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Part II: Enhanced Performance of Concentrating Photovoltaic-Thermal Air Collector with Fresnel Lens and Compound Parabolic Concentrator (CPC)

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ABSTRACT

In Part I of this study, the literature study on the types of methodologies applied by previous studies and the methodologies the suitable applied for this experimental study was provided. In this study (Part II), the methodologies are applied and the concentrating PVT air collector is fabricated based on the adopted methodologies. The heat is extracted by a working fluid (air), which can be collected and utilized for other domestic and industrial purposes. The highest thermal and electrical efficiencies of the cPVT collector in the present study were approximately 50 % and 12.9 % respectively; and achieved a total combined efficiency of approximately 80 % at average solar irradiation level of 750 W/m2, mass flow rate of 0.03 kg/s with the geometric concentration ratio of FL and CPC at 1.65 and 1.78 respectively.

Keywords:
CPC, fresnel Lens, total energy

1. Introduction

The PVT technology has been studied since the early 1970s [1]. Since then, various studies ranging from mathematical simulations [2, 3] to experimental studies [4] and computer simulations have been conducted to study the parametric influence and performance enhancement of the PVT collector systems. Water and air are the common working fluids of the PVT system.

One-, two- and three-dimensional mathematical [5-8] were developed determine the best dimensions and designs of PVT collectors that will best fit the requirement of the application. The models were then compared experimentally to validate the mathematical models developed.

The experiments involved the developmental process of the enhancement components such as the fluid flow channels [9, 10] heat convection surface area extension with fins [11, 12], integration of reflectors such as CPC and parabolic troughs [12-14] and addition of Fresnel lens.

The advantage of concentrating PVT systems can provide higher thermal performance is the main motivation for this research. In Part I of this research, the adopted enhancement methods have been studied and chosen based on this suitability and performance. In this study, a hybrid PVT collector

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that combines Fresnel lens as a primary concentrator and CPC as a secondary concentrator (cPVT) was fabricated. Air was used as the working fluid, and a double-pass airflow configuration was designed to increase the convective heat transfer. The investigation of the thermal, electrical and total combined performance of the concentrating PVT (cPVT) collector under the conditions of different solar intensities and air flow rates were carried out.

2. Experimental Setup

2.1 Experimental Setup and Hybrid System Design

The cPVT collector (Figure 1) was fabricated with 16 polycrystalline silicon solar cells seated parallel to each other in four rows with a total surface area of 0.6 m^2. The top cover was integrated with Fresnel lens with geometric CR of 1.65 which acted as a primary concentrator, and CPC with CR of 1.78 as a secondary concentrator.

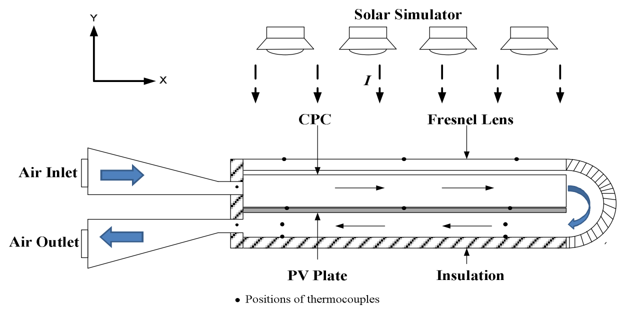


Fig. 1. Schematic of the concentrating PVT collector with Fresnel lens and CPC

Eq. 1 was adopted and modified to calculate the geometric CR [15, 16]. The upper and lower air channels were fixed at 0.17 m and 0.07 m respectively. Temperatures were measured by k-type thermocouples, air velocity was measured by a hotwire anemometer, and the electrical output was measured by using an electrical load resistor connected to a power meter. The data was collected and recorded by a data acquisition system.

$$CR = \frac{A_L}{A_{cell}} \tag{1}$$

where A_L is the aperture of the CPC opening or the area of FL and A_{cell} is the area of the solar cell.

2.2 Experimental Procedures

A double-pass airflow channel PVT solar collector with forced convection was used in the present investigation. Fresnel lens was used as glazing which also acts as a primary concentrator and CPC as secondary concentrators. The dimensions of the collector are as presented in Table 1. The experiments were carried out indoors whereby, the Sun was simulated by a solar simulator. The radiation intensity was set ranging from 450 – 750 W/m^2. An air blower was used to extract the heated air in an effort to cool down the PV plate. Temperatures recording were started after the solar collector has reached a steady-state [17] condition where the data were collected by a data acquisition system (DAQ).

Table 1
The specification of the cPVT collector system and its components

Specification	Value	Specification	Value
Collector length	0.82 m	Absorber thickness	0.002 m
Collector width	0.64 m	Fresnel lens length	0.77 m
Upper channel depth	0.17 m	Fresnel lens thickness	0.003 m
Lower channel depth	0.07 m	$CR_{Fresnel}$	1.65
Fin/tube height	0.00156 m	CR_{CPC}	1.78
Fin/tube thickness	0.00156 m	Air blower	45 W
Absorber length	0.65 m	Temperature sensors	k-type thermocouples
Absorber width	0.60 m	Airflow meter	Hot-wire anemometer

3. Results and Observations

The results are as depicted in Fig. 3 – Fig. 8.

3.1 Thermal Performance

The thermal efficiency is determined based on the solar radiation, *I*, the difference between the air inlet and outlet temperature, $\Delta T = T_{out} - T_{in}$, the mass flow rate, $\dot{m}$ and per unit area exposed to the light. The corresponding equation to determine the thermal efficiency is [18]:

$$\eta_{th} = \frac{\dot{m}C(T_{out} - T_{in})}{A_c I} \quad (2)$$

where,
η_{th} = thermal efficiency
A_c = Collector area (m^2)
$\dot{m}$ = air mass flow rate (kg/s)
I = Solar Intensity (W/m^2)
C = Air specific heat (J/kg K)

As depicted in Figure 2, the increase in PV plate temperature and the outlet air temperature is proportional to the solar radiation intensity. The maximum plate temperature achieved was 74 ^{o}C with highest outlet air temperature of 42 ^{o}C at the solar intensity of 750 W/m^2. These high temperatures were achieved at the lowest mass flow rate of 0.0035 kg/s. The low flow rate was able to produce a high outlet temperature rise, but this has a penalty on the PV cells conversion efficiency due to the high PV plate temperature.

The variation of air outlet temperature and thermal efficiency corresponding to change in air mass flow rates at different solar intensities are illustrated in Figure 3(a) and 3(b). It was observed that the air outlet temperature decreases while the thermal efficiency increases with mass flow rate. During high mass flow rates, the volume of air in the channels was bigger, providing more air for heat extraction and the higher speed of air causes the air to stay in the channels for a short time which in consequence reduced the outlet air temperature. Thermal performance increased with both intensity and mass flow rate from 15 – 50 %. The addition of Fresnel lens provided a refracted light rays which converged onto the solar cells, causing the PV plate temperature to increase and consequently increased the thermal efficiency.

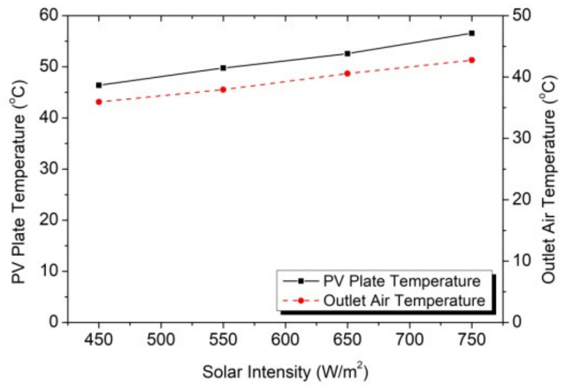
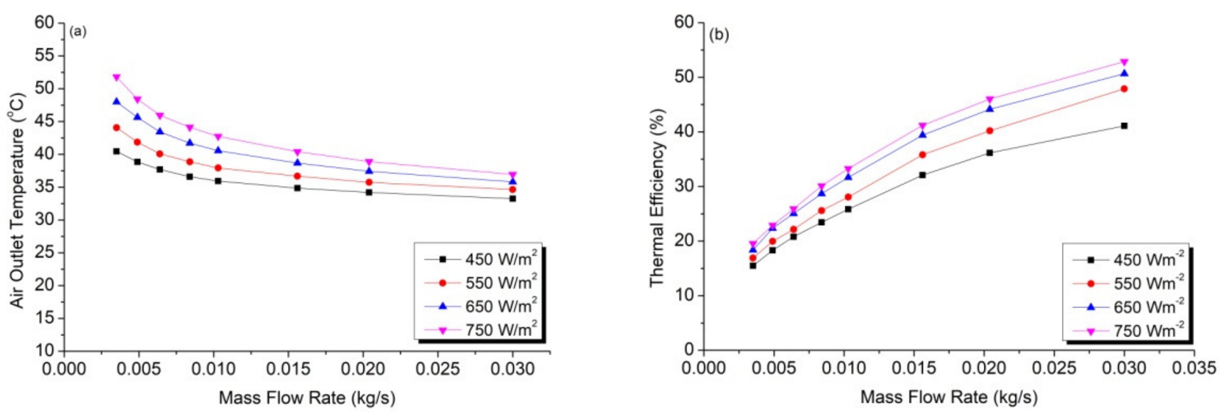


Fig. 2. Variation of air outlet temperature and PV plate temperature with solar radiation intensity at mass flow rate 0.0103 kg/s



(a) (b)

Fig. 3. (a) Air outlet temperature and (b) thermal efficiency of cPVT collector at different intensities (*I*) corresponding to different mass flow rates ($\dot{m}$)

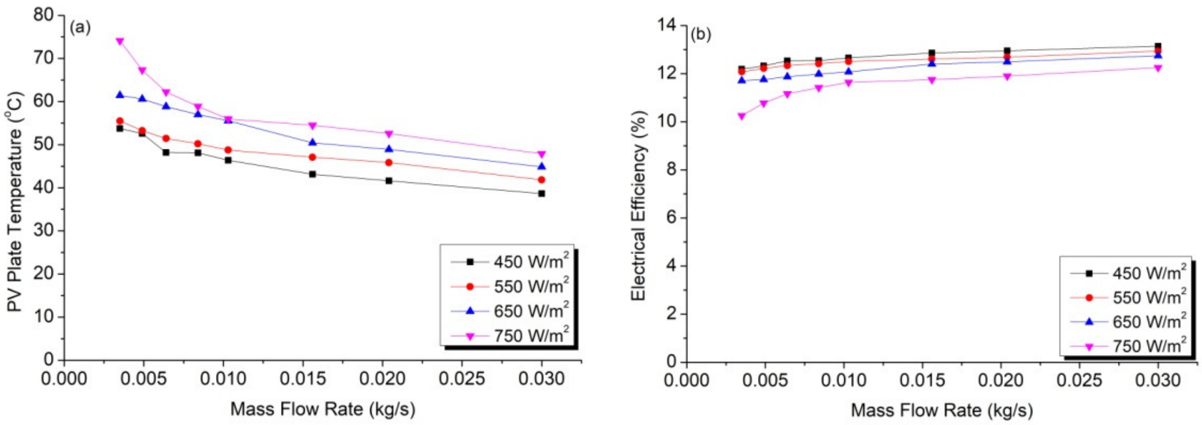
3.2 Electrical Performance

The electrical efficiency of a PV plate (solar cells) depends mainly on the incoming solar radiation and the PV plate (cells) temperature. The equation used to calculate the electrical efficiency is as in Eq. 3.

$$\eta_{el} = \eta_{ref}\left[1 - \beta\left(T_p - T_{ref}\right)\right] \quad (3)$$

where η_{ref} is the nominal cell efficiency at the reference temperature, T_{ref}. β is the temperature coefficient.

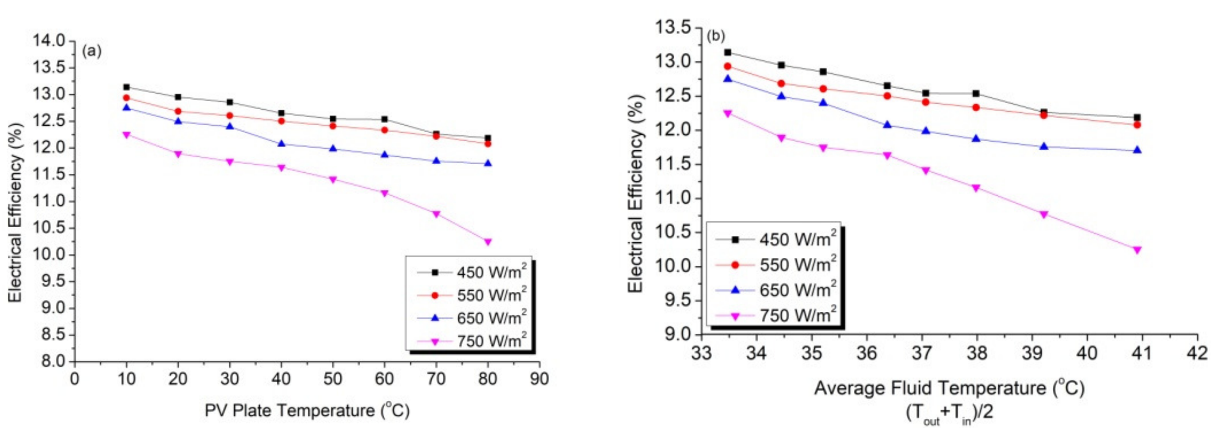
Figure 4(a) and 4(b) shows the variation of PV plate temperature and electrical efficiency with mass flow rates at different intensities, respectively. The PV temperature increases with intensity but decreases with mass flow rate. It was also observed that the electrical efficiency increases with mass flow rates for all intensities. The highest electrical efficiency is 12.9 % at the solar intensity of 450 W/m^2 and mass flow rate of 0.03 kg/s. This efficiency was approximately 5 % higher than the efficiency at the higher solar intensity of 750 W/m^2. At lower intensity, PV plate has lower surface temperature and thus has contributed to this better electrical performance. Furthermore, at a higher mass flow rate, a bigger volume of air available in the channel for heat extraction.



(a) (b)

Fig. 4. Variation of (a) PV plate temperature and (b) electrical efficiency (η_{el}) of cPVT collector with mass flow rates ($\dot{m}$) at different intensities (I)

As shown in Figure 5, the electrical efficiency is inversely proportional to PV plate and average air temperature. The electrical efficiency was higher at lower PV plate temperature and solar radiation intensity. At radiation intensity 750 W/m^2, the electrical efficiency was noted to drop drastically after the PV plate temperature reached 50 ^{o}C and an average air temperature of approximately 37 ^{o}C. This temperature effect reduced the amount of light converted to electricity by the solar cells. It increased the current produced by the solar cells but reduced the voltage produced which resulted in lower power output as shown in Figure 6 below.



(a) (b)

Fig. 5. Variation of electrical efficiency of cPVT collector with (a) PV plate temperature (b) average fluid temperature at different solar radiation intensities

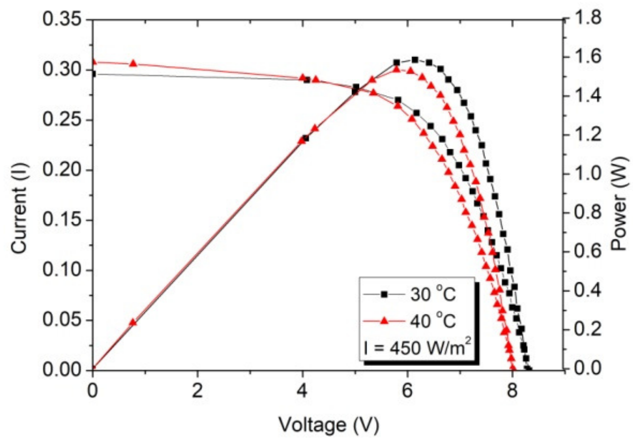


Fig. 6. Current and power characteristics of cPVT solar collector under solar radiation intensity of 450 W/m^2

3.3 Overall PVT Collector Performance

The equation used to calculate the total efficiency is given by Eq. 4 [19]. The overall performance or the total efficiency of the cPVT collector increased with both intensity and mass flow rate (Figure 7). But the electrical efficiency did not increase significantly. One of the reasons for this electrical behavior was that the integration of Fresnel lens converged the light which also escalated the PV plate temperature. This higher temperature limited the electrical output of the collector. Additionally, the refracted light also created irregularity of light distribution on the solar cells. On account of these, the electrical output of cPVT collector was limited.

$$\eta_{total} = \eta_{th} + \frac{\eta_{el}}{0.38} \quad (4)$$

The total efficiency of the PV-T collector ranged from 45 – 80 %. Insignificant overall efficiency between the intensity of 650 W/m^2 and 750 W/m^2 was observed. The high PV plate temperature which reduced the electrical efficiency at solar radiation intensity 750 W/m^2 was found to affect the total efficiency at these radiation level.

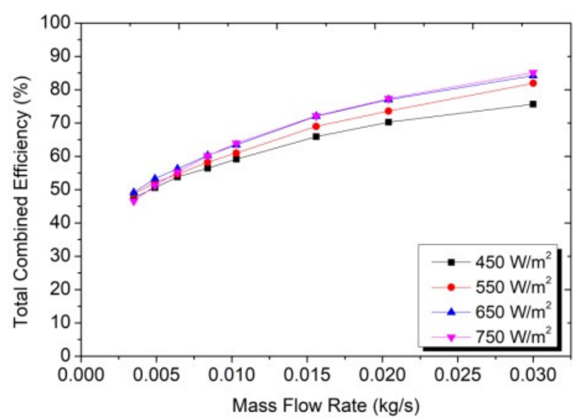


Fig. 7. Variation of total combined efficiency with different mass flow rates

3.4 Useful Energy (Watt)

The thermal performance (power) based on the useful energy per unit collector area is as shown in Figure 8. The amount of heat gained by the working fluid is computed from the numerator of Eq. 2. It was indicated that the maximum performance was 370 W/m^2 during the highest air mass flow rate of 0.03 kg/s and solar intensity of 750 W/m^2. The higher plate temperature under higher intensity and also more air volume available at higher mass flow rates are the factors contributed to this high performance. According to Figure 8, approximately 50 % of heat is harnessed by the fabricated PV/T solar air collector.

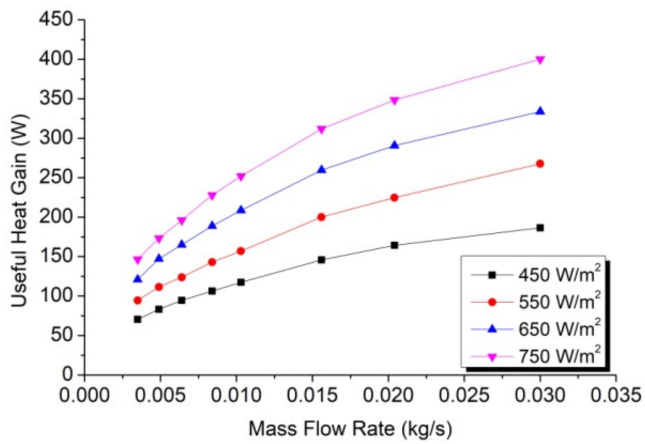


Fig. 8. Useful energy gain (power) of cPVT collector system

3.5 Experimental Uncertainty Analysis

The experiments were conducted under the solar simulator indoors in Solar Energy Research Institute. The parameters measured in the experiments include the radiation intensity, mass flow rate, fluid and collector surfaces temperatures were conducted to determine the experimental uncertainties. The mean average percentage deviation (*MAPE*) methods adopted from [20] was used in the uncertainty analysis.

Therefore, the maximum uncertainties for the PVT collector's electrical and thermal efficiencies are ± 0.718 % and ± 13.39 % respectively.

4. Conclusions

This study dealt with performance evaluation of a hybrid concentrating PVT collector systems where Fresnel lens and CPC were used as primary and secondary concentrators, respectively. From the study, the following conclusion can be made:

a. The combination of both concentrators, FL and CPC also increased the thermal performance of the cPVT collector. The thermal efficiency ranged from 15 – 50 % and the electrical efficiency achieved ranged from 10 – 12.9 %. The total combined efficiency of the cPVT system was 51 – 80 %.

b. The converged and reflected light by FL and CPC increased the PV plate temperature and caused a limitation in the electrical output of cPVT collector systems.

5. Recommendations

Considering the above conclusions, the efficiency of air as heat extracting fluid was not sufficient to extract significant heat from the concentrated PVT collector due to its low specific heat capacity and maintain the PV plate electrical efficiency, especially at high solar radiation intensity. Therefore, in order to improve the electrical and thermal performances, a more efficient working fluid with higher specific heat capacity, such as water will be used as an additional heat extracting fluid for the future study.

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