EXPERIMENTAL STUDY ON A HIGH CONCENTRATION PHOTOVOLTAIC/THERMAL SYSTEM WITH PLANE MIRRORS ARRAY

by

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A high concentration photovoltaic/thermal system based on plane mirrors array has been developed and analyzed. It is found that the system with plane mirrors array not only can reduce the cost but also achieve a uniform illumination and adjustable concentration ratios. The system produces both electrical and thermal energy, with the electrical efficiency above 22% and the thermal efficiency above 47%. The experimental results show that the temperature coefficient of open circuit voltage in this photovoltaic module is around –0.12 V/°C. Moreover, when the concentration ratio varies between 200 and 450, the decrease of electrical efficiency with the temperature is 0.08% per °C.

Keywords: *photovoltaic/thermal conversion, high concentration ratio, plane mirrors array, solar energy*

Introduction

Many types of solar concentrators have been designed and studied, including dish, trough, Fresnel, compound parabolic concentrators and so on [1]. The hybrid photovoltaic (PV) thermal technology can increase the electrical efficiency of PV cell and increase the total efficiency of the systems [2]. Prakash [3] presented a theoretical study of the hybrid PV thermal solar system. As a result, concentration photovoltaic/thermal (CPV/T) technology is developed and many CPV/T systems have been designed over last ten years. Rosell *et al*. [4] designed and simulated a low concentrating PV/T system based on linear Fresnel lens. Kribus *et al*. [5] designed a miniature CPV/T system that produced about 140 W of electricity and 400 W of heat. Buonomano *et al*. [6] analyzed the performance of the CPV/T solar collectors, which was based on a combination of a parabolic dish thermal collector and a solar PV collector. Chaabane *et al*. [7] gave the evaluation of the experimental performance of low CPV and PV/T systems. Kong *et al*. [8] investigated the outdoor performance of a low CPV/T system with crystalline silicon solar cells, which had a thermal efficiency of 56% and electrical efficiency of 10%.

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As for the system with a high concentration ratio, it calls for more complicated tracking and cooling technologies, resulting in higher cost. Therefore, it is usually applied in the place where high subsidies are provided. High concentration dish systems usually use parabolic structure which is difficult to achieve uniform illumination and has lower electrical efficiency of PV cells. Besides, over-heating of PV cells often occurs in such structure, which will further reduce the electrical efficiency.

In order to solve the problems of high cost and non-uniform irradiance distribution in high CPV/T (HCPV/T) system, this study presents a HCPV/T system using the concentration structure of plane mirrors array instead of continuous parabolic. This kind of structure can not only produce much more uniform sunlight and reasonably high concentration ratio, but also reduce the cost and has higher ability to resist strong winds. Heat transfer fluid to remove the extra heat from PV cells is circulated from the cooling device to a storage tank, which can be used for heating water and even industrial heating. The thermal energy at higher temperature is more valuable, hence a compromise should be found to get thermal product at a higher temperature, while not decreasing the electrical efficiency of the system much. An experimental test system is built to investigate the performance of this HCPV/T system and the effect of the temperature on system efficiency.

Design development

The high CPV/T system mainly consists of a reflector, a heat exchange device and a tracking system. A parabolic dish system was developed in the early study. However, the irradiance distribution was uneven in this system and produced a much higher temperature in some parts of the system which resulted in lower efficiency. And due to the action of stress on the dish, the structure of dish deformed more or less with time, which changed the distribution and seriously affected the electrical property of PV cells.

In this study, as shown in fig. 1, the reflector here uses the plane mirror concentration array structure, and the mirrors are of equal area. It is more economical than parabolic dish structure and can get a more uniform distribution of illumination. As shown in fig. 2, a unit named *universal joint* is designed, which could adjust the position of the mirror in two dimensions to make sure that each mirror refocuses light uniformly on the receiver. And with this structure, the system can easily change its concentration ratio by increasing or reducing the number of mirrors. A two-axe tracking system is adopted in order to assure the HCPV/T system accurately tracked and the reflector perpendicular to direct solar radiation.

Figure 1. A high concentration PV system with plane mirrors array

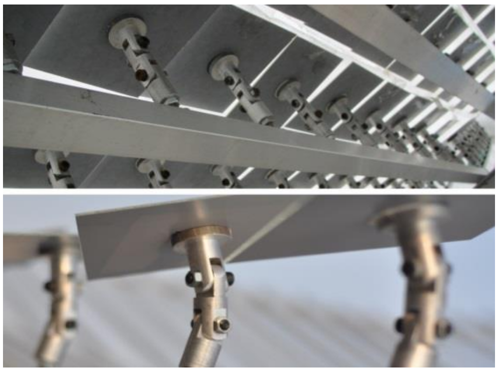

Figure 2. The photograph of universal joint using in plane mirror system

The cooling device made of Cu is placed at the focal area of the mirrors. In order to reduce contact resistance, a PV module is welded directly on the front face of the cooling device under low temperature. The PV module has 30 pieces of triple junction cells (GalnP/GalnAs/Ge), and all of them are connected in series. The cooling device removes the heat from PV cells to the coolant fluid. The coolant fluid used here is water and in a closed circuit. The hot water finally can be used domestically and industrially.

Energy conversion analysis

The HCPV/T system can provide both electrical energy and thermal energy. The overall energy produced by the system can be described:

$$P = E_e + Q_t \tag{1}$$

where P, Q_t, and E_e are overall energy output, thermal energy output, and electrical energy output, respectively. Each of these energy products can be evaluated by a separate efficiency.

Electrical efficiency

The electrical efficiency is:

$$\eta_e = \frac{E_e - E_{loss}}{G_e} \tag{2}$$

where G_e is the radiation flux on the surface of PV module and E_{loss} is energy losses from the tracking system and water pump. If the pressure drop in water flow is not large, the required pump power is small. As the tracking system works intermittently, the average required power is also small in a single system. However, the energy loss E_{loss} can not be ignored in a large power plant.

Electrical output is influenced by optical loss, cell efficiency and irradiance. It can be given by:

$$E_e = \eta_{PV} G_e \tag{3}$$

$$G_e = n_{opt} C I A_{PV} \tag{4}$$

where C is the concentration ratio of the system, I – the direct irradiance, and A_{PV} – the area of PV module. Parameter n_{opt} is optical loss of incident sunlight and η_{PV} is photoelectric conversion efficiency of the PV module.

Optical loss mainly depends on the reflectivity of mirrors and the absorbance of the PV module. The system uses common glass mirrors with a silver back-coat and the reflectivity is 0.91. The front face of PV cells has a silicon rubber layer to protect PV cells from the ambient and the absorbance of the PV module is 0.93.

It is known that the cell efficiency varies with incident radiation and the cell temperature. Since the manufacturer can supply the values of open-circuit conditions, short–circuit conditions, maximum-power conditions, the temperature coefficient of short-circuit current and the temperature coefficient of open-circuit voltage, the relationships of cell efficiency with various radiation and various cell temperatures can be calculated with the well-known equivalent diode circuit [9].

Thermal efficiency

The thermal efficiency is:

$$h_t = \frac{Q_w}{G_e} \tag{5}$$

$$Q_\mathrm{w} = C_\mathrm{w}\dot{m}(T_\mathrm{out} - T_\mathrm{in}) \tag{6}$$

where Q_w is the effective heat that transfers from the PV module to water, C_w – the specific heat capacity at the average water temperature, and $\dot{m}$ – the mass flow of water. The T_in and T_out are the inlet and outlet temperatures of water, respectively.

The radiation flux absorbed by the PV module will be converted to electrical energy and extra heat. Most part of the extra heat can be removed by water flow, and the rest will dissipate to the environment from the front and back faces.

– Q_f is heat loss from the front face:

$$Q_\mathrm{f} = h_\mathrm{f} A_\mathrm{f} (T_\mathrm{f} - T_\mathrm{e}) + \varepsilon_\mathrm{f} A_\mathrm{f} \sigma (T_\mathrm{f}^4 - T_\mathrm{e}^4) \tag{7}$$

– Q_b is heat loss from the back face:

$$Q_\mathrm{b} = h_\mathrm{b} A_\mathrm{b} (T_\mathrm{b} - T_\mathrm{e}) + \varepsilon_\mathrm{b} A_\mathrm{b} \sigma (T_\mathrm{e}^4 - T_\mathrm{e}^4) \tag{8}$$

Subscripts f and b mean the front and back surface. The convective heat transfer coefficient is given by:

$$h_\mathrm{f} = h_\mathrm{b} = 3.8u + 5.7 \tag{9}$$

where u is wind velocity [10].

To keep the model analysis simple, the cooling device has a uniform temperature and the system is at a steady-state operation. Then T_c is given by [11]:

$$\frac{T_c - T_\mathrm{in}}{T_c - T_\mathrm{out}} = \exp\left(-\frac{h_\mathrm{w} A_\mathrm{w}}{C_\mathrm{w}\dot{m}}\right) \tag{10}$$

The convective heat transfer coefficient h_w is given by:

$$h_w = \frac{\mathrm{Nu}_d k_w}{d} \tag{11}$$

$$\mathrm{Nu}_d = 0.023 \mathrm{Re}_d{}^{4/5} \mathrm{Pr}^{2/5} \tag{12}$$

From the previous equations, heat loss, the efficiency can be calculated, when the initial conditions of inlet water temperature and environment parameters are given.

Experimental analysis

Experimental rig design

The HCPV/T system using plane mirrors array structure was set up and the specific structural parameters and materials are shown in tab. 1. The experimental test system is shown in fig. 3. The key test instruments are listed in tab. 2. The direct radiation was measured using a pyrheliometer, the flow rate was measured with a flowmeter, the temperatures were measured

Table 1. The structural parameters of the HCPV/T system

Component	Material	Parameter
Reflector	Glass mirrors	200-450 suns
Cooling device	Copper	10 cm × 10 cm
Tracking system	Aluminum	–
PV cells	GalnP/GalnAs/Ge	7 cm × 7 cm

with T-type thermocouples, and the current-voltage characteristic of PV module was measured with a PV analyzer.

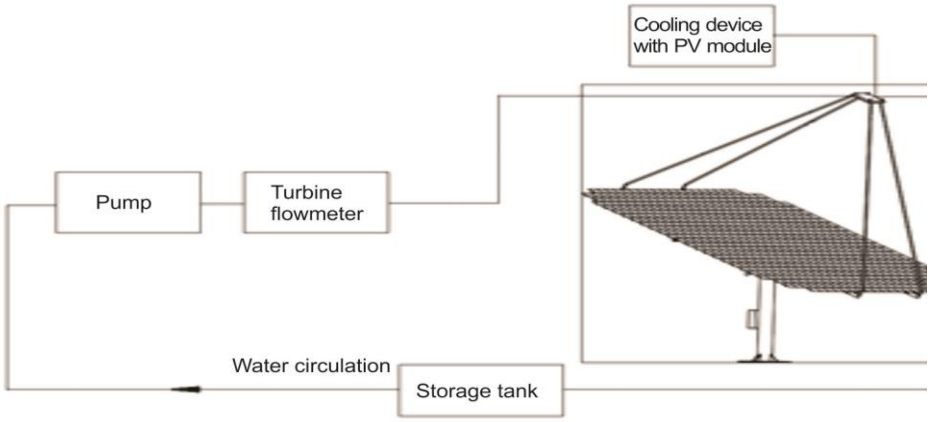

Figure 3. The experimental test system of the HCPV/T system

Table 2. The major test instruments of the experimental system

Equipment	Specification	Precision
Pyrheliometer	TBS-2-2	2%
Flowmeter	LWGY-10	1%
Thermocouple	T-type copper-constantan	±0.3 °C
PV analyzer	I-V 400	1%
Data logger	Agilent 34970A	–

Experimental result

The experiments were conducted in Guangdong Province, China (N23°02′52″, E113°40′37″). Figure 4 shows the direct irradiance and environment temperature of a day from 10:00 to 16:00 in the summer (August 2, 2013), during which the values remain relatively stable. The concentration ratio of this high CPV/T system was modified by changing the number of mirrors. The experimental results of the system under different concentration ratio and different water flow are listed in tab. 3.

The actual temperature of the PV module could not be measured in this experiment. However, the PV module is welded directly to the cooling device and the thermal resistance between them can be ignored. Then the temperature, T_c, can be considered as the mean temperature of the heat exchange device, which includes both PV cells and the cooling device. The T_c can be calculated from eq. (10). Table 4 shows the temperature of T_c under different concentration ratios and water flow rates.

When the temperature T_c increases, due to the increasing temperature of PV cells, the electrical efficiency will gradually decrease while the thermal efficiency increases correspondingly. However, when the concentration ratio of the system varies from 200 to 450, the electrical efficiency is always above 20%, and the thermal efficiency is always higher than 47%. When the concentration ratio is 450, the temperature of PV cells is over 90 °C. However, the temperature rise will inevitably lead to a decline in electrical efficiency of the PV cells. Considering the working temperature of PV cells, by changing the water flow rate of the system, the electrical efficiency can be over 22%. And if the concentration ratio still increases (more than 500 suns), the water flow rate should also increase to ensure the electrical efficiency stay at a high value.

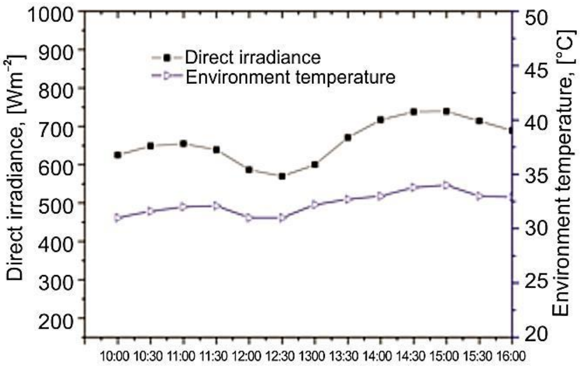

Figure 4. Direct irradiance and environment temperature vary with local time

Table 3. List of experimental results of the system under different concentration ratios and water flow rates

Concentration ratio	Average water flow [kg/s]	Average inlet water temperature [°C]	Average outlet water temperature [°C]	Average thermal efficiency	Average PV cells electrical efficiency
200	0.3	28.93	29.4	0.471	0.251
200	0.2	29.65	30.39	0.476	0.24
200	0.1	30.6	32.09	0.487	0.23
368	0.3	32.1	33.01	0.504	0.225
368	0.2	33.1	34.68	0.507	0.205
450	0.3	36.56	37.86	0.491	0.22
450	0.24	38.83	40.51	0.513	0.211
450	0.15	41.14	43.8	0.519	0.208

Table 4. The temperature of T_c under different concentration ratios and water flow rates

Concentration ratio	200	200	200	368	368	450	450	450
Water flow rate	0.3	0.2	0.1	0.29	0.19	0.3	0.24	0.15
T_c	49.11	50.96	52.43	69.89	76.36	92.38	96.71	98.93

In general, cell conversion efficiency is influenced by variable solar radiation and temperature. When the total irradiance is fixed, the electrical efficiency depends on absolute temperature of the PV module. Total irradiance is the multiplication of concentration ratio, optical efficiency, and direct irradiance. This is only true if the concentration ratio, optical efficiency and direct irradiance are all fixed. The two axes tracking of the system probably allows for the concentration ratio and optical performance to be approximated as fixed, but does not allow for the assumption that direct irradiance was fixed. However, when concentration ratio varies between 200 and 500, the effect of total radiation on the cell electrical efficiency is not significant [12, 13]. It is possible to discuss the effect of temperature on the electrical efficiency without considering the variable solar radiation, when the concentration ratio only varies between 200 and 450. The electrical efficiency varies with the temperature, T_c, is shown in fig. 5. And by fitting the experimental data, the electrical efficiency can be given by:

$$\eta_e = 0.266 - 0.00078(T_c - 25\,^\circ\mathrm{C}) \tag{13}$$

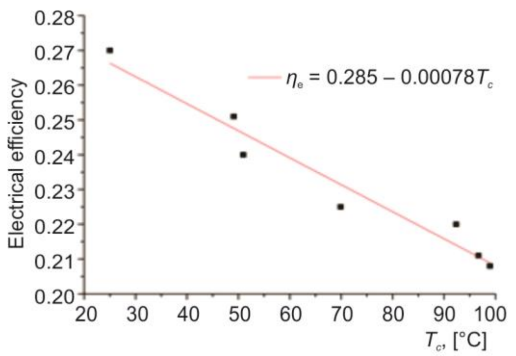

Figure 5. The electrical efficiency varies with T_c

Thus the electrical efficiency of the system can be predicted when the operating condition of the system changes.

If the reflectivity, absorbance and emissivity are assumed not affected by the various temperatures, optical loss can be a constant when the concentration ratio varies. And optical loss caused by the PV module and the plane mirrors is 18%, which can be seen as a main energy loss in the HCPV/T system. Therefore, increasing the reflectivity of mirrors and absorbance of the PV module are very important to improve the performance of the HCPV/T system.

Figure 6 shows I-V curves of the PV module under different concentration ratio. The current of the PV module increases with the increase of the concentration ratio, and the open circuit voltage is just the opposite to the theory that the open circuit voltage will increase slightly with the increase of the concentration ratio. This is caused by the rise of the temperature of the PV module. When concentration ratio varies between 200 and 500, data fitting shows that the temperature coefficient of open circuit voltage in this PV module is around –0.12 V per °C, that is –4 mV per °C for a single cell.

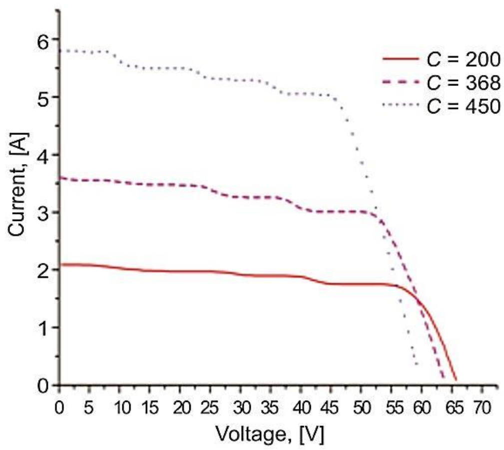

Figure 6. The I-V curves of the PV module under different concentration ratio

The I-V curve has a large number of steps down when the current decreases with voltage. It is non-uniform voltage production across the various cells of the device. This phenomenon is more and more obvious with the increasing of concentration ratio. When the concentration ratio is lower than 200, it does not present such steps. However, when the concentration ratio is higher than 450, these steps are obvious and negative to the electrical performance of the system.

This is owing to the non-uniform illumination and the non-uniform temperature distribution on PV cells. The number of plane mirrors increases with the increase of concentration ratio, which makes it difficult to ensure the irradiance completely uniform. Heat transfer along the water flow direction leads to a temperature gradient that will also become larger with the increase of the concentration ratio. Therefore, in order to make sure the electrical performance of the system still at a high value, the area of the PV module or the number of PV cells should be reduced when the concentration ratio is over 500.

Error analysis

The experimental error of the dependent variables is calculated from the experimental error of the independent variables which is determined by the accuracy of the corresponding instrument. Gang *et al*. [14] calculated the relative error (*RE*) of *y*:

$$RE = \frac{\mathrm{d}y}{y} = \frac{\partial f}{\partial x_1}\frac{\mathrm{d}x_1}{y} + \frac{\partial f}{\partial x_2}\frac{\mathrm{d}x_2}{y} + ... + \frac{\partial f}{\partial x_n}\frac{\mathrm{d}x_n}{y} \tag{14}$$

where $\partial f/\partial x_i$ (i = 1,…, n) is the error transferring coefficient of the variable. The experimental relative mean error (*RME*) is:

$$RE_{\eta_t} = \frac{\mathrm{d}\eta_\mathrm{t}}{\eta_\mathrm{t}} = \frac{d\left[\dot{m}_\mathrm{w} C_w (T_\mathrm{out} - T_\mathrm{in})/G\right]}{\dot{m}_\mathrm{w} C_\mathrm{w} (T_\mathrm{out} - T_\mathrm{in})/G} \tag{15}$$

$$RE_{\eta_e} = \frac{\mathrm{d}\eta_\mathrm{e}}{\eta_\mathrm{e}} = \frac{\mathrm{d}\left(\dfrac{E}{G}\right)}{\dfrac{E}{G}} \tag{16}$$

Thus,

$$RME = \frac{\sum_1^N |RE|}{N} \tag{17}$$

Therefore, the experimental *RME* of thermal efficiency and electrical efficiency are 4.5% and 3%, respectively.

Conclusions

A HCPV/T system is presented, which can provide both electrical energy and thermal energy. The system uses plane mirrors array structure as a reflector. This structure is more economical and can provide a uniform light intensity distribution and an adjustable concentration ratio.

An experimental system has been set-up to analyze the performance of HCPV/T system under different concentration ratio and mass flow rate of cooling water. The experimental result shows that the electrical efficiency is above 22% and the thermal efficiency is more than 47%. When the temperature of the PV module increases, the electrical efficiency will gradually decrease and the thermal efficiency increases correspondingly. As a result, if the concentration ratio increases more than 500 suns, the water flow rate should also increase to ensure the temperature of the PV module at a low value. The optical loss caused by the PV module and the plane mirrors is 18%, which can be seen as a main energy loss in the HCPV/T system. The experiment results also show that the temperature coefficient of open circuit voltage in this PV module is around –0.12 V/°C, and the temperature coefficient of system electrical efficiency is –0.08%/°C.

Acknowledgment

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Nomenclature

A	– area, [m^2]
C	– concentration ratio
C_w	– specific heat, [Jkg^{-1}K^{-1}]
d	– diameter, [m]
E	– electric power, [W]
G	– radiation flux in concentrator, [W]
h	– heat transfer coefficient, [Wm^{-2}K^{-1}]
I	– direct irradiance, [Wm^{-2}]
k_w	– coefficient of heat conduction, [Wm^{-1}C^{-1}]
$\dot{m}$	– water flow rate, [kgs^{-1}]
Nu	– Nusselt number
n	– parameter
P	– overall energy
Pr	– Prandtl number
Q	– heat power, [W]
Qw	– effective heat, [W]
Re	– Reynolds number
T	– temperature, [°C]
T_c	– coolant temperature, [°C]
u	– velocity, [ms^{-1}]

Greek symbols

α	– absorbance
ε	– emissivity
η	– efficiency
σ	– Stefan-Boltzman constant

Subscripts

b	– back surface
e	– environment or electrical
f	– front surface
opt	– optical
PV	– PV cells
t	– thermal
w	– water

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