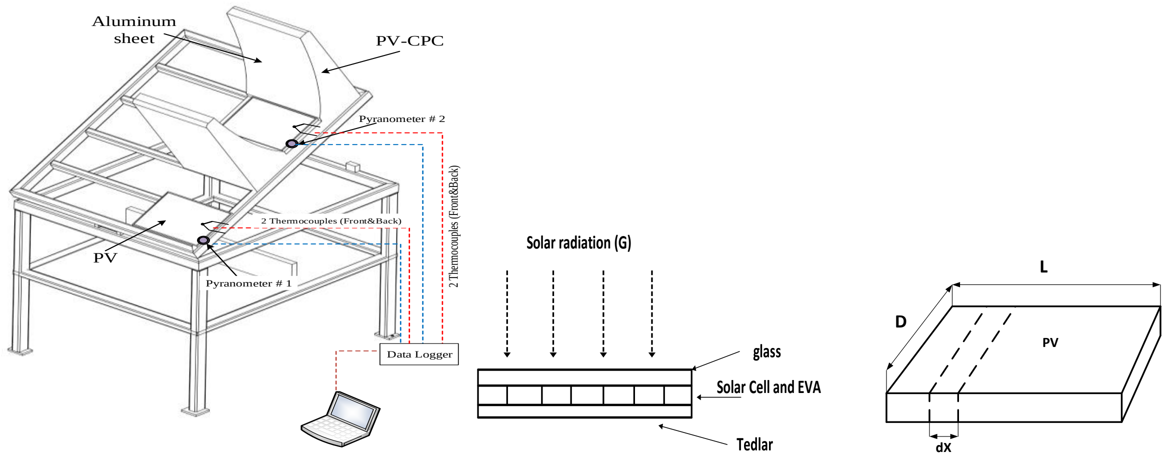


Figure 1: Schematic diagram and cross-sectional view of a (PV-CPC) collector

Table 1: The Values of Climatic, Operating and Design Parameters of the system.

Module type	Polycrystalline (ICO-SPC-10 W)
The length of PV module, L1	0.35 m
The width of PV module, L2	0.245 m
The number of modules in series per string, Nm	1
The number of cells in series in the module, NC	36
The short-circuit current at the reference conditions, $I_{SC,ref}$	o.61 A
The open-circuit voltage at the reference conditions, $V_{OC,ref}$	22.41 V
The maximum power point current at the reference conditions, $I_{mp,ref}$	0.56 A
The maximum power point voltage at the reference conditions, $V_{mp,ref}$	17.9 V
The solar cell temperature at reference conditions, $T_{SC,ref}$	298.15 K
The electrical efficiency at the reference conditions, η_{e1}	12 %
The current temperature coefficient, μ_{Isc}	(.010+/- 0.01) %/ ℃
The voltage temperature coefficient, β	- (0.38 +/-0.01) %/ ℃

2.1. Thermal model

Energy balance principle for the components of a (PV-CPC) collector is applied to calculate the cell and back temperatures. Figure 2 gives the thermal resistant circuit of the different sections of the PV system. The energy balance equations for the overall Glass-Tedlar PV Module reveals that the rate of absorbed solar energy by solar cell and tedlar equals the sum of overall heat loss from the system. The components of the heat losses are (i) heat loss from the top surface of PV cell to ambient, (ii) heat transfer from PV cell to the back surface of panel, and (iii) the rate of electrical energy produced.

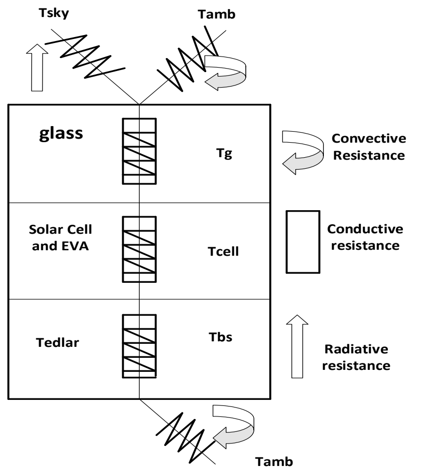


Figure 2: Thermal resistance circuit diagram for a PV-CPC collector

The proof of governing equations on the thermal analysis of PV-CPC collector is not included to have a brief note. More details of the derivation of governing equations are found in (Hedayatizadeh et al. 2013).

The solar cell temperature as a function of back surface temperature of PV panel can be given as:

$$T_{sc} = \frac{(\alpha\tau)_{eff} G + U_t T_{amb} + U_T T_{bs}}{U_T + U_t} \qquad (1)$$

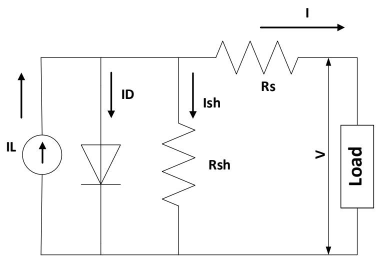
The module back surface temperature is given as:

$$T_{bs} = \frac{\left[h_{p1} (\alpha\tau)_{eff} G + U_{tT} T_{amb} + U_b T_{amb}\right]}{U_b + U_{tT}} \qquad (2)$$

2.2. Electrical Model

The Five-parameter photovoltaic model by (De Soto, Klein, and Beckman 2006) is utilized in this study for the estimation of the electrical parameters. The solar PV cell is represented by an equivalent electrical circuit which describes the cell as a diode as shown in Fig. 3 and Eq. 3.

$$I = I_L - I_o \left[\exp\left(\frac{V + I.R_S}{a} \right) - 1 \right] - \frac{(V + I.R_S)}{R_{sh}}$$



Equation 3: an equivalent electrical circuit of PV module

Figure 3 : Equivalent circuit of a PV cell

Where:

- I, V = Current and voltage at load (A , V)
- α = ideality factor
- I_L = light current (A)
- I_o = diode reverse saturation (A)
- R_S = series resistance (ohm)
- R_{Sh} = shunt resistance (ohm)

The proof of governing equations on the electrical model of PV-CPC collector is not mentioned to have a brief note. More details of the calculation of five parameters are found in (De Soto, Klein, and Beckman 2006) . The value of five parameters (α_{ref}, $I_{L, ref}$, $I_{o, ref}$, $R_{S, ref}$ and $R_{Sh, ref}$) are obtained by solving five non-linear equations at reference conditions ($G_{, ref}$ =1000 W/m^{2,} $T_{amb, ref}$ = 25 C°). Next, the five parameters at new climate and operating conditions ($G_{, new}$, $T_{cell, new}$) are calculated (Sobhnamayan et al. 2014).

The maximum power current (I_{mp}) and voltage (V_{mp}) are obtained by simultaneously solving the following equations utilizing the electrical parameters calculated as (H. Bahaidarah et al. 2013):

$$\frac{I_{mp}}{V_{mp}} = \frac{\frac{I_O}{a}\exp\left(\frac{V_{mp}+I_{mp}R_S}{a}\right)}{1+\frac{R_S}{R_{Sh}}+\frac{I_O R_S}{a}\exp\left(\frac{V_{mp}+I_{mp}R_S}{a}\right)} \tag{4}$$

$$I_{mp} = I_L - I_O\left[\exp\left(\frac{V_{mp}+I_{mp}R_S}{a}\right)-1\right]-\left[\frac{V_{mp}+I_{mp}R_S}{R_{Sh}}\right] \tag{5}$$

The maximum power (P_{mp}) extracted from the module and maximum power point efficiency (η_{mp}) can be estimated from:

$$P_{mp} = I_{mp}V_{mp} \tag{6}$$

$$\eta_{mp} = \frac{I_{mp}V_{mp}}{G\,A_m} \tag{7}$$

3. EXPERIMENTAL SETUP AND PROCEDURES

An experimental setup has been developed to investigate and evaluate the thermal and electrical performance of PV-CPC system as compared to PV-panel without CPC system. A symmetric 2-dimensional CPC has been designed and fabricated. Mirror aluminum sheets are used as reflecting material for the CPC which has good reflectivity and low cost. A photograph of the experimental setup is shown in Fig. 4 and it consists of the following main components: two identical polycrystalline photovoltaic modules (10W rated power), variable load resistance, CPC concentrator, digital ammeter and weather station. To collect the maximum amount of solar radiation, the tilt angles of the two PV modules and reflectors are selected to be equal the latitude. The PV-CPC trough and PV module were positioned on East-west axis with the aperture tilted 30° from the horizontal toward south. In order to measure the daily global solar radiation incident on the two panels in W/m^2, two pyranometer are used. One for the reference PV panel and the other for the concentration one. The first one was attached beside the reference module whereas the other pyranometer was attached inside the concentrator beside the concentrated panel. The solar cell front and back temperatures were measured using four standard type K thermocouples attached on the front and at the rear of the panels. Two thermocouples are installed on the front surface of the two modules and the other two are installed on the rear surface of the modules. Wind speed and ambient temperature were measured by Port Log weather station installed beside the proposed system as shown in Fig. 5. Measuring output maximum voltage and current were done manually by utilizing the variation of an Ohmic load. The experimental measurements were recorded every one hour from 08:00 AM to 04:00 PM during a clear day (2nd of March 2015) on the roof top of the Energy Resources Engineering (ERE) department building at Egypt-Japan University of Science and Technology (E-JUST) in new Borg El-Arab city, Alexandria-Egypt.

Figure 4: a photograph of Experimental setup

Figure 5: a photograph of the portable meteorological weather station

4. RESULTS AND DISCUSSION

4.1. Daily variation of climatic conditions

Climate conditions such as ambient temperature and wind velocity have a great impact on the performance of PV system. The hourly variations of the wind speed and ambient temperature during the test day are shown in Fig 6. Maximum ambient temperature at noon time, daily average temperature and the daily average wind speed were found to be 23℃, 19℃ and 1.4 m/s, respectively.

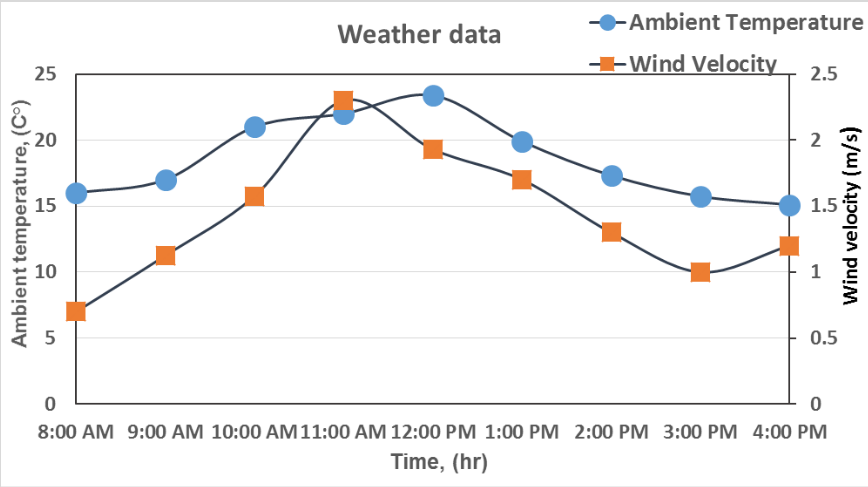


Figure 6: Variation of ambient temperature and wind velocity during the day

4.2. Numerical results

The variations of front and back cell temperatures of flat PV module and PV–CPC system are shown in Fig 7. The measured solar radiation for both systems also superimposed on the figure. As expected, the figures indicate that the front cell temperature is always bigger than the back cell temperature and the cell temperatures increase with the increase of solar intensity. The maximum cell temperature occurs at noon (12:00 PM) when the solar intensity is peak. The maximum front and back cell temperatures of PV– CPC system are about 79°C and 69°C, respectively, while those for flat PV module are about 51°C and 45°C, respectively. This indicates that the cell temperature increases as the amount of absorbed radiation increases.

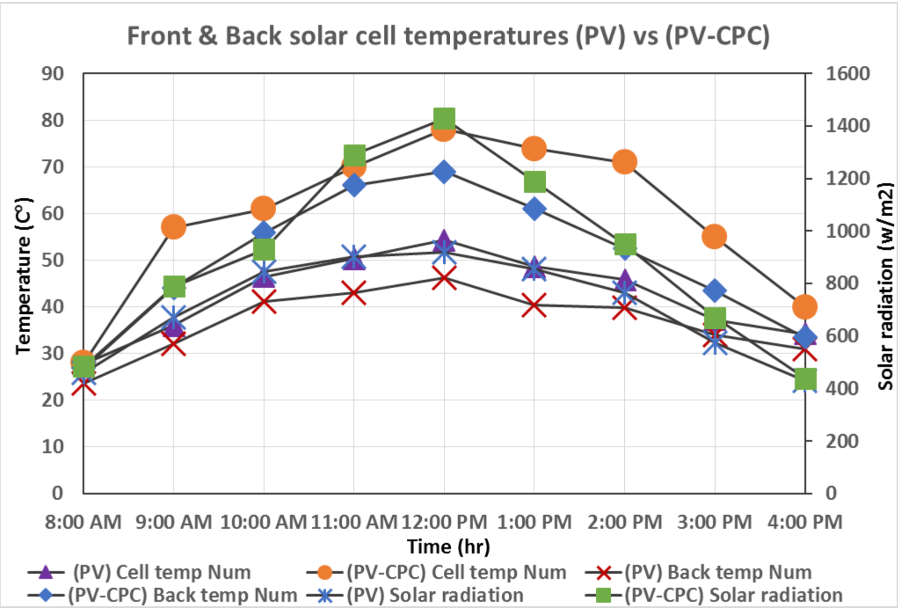


Figure 7: Variations of front and back solar cell temperatures for the two systems

The effect of using CPC concentration system on the short circuit current and open circuit voltage of the PV module are shown in Fig. 8. The figure shows the increase of the short circuit current with increasing the measured solar radiation for both systems. A maximum short circuit current of 0.96 A is obtained with the use of the concentration system at 12:00 PM when the maximum solar intensity was achieved. However, the maximum short circuit current is 0.59 A at the same time for PV without CPC. This reveals that using CPC system increases the short current system by about 70 %. The increase of the short circuit current with using CPC system can be attributed to the increase of the solar radiation received by the PV-CPC system as compared to the flat PV system and to the linearity relation between short circuit current and radiation along the day. In case of open circuit voltage, a minimum open circuit voltage of 18.6 V is obtained with the use of concentration system at noon (12:00 PM) when the maximum solar intensity was achieved. However, the minimum open circuit voltage is 20.1V was achieved at the same time by PV modules without CPC concentration. This reveals that using CPC concentration system reduces the open circuit voltage from PV module by 8%. The decrease of the open circuit voltage by using CPC concentration system can be attributed to the increase in module temperature (see Fig. 7).

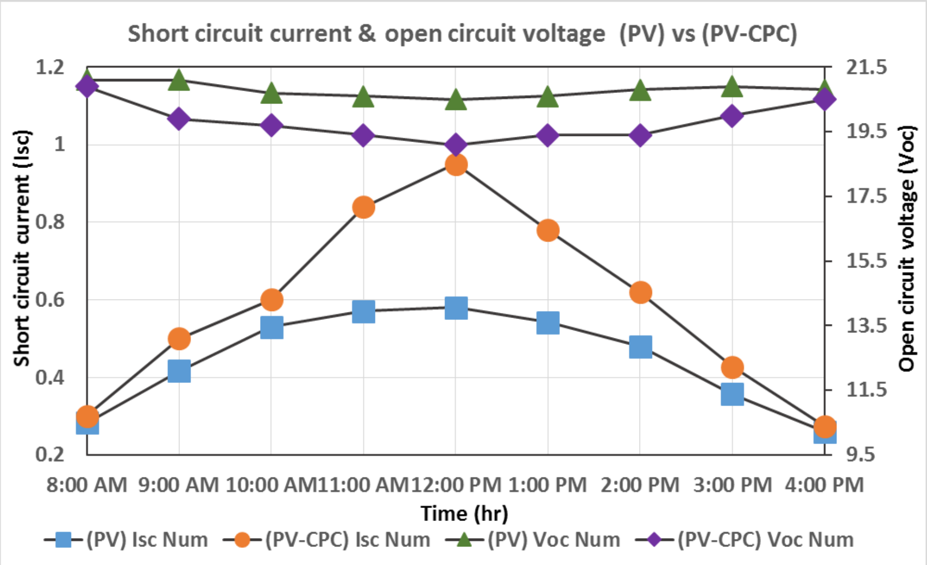


Figure 8: Variations of short circuit current and open circuit voltage for the two systems

Fig. 9 shows the variation of the electrical power and the electrical efficiencies along the day time for both flat PV panel and the PV–CPC system. It is clearly shown from the figure that the power outputs of the PV system and PV-CPC system are peaks at 12:00 PM when the maximum solar intensity was achieved. Also, it can be seen from the figure that at any time the PV–CPC system produces higher power compared to flat PV panel for the same ambient conditions. The improvement in power produced due to using CPC system increases with increasing the solar intensity. The results reveals that the daily average and maximum power output s of the CPC system obtained at the noon time are higher than those obtained by the flat PV panel by about 18% and 50%, respectively. In case of electrical efficiency. It is clearly shown that the (PV-CPC) system has lower electrical efficiency than the flat PV system. A minimum electrical efficiency of 9.6 % was obtained with the use of the proposed concentration system at noon (12:00 PM) when the solar radiation is maximum. However, the minimum electrical efficiency was 10.7 for PV systems without concentration at the same time. This may be attributed to that the increase of the module losses with the increase of the module temperature which increases with the increase of the absorbed solar radiation. This makes the rate of increase in power of the (PV-CPC) system is lower than the rate of increase in absorbed radiation as the increase in solar radiation is about 30 % due to using concentration system while the increase in the output power was about 18 %. Therefore, it can be concluded that the efficiency of the proposed CPC concentrating system is lower than the flat PV system.

It is should to be noted that the CPC used in this experiment had a theoretical concentration ratio of 2.4, hence, the output maximum power of the (PV-CPC) system was expected to increase by a factor of 2.4. However, the results in fig (9) showed that the output power with using the CPC trough increased by about (18%). This may be attributed to more than one factor. Firstly, the increase in power output due to high concentration is not directly proportional with the solar radiation concentration due to increased ohmic losses in the module. Secondly, high cell temperatures observed by the (PV-CPC) system results in a lower open-circuit voltage as previously mentioned in figure (8). Finally, the observed non-uniform illumination and optical losses which would cause high ohmic losses and produce internal current flow which has negative impact on the panel efficiency.

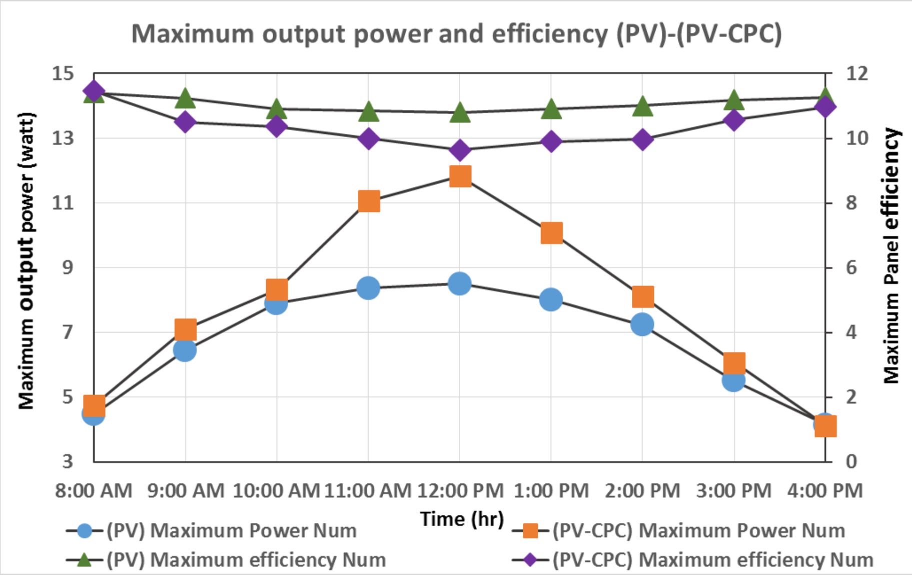


Figure 9: Variations of maximum power point and electrical efficiency for the two systems

4.3. Model validation and comparison between numerical and experimental results

In order to validate the numerical model, the model results are verified with the measured experimental data for both of CPC and flat PV systems. The correlation coefficient (r) and the root mean square percent deviation (e) defined by the following equations are used as measurable of agreements between the numerical and experimental results (H. Bahaidarah et al. 2013) :

$$RMSE(e) = \sqrt{\frac{\sum\left[100\times\left(X_{\exp,i} - X_{sim,i}\right)/X_{\exp,i}\right]^2}{n}} \quad (8)$$

$$r = \frac{n\left(\sum X_{\exp}\cdot X_{sim}\right) - \left(\sum X_{\exp}\right)\cdot\left(\sum X_{sim}\right)}{\sqrt{n\cdot\left(X_{\exp}^2\right) - \left(\sum X_{\exp}\right)^2}\sqrt{n\cdot\left(X_{sim}^2\right) - \left(\sum X_{sim}\right)^2}} \quad (9)$$

Where:

- X_{exp} = the values of the experimentally measured parameters
- X_{sim} = the values of the numerically estimated parameters
- n = the number of the experiments data points.

In order to have a brief note, the comparison of numerical and experimental results for modules temperatures, and modules efficiencies only are shown in figures 10 and 11, however the correlation coefficient (r) and the root mean square percent deviation (e) of these comparison are given in Table 2. Figures [10, 11] and Table 2 show that the numerical results are in a good agreement with the experimental results for all of the parameters.

Table 2: Validation of numerical model

	PV System		PV-CPC System	
Parameter	correlation coefficient (r)	Root Mean square percent deviation (e)	correlation coefficient (r)	Root Mean square percent deviation (e)
Module front temperature	0.99	2.41	0.98	5.44
Module back temperature	0.98	4.1	0.96	5.1
Maximum Output power	0.99	1.1	0.99	1.15
Module efficiency	0.89	1.25	0.97	1.9
Short circuit current	0.99	1.1	0.99	1.15
Open circuit voltage	0.92	1.25	0.97	1.9

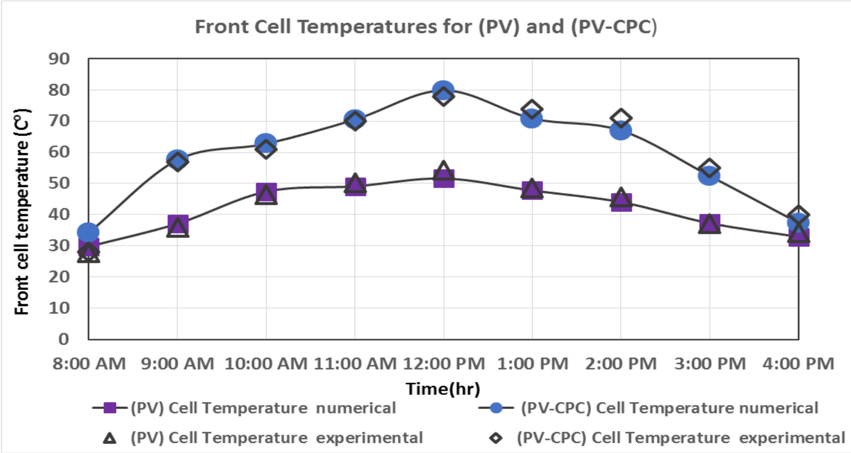


Figure 10: Comparison between numerical and experimental results of Front cell temperatures with and without concentration

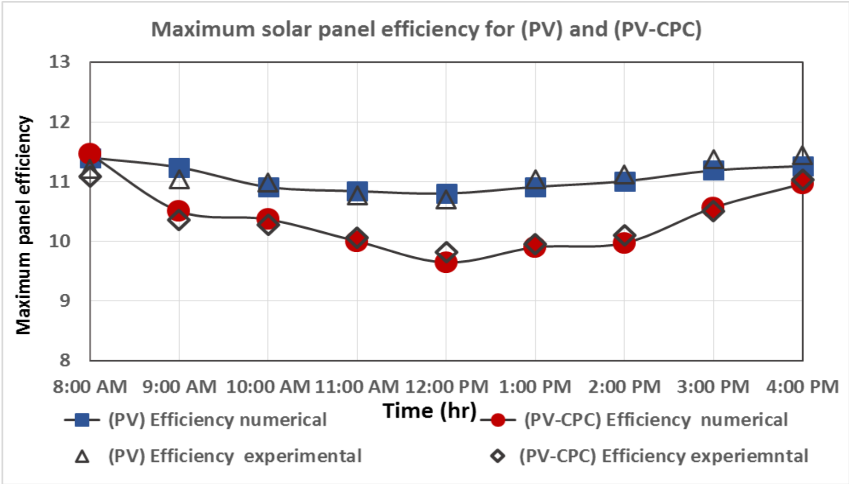


Figure 11: Comparison between numerical and experimental results of maximum output efficiency with and without concentration.

4.4. I-V and P-V curves

Figures 12 shows the average I–V and P-V characteristics values of the two systems obtained from the experimental data. The figure clearly shows that the I–V and P-V curves of the PV-CPC system is higher than that of the PV system without CPC. This reveals that the PV-CPC system provides considerable improvement in the short circuit current and maximum power output with an average increase of 32 % and 18 % respectively. But, it has also a slightly negative impact on the open circuit voltage with an average decrease of 5 %.

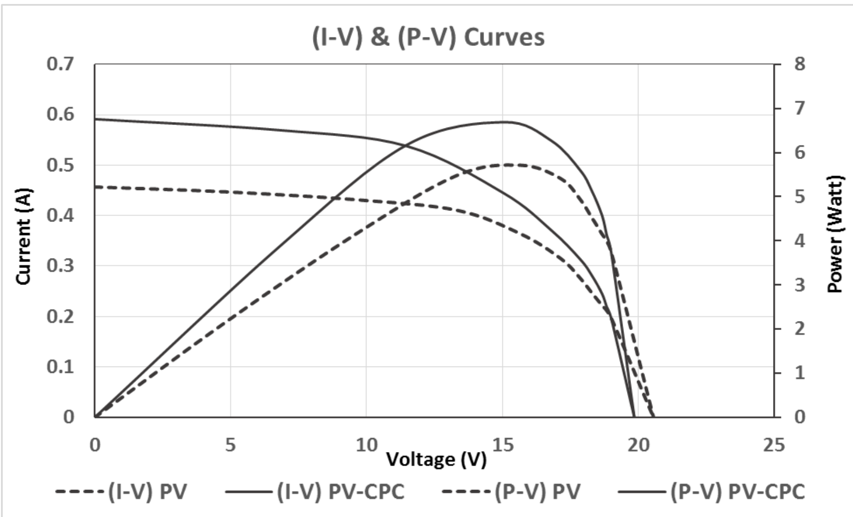


Figure 12: Comparison of (I-V) and (P-V) curves with and without concentration

5. CONCLUSION

Experimental and numerical comparative study have been carried out to study the performance of photovoltaic panel with and without a symmetric compound parabolic concentrator (CPC) in hot arid area. A numerical (thermal and electrical) model has been developed to study different thermal and electrical parameters related to the performance of the proposed system using MATLAB software environment. The results showed that the CPC-PV proposed system is more effective for high levels of solar radiation. In addition, the system has a considerable positive effect on the maximum output power and the short circuit current with an average increase of 32 % and 18 %, respectively. Conversely, it has a negative impact on open circuit voltage with an average decrease of 5 % due to the higher cell temperature achieved by the system. Numerical results are validated with the experimental results and a good agreement are found. In order to further improve the performance of the (PV-CPC) system, a proper cooling system is recommended. The study reveals that the proposed PV-CPC system can provide a cost effective electrical power generation source integrated with buildings.

6. ACKNOWLEDGMENT

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