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Electrical and thermal output characteristics investigation on a solar trough concentrating PV/T system

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A solar through concentrating photovoltaic/ thermal system with 1.8m^2 concentrator was constructed and characterized. The space silicon solar cells were employed as the electricity output unit. The electrical output characteristic and the thermal output characteristic of the system were thoroughly investigated when the PV/T composite receiver was placed ahead of the focal plane at different defocus distances. The effect of the aperture width of the concentrator on the performance of solar cells was also investigated. The maximum output power of solar cells was 22.37W and the solar cells' efficiency was 2.74% when the PV/T composite receiver was 5cm ahead of the focal plane and the aperture width was 157cm. The output power 17.92W and the maximum efficiency 5.71% of solar cells were achieved when the PV/T composite receiver was 3cm ahead of the focal plane and the aperture width was 57cm. The maximum system thermal efficiency of 58.9% was reached when the PV/T composite receiver was 1cm ahead of the focal plane and the aperture width was 157cm. With the condition, the temperature rise of the working medium was 0.68℃ and the solar cells' efficiency was 2.2%.

Keywords: solar trough concentrator, PV/T, electrical output characteristic, thermal output characteristic

INTRODUCTION

Photovoltaic power generation has become one of the important ways for the utilization of renewable energy. However, the low energy flux density and uneven distribution of solar irradiation have a negative impact on the performance and cost of photovoltaic power generation. The concentrating technology can significantly increase the energy flux density on the solar cells' surface and the power generation per unit area solar cell, however it makes the solar cells' temperature rise and deteriorates the efficiency. The forced circulation of the cooling working fluid on the back of solar cells can maintain the electrical performance of solar cells, and recover the heat generated under the condition of solar concentration, thus improve the comprehensive utilization of solar energy and realize the combined heat and power generation.

In the late 1970s and early 1980s, Russel [1,2], Florschuetz [3] and Hendrie [4], adopted firstly the forced circulation of the working fluid on the back of the solar panel to cool the solar cell and recover the heat energy. Dupevrat employed a simple 2D model to study some configurations of glazed PV/T collector, and selected the most appropriate concept configuration and suitable material properties [5]. Amrizal proposed a hybrid PV/T dynamic model to predict the power output in any climate [6]. Silva employed the modular environment of Simulink/ Matlab to model individual PV/T system components, and simulated hybrid PV/T systems [7]. Kumar analyzed the life cycle cost of a single slope passive and hybrid photovoltaic (PV/T) active solar stills, and estimated the payback periods [8]. Sok conducted outdoor experiments with a prototype PV/T water-heating system. The annual thermal and electrical performances were analyzed under the climatic conditions of Beijing [9]. Huang introduced the concept of primary-energy saving efficiency to evaluate a PV/T system, and demonstrated a good thermal efficiency of the solar PV/T collector made from a corrugated polycarbonate panel [10]. Bernardo proposed a complete methodology to characterize, simulate and evaluate concentrating PV/T system and experimentally determined the hybrid parameters [11]. Pei presented a heat pipe-type PV/T system and studied the performances of the system with/without glass cover. The glass-covered system had a higher average photothermal efficiency, however a lower photoelectric efficiency [12]. Shan proposed a dynamic performances modeling of a PV/T collector with water heating in buildings and concluded that the less series-connected PV modules, the lower inlet temperature of water and the higher mass flow rate of water resulted in the high photovoltaic efficiency [13]. Chaabane established a low concentrating PV system and a PV/T system, and tested their output performances in spring climatic condition of Tunisia [14]. Jiang established the optical model of a two-stage

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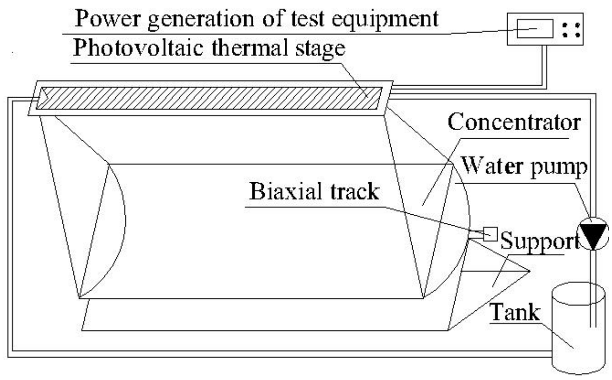
parabolic trough concentrating PV/T system based on spectral beam splitting technology. With the beam splitting filter, the heat load of the cells was reduced by 20.7%, and the overall optical efficiency was about 0.764 [15]. Francesco proposed a finite-volume model for a parabolic trough PV/T receiver, and carried out energetic and exergetic analyses [16,17]. Kalogirou proposed a model for analyzing the thermal performance of parabolic trough collector receiver [18]. Zhai proposed a small scale hybrid solar heating, chilling and power generation system. The evaluation of an annual energy and exergy efficiency under the climate of northwestern China found that the main energy and exergy loss were brought by the parabolic trough collector [19]. Khaled presented a new design of hybrid collectors for domestic air heating and electricity production, which gave good thermal and electric performances compared to the traditional hybrid collectors. Besides the guaranteed supply of electric power, the useful thermal power obtained was about 290 W while thermal efficiency was around 48% [20]. Karima designed different (PV/T) hybrid solar collectors and conducted outdoor test in Iraq climate conditions. The combined efficiency of collector model with double duct and single pass is higher than that of model with single duct and double pass and model with single duct and single pass [21]. Li characterized the electrical and thermal performances of a $2m^2$ TCPV/T system with an energy flux ratio 10.27 and a $10m^2$ TCPV/T system with an energy flux ratio of 20 [22-24]. Ji developed a two-stage PV/T system and studied energy comprehensive utilization of the system [25,26].

The paper developed a solar trough concentrating photovoltaic/thermal system (TCPV/T) with $1.8m^2$ trough concentrator. The composite receiver with solar cells on its surface was placed on the focal plane, ahead of the focal plane to characterize the electrical and thermal output performance of the system. The effect of the aperture width of the trough concentrator on the performance of solar cells was also investigated.

EXPERIMENTAL SETUP

Fig.1 is the schematic diagram and photo of the solar trough concentrating PV/T system. The combined heating and power system is composed of trough concentrator, composite receiver, two axis sun tracking unit, pump for driving working fluid and water storage tank. The composite receiver is made of aluminium with small thermal resistance and good thermal conductivity. The space single crystal silicon solar cell is adhered on the surface of the composite receiver by employing insulating and heat conduction double-sided tape. The trough concentrator driven by a two-axis sun tracking unit converged solar irradiation on the solar cells. The energy flux density on the solar cells increased significantly (the concentration ratio of the system 10.3). The working fluid - water is driven to flow through the back cavity of the composite receiver by a pump and carries away the produced heat. Therefore, the solar cells work at a relatively low temperature, and their efficiencies are improved. At the same time, the thermal energy at a certain temperature is output.



(a)Schematic view of PV/T system

(b)Picture of Solar trough concentrating PV/T system

Fig.1. Solar trough concentrating PV/T system

The area of the trough concentrator is $1.8m^2$ (length 1.16m, aperture width 1.57m), the focal length is 1.06m, and the mirror optical efficiency is 0.7. The tracking accuracy of the dual axis tracking unit with photoelectric passive sensor, is 0.85. The electrical output unit is composed of 9 space silicon solar cell in series, each of which is 71mm×62mm, with short circuit current 1.45A and open circuit voltage 0.5V. The length of the composite receiver is 80cm. TRM-2 and TRM-FD1 were respectively employed to record the meteorological data and the working fluid's temperatures in different positions. The soar direct radiation was recorded by direct radiation meter TBS-2-2 with the precision of 2%. The temperatures of the working fluid were sensed by the thermocouples with the precision of 0.2℃. The mass flow rate of the working fluid was measured by the turbine flowmeter with the precision of 1%. The air velocity transducer EC-9S (X) with the precision (0.3+0.03V) was adopted to measure the wind speed and wind direction. The above instruments are all produced by China Jinzhou Sunshine Tech. Co., Ltd. The Fluke infrared thermometer with the accuracy of 1% was used to measure the solar cells' temperature.

RESULTS AND DISCUSSIONS

In our PV/T system, the maximum power(P_m) and efficiency(η_{elec}) of solar cell can be obtained as,

$$P_m = I_{mp} V_{mp} \quad (1)$$

$$\eta_{elec} = \frac{P_m}{\mu A G_D} \quad (2)$$

Where, P_m is the maximum power; I_{mp} is the current corresponding to the maximum power; V_{mp} is the voltage corresponding to the maximum power; η_{elec} is solar cell efficiency; μ is the optical efficiency of the trough concentrator, 0.7; A is the effective area of the trough concentrator; and G_D is the direct solar radiation.

The instantaneous thermal efficiency (η_{th}) is obtained as,

$$\eta_{th} = \frac{\dot{m} c_p (T_o - T_i)}{A G_D} \quad (3)$$

Where, m is the mass flow rate of working fluid, C_p is the specific heat capacity of fluid at constant pressure, T_0 is the temperature of water at outlet and T_i is the temperature of water at inlet.

Tab.1 is the output performance of solar cells on different defocus planes with different aperture widths of trough concentrator. On the same defocus plane, with the decrease of the aperture width of the trough concentrator, the efficiency of solar cells increases and the maximum output power decreases.

With the same aperture width of the trough concentrator, the output performance of solar cells enhances with the increase of the distance between solar cells' surface and focal plane. When the aperture width is 157cm, the maximum output power increases from 20.45W to 22.37W, increased by 9.39% and the solar cells' efficiency increases from 2.20% to 2.74%, increased by 24.55%, with the increase of the defocus distance from 1cm to 5cm. When the aperture width is 117cm, the maximum output power increases from 19.04W to 22.21W, increased by 16.63%, and the solar cells' efficiency increases from 3.07% to 3.43%, increased by 11.73%, with the increase of the defocus distance from 1cm to 5cm. When the aperture width is 97cm, the maximum output power increases from 18.77W to 21.50W, increased by 14.53%, and the solar cells' efficiency increases from 3.29% to 4.12%, increased by 25.23%, with the increase of the defocus distance from 1cm to 5cm. When the aperture width is 77cm, the maximum output power increases from 17.95W to 21.90W, increases by 22.01%, and the solar cells' efficiency increases from 4.01% to 4.98%, increased by 24.19%, with the increase of the defocus distance from 1cm to 5cm. It results from that the larger the defocus distance is, the larger and the closer to the width of the space silicon solar cells the spot width is. The lower the concentration ratio is, the more uniform the energy flux on the solar cells' surface is. Therefore, the better output performance of the solar cells is achieved.

Table 1. Output performance of solar cells on different defocus planes with different aperture widths of trough concentrator

Ⅰ	Ⅱ	Ⅲ	Ⅳ	Ⅴ	Ⅵ
cm	cm	°C	$w \cdot m^{-2}$	W	%
157	1	37	1057.2	20.45	2.20
	3	32	976	21.57	2.51
	5	25	929	22.37	2.74
117	1	53	947.4	19.04	3.07
	3	66	998	20.16	3.08
	5	40	987	22.21	3.43
97	1	46	1051	18.77	3.29
	3	57	1007	19.62	3.59
	5	40	961	21.50	4.12
77	1	39	1038.8	17.95	4.01
	3	58	996	19.41	4.52
	5	33	1019	21.90	4.98
57	1	30	1024.75	16.80	5.13
	3	56	983	17.92	5.71
	5	40	1016	17.03	5.25

Ⅰ. Aperture width of trough concentrator, Ⅱ. Distance between solar cells' surface and focal plane, Ⅲ. Surface temperature of solar cell, Ⅳ. Solar direct radiation, Ⅴ. Maximum power of solar cell, Ⅵ. Efficiency of solar cell

When the distance from the focal plane is 5cm and the aperture width is 157cm, the maximum power of solar cell reaches the maximum value of 22.37W, and the solar cells' efficiency is 2.74%.

When the distance from the focal plane is 3cm and the aperture width is 57cm, the solar cells' efficiency reaches the maximum value of 5.71%, and the maximum output power is 17.92W.

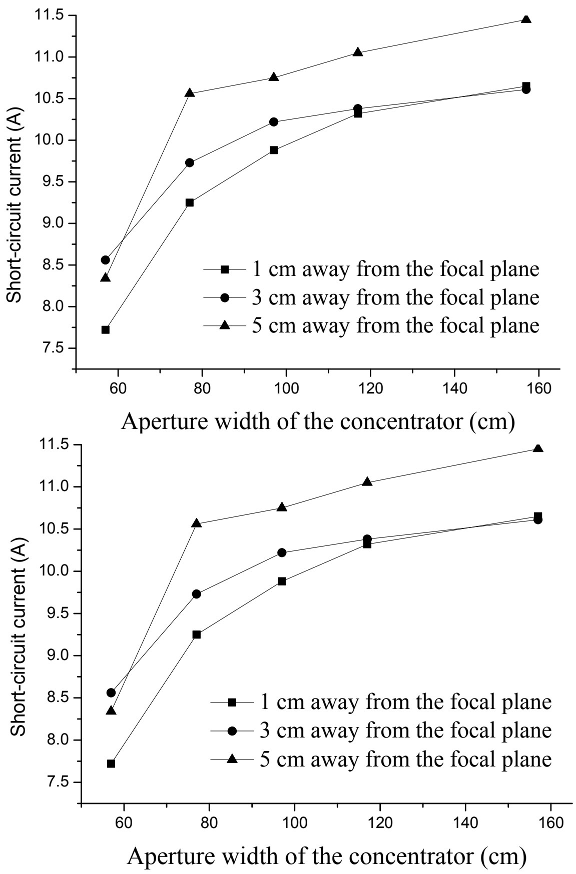


Fig.2. Short circuit current and maximum power

Fig.2 shows the short circuit current and the maximum power under different aperture widths of trough concentrator. The short-circuit current and the maximum power decrease with the decrease of the aperture width. The short-circuit current decrease from 10.65A to 7.72A with the decrease of the aperture width from 157cm to 57cm when the distance between the composite receiver and the focal plane is 1cm, and the maximum power decrease from 20.45W to 16.80W. The short-circuit current decrease from 10.61A to 8.56A with the decrease of the aperture width from 157cm to 57cm when the distance between the composite receiver and the focal plane is 3cm, and the maximum power decrease from 21.57W to 17.92W. The short-circuit current decrease from 11.45A to 8.34A with the decrease of the aperture width from 157cm to 57cm when the distance between the composite receiver and the focal plane is 5cm.

With the decrease of the aperture width of the trough concentrator, the maximum power overall shows a downward trend, whereas it increases a little bit when the aperture width is 77cm, which is attributed to the influence of solar cells temperature and the irradiance. The drop rate of the maximum power is smaller than that of the short-circuit current. The reason is that the photocurrent decrease with the decrease of the aperture width, and the influence of photocurrent on power is smaller than that of series resistance of solar cells on power loss.

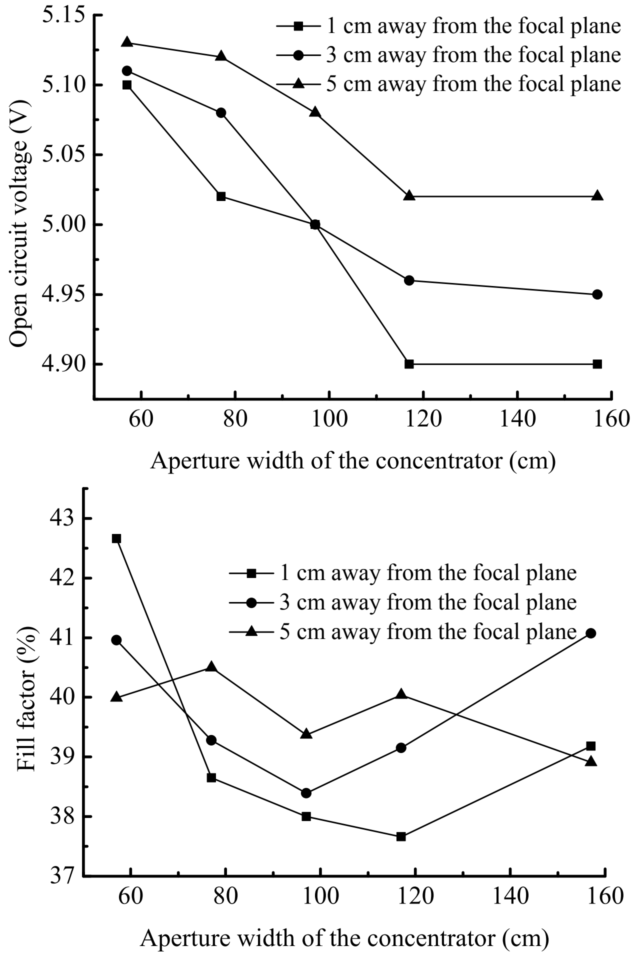


Fig.3. Open circuit voltage and fill factor

Fig.3 shows the open circuit voltage and the fill factor (the ratio of the product of current and voltage at the maximum output power point to the product of open-circuit voltage and short-circuit current can be obtained in the working curve of solar cells, which reflects the changing characteristics of the output power of solar cells with load) under different aperture widths of trough concentrator. When the distance between the composite receiver and the focal plane is 1cm, the open circuit voltage increase by 4.08% from 4.9V to 5.1V with the decrease of the aperture width from 157cm to 57cm. When the distance between the composite receiver and the focal plane is 3cm, the open circuit voltage increased by 3.23% from 4.95V to 5.11V with the decrease of the aperture width from 157cm to 57cm. When the distance between the composite receiver and the focal plane is 5cm, the open circuit voltage increased by 2.19% from 5.02V to 5.13V with the decrease of the aperture width from 157cm to 57cm.

The maximum fill factor of 42.66% is obtained when the aperture width is 57cm and the distance between the composite receiver and the focal plane is 1cm. When the aperture width decreases from 157cm to 57cm, the open-circuit voltage increases by 4.08%, the short-circuit current decreases by 27.51%, thus the maximum output power decreases by 17.86%.

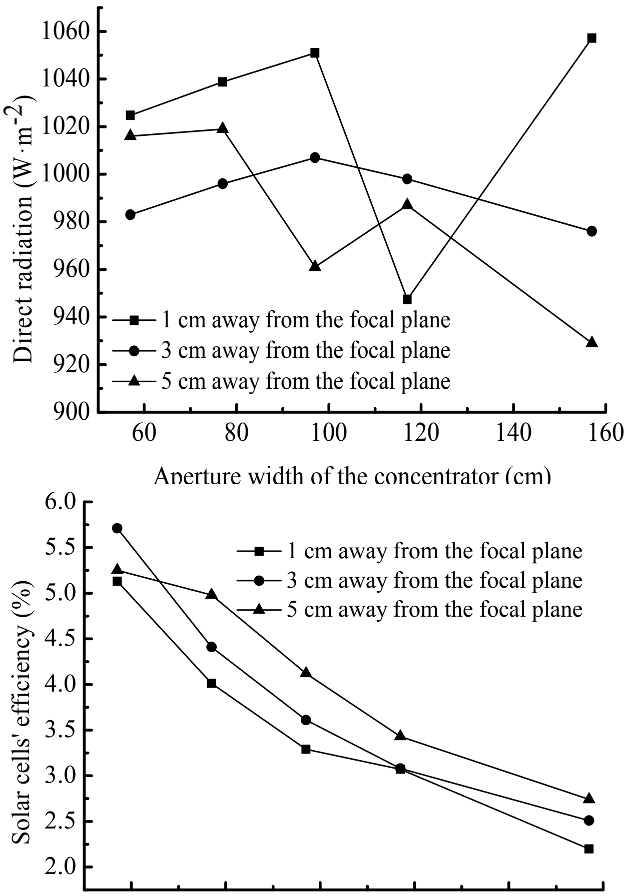
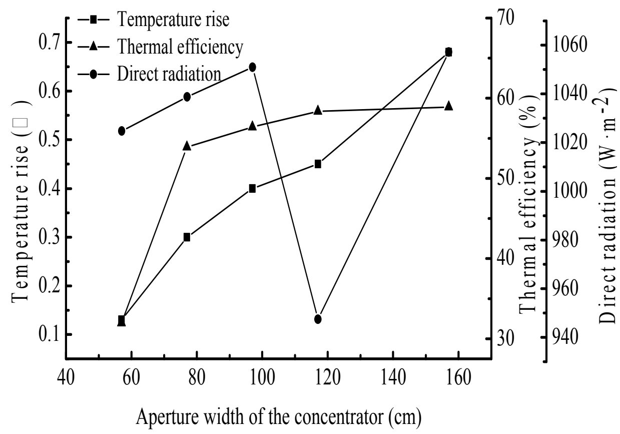
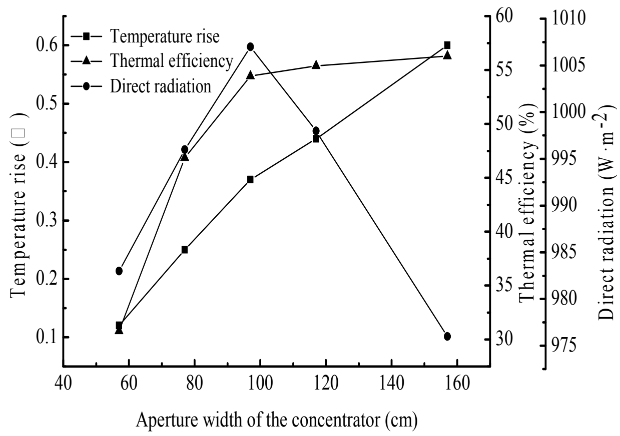


Fig.4. Direct radiation and solar cells' efficiency

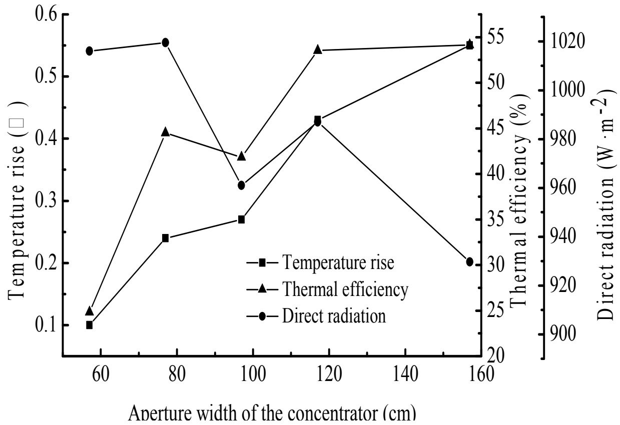
Fig.4 shows the direct radiation and the solar cells' efficiency under different aperture widths of trough concentrator. The solar cells' efficiency decreases by 57.12% from 5.13% to 2.2% with the increase of the aperture width from 57cm to 157cm when the distance between the composite receiver and the focal plane is 1cm. The solar cells' efficiency decreases by 56.04% from 5.71% to 2.51% when the distance between the composite receiver and the focal plane is 3cm. The solar cells efficiency decreased by 47.81% from 5.25% to 2.74% when the distance between the composite receiver and the focal plane is 5cm.



(a)1 cm ahead of the focal plane



(b)3 cm ahead of the focal plane



(c)5cm ahead of the focal plane

Fig.5. Thermal output characteristic of the PV/T system

The reason is that with the increase of the aperture width, the maximum peak energy flux density increases, the energy flux uniformity decreases and the solar cells' efficiency declines when the distance between the composite receiver and the focal plane is same.

Fig.5 shows the thermal output characteristic of the PV/T system. When the distance between the composite receiver and the focal plane is 1cm, the temperature rise of the cooling working fluid flowing through the back cavity of the composite receiver are 0.68℃, 0.45℃, 0.4℃, 0.3℃ and 0.13℃when the aperture width are respectively 157cm, 117cm, 97cm, 77cm and 57cm. The system thermal efficiency of are 58.9%, 58.36%, 56.4%, 53.91% and 32%, respectively as shown in Fig.5(a). The temperature rise and the thermal efficiency decreases by 80.88% and 45.67%, respectively when the aperture width decreases from 157cm to 57cm.

When the distance between the composite receiver and the focal plane is 3cm, the temperature rise of the cooling working fluid are 0.6℃, 0.44℃, 0.37℃, 0.25℃ and 0.12℃, respectively when the aperture width of mirror are respectively 157cm, 117cm, 97cm, 77cm and 57cm, and the system thermal efficiency are 56.29%, 55.4%, 54.45%、46.86% and 30.79%, respectively as shown in Fig.5(b). The temperature rise and the thermal efficiency decreases by 80% and 45.3%, respectively when the aperture width decreases from 157cm to 57cm.

When the distance between the composite receiver and the focal plane is 5cm, the temperature rise of the cooling working fluid are 0.55℃, 0.43℃, 0.27℃, 0.24℃ and 0.1℃, respectively when the aperture width are respectively 157cm, 117cm, 97cm, 77cm and 57cm, and the system thermal efficiency are 54.17%, 53.53%, 41.83%, 44.49% and 24.82%, respectively as shown in Fig.5(c). The temperature rise and the thermal efficiency of system decrease by 81.82% and 54.18%, respectively when the aperture width decreases from 157cm to 57cm.

The thermal efficiency decreases with the decrease of the aperture width when the distance between the composite receiver and the focal plane is the same. The reason is that the small aperture width would result in the small solar collection area and the small concentrating ratio of the system, thus both the energy flux density gathered on the surface of solar cells and the system thermal efficiency would decrease. The maximum thermal efficiency of 58.9% could be obtained and the temperature rise of the cooling working fluid is 0.68℃ when the distance between the composite receiver and the focal plane is 1cm and the aperture width is 157cm.

CONCLUSIONS

The trough concentrating photovoltaic/thermal system with 1.8m^2 concentrator is established with the space silicon solar cells as the electricity output unit, and the experiments are conducted. Experimental results indicate that the maximum output power of solar cells is 22.37W and the solar efficiency is 2.74% when the distance between the composite receiver and the focal plane is 5cm and the aperture width of the trough concentrator is 157cm. The maximum output power of solar cells is 17.92W. The maximum solar cells' efficiency of 5.71% could be obtained when the distance between the composite receiver and the focal plane is 3cm and the aperture width is 57cm. The maximum system thermal efficiency is 58.9%, the temperature rise of the cooling working fluid is 0.68℃ and the solar cells' efficiency is 2.2% when the distance between the composite receiver and the focal plane is 1cm and the aperture width is 157cm.

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