Performance analysis of solar cell arrays in concentrating light intensity*

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Abstract: Performance of concentrating photovoltaic/thermal system is researched by experiment and simulation calculation. The results show that the *I–V* curve of the GaAs cell array is better than that of crystal silicon solar cell arrays and the exergy produced by 9.51% electrical efficiency of the GaAs solar cell array can reach 68.93% of the photovoltaic/thermal system. So improving the efficiency of solar cell arrays can introduce more exergy and the system value can be upgraded. At the same time, affecting factors of solar cell arrays such as series resistance, temperature and solar irradiance also have been analyzed. The output performance of a solar cell array with lower series resistance is better and the working temperature has a negative impact on the voltage in concentrating light intensity. The output power has a –20 W/V coefficient and so cooling fluid must be used. Both heat energy and electrical power are then obtained with a solar trough concentrating photovoltaic/thermal system.

Key words: trough concentrating; photovoltaic/thermal system; energy efficiency; series resistance

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1. Introduction

At present attention is being paid to renewable energy all over the world because the energy crisis badly hinders social advancement and economic development. Solar energy, especially photovoltaic systems will be the main body of the energy framework. But there are two disadvantages, including costly material and low photoelectric conversion efficiency, which cannot be solved in the short-term. Concentrating photovoltaic/thermal (CPV/T) systems are focused on by scholars for they can not only improve the photoelectric conversion efficiency but also can produce equal amounts of electricity with low-cost concentrating materials substituting for costly solar cells. In the early 1980s American researchers began working on combined photovoltaic and thermal systems[1,2], and simulation calculation and experimental work were done in succession[3–8]. Research on run cost and system economic performance showed that there are some advantages such as low cost, expedient control and preferable technology by using trough concentrating to drive the PV/T system[9,10]. The efficiency of solar cells used in trough concentrating photovoltaic/thermal (TCPV/T) systems can reach 22% and the cost of producing electricity can be reduced 40%, as demonstrated at the Renewable Research Institute of the Australian National University[11]. The University of Science and Technology of China and Shanghai Jiaotong University has investigated PV/T systems in China[12,13], but research on the performance of solar cell arrays has not been reported. This paper focus on the performance of crystal silicon solar cell arrays and GaAs cell arrays adopted in the TCPV/T system, and simulation calculations and experimental work have been done.

2. Experiment

2.1. Parameters of the TCPV/T system

Figure 1 shows the working principals of a 2 m^2 TCPV/T system which has 16.92 theoretical concentrating ratios. The area of the reflecting mirror is 1.44×1.45 m^2 and the optical efficiency of the mirror is 0.69. The actual concentrating time of the system, which is tested by laser power instruments in experiment, is 10.23. Solar cell arrays which are stuck on the inner cavity produce electric power when concentrating light is reflected and focused on the cell arrays and cooling liquid flows in the cavity in order to reduce the temperature of the cell. Hot liquid is stored in a water tank. In order to maintain the system's thermal efficiency, the inner cavity is encased in insulation material.

The length, width and height of the inner cavity are 1.5, 0.12 and 0.09 m respectively. The inside diameter of tube is 0.03 m. The single crystal silicon solar cell, polycrystalline silicon solar cell, super cell and GaAs cell are used as solar cell arrays for test. The focused line width of concentrating light is 0.1 m. The specification of the solar cell arrays and heat transmission of the TCPV/T system are shown in Table 1 to Table 3.

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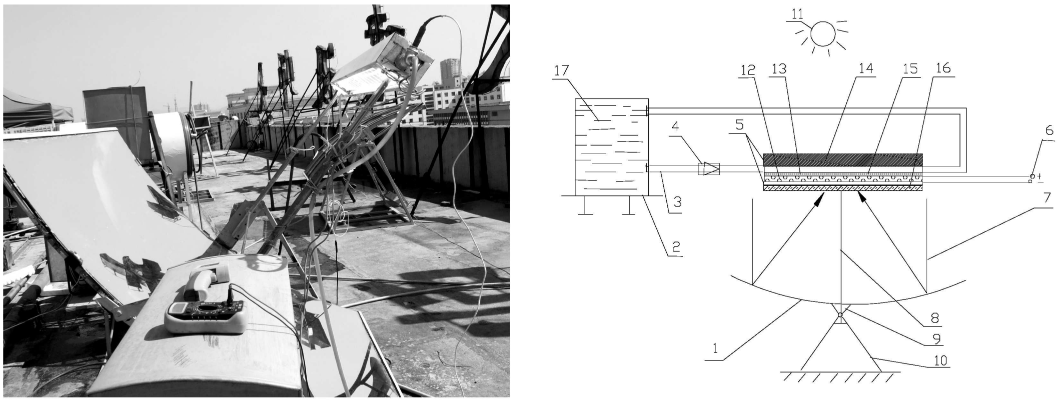

1. Trough reflecting mirror 2. Storage 3. Tube 4. Pump 5. Receiver 6. Electrodes 7. Sunlight 8. Supporting staff 9. Swiveling axis 10. Backstop 11. Sun 12. Solar cell array 13. Thermally conductive adhesive 14. Insulating layer 15. Inner cavity 16. Outer cavity 17. Cooling fluid

Fig.1. Trough concentrating TCPV/T system.

Table 1. Specification of four solar cell arrays.

Parameter	Single crystal silicon solar cell array	Polycrystalline silicon solar cell array	Super cell array	GaAs cell array
Area (m^2)	0.103 × 0.0515	0.117 × 0.075	0.071 × 0.062	0.04 × 0.03
Piece	10	10	16	40
Linking	In series	In series	In series	In series

Table 2. Heat transmissions of the TCPV/T system using single crystal silicon and polycrystalline silicon solar cell arrays.

Parameter	Single crystal silicon solar cell array					Polycrystalline silicon solar cell array				
	Cell	Thermally conductive adhesive	Plate	Tube	Insulating layer	Cell	Thermally conductive adhesive	Plate	Tube	Insulating layer
λ ($W \cdot m^2 \cdot K^{-1}$)	150.00	0.42	107.00	107.00	0.04	175.00	0.42	107.00	107.00	0.04
a	0.95	—	0.10	—	0.20	0.35	—	—	—	0.20
p	0.35	—	0.10	—	0.20	0.35	—	0.10	—	0.20
d (mm)	0.25	0.40	5.00	4.00	42.50	0.30	0.40	5.00	4.00	42.50

Table 3. Heat transmissions of the TCPV/T system using single super cell and GaAs cell arrays .

Parameter	Super cell array					GaAs cell array				
	Cell	Thermally conductive adhesive	Plate	Tube	Insulating layer	Cell	Thermally conductive adhesive	Plate	Tube	Insulating layer
λ ($W \cdot m^2 \cdot K^{-1}$)	150.00	0.42	107.00	107.00	0.04	55	0.42	107.00	107.00	0.04
a	0.80	0.30	0.37	—	0.20	0.85	0.30	0.37	—	0.20
p	0.35	—	0.10	—	0.20	0.30	—	0.10	—	0.20
d (mm)	0.30	0.40	5.00	4.00	42.50	0.70	0.40	5.00	4.00	42.50

2.2. Establishing a mathematical model for a TCPV/T system using crystal silicon solar cell and GaAs cell arrays

Figure 2 shows the energy transfer and hot resistance of the TCPV/T system. Solar energy gets into the system via the solar cell arrays and plate. A little energy will be lost on hot resistance when solar energy is transferring into the system. The remaining energy will be changed into electricity and thermal energy. The mold of the TCPV/T system has been established and the simulation work has been done in this paper.

The current equations of a crystal silicon cell are shown as[14]

$$I = (I_L + I_0) - I_0 \exp \frac{qV + nqIR_s}{nAkT_c}, \tag{1}$$

$$I_0 = \frac{I_L}{\exp \frac{V_{oc} q}{nAkT_p} - 1}. \tag{2}$$

Because the structure of the GaAs cell is different from that of a crystal silicon cell, its current equation is not given by Eq. (1) but could be described by simulating with a nonlinear least

Table 4. Simulation calculation results and experimental testing data for the TCPV/T system.

Solar cell array	t (h)	I_d (W/m^2)	v_f (L/h)	v_w (m/s)	T_a (°C)	T_i (°C)	T_o (°C)		T_c (°C)	
							data	results	data	results
Single crystal	2	976.61	21.42	2.00	20.00	25.91	46.19	44.90	78.36	77.40
Polycrystalline silicon	2	885.16	25.00	2.60	15.00	17.60	40.6	41.2	68.00	70.00
Super cell	3	941.67	40.00	2.00	19.90	26.15	45.33	41.81	61.00	60.80
GaAs	3	750.00	112.00	1.20	27.50	37.7	44.30	44.68	58.00	57.63

Solar cell array	η_{pv} (%)		η_{th} (%)		$\eta_{pv,ex}$ (%)		$\eta_{th,ex}$ (%)		$\eta_{total,ex}$ (%)	
	data	results	data	results	data	results	data	results	data	results
Single crystal	1.22	1.18	35.23	33.60	0.47	0.46	1.35	1.22	1.82	1.67
Polycrystalline silicon	0.81	0.83	38.67	39.68	0.45	0.44	1.76	1.85	2.22	2.29
Super cell	4.60	4.16	42.03	40.00	2.37	2.18	2.44	1.79	4.82	3.97
GaAs	9.51	9.44	34.38	35.76	7.41	7.75	3.34	3.58	10.75	11.33

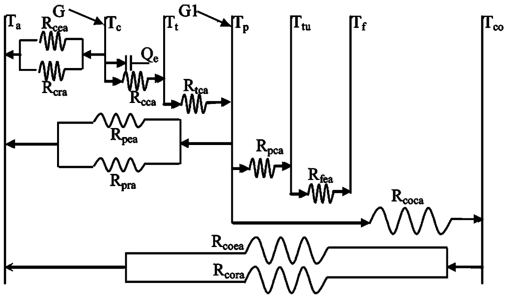

Fig. 2. Energy transfer and hot resistance of the TCPV/T system.

square method[15]. The equation is shown as

$$I = X + Y\sqrt{2}\Big/Z\sqrt{\pi} \times \mathrm{e}^{-2[(V-W)/Z]^2}. \tag{3}$$

After simulation, X, Y, Z and W will be given.

In order to describe the system output power performance produced by solar cell arrays, the system's electrical efficiency is shown as

$$\eta_{pv} = \frac{P_m}{A_m I_d}. \tag{4}$$

The system's energy equations are shown as

$$\frac{T_c - T_a}{R_{cea}} + \frac{T_c - T_a}{R_{cra}} + \frac{T_c - T_t}{R_{cca}} + Q_e - G = 0, \tag{5}$$

$$\frac{T_c - T_t}{R_{cca}} + \frac{T_t - T_p}{R_{tca}} = 0, \tag{6}$$

$$\frac{T_P - T_t}{R_{pca}} + \frac{T_P - T_{co}}{R_{coca}} + \frac{T_P - T_a}{R_{pea}} + \frac{T_P - T_a}{R_{pra}} - \frac{T_t - T_p}{R_{tca}} - G_1 = 0, \tag{7}$$

$$\frac{T_p - T_t}{R_{pca}} + \frac{T_t - T_f}{R_{fea}} = 0, \tag{8}$$

$$\frac{T_p - T_{co}}{R_{coca}} - \frac{T_{co} - T_a}{R_{coea}} - \frac{T_{co} - T_a}{R_{cora}} = 0, \tag{9}$$

$$\frac{T_t - T_f}{R_{fea}} - mc_{p,f}(T_o - T_i) = 0, \tag{10}$$

$$\frac{T_t - T_o}{T_t - T_i} - \exp\left(-\frac{mc_{p,f}}{A_t h_{fe}}\right) = 0. \tag{11}$$

When the cooling water flows through tube, it becomes heated water. The thermal efficiency is thus given to describe the cooling performance. The system's thermal efficiency is given by

$$\eta_{th} = \frac{mc_{p,f}(T_o - T_i)}{I_d A_m}. \tag{12}$$

References [16, 17] give the calculations for hot resistance and heat transfer coefficients.

Because electricity and thermal energy have different values, taking the exergy efficiency provides values for thermal performance and electric performance; it is shown as[18]

$$\eta_{exergy} = \frac{\eta_{pv} I_d A_m + mc_{p,f}\{[h-(T_a+273.5)\,s]_{out} - [h-(T_a+273.5)\,s]_{in}\}}{I_d A_m\left(1 - \dfrac{T_a + 273.5}{5777}\right)}. \tag{13}$$

Simulation results and an analysis of exergy have also been reported in Refs. [10, 19].

3. Experimental results and analysis

3.1. Performance of the TCPV/T system

Theoretical calculation results and experimental testing data are shown in Table 4.

From Table 4, it can be seen that the error is less than 5% between the simulation results and the experimental testing data. So the mold could accurately represent TCPV/T performance. The results show that the exergy efficiency translated by thermal efficiency is much lower than that translated by electrical efficiency, because electricity is a highly useable energy. For example, the exergy produced by 1.22% electrical efficiency of the single crystal silicon cell array can reach 25.82% system exergy, but 35.23% thermal efficiency could only produce 74.78% exergy. At the same time the exergy produced by 0.81% electrical efficiency of the polycrystalline silicon cell array and 4.61% electrical efficiency of super cell

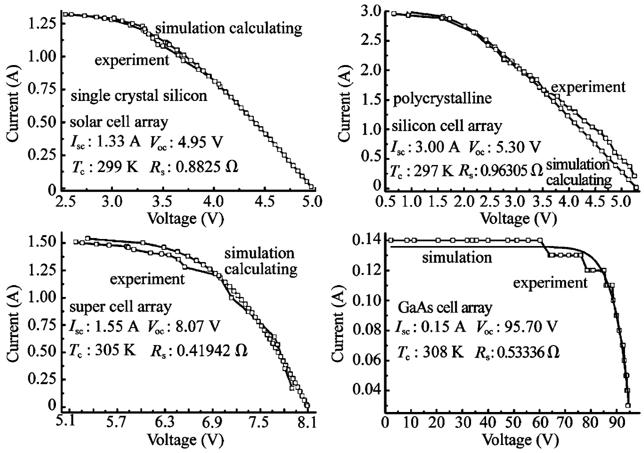

Fig. 3. *I–V* characteristic curves of four solar cell arrays in 1 sun.

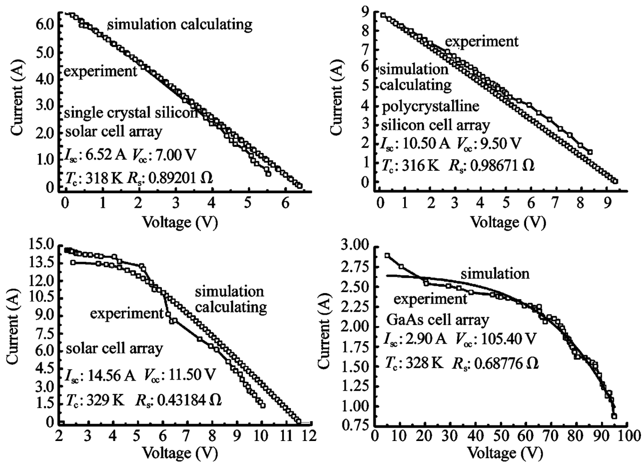

Fig. 4. *I–V* characteristic curves of four solar cell arrays in concentrating light.

array can respectively reach 20.27% exergy and 49.17% exergy. In the TCPV/T system using the GaAs cell array, the system electrical efficiency can reach 9.51% and the system thermal efficiency is 34.38%, which are the same as those reported in Refs. [9–11, 20–22]. In the GaAs system, 9.51% electrical efficiency can produce 68.93% system exergy. Analysis of the results shows that the exergy produced by electricity is responsible for the majority of the exergy. If the electrical efficiency of a solar cell array is as high as possible, more exergy can be obtained from the TCPV/T system. So increasing the output power of solar cell arrays and improving the value of the system are important to TCPV/T systems, and performance analysis of solar cell arrays must be done in order to improve the output of cell arrays.

3.2. Analysis of solar cell arrays

I–V characteristic curves of solar cell arrays are shown in Figs. 3 and 4 through experimental testing and theoretical calculation. The *I–V* curve and characteristic parameters are very good when the solar cell arrays work in 1 sun. But in conditions of concentrating light intensity, the *I–V* curves of the single crystal silicon solar cell array and polycrystalline silicon cell array become almost linear and output performances drop a lot. Otherwise, the *I–V* curves and performances of

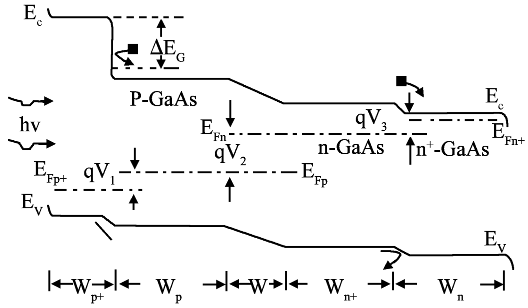

Fig. 5. Energy band diagram of a p$^+$-AlGaAs/p-n-n$^+$-GaAs cell.

super cell arrays and GaAs cell arrays are preferable to those of the single crystal silicon solar cell array and polycrystalline silicon cell array. All of the solar cell arrays' characteristic parameters are worse in 1 sun than in concentrating light. The reason for this can be found from the following expression.

$$P_{\rm m} = \frac{nAkTI}{q}\ln\left(\frac{I_{\rm L}-I}{I_0}+1\right)-I^2R_{\rm s}. \qquad (16)$$

The output power loss on series resistance is very large when a large current flows in cell arrays, which is produced by concentrating light. Series resistance increases a great deal, and temperature rises in high light intensity, which is another reason for output power drop. Reference [23] reported correlating research. The output performance of the GaAs cell array and super cell array is better than that of the single crystal silicon solar cell array and polycrystalline silicon cell array because of their lower series resistance. From Figs. 3 and 4, it can be seen that the output performance of the GaAs cell array is better than that of silicon cell arrays whose structure is different from silicon. Figure 5 is an energy band diagram of the p$^+$-AlGaAs/p-n-n$^+$-GaAs cell used in the TCPV/T system. The absorption coefficient of GaAs is large because the photo-generated carrier of GaAs produced by sun excitation is direct transition. GaAs also has other excellent characteristics, such as bandwidth ($E_{\rm g}$ = 1.43 eV) matching well with the solar spectrum, large electron mobility, strong anti-radiation and good performance in high temperature[24–26]. So the high-point efficiency of a cascade GaAs cell can reach 40% and the efficiency can stay at 25% in 500–1000 suns[27, 28].

Because series resistance has a huge effect on solar cell array performance, a simulation calculation for the *I–V* curves in different series resistances has been done. Figure 6 shows that the *I–V* characteristic curve is much better when series resistance is lower. In concentrating light intensity, when series resistance is less than 0.25 Ω, *I–V* curves of single crystal silicon and polycrystalline silicon cell arrays become better, and super cell arrays have a better *I–V* curve when the series resistance is less than 0.4 Ω. The *I–V* curve of GaAs cell arrays is better when the series resistance is less than 0.7 Ω.

External parameters, including wind speed, ambient temperature, cooling fluid velocity and direct irradiance also have an effect on the performance of solar cell arrays. For example, wind speed, ambient temperature, and cooling fluid velocity can impact cell temperature, and direct irradiance has an influence on the short circuit current of cells.

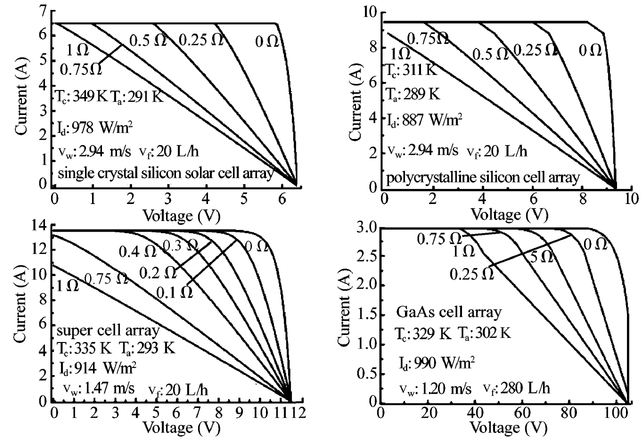

Fig. 6. *I–V* characteristic curves of four solar cell arrays with different resistances.

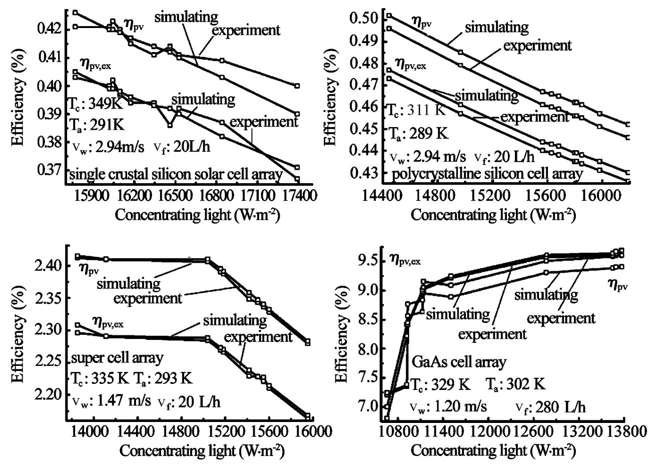

Fig. 7. TCPV/T system electrical and exergy efficiency of four solar cell arrays with different concentrating lights.

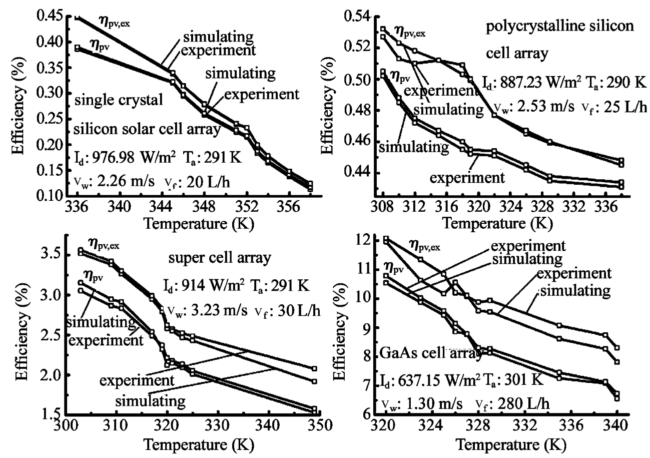

Fig. 8. TCPV/T system electrical and exergy efficiency of four solar cell arrays with different temperatures.

Figures 7 and 8 show the relationship between the system electrical efficiency and exergy efficiency of solar cell arrays with different direct irradiances and working temperatures. The system electrical and exergy efficiency of crystal silicon cell arrays descends as direct irradiance increases, and the efficiency of single crystal silicon and polycrystalline silicon cell arrays drops very quickly. The efficiency of super cell arrays first drops a little; however, when the concentrating light intensity increases to 15000 W/m^2 the efficiency begin falling drastically. The electrical efficiency of the GaAs cell array increases as direct irradiance increases, which first goes up quickly and then rises slowly. It can be seen from Fig. 8 that temperature has a negative effect on all solar cell arrays. The efficiency of cell arrays drops as temperature rises, and when the voltage falls by 0.1 V, produced by the temperature rising, the output power of the GaAs cell array reduces by 2 W. For the TCPV/T system cooling water is used to take heat away from the cell and avoid high temperatures; at the same time, both heat energy and electric power can be obtained with the TCPV/T system.

4. Conclusions

(1) Research work about crystal silicon solar cell arrays and GaAs cell arrays has been carried out based on the TCPV/T system. The output performance of GaAs cell arrays is better than that of crystal silicon solar cell arrays. The research results also show that exergy efficiency translated by thermal efficiency is much lower than that translated by electrical efficiency.

(2) It can be seen from both simulation calculation results and experimental tests that the series resistance, temperature and concentrating light intensity have a huge effect on the output performance of solar cell arrays. High light intensity can improve output power by increasing the cell current. Reducing the series resistance by using lower resistance solar cells can also increase output power; the descending temperature of cell arrays can get more electricity when cooling fluid is used. Both heat energy produced by the fluid and electric power produced by solar cell arrays can be obtained with the TCPV/T system.

Appendix: Nomenclature

A: diode quality factor
I: current, A
I_0: reverse saturation current, A
I_L: light generated current, A
V: voltage, V
V_{oc}: shut circuit voltage, V
k: Boltzmann constant
λ : conduction coefficient, W·m^2/K
a: absorptivity
p: emissivity
d: thickness, mm
q: free charge
n: pieces of solar cell
G, G_1: solar irradiance ,W/m^2
R_s: series resistance of solar cell, Ω
T_c: temperature of solar cell array , K
T_a: ambient temperature, K
T_p: plate temperature, K
T_{tu}: tube temperature, K

T_f: cooling fluid temperature, K
T_{co}: cover temperature, K
T_i: inlet temperature of cooling water, K
T_o: outlet temperature of cooling water, K
m: fluid mass, kg
$C_{p,f}$: specific heat-capacity, kJ/(kg·K)
I_d: direct irradiance, W/m^2
A_m: reflecting mirror area, m^2
h: specific enthalpy, kJ/kg
s: specific entropy, kJ/(kg·K)
v_f: velocity of flow, L/h
v_w: wind velocity, m/s
R_{cea}: thermal resistance for transfer of solar cell, Ω
R_{cra}: thermal resistance for radiation of solar cell, Ω
R_{cca}: thermal resistance for conduction of solar cell, Ω
R_{tca}: thermal resistance for conduction of thermally conductive adhesive, Ω
R_{coca}: thermal resistance for conduction of cover, Ω
R_{coea}: thermal resistance for transfer of cover, Ω
R_{cora}: thermal resistance for radiation of cover, Ω
R_{pca}: thermal resistance for conduction of plate, Ω
R_{pea}: thermal resistance for transfer of plate, Ω
R_{pra}: thermal resistance for radiation of plate, Ω
R_{fea}: thermal resistance for convection of fluid, Ω
η_{pv}: system electrical efficiency
η_{th}: system thermal efficiency
η_{exergy}: exergy efficiency
$\eta_{pv,ex}$: system electrical exergy efficiency
$\eta_{th,ex}$: system thermal exergy efficiency
$\eta_{total,ex}$: system total exergy efficiency

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