COMPARATIVE STUDY ON TWO PHOTOVOLTAIC AND THERMAL SOLAR MODULEDS WITH POINT-FOCUS FRESNEL CONCENTRATOR

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Abstract

In this paper, the electrical and thermal performances of both Fresnel concentrator photovoltaic/thermal (FCPV/T) modules with thermal collector and FCPV modules with passive cooling heat-sinks are investigated in experimental method. Both types of modules are equipped with triple-junction solar cells. Their geometric concentrating ratio is as high as 1090×. Comparative analysis has been conducted based on experimental data. The experimental results have been analyzed from the viewpoint of thermodynamics. From the first law point of view, it is found that the overall efficiency of the FCPV/T modules can exceed 80% but it drops significantly as the coolant water is heated up. Meanwhile, the electrical efficiency of the two types of modules can reach up to 28.9%. While from the second law point of view, a highest exergetic efficiency of 33.9% and 28.9% can be produced by the FCPV/T modules and the FCPV modules, respectively. Water temperature is found to play an insignificant role on the exergetic efficiency and irradiation influences dominantly. Besides, the electrical outputs of the two types of modules are almost equal at the same time even if notable operating temperature difference between their cells exists. Thermal profile of the CPV/T receiver has been simulated on the basis of a 3D heat transfer model developed in the thermal analysis software Comsol. The influence of beam irradiance and cell temperature on electrical efficiency is further studied. The results indicate that electrical performance of these modules is affected mainly by beam irradiance, and it is influenced little by cell operating temperature, which greatly differs from flat-plate PV/T modules.

Keywords: *PV/T, point-focus Fresnel, efficiency, exergy analysis, Comsol*

1. Introduction

A photovoltaic/thermal (PV/T) system is an integration of PV cells and solar thermal collectors which produces both electricity and heat simultaneously to increase its overall efficiency. The first investigation on PV/T system was presented by Martin Wolf (Wolf, 1976) in 1976. A large amount of experimental and theoretical studies on PV/T technology have been conducted during the decades (Amrizal, et al., 2013; Gang, et al., 2012; Tiwari, et al., 2009). Respect with the merit of a PV/T system lies in the reduction of demands on physical space and the equipment cost through the use of common frames and brackets as compared to the separated PV and solar thermal systems placed side by side, the cost of large area of photovoltaic cells is still higher than traditional power. Concentrator photovoltaic (CPV) system can reduce the area of solar cells by concentrating solar radiation onto small solar cells. If the cost of tracking assembly and concentrator is less than the cost of the saved solar cells, it could be an effective way to reduce the total cost of the system (Rabl, 1976). On the other hand, high efficient multi-junction solar cells are usually equipped in CPV systems to enhance the photovoltaic efficiency, which is rarely employed in systems without concentrator due to lack of economics. High efficient multi-junction solar cells have been developed and manufactured in both laboratories and factories. The efficiency of them is reported to be above 40% (Dimroth, et al., 2014; Green, et al., 2012; King, et al., 2012). On the CPV module level, photovoltaic efficiency over 35% have been reported (Ghosal, et al., 2014; Green, et al., 2015; Steiner, et al., 2015).

CPV systems can be generally classified as compound parabolic concentrator type (CPC) (Brogren, et al., 2001; Li, et al., 2014), parabolic trough type(Akbarzadeh and Wadowski, 1996; Coventry, 2005; Luque, et al., 1997), dish type (Chen, et al., 2014; Kribus, et al., 2006), linear Fresnel type (Liu, et al., 2014; Rosell, et al., 2005) and point-focus Fresnel type (Chengdong, et al., 2013; Wu, et al., 2012) according to the concentrator type. Among the CPV modules/systems, those with point-focus Fresnel lens recently have received more attention because of its advantages such as small volume, light-weight, mass production with low cost as well

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as effectively increasing the energy density. Xie et al. (Xie, et al., 2011) give a review on concentrated solar energy applications using Fresnel lenses in the last two decades, the highest photovoltaic conversion efficiency based on imaging Fresnel lens and non-imaging Fresnel lens is reported as over 30% and 31.5±1.7%, respectively. Amongst the existed point-focus Fresnel CPV systems, almost all the modules are passively cooled. Royne et al. (Royne, et al., 2005) believe that passive cooling could work well for single-cell geometries with flux level as high as 1000× suns, because there is large area available for heat sinking. However, for passively cooled CPV modules, the truth is that a large part of the already collected solar energy is dissipated as heat to the environment. Integrating the thermal collectors into a CPV module with point-focus Fresnel lens could be one of the potential solutions. Nevertheless, reports on point-focus Fresnel concentrator photovoltaic/thermal (FCPV/T) modules/systems are fragment. It is meaningful to investigate whether a FCPV/T system is better than a FCPV system whose cells are cooled passively, especially when they are close in manufacture cost.

In this study, an experimental rig containing two FCPV/T modules with thermal collector and two FCPV modules with passive cooling receivers were built. The modules are equipped with high-efficiency InGaP/GaAs/Ge triple-junction solar cells and the FCPV/T module was originally presented. The comparative investigation was conducted based on outdoor experimental data. The overall performance of these two types of modules were evaluated by energetic analysis and exergetic analysis. Thermal profile of the FCPV/T receiver was also analyzed with the employment of Comsol, a powerful thermal analysis software developed for various physics and engineering applications. The influence of beam irradiance and cell operating temperature on electrical efficiency is further studied on module level.

2. Description of the experimental setup

The photograph of the experimental setup is shown in Fig. 1. The experimental setup is built in Huainan (32.37 °N 116.59 °E), Anhui Province, China. It mainly consists of four parts, namely two FCPV/T modules and two FCPV modules, the two-axis tracking system, the water circulation system and the data acquisition system. The modules are equipped with high-efficiency InGaP/GaAs/Ge triple-junction solar cells whose photovoltaic efficiency is 31.4% (AM1.5D, 25 ºC) under one sun. Two identical FCPV/T modules and two identical FCPV modules are mounted parallel in the same holder for comparison, as shown in Fig. 1. Each module consists of 15 receivers and 15 point-focus Fresnel lenses, mounting one for one in a 5×3 matrix. The area of each Fresnel lens is 330.2×330.2 mm^2, and the size of each solar cell is 10×10 mm^2, which means the geometric concentrating ratio of the modules is 1090×. For a single module, all the 15 solar cells are connected in series. The two FCPV/T modules are connected in series, so are the two FCPV modules. The electrical characteristics of the module are listed in Table 1, which is achieved by indoor testing under steady condition (DNI 900W/m^2, 20 ºC, 4 m/s) and they are offered by the manufacturer. The two-axis tracking system maintains the modules tracking the sun automatically within a range of 0.3°.

Fig. 1: Photograph of the experimental rig

Tab. 1: Electrical characteristics of a module

Parameter	Variable	Value
Maximum power	P_{max}	402W±5%
Voltage@ P_{max}	V_{max}	38.3V
Current@ P_{max}	I_{max}	10.5A
Open circuit voltage	V_{OC}	45.2V
Short circuit current	I_{SC}	11.1A

The main difference between these two types of modules lies in their receivers. Both types of receiver consist of a solar cell and an aluminum heat-sink, as shown in Fig. 2. The solar cell is pasted at the center of front side of the heat-sink by thermal conductivity silica gel. The optical prism is pasted on the solar cell by optical silicone. A ceramic housing is arranged to surround the solar cell, which protects the solar cell against interference of unnecessary illumination. For the CPV/T receiver, an axial grooved tube is designed on the rear side of the heat-sink, through which water flows and takes heat away. The groove could increase the heat exchange area and it also enhances the convective heat transfer by disturbing the fluid. Therefore, the heat-sink of the CPV/T receiver serves as the thermal collector. Threads are made at both ends of the tube for pipe connection. As to the CPV receiver, large-area fins are employed to increase heat exchange area. Although the pipe connection increases the cost of FCPV/T module, the volume of its heat-sinks is smaller than the FCPV module's. Besides, there is no difference between the fabrication technologies for both types of receivers. As a consequence, the costs for the FCPV/T module and the FCPV module are almost the same.

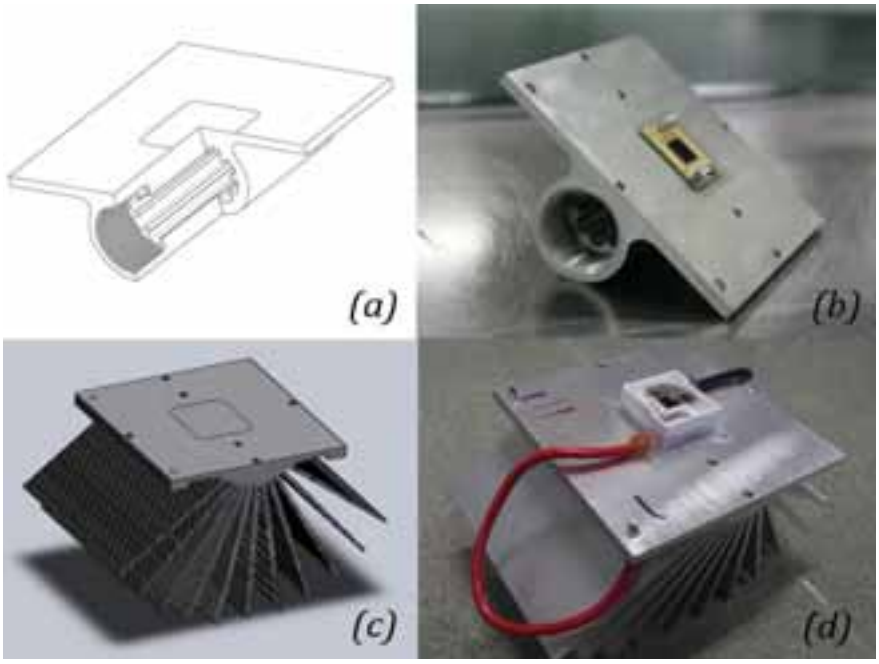

Fig. 2: Schematic and photograph of the FCPV/T and FCPV receiver

Fig. 3 shows the schematic of the water circulation in the FCPV/T system. Water is pumped from the bottom of the storage tank and flows through the tubes below the heat-sinks. Hot water flows back to the tank. The whole water circulation is a closed loop without secondary heat exchanger. Every 10 heat-sink tubes are connected in series by pipes. This arrangement divides the water circulation system into three branches and it also decreases the temperature difference on the water flow direction due to short flow distance, thus decreasing the impact on solar cells caused by water temperature gradient. At the inlet of each branch, a valve and a flow meter are installed to control and measure the water flow rate, respectively. Two pressure gauges are installed at the inlet and outlet of the main pipeline, respectively. All pipes and heat-sink tubes are insulated by insulation cotton with a thickness of 15mm. The volume of the tank in this system is 75L.

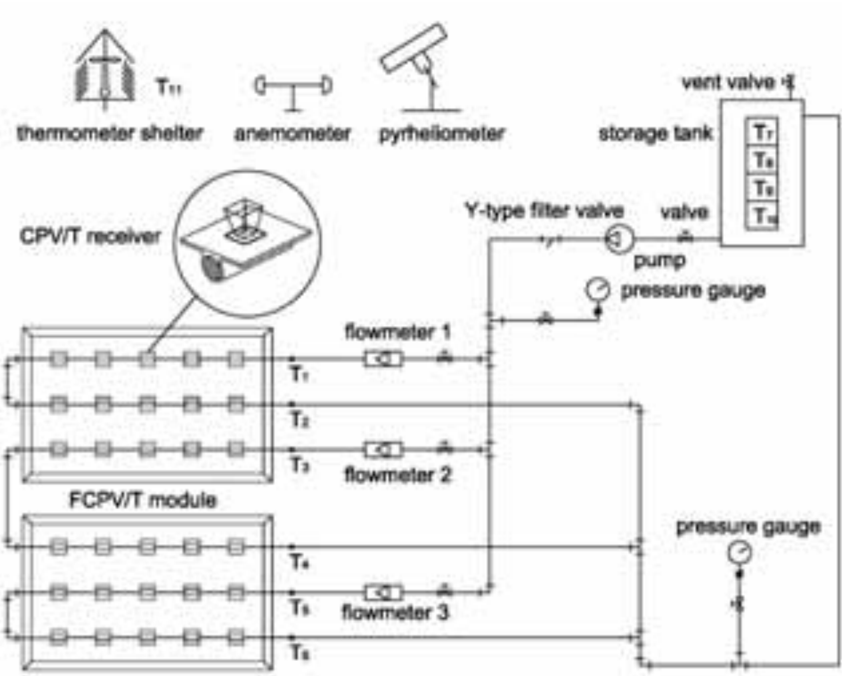

Fig. 3: Schematic of water circulation in FCPV/T system

The data acquisition system mainly consists of sensors and a data logger. The locations of sensors are also illustrated in Fig. 3. Inlet and outlet temperatures for each branch are measured by platinum resistances. The ambient temperature and the tank water temperatures are measured by T-type thermocouples. To eliminate the measurement error caused by temperature gradient in the tank, four equidistant temperature measuring points are arranged. The beam irradiance is measured by a pyrheliometer. Both temperature and beam irradiance are recorded by a data logger (Agilent 34970A) at an interval of 10s. Pressure and water flow rate are also recorded. A photovoltaic analyzer is used to measure and record the electrical output of the modules. The electrical data is recorded every 5 minutes. A thermal infrared imager is also employed to record the thermal profiles of the modules. Details of all the measurement instruments are listed in Table 2.

Tab. 2: Characteristics of sensors and measurement instruments

Device	Accuracy	Specification
Thermocouple	±0.2°C	T-type
Thermal resistance	±0.1°C	Pt 100
Pyrheliometer	2%	TBS 2-2
Data logger		Angilent 34970A
Flow meter	1%	Lmag_W800
Photovoltaic analyzer	1%	HT I-V400
Thermal infrared imager	±2°C	Fluke Ti400

3. Analysis methods

The overall performance of a PV/T system can be evaluated according to thermodynamics, economics, marketing and environmental implications, as demonstrated by Coventry and Lovegrove (Coventry and Lovegrove, 2003). Among the evaluation methods, the thermodynamic approach is popularly used in optimizing an engineering system that owe their thermodynamic imperfection to heat transfer, fluid flow and mass transfer irreversibility. Bosanac et al. (Bosanac, et al., 2003) believed that the economical and marketing approaches are affected by the political environment and are never universally valid. The thermodynamic approach based on energy and exergy analysis is more objective. Therefore, the analysis in this study is mainly from the viewpoint of thermodynamics.

3.1. First law efficiency of thermodynamics

From the first law of thermodynamics, the overall performance of a PV/T system can be evaluated by the energetic (first law) efficiency η_{PVT}. It is widely used in previous studies (Chow, et al., 2009; Ji, et al., 2007), which directly reflects the overall performance of a PV/T system. The first law efficiency is defined as follows:

$$\eta_{PVT} = \frac{E_t + E_{PV}}{A_F \int_{t_1}^{t_2} G_b dt} = \eta_t + \eta_{PV} \quad \text{(eq. 1)}$$

$$E_t = c_p m (T_2 - T_1) \quad \text{(eq. 2)}$$

$$E_{PV} = \int_{t_1}^{t_2} P_m dt \quad \text{(eq. 3)}$$

where E_t and E_{PV} are the thermal energy output and electrical output of a module, respectively. c_p is the specific heat of water, m is the mass of water in storage tank, and T_2 and T_1 represent the final and initial water temperature during the time period from t_1 to t_2, respectively. A_F is the area of Fresnel lens in a module and G_b is the beam irradiance measured by the pyrheliometer. η_t and η_{PV} are the thermal efficiency and the electrical efficiency of the module, respectively.

3.2. Second law efficiency of thermodynamics

Although the first law efficiency reveals the overall performance of a PV/T system intuitively, it ignores the difference between thermal energy output and electrical output produced by the modules in "quality", even if they are the same in "quantity" and measurable by the same physical unit. In fact, thermal energy cannot produce work until a temperature difference exists between a high temperature heat source and a low temperature heat-sink, while electrical energy can completely transform into work irrespective of the environment. In other words, the second law efficiency, namely the exergetic efficiency, offers a qualitative and standardized evaluation for the overall performance of a PV/T system. Exergy is simply the available energy obtained by subtracting the unavailable energy from the total energy, and is equivalent to the work transformable.

According to the work conducted by Fujisawa and Tani (Fujisawa and Tani, 1997), the second law efficiency of a PV/T system is expressed as eq. 4. This definition is on the basis of the assumption that the initial temperature of the fluid medium is equal to the ambient temperature.

$$\varepsilon_{PVT} = \varepsilon_t + \varepsilon_{PV} = (1-\frac{T_a}{T_2})\eta_t + \eta_{PV} \quad \text{(eq. 4)}$$

where ε_t and ε_{PV} are the exergetic efficiency of solar cells and thermal collectors, respectively. T_a is the ambient temperature and T_2 is the final water temperature.

In eq. 4, the calculation of the exergy of solar radiation is not considered. Instead, the energy of radiation is taken as the exergy of radiation directly. Exergetic efficiency is the ratio of total exergy output to total exergy input (Hepbasli, 2008). Therefore, the exergetic efficiency can be defined as

$$\varepsilon_{PVT} = \frac{Ex_t + Ex_{PV}}{A_F \int_{t_1}^{t_2} \dot{E}x_{sun} dt} = \varepsilon_t + \varepsilon_{PV} \quad \text{(eq. 5)}$$

where Ex_t and Ex_{PV} are the thermal exergy output and electrical exergy output of a module, respectively. $\dot{E}x_{sun}$ is the exergy input of solar radiation. The exergy outputs are related to the energy outputs as follows:

$$Ex_t = (1-\frac{T_a}{T_2})E_t \quad \text{(eq. 6)}$$

$$Ex_{PV} = E_{PV} \quad \text{(eq. 7)}$$

There are different methods to determine the exergy of radiation in evaluating the performance of PV/T system when using the exergy method. Among them, three most commonly used calculation methods are summarized by Chow, et al. , i.e.

$$\dot{E}x_{sun} = [1+\frac{1}{3}(\frac{T_0}{T_{sun}})^4 - \frac{4T_0}{3T_{sun}}]G_b \quad \text{(eq. 8)}$$

$$\dot{E}x_{sun} = [1-\frac{4T_0}{3T_{sun}}]G_b \quad \text{(eq. 9)}$$

$$\dot{E}x_{sun} = [1-\frac{T_0}{T_{sun}}]G_b \quad \text{(eq. 10)}$$

where T_0 is the environment temperature and T_{sun} is the solar radiation temperature at 6000 K. Actually, the difference between results calculated by these three methods are less than 2%. In this study, eq. 10 was adopt.

3.3. Evaluation of thermal profile of the receiver

Cell operating temperature is believed to play a significant role in evaluation of performance of a PV/T system because it greatly influences the electrical output. However, it is difficult to measure cell temperature directly because of the lamination connection between solar cell and heat-sink. Fernandez et al. (Fernandez, et al., 2014) proposed four methods to calculate the cell temperature of a high concentrator photovoltaic module, but they are either oversimplified (such as one-dimensional model) or required with adequate measurable data (such as ANN method). There is no doubt that a 3D thermal model can better describe the real thermal profile of the receivers. A number of thermal analysis software could be adopted to establish the 3D thermal model, and the core issues are providing the boundary conditions accurately. For the FCPV modules, their boundary conditions mainly include the beam irradiance, ambient temperature, and wind speed as well as wind direction. However, the wind direction is difficult to define because the modules always move. While for the FCPV/T modules, the boundary conditions primarily consist of beam irradiance, water temperature and ambient temperature. Fortunately, these parameters could be measured precisely. Therefore, the 3D thermal model of the CPV/T receiver could be solved in a more rational way by virtue of a thermal analysis software.

In this study, a powerful thermal analysis software Comsol is employed to simulate the thermal profile of the CPV/T receiver. Comsol is a finite element analysis, solver and simulation software for various physics and engineering applications, especially coupled phenomena or multiphysics. A 3D transient heat transfer model was developed as the simulation process described in Fig. 4. The 3D geometric model of the CPV/T receiver is firstly imported into the software, followed by mesh generation automatically. After defining the initial values and boundary conditions, the thermal profile of the receiver can be obtained by the solver. In this way, the thermal profile, especially cell temperature under a particular condition can be calculated. The cell temperature is treated as the average temperature of cell region on the CPV/T receiver.

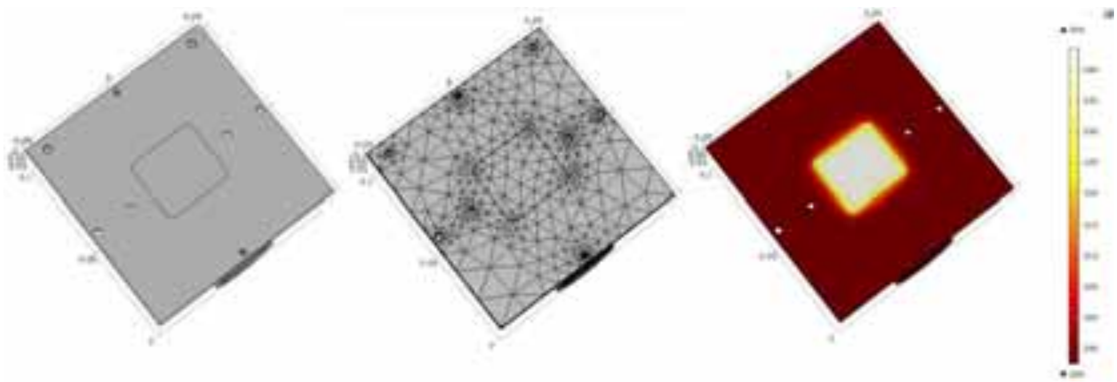

Fig. 4: Thermal analysis process by Comsol on a FCPV/T receiver

4. Results and discussion

A typical daily data in November 7th, 2014 is selected to show the results and followed by detailed discussions. Fig. 5 shows changes of measured weather data and temperature of water in storage tank from 10:00 am to 15:30 pm. As seen in Fig. 5, the ambient temperature changes in a small range between 15~17 °C, and the beam irradiance changes between 300~700W/m^2 with a steady stage from 11:00 am to 12:00 am. Water is heated from 25 °C to near 55 °C and water temperature drops a little after 14:30 pm. Wind speed in the daytime is always below 2m/s. Water flow rate of each branch is controlled at 0.33m^3/h which ensures water flows turbulently.

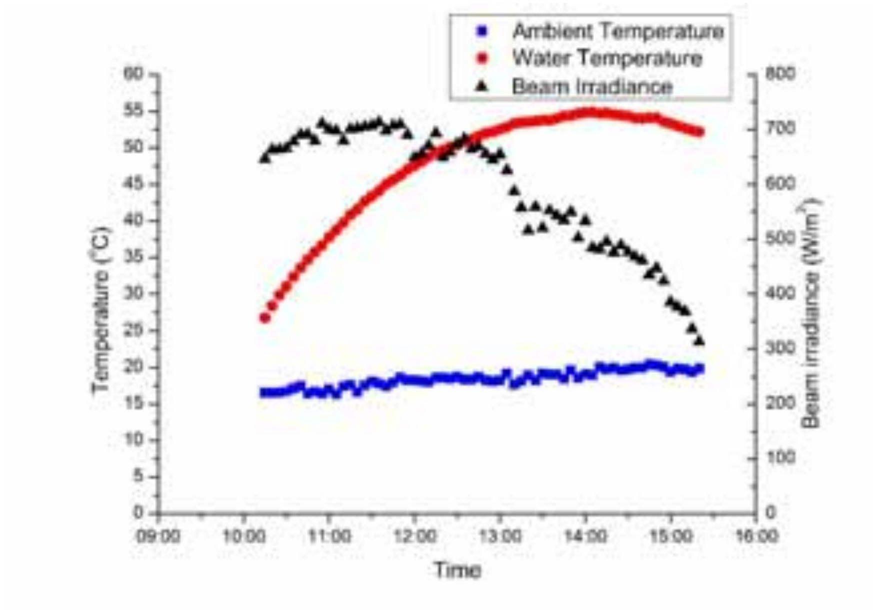

Fig. 5: Measured weather data and water temperature during experimental test

Electrical power yield of one FCPV/T module and one FCPV module are illustrated in Fig. 6. It is obvious that the higher beam irradiance is, the larger the power yield is. Power yield by both types of modules remain almost equal at the same time, regardless of how much irradiation they receive. Fig. 7 depicts the thermal profiles of the modules, which is captured by a thermal infrared imager. At the given moment, the temperature of CPV receiver is found to be higher than that of CPV/T receiver, as shown in Fig. 7. However, the corresponding power yields shows no difference. Considering the temperature difference between the two types of receivers, it can be deduced that cell operating temperature is not the dominant factor that influences the electrical performance of these modules. This feature is greatly different from flat-plate PV/T modules. Stated another way, the increase of water temperature would not lower the electrical efficiency of the FCPV/T modules significantly.

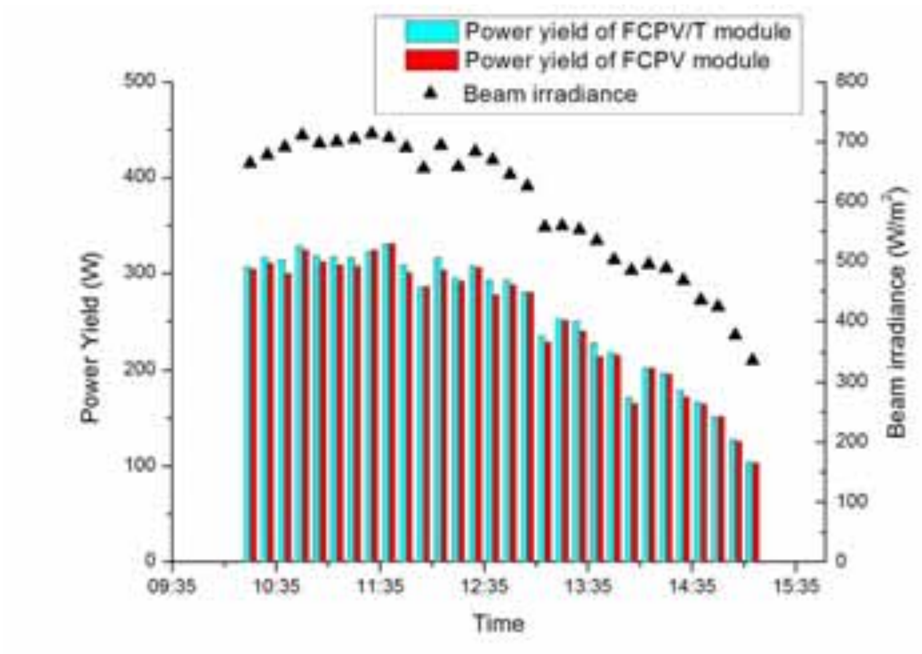

Fig. 6: Electrical power yield of FCPV/T module and FCPV module

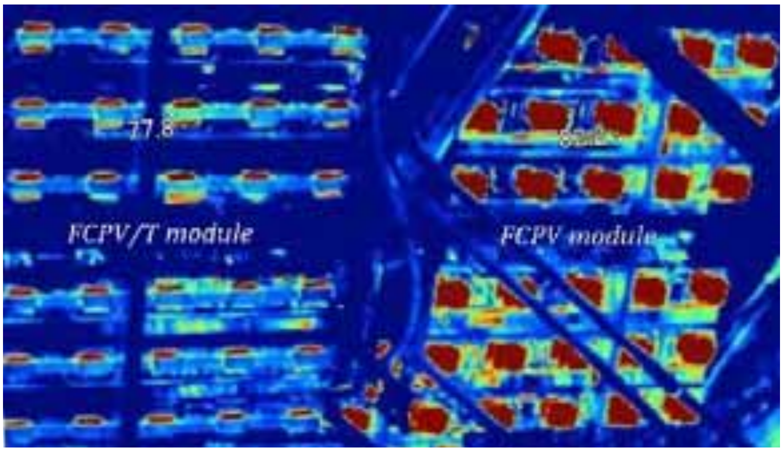

Fig. 7: Thermal profile of FCPV/T module and FCPV module

The variation of overall efficiency of the FCPV/T module and the FCPV module are shown in Fig. 8. From the viewpoint of the first law of thermodynamics, an overall efficiency of 80% can be obtained at the start of the experiment. It drops due to the decrease of thermal efficiency, which can be attributed to the descending irradiance and the decreasing temperature difference between cell temperature and water temperature. Besides, a highest electrical efficiency of 29.3% can be obtained and it changes with narrow fluctuation between 20.7% and 29.3%. On the other side, water temperature is found to play an insignificant role when the overall performance is viewed from the second law point. A highest exergetic efficiency of 33.9% and 28.9% can be produced by the FCPV/T module and the FCPV module, respectively. The exergetic efficiency is mainly affected by irradiance.

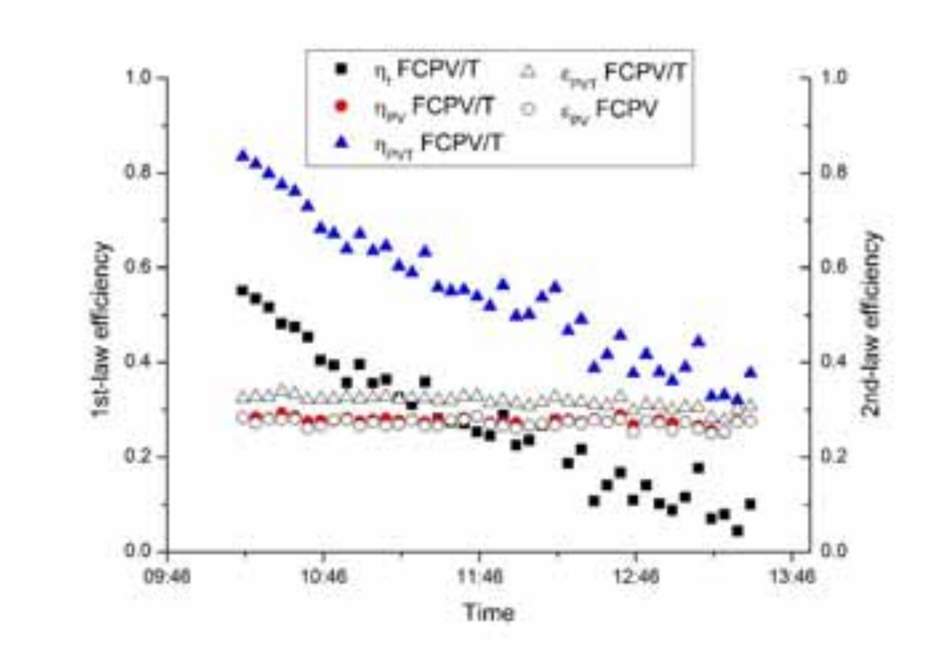

Fig. 8: Variation of overall efficiency of FCPV/T module and FCPV module

Fig. 9 depicts the variation of module electrical efficiency with beam irradiance and cell temperature. For better identification, the "beam irradiance-electrical efficiency" projection and the "cell temperature-electrical efficiency" projection are also marked in Fig. 9. Cell temperature is obtained by Comsol with the method proposed above, and the boundary conditions are based on experimental data. The calculation shows cell temperature changes between 60 °C and 90 °C, which is always lower than the design ceiling cell operating temperature of 100 ºC. It can be seen that the electrical efficiency of the system is affected by cell temperature and beam irradiance together. Among the results, the highest electrical efficiency occurs under high irradiance condition (where beam irradiance is near 700W/m^2) with a value of 29.3%. It decreases as the cell temperature increases within a narrow range. The electrical efficiency remains in a narrow range between 27% and 29% when beam irradiance is over 600W/m^2. However, the electrical efficiency drops steeply with the decrease of beam irradiance when beam irradiance is below 600W/m^2. This indicates beam irradiance has a dominated effect on module electrical efficiency, although cell temperature affects it as well.

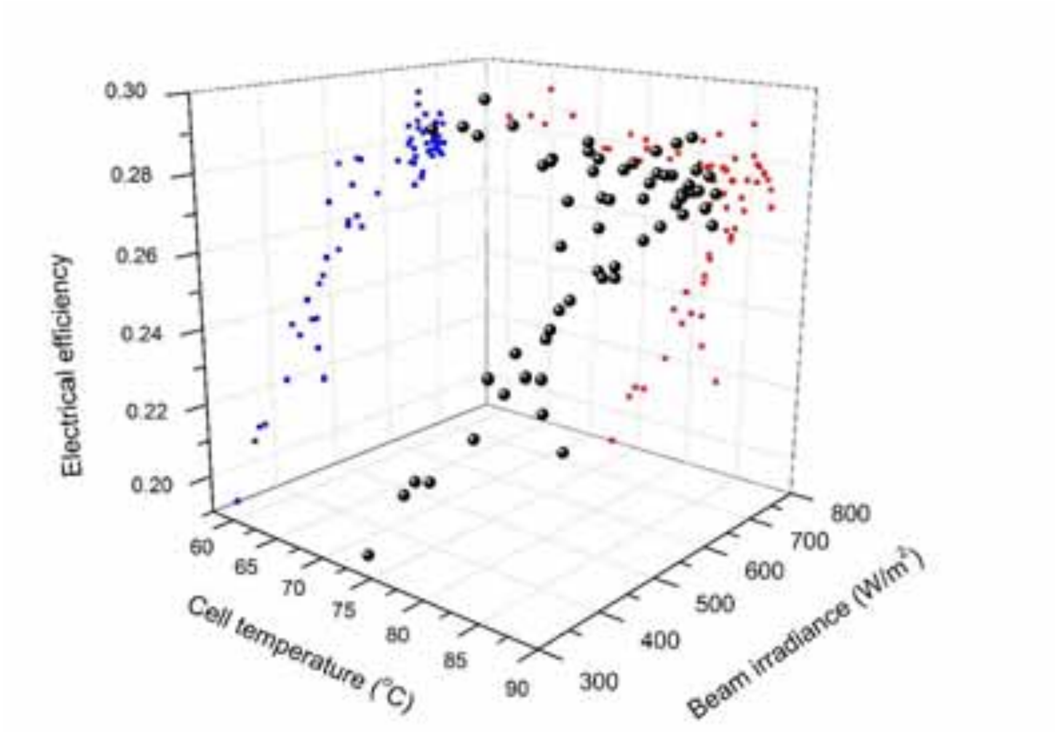

Fig. 9: Variation of electrical efficiency with irradiation and cell temperature

5. Conclusions

A comparative study on FCPV/T module with thermal collector and FCPV module with passive cooling heat-sinks were conducted. The overall performance of these two types of modules were evaluated by energetic analysis and exergetic analysis. The results show that the FCPV/T module can obtain an instantaneous electrical efficiency of 27% and a highest instantaneous thermal efficiency of 54%, which means its overall energetic efficiency can exceed 80%. From the second law point of view, a highest exergetic efficiency of 33.9% and 28.9% can be produced by the FCPV/T module and the FCPV module, respectively.

Electrical outputs of the two types of modules are found to be almost equal under the same environmental condition, even if distinct temperature difference between two kinds of module receivers exists. This indicates that cell temperature does not influence the electrical performance of the modules predominantly, which is greatly different from flat-plate PV/T modules.

Thermal profile of the CPV/T receiver has been simulated based on a 3D transient heat transfer model in Comsol. The boundary conditions of the model is acquired from experimental data. With the calculation, the influence of beam irradiance and cell temperature on electrical efficiency is further investigated. It can be concluded that beam irradiance has a dominated effect on the electrical efficiency of the modules, although cell temperature affects it as well. The electrical efficiency of the modules remains in a narrow range between 27% and 29% when beam irradiance is over 600W/m^2, but it drops steeply with the decrease of beam irradiance when beam irradiance is below 600W/m^2.

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