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Indoor Characterization of a Reflective Type 3D LCPV System

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Abstract. Low concentrating photovoltaic (LCPV) systems produces higher electrical output per unit solar cell compared to typical PV systems. The high efficiency Si solar cells can be utilized with little design and manufacturing changes for these applications. However, a key barrier towards achieving economic viability and the widespread adoption of LCPV technologies is the losses related to high operating temperature. In the present study, we evaluate the performance 3D low concentration system designed for 3.6×, using a reflective Cross compound parabolic concentrator (CCPC) and a Laser Grooved Buried Contact solar cell having an area of 50*50mm^2. Results demonstrate the losses occurring due to the temperature rise of the solar cell under concentration and we analyze the potential which could be utilized for low grade heating applications.

INTRODUCTION

Solar energy is known to be an infinite source of energy whose potential remains untapped due to the technological, financial and policy limitations in several countries around the world. Typical uses of solar energy include electricity generation using photovoltaic systems or hot water generation using solar thermal collectors. An effective way to enhance the power produced by solar cells is to concentrate the incoming light using an optical concentrator. A Low concentrating Photovoltaic (LCPV) system has a concentration ratio 1-10×. Typically, these systems require seasonal or no tracking at all for concentrating sunlight over the solar cells. Standard PV modules can be used with this type of concentrating system without much modification. A number of systems have been developed in the past few decades utilizing this concept essentially for building integration1-4.

The Compound Parabolic Concentrator (CPC) is the most commonly used design enabling the capture of huge amounts of solar energy and transferring it to the solar cell. Typically two dimensional designs[4, 5] have been developed previously for solar applications. The three dimensional CPC design having both a circular entry and exit aperture typically finds its application in the LED industry where it is uses for reflecting the light. However, the design could not be easily implemented for solar cell applications as the solar cells have a square or rectangular shape. Both reflective[6] and refractive[7] based three dimensional Cross Compound Parabolic Collectors (3DCCPC) have been developed and demonstrated previously to overcome this barrier and to be utilized for such applications. These systems used smaller sized Laser grooved buried contact solar cells admeasuring about 1cm^2. Results indicated an increased electrical performance due to light concentration over a range of incident angles. The reflective type concentrator showed lower optical efficiency than the modeled values primarily due to the limitation

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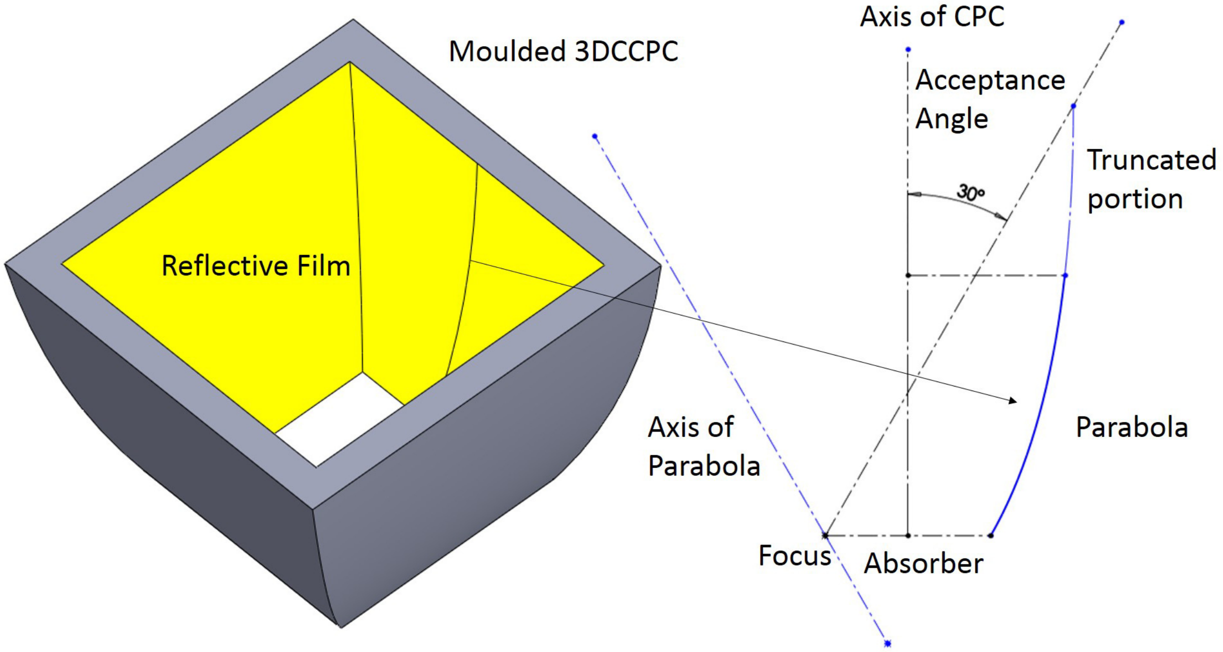
of the reflectance values of the surface used during the experiment. The refractive type on the other hand experienced optical losses through the encapsulating material which was improved by light trapping.

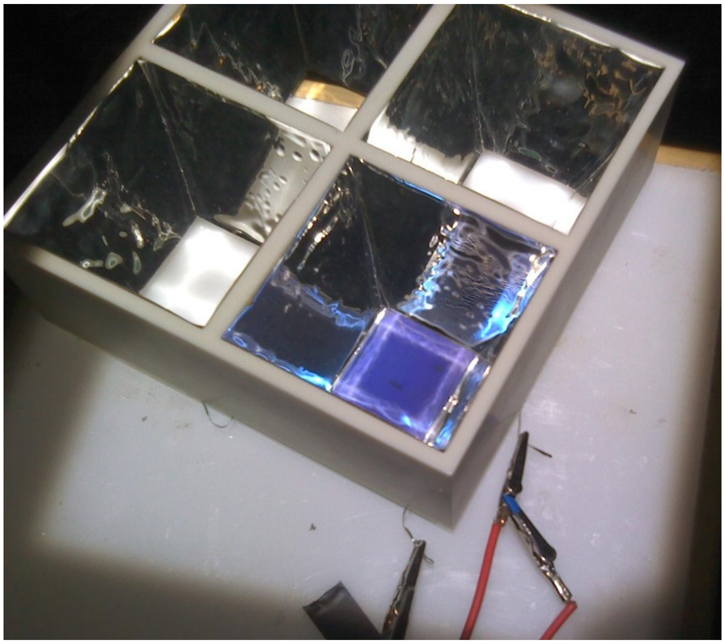
The process of optical concentration on one hand increases the light impinging on the solar cells and their power output, but on the other hand leads to higher operating solar cell temperature[8] and non-uniform illumination[9]. This high temperature degrades the performance of the solar cell and reduces its lifetime. This shortcoming can be overcome using a cooling unit behind the solar cells to keep them cool and utilize the dissipated thermal energy for low grade heat applications. Addition of cooling system additionally offers better efficiency of the solar cell and improved lifetime. In the present study we have performed an indoor characterization of a reflective type LCPV system particularly to understand the available thermal potential available in this system and exploit options for utilizing it. We have utilized a bigger sized solar cell admeasuring 50mm*50mm for harnessing a greater thermal output.

SYSTEM DESIGN AND MANUFACTURE

The system is designed using the CPC profile with an acceptance angle of 30° and sweeping it around a square cross section for a geometric concentration of 4×. Truncation is carried out for optimal performance[6], making the effective Geometric concentration of 3.6× which corresponds to a truncated height of 80mm as shown in FIGURE 1. The concentrator is made of thermoplastic material using molding process and a reflective film is glued on the surface. Using a laser cutting procedure the reflective films are cut to match the exact parabolic profile before being attached to the concentrator. Once the concentrator is prepared a LGBC silicon solar cell is attached at the exit aperture as shown in Figure 1(c).



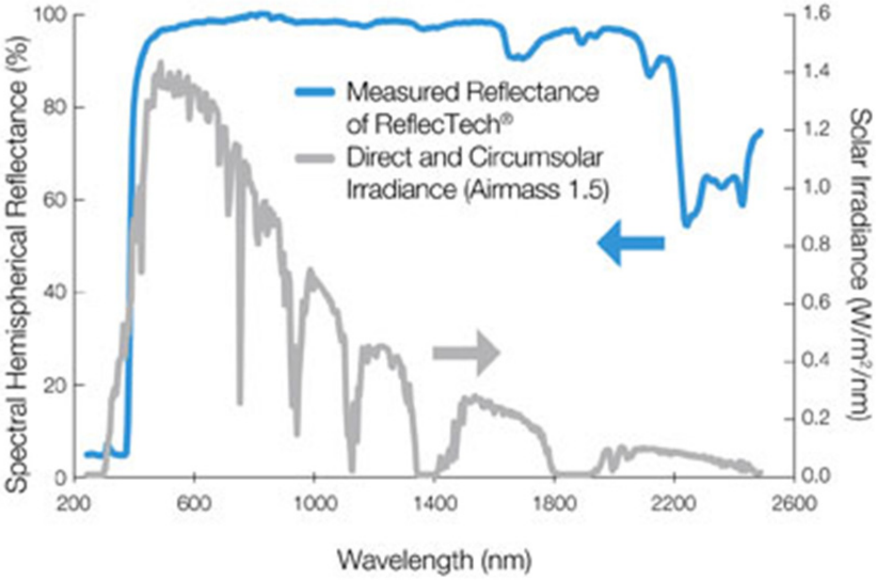
(a) (b)



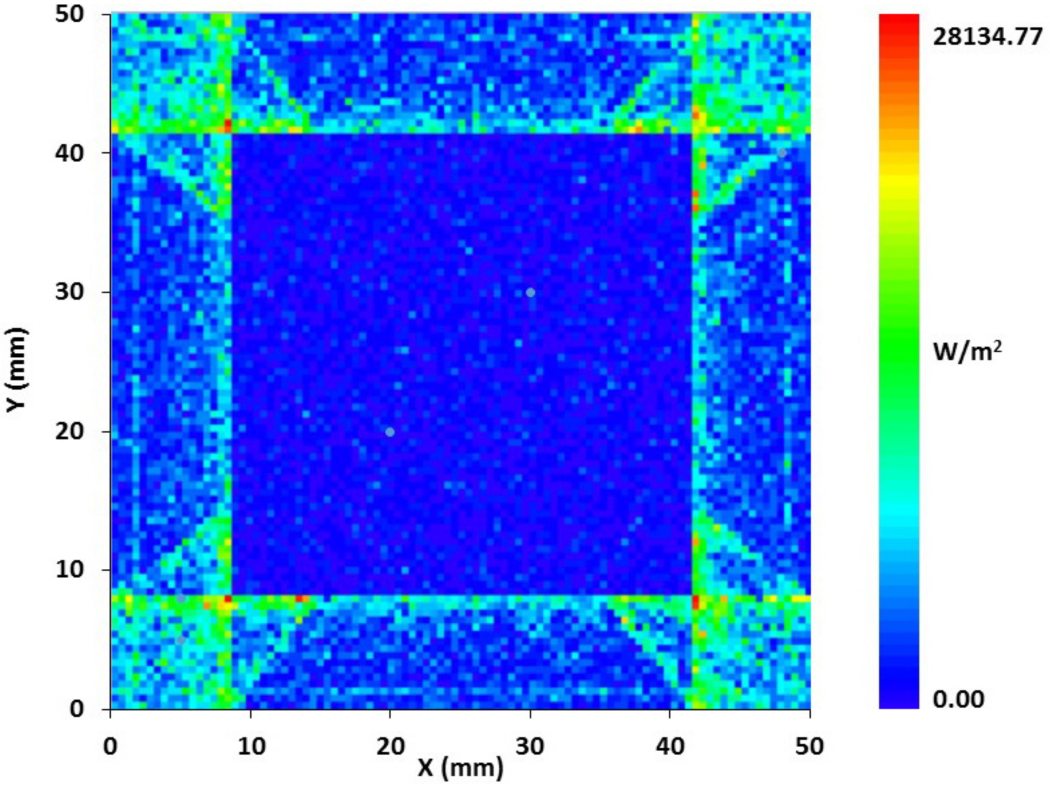
(c)

FIGURE 1. (a) Schematic of a unit reflective 3DCCPC (b) The design of the CPC (c) Unit module of the CPV system

The reflectance of the film used in the present study is shown in FIGURE 2(a). The average reflectance of this film is around 94% across the spectral range of 300-1200nm. A ray trace simulation is performed using these reflectance properties and using a standard AM1.5G spectrum under an incoming solar radiation of 1000 W/m^2. FIGURE 2(b) shows the flux distribution expected to be impinging on the solar cell surface. Peak irradiance levels going upto 28 suns could be seen at few points on the surface. The irradiance is averaged and it is found that the about 3370 W/m^2 is expected to reach the solar cell surface under normal incidence.



(a)



(b)

FIGURE 2. (a) The reflectance properties of the film used in the construction of the concentrator (b) The flux distribution on the solar cell

EXPERIMENTAL SETUP

In an indoor controlled environment, experimental setup was made to evaluate the performance of the LCPV unit. A solar simulator (Class A+A+A+, AM 1.5G irradiation spectrum) was used as the source of the light. The I-V characteristics of the bare solar cell were initially recorded. Further the 3DCCPC module was placed over the solar cell to measure the electrical power output of the solar cell. Later both the solar cell temperature with and without the concentrator were monitored as a function of time under constant irradiance levels.

RESULTS

The I-V characteristics were recorded for the solar cell with and without the concentrator using the solar simulator setup similar to one reported earlier[10]. The photocurrent generated by the solar cell increases proportional to the incident light and is a good measure of estimating the amount of concentrated light reaching the solar cell. Results from this analysis are shown in FIGURE 3. The short circuit current increases from 880 mA to 2450 mA due to light concentration.

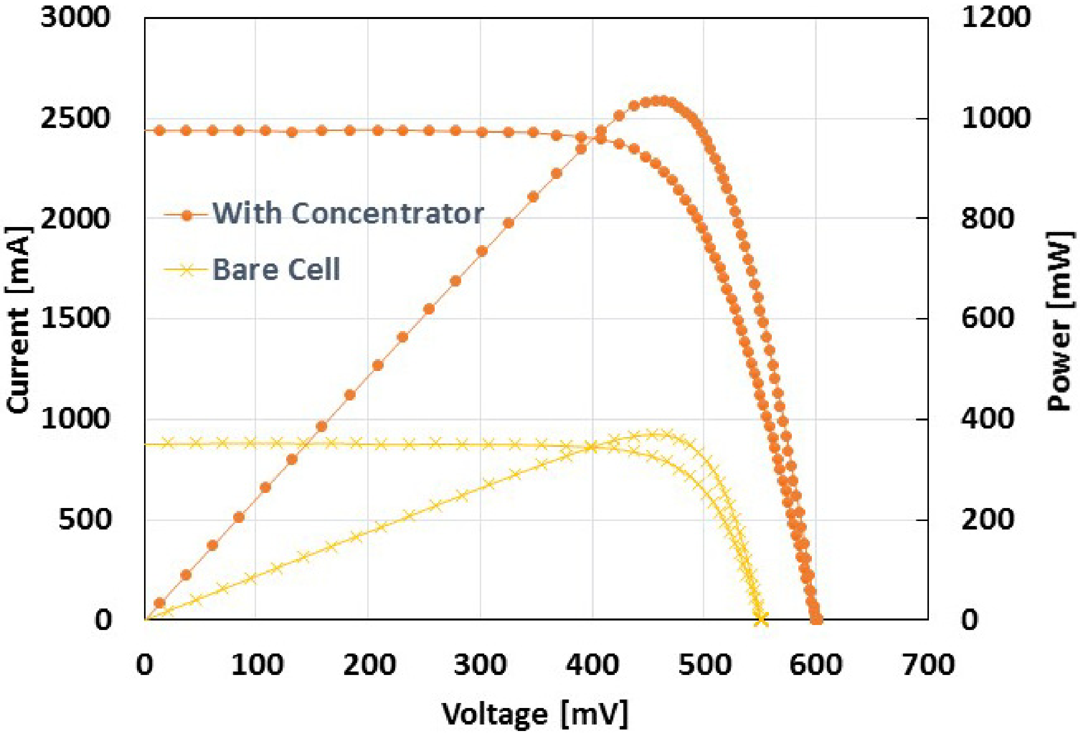


FIGURE 3. I-V characteristics of the solar cell with and without the concentrator

The open circuit voltage was also found to increase from 550 mV to 600 mV with and without the concentrator. A maximum power of 371 mW was recorded for the bare solar cell and about 1036 mW under concentration. This represents a power ratio of 2.8 and an optical efficiency[10] of 78 %. This value is about 3% to that reported in the smaller sized model[6]. The fill factor of the solar cell was found to drop from 0.76 to 0.71 when placed under concentration. One of the key reasons for the reduced optical efficiency was due to the air bubbles on the reflective surface which can tend to deteriorate the optical performance of the system.

Thermal Performance

In order to understand the thermal potential that could be extracted from the device, a unit concentrator was used whilst using a glass plate as the back surface of the solar cell. The temperature of the solar cell was monitored using a thermal imaging camera as a function of time. FIGURE 4 shows the temperature distribution across the solar cell recorded at different time intervals under 1000W/m^2. It was observed that the solar cell temperature increased to a maximum of 88°C when placed under concentration.

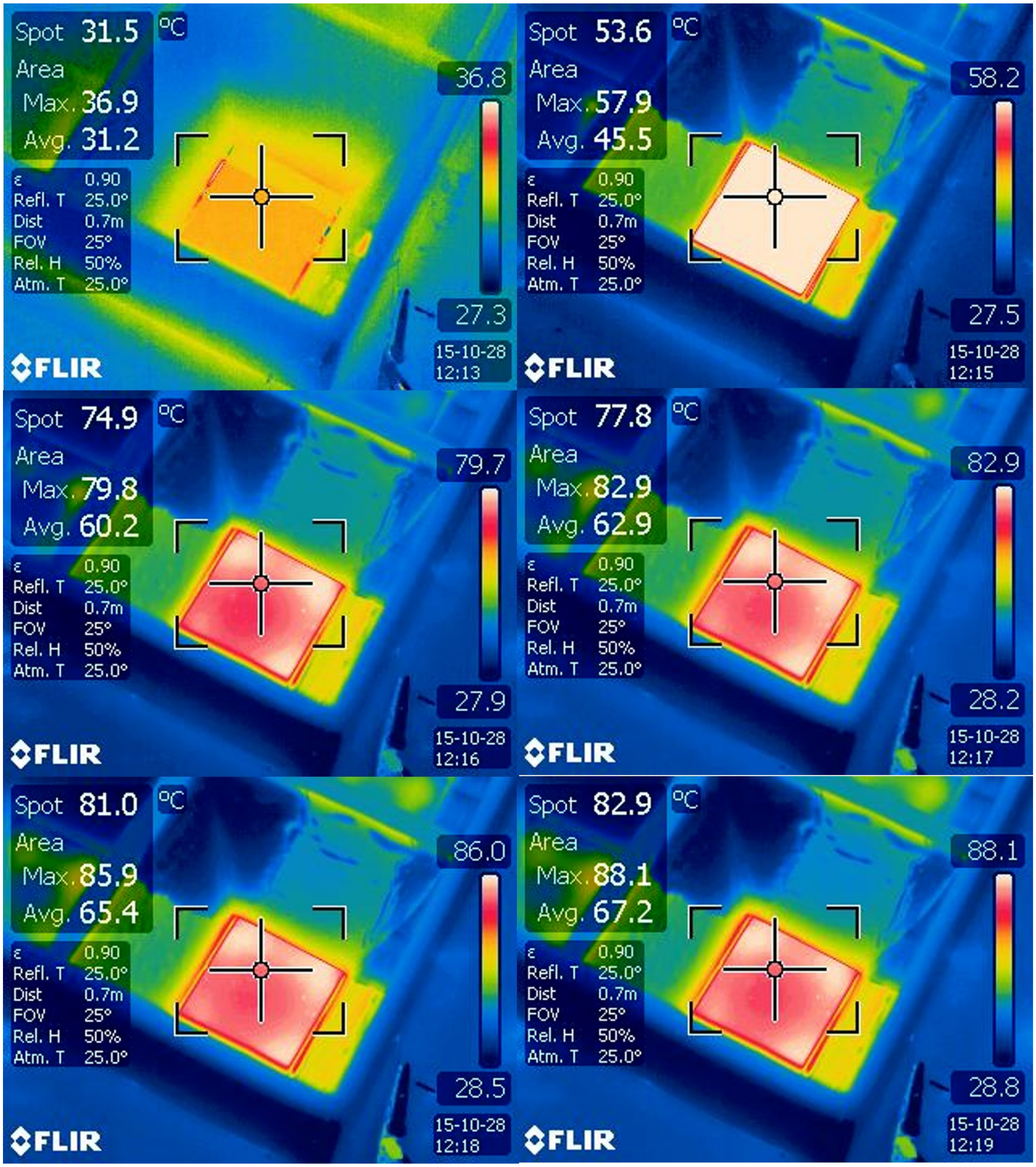


FIGURE 4. Temperature of the solar cell as a function of time of a unit concentrator

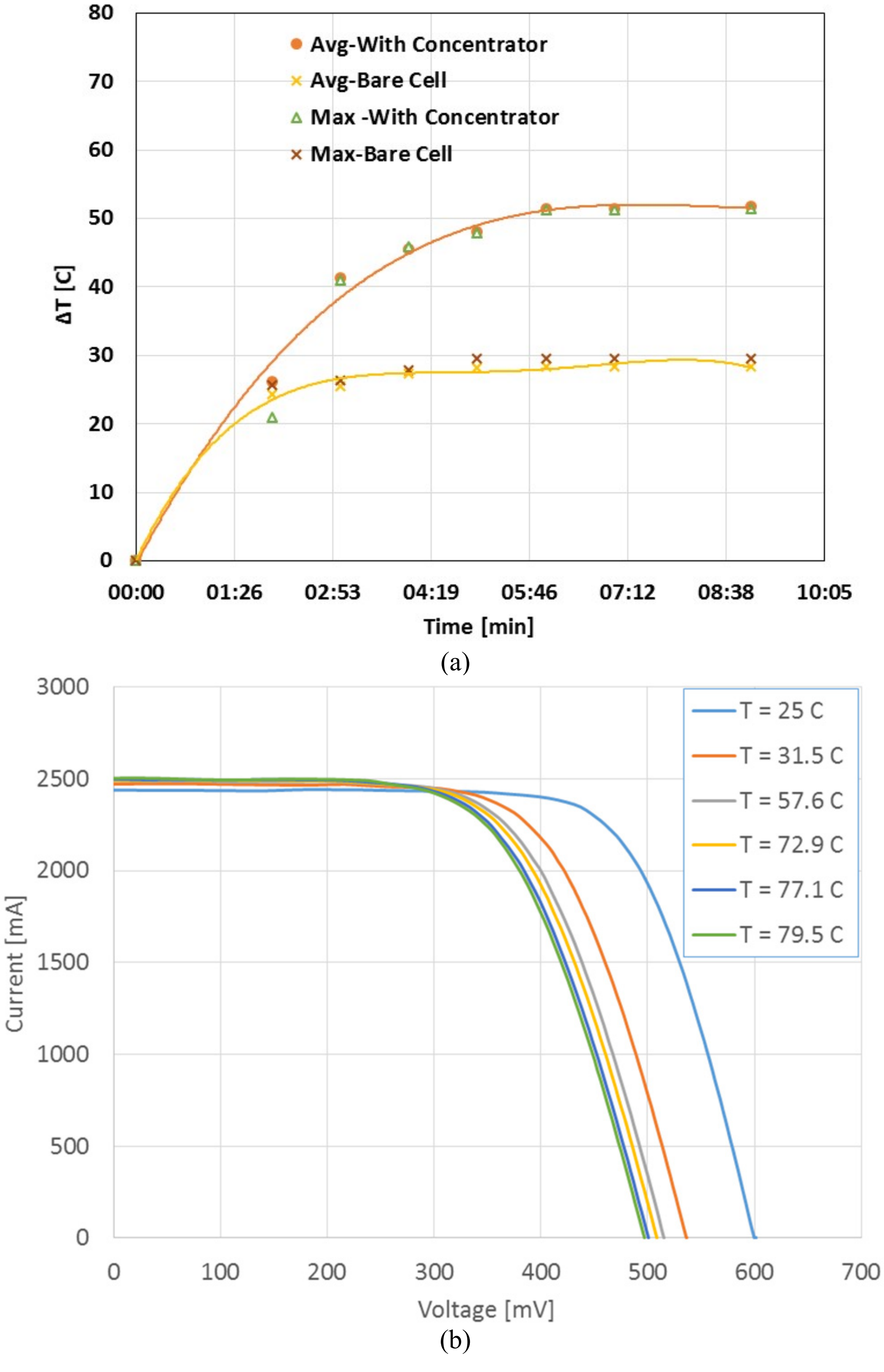


FIGURE 5. a) Temperature rise in the solar cell when placed with and without the concentrator (b) I-V curves as a function of solar cell temperature

A comparison of the temperature rise was carried out while using the same solar cell without a concentrator exposed to 1-Sun conditions as shown in FIGURE 5(a). It was found that the temperature rise (ΔT) of the solar cell was 28.3°C until it achieved a steady state. In the case of the concentrating system the ΔT was found to be 51.4°C until a steady state of operation was reached.

Electrical Output as Function of Temperature

Direct measurements of a unit CPV system are carried out and compared with the system without a concentrator. I-V curves of a unit concentrator under 1000 W/m^2 with increasing temperature are shown in FIGURE 5(b). The power output and the fill factor of the system as a function of temperature is shown in Table 1. It can be seen that both are impacted severely due to the increasing temperature. The temperature coefficient of power output was found to be 0.0044mW//°C.

TABLE 1. Variation of the maximum power output and the fill factor with the operating temperature

Operating Temperature	Power output (mW)	Fill factor
25.0 C	1035.1	0.707
31.5 C	873.6	0.659
57.6 C	826.7	0.644
72.9 C	811.8	0.641
77.1 C	793.0	0.634
79.5 C	785.0	0.631

Thermal Heat Extraction

As seen in the earlier sections only a fraction of the incident sunlight is converted to electrical energy and the rest is dissipated in the form of heat. Cooling of the LCPV system unit can help in improving its electrical performance in addition to providing a source of thermal energy. The excess heat from the back of the solar cell can be removed using either passive or active cooling techniques. Use of fins or a heat exchanger can be made in order to achieve this task. FIGURE 6 shows the schematic of the cooling unit that can be employed beneath the solar cell attached using a thermally conductive adhesive.

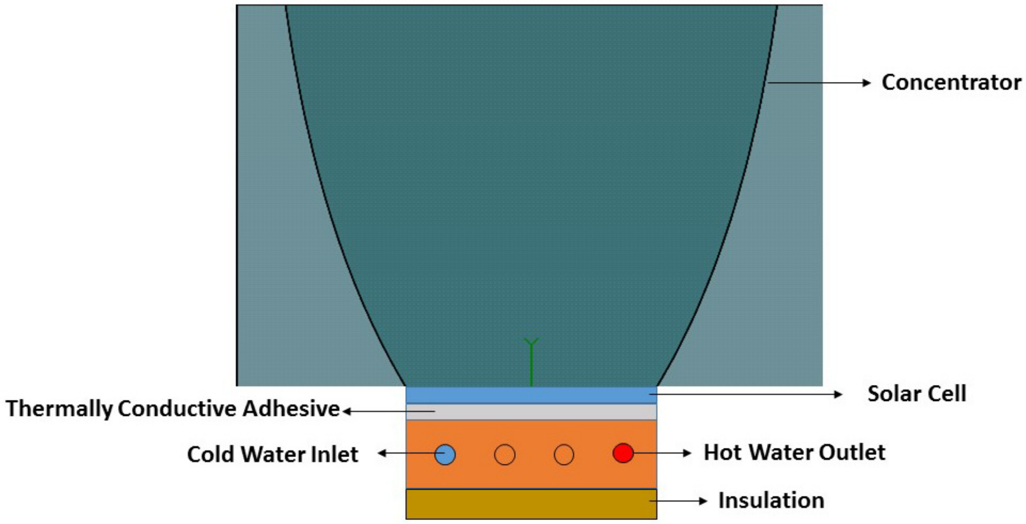


FIGURE 6. Thermal energy extraction using a heat exchanger

Cold water flows inside the heat exchanger, receives the heat rejected from the solar cell via conduction and maintains the solar cell at a desired lower temperature. The rate of heat exchange can be controlled by the flow rate and the temperature of the incoming cold water. Further studies will be performed to demonstrate this concept.

CONCLUSIONS

Theoretically when using the 3DCCPC having 3.6×, with a surface having 94 % reflectance we except to achieve a power gain of about 3.3. From the indoor experiments, it was found that the introduction of the 3DCCPC boosts the power output by a factor of 2.82 when compared with the non-concentrating PV system. This corresponds to a maximum optical efficiency of 79 % against an expected optical efficiency of 93.8%. The solar cell temperature without the concentrator was found to stabilize at around 56 °C while introducing the concentrator on top increased the solar cell temperature to a maximum of 79 °C. A huge thermal potential is available on the back side of the solar cell when used in a LCPV system. Further study need to be performed to evaluate the effectiveness of the thermal potential both numerically and experimentally.

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