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Optimization and experimentation of concentrating photovoltaic/cascaded thermoelectric generators hybrid system using spectral beam splitting technology

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Abstract. The concentrating photovoltaic-thermoelectric (PV-TE) hybrid system by using spectrum splitting technology had been considered to be a promising system. The IR-wavelength light, which can’t generally be converted by solar cells, can be separated from the full solar spectrum in this system and then be appropriately converted by thermoelectric generators based on Seebeck effect. The overall system efficiency might be improved due to the additional contribution of thermoelectric generation. In this paper, a prototype PV-TE hybrid system and a numerical model for the evaluation of the whole system are presented. In order to convert IR-wavelength light into electricity sufficiently, we proposed the cascaded thermoelectric module for thermoelectric generation, which consists of two individual TE stages. These are middle-temperature thermoelectric materials, CoSb₃ and low-temperature thermoelectric materials, Bi₂Te₃ which are configured in tandem. The numerical model was established to optimize thermoelectric module geometries and the optical concentration ratio. In addition, such a novel PV/cascaded TE generators hybrid system had been constructed and experimentally researched in practical conditions. Meanwhile, the effects of the direct normal irradiation (DNI) on the temperature of the thermoelectric module and the overall output power of the hybrid system are experimentally investigated. The optimized results showed that the DNI, optical concentration ratio and the height ratio of two TE stages could significantly affect the performances of this hybrid system. The TE subsystem efficiency $\eta_{TE}$ can reach to 8%, the PV subsystem efficiency $\eta_{PV}$ can reach to 44%, and total hybrid system efficiency $\eta_{PV-TE}$ can reach to 35% under the conditions that DNI=1000 W/m², optical concentration ratio $C_F = 1000$, optimized height ratio of two TE stages $\tau = 0.6$. The experimental research results revealed that output power of PV and TE subsystem could reach to 22 W and 1.9 W respectively.

Nomenclature

| Symbol | Description |
|--------|-------------|
| A      | area ($m^2$) |
| $C_F$  | geometrical concentration ratio |
| $E_{SW}$ | incident solar radiation ($W/m^2$) |
| $E_{PV}$ | solar energy directed to PV unit (W) |
| $E_{TEG}$ | solar energy directed to TE unit (W) |
| $V_{OC}$ | open circuit voltage of the solar cell (V) |
| $\varepsilon$ | emissivity |
| $\alpha$ | Seebeck coefficient of TE materials (V/K) |
1. Introduction

Concentrating photovoltaic (CPV) technology, which use optical elements to focus light onto small-area solar cells, has long been considered as a way to minimize the costs, while improving efficiency, of photovoltaic technology. Because of the limit of the band-gap of the semiconductor materials consisting of the solar cells, only sunlight with wavelengths below approximately 900-1100 nm, which are the ultraviolet light (UV) & visible light, can be converted into electricity \[1\]. The remaining irradiance, infrared (IR) light, which takes a large proportion of the overall incoming solar energy, will be wasted and then be finally converted into heat. These may result in the cell temperature rising rapidly under the concentrated irradiation condition \[2\]. In order to avoid the waste of IR energy, the hybrid photovoltaic thermal (PV/T) system has been proposed to produce both heat and electricity by combining photovoltaic (PV) device and solar thermal collector \[3, 4\]. Mostly, the heat transfer fluid, such as air or water, is generally used to transfer heat and to limit the high operating cell temperature. However, the waste heat is merely recovered as low-temperature heat energy corresponding to hot water applications in these technologies. In our previous research, an idea is to incorporate the solar cell as a component in a hybrid system also consisting of a thermoelectric element as another component. In the hybrid system, the waste heat can be recovered directly as a high level of electric energy.

It is well known that thermoelectric (TE) generators can directly convert thermal energy into electricity based on Seebeck effect \[5-7\] and have many advantages over conventional electric generators, such as compact in size, high reliability, no moving parts and no working fluid. Hence, the CPV-TE hybrid system was proposed to increase the overall efficiency and decrease the solar cells temperature by using a wavelength separating device to separate the incoming solar radiation into two parts.

A number of such hybrid systems have been studied recently. R. Björk\[8\] examined the performance of a combined solar photovoltaic (PV) and thermoelectric generator (TEG) system by using an analytical model for four different types of commercial PVs and a commercial bismuth telluride TEG. Cui\[9\] performed a thermoelectric (TE) generators attached directly to the back of the PV cell to absorb thermal heat and convert them into electricity. Mizoshiri M\[10\] fabricated the thin-film thermoelectric modules for thermal–photovoltaic hybrid solar generator. Ju X\[11\] adopted spectral beam splitting technology to divide incoming solar energy into two different parts supplying
for PV system and TE system respectively. These approaches can generally obtain high efficiency for the whole system. Arora and Kaushik\cite{12} proposed a thermodynamic model of two-stage thermoelectric generators in electrically series and parallel configuration. They also optimized multi-objective parameters. Meng and Chen\cite{13} used a two-stage thermoelectric generator to drive two-stage thermoelectric refrigerator system and optimized the performances of the system. However, both their works investigated only one thermoelectric material. Actually, different thermoelectric materials reach their optimal efficiency in different temperature, the optimal value of dimensionless thermoelectric coefficient (ZT) correspond to different temperatures for different materials\cite{14,15}. Besides, almost most previous works about two-stage TE generators hadn’t combined with PV system\cite{12,16,17}, or they just used one TE generator\cite{18-21}.

In order to convert IR-wavelength light into electricity sufficiently, we proposed concentrating photovoltaic/cascaded thermoelectric generators hybrid system using spectral beam splitting technology. Here, the cascaded thermoelectric modules for thermoelectric generation are proposed, which consists of two individual TE stages. These are middle-temperature thermoelectric materials, CoSb3 and low-temperature thermoelectric materials, Bi2Te3 and are configured in tandem. The numerical model was established to optimize thermoelectric module geometries and the optical concentration ratio. To obtain the optimal efficiency of this hybrid system, we optimized the height ratio of two TE generators in this hybrid system and investigated the influence of the ratio of optical concentration and direct normal irradiation (DNI). Finally, we have experimentally evaluated the performance of the hybrid system and verified the theoretical results.

2. Structure of the hybrid system and experimental setup

The structure of the concentrating photovoltaic-thermoelectric (PV-TE) hybrid system by using spectrum splitting technology in this paper consists of two parts, photovoltaic and thermoelectric. The detail schematic photograph of this numerical model is illustrated in Fig. 1. In the experimental setup, a Fresnel lens is employ to concentrate solar energy on to a wavelength splitter, which can separate solar spectrum into two different parts, UV & visible spectrum and IR spectrum. In the photovoltaic unit, UV & visible light can be converted into electricity by solar cell directly, due to the concentration of Fresnel lens may lead to a high temperature of PV cell, we have a paralleled fin heat sink to lower the temperature generated by the solar cell. In the thermoelectric unit, IR will firstly be concentrated into a thermal absorber, and then be delivered to cascaded thermoelectric generators. The middle-temperature materials CoSb3 is placed on the top stage and the low-temperature materials Bi2Te3 is placed on the bottom stage that can utilize different range temperature to convert into electricity. To prevent heat convection and radiation, thermal baffle and thermal insulator are used to reduce heat loss, thermal grease is conducted heat flow between two thermoelectric generators, and a paralleled fin heat sink is placed to ensure temperature difference of the TE generators.

According to the above structure of the hybrid system, an experimental research was investigated to test the feasibility of this hybrid system. This experimental setup includes two-axis sun tracker, Fresnel lens, irradiation meter and CPV/cascaded TE unit showed in Fig. 2(a). The EKO I-V Curve Tracer MP-160 is to measure the I-V curve for PV/cascaded TE unit and HIOKI data recorder to measure temperature and direct normal irradiance showed in Fig. 2(c)-(d) respectively. All the experiments were carried on in sunny days at Wuhan city, China. Owing to the obstacle of high buildings, the experimental setup can only accept solar energy from 7:00 AM to 17:00 PM during a day.
Fig. 1. The schematic photograph of concentrating photovoltaic/cascaded thermoelectric generators hybrid system.

Fig. 2. The photographs of the experimental setup (a), PV/cascaded TE unit (b) and test equipment (c-d).

3. The numerical model of concentrating PV-TE hybrid system

The concentrating photovoltaic/cascaded thermoelectric generators hybrid system using spectral beam splitting technology has a works under high solar concentration and high temperature conditions. To comprehend flow path of energy and simulate the thermal and electric performance of the hybrid system, a 1-dimensional numerical model was established in Fig. 3. For that some factors are uncontrollable for considering, we assumed that: (1) the thermal grease between two TE generators has high performance to ensure that cold side of CoSb₃ TE generator and hot side of Bi₂Te₃ generator have the same temperature; (2) the heat loss to the environment through radiation and convection by...
TE generators is neglected; (3) due to solar cell is very thin and has high thermal conductivity, temperature gradients of solar cell is ignored; (4) the electric contact resistance and thermal contact resistance between semi-conductor are neglected in TE model for simplification.

Fig. 2 shows the heat transfer and energy conversion of the PV-cascaded TE hybrid system. The energy directed to the TE unit and the PV unit can be calculated by following formula, where \( \lambda_k \) is the cutoff wavelength decided by wavelength splitter; \( E_{TE} \) is the solar energy separated to the TE unit (from \( \lambda_k \) to 4000 nm), \( E_{PV} \) is the another part of solar energy separated to the PV unit (from 280nm to \( \lambda_k \)); \( \eta_{opt} \) is the efficiency of the optical system including Fresnel lens and wavelength splitter, \( F(\lambda) \) is the spectral irradiance in AM 1.5D conditions. The concentration ratio is defined as the ratio of the Fresnel lens area \( A_{lens} \) to the device surface area, \( C_F = A_{PV}/A_{lens} \) or \( C_F = A_{TA}/A_{lens} \), where \( A_{PV} \) and \( A_{TA} \) are the area of the solar cell and thermal absorber respectively.

\[
E_{TE} = \int_{\lambda_{min}}^{\lambda_{max}} \eta_{opt} A_{TA} C_F F(\lambda) d\lambda
\]

\[
E_{PV} = \int_{\lambda_{min}}^{\lambda_{max}} \eta_{opt} A_{PV} C_F F(\lambda) d\lambda
\]

For the TE unit, most of solar energy \( E_{TE} \) is absorbed by thermal absorber and converted into thermal energy. The heat losses of the thermal absorber are caused by radiation and natural convection, and they are expressed as following formula,

\[
Q_{rad,TE} = \varepsilon T_e A_{TA} \sigma_{SB} (T_{TA}^4 - T_{AIR}^4)
\]

\[
Q_{conv,TE} = h_{nc} A_{TA} (T_{TA} - T_{AIR})
\]

where \( \varepsilon_{TA} \) is the emissivity of the thermal absorber, \( \sigma_{SB} \) is the Stefan-Boltzmann constant, \( T_{TA} \) and \( T_{AIR} \) are the temperature of the thermal absorber and ambient air respectively, and \( h_{nc} \) is natural convection heat transfer coefficient.

The heat sink remove heat can’t be used in TE unit and rejected by the cold junction of the Bi2Te3 TEG, can be expressed as,

\[
Q_{cool,TE} = h_{sink} A_{TA} (T_{sink} - T_{sink})
\]

where \( T_{c} \) is average temperature of cold-junction and \( T_{sink} \) is average temperature of heat sink, \( h_{sink} \) is the heat transfer coefficient of heat sink, \( A_{HS} \) is the effective surface area for heat transfer between the heat sink and the cold-junction of the Bi2Te3 TE generator.

The heat absorbed by the hot-junction of the CoSb3 TE generator can be expressed as,

\[
Q_{abs,TE} = \alpha_{TA} E_{TE} - Q_{rad,TA} - Q_{conv,TE}
\]

where \( \alpha_{TA} \) is the absorptivity of the thermal absorber surface.

Hence, the generated power of the TE unit is,

\[
P_{TE} = Q_{abs,TE}
\]

And the conversion efficiency of the TE unit is,

\[
\eta_{TE} = \frac{P_{TE}}{(A_{TA} \cdot E_{TE})}
\]

Analogously,

\[
Q_{rad,PV} = \varepsilon_{PV} A_{PV} \sigma_{SB} (T_{PV}^4 - T_{AIR}^4)
\]

\[
Q_{conv,PV} = h_{nc} A_{PV} (T_{PV} - T_{AIR})
\]

\[
Q_{cool,PV} = h_{cool} A_{HS} (T_{PV} - T_{sink})
\]

\[
P_{PV} = \alpha_{PV} E_{PV} - Q_{rad,PV} - Q_{conv,PV} - Q_{cool,PV}
\]

\[
\eta_{PV} = \frac{P_{PV}}{(A_{PV} \cdot E_{PV})}
\]

where \( \varepsilon_{PV} \) is the emmissivity of the solar cell surface, \( T_{PV} \) is the average temperature of the solar cell, and \( \alpha_{PV} \) is the absorptivity of the solar cell.

And the total conversion efficiency of this hybrid system is,

\[
\eta_{total} = \frac{(P_{TE} + P_{PV})}{(A_{c} \cdot E_{c})}
\]

Equations. (1-14) illustrate the energy conversion of this hybrid system, however, the temperature
distribution of the TE model needs to be figured out, it’s necessary to establish the thermal-electric models for the TE module.

Fig. 4. shows the Schematic diagrams of two stage TEG in electricity series configuration. The TE unit consists of a top stage with and m pairs of thermoelectric elements and a bottom stage with n pairs of thermoelectric elements, their heights are \( H_m \) and \( H_n \) respectively. The two stage TEG are in electricity series configuration, therefore, they have the same electrical current \( I \). The bottom temperature of top stage and the top temperature of bottom stage can be regarded as the same, that is \( T_m \). The temperature difference between hot-junction and middle tier \((T_h - T_m)\) is higher than the temperature difference between middle tier \((T_m - T_l)\), on account of different temperature thermoelectric materials can achieve optimal efficiency to corresponding temperature difference. We assume that cross-sectional areas of P-leg and N-leg in each TE stage are the same, they are \( A_h \) and \( A_l \). According to the thermodynamic theory, equilibrium equation can be expressed as,

\[
Q_{h,TE} = m[a_h IT_h - \frac{1}{2} I^2 R_h + K_h(T_h - T_m)]
\]

\[
Q_{m,TE} = n[a_l IT_m - \frac{1}{2} I^2 R_m + K_m(T_m - T_l)]
\]

\[
Q_{n,TE} = n[a_l IT_l - \frac{1}{2} I^2 R_l + K_l(T_l - T_m)]
\]

\[
Q_{cool,TE} = n[a_l IT_l - \frac{1}{2} I^2 R_l + K_l(T_l - T_m)]
\]

The electrical resistance of a pair of thermoelectric elements for top stage and bottom stage are \( R_h \) and \( R_l \) respectively, can be obtained as,

\[
R_h = \frac{\rho_{p,h} H_h}{A_h} + \frac{\rho_{n,h} H_h}{A_h}, \quad R_l = \frac{\rho_{p,l} H_l}{A_l} + \frac{\rho_{n,l} H_l}{A_l}
\]

The thermal conductivity a pair of thermoelectric elements for top stage and bottom stage are \( K_h \) and \( K_l \) respectively, can be obtained as,

\[
K_h = \frac{\kappa_{p,h} A_h}{H_h} + \frac{\kappa_{n,h} A_h}{H_h}, \quad K_l = \frac{\kappa_{p,l} A_l}{H_l} + \frac{\kappa_{n,l} A_l}{H_l}
\]

The Seebeck coefficient of a pair of thermoelectric elements for top stage and bottom stage are \( \alpha_h \) and \( \alpha_l \) respectively, can be obtained as,

\[
\alpha_h = \alpha_{p,h} + \alpha_{n,h}, \quad \alpha_l = \alpha_{p,l} + \alpha_{n,l}
\]

where \( \rho_{p,h} \) and \( \rho_{n,h} \) are the electrical resistivity of P-leg and N-leg for top TE stage respectively, \( \rho_{p,l} \) and \( \rho_{n,l} \) are the electrical resistivity of P-leg and N-leg for bottom TE stage respectively; \( \kappa_{p,h} \) and \( \kappa_{n,h} \) are the thermal conductivity of P-leg and N-leg for top TE stage respectively, \( \kappa_{p,l} \) and \( \kappa_{n,l} \) are the thermal conductivity of P-leg and N-leg for bottom TE stage respectively; \( \alpha_{p,h} \) and \( \alpha_{n,h} \) are the Seebeck coefficient of P-leg and N-leg for top TE stage respectively, \( \alpha_{p,l} \) and \( \alpha_{n,l} \) are the Seebeck coefficient of P-leg and N-leg for bottom TE stage respectively.

Eliminate \( T_m \), here we can get.

\[
Q_{h,TE} = m[a_h IT_h - \frac{1}{2} I^2 R_h + K_h(T_h - T_m)] + \frac{1}{2} \left[ \frac{mI^2 R_h + nI^2 R_l + mKT_h + nKT_l}{\alpha_h I - n\alpha_l I - mK_h - nK_l} \right] K_h
\]

\[
Q_{cool,TE} = n[a_l IT_l - \frac{1}{2} I^2 R_l + K_l(T_l - T_m)] - \frac{1}{2} \left[ \frac{mI^2 R_h + nI^2 R_l + mKT_h + nKT_l}{\alpha_h I - n\alpha_l I - mK_h - nK_l} \right] K_l
\]
4. Individual parameter analysis and results

Some parameters can affect performance of concentrating photovoltaic/cascaded thermoelectric generators hybrid system, which are optical concentration ratio $C_F$, direct normal irradiation DNI, height ratio of two TE stages $\tau$. In order to investigate the effects of these factors on the performance of this hybrid system, we let one parameter changed and rest keep the same value. The purpose of individual parameter investigation includes three aspects: (1) which parameter is the most sensitive for the performance of hybrid system, (2) how the parameter influence the performance of hybrid system, (3) whether the parameter has an optimal value.

4.1. Effects of the height ratio of two TE stages

In this paper, we give the total length ($L$) of two-stage TEG referring to specific conditions, $L = H_h + H_t = 0.0145 \text{ m}$, $\tau = H_h/L$.

Fig. 5(a) shows the efficiency of top TE stage is affected by height ratio of two TE stages $\tau$. When optical concentration ratio $C_F$ increases, the growth rate of top TE stage efficiency $\eta_{\text{top stage}}$ increases. Because of the height of top TE stage $H_h$ increase with the increase of the height ratio $\tau$, so the temperature difference of top TE stage $(T_h - T_m)$ increase. As a result, the output power and efficiency of the top TE stage come to rise. Under the conditions of optical concentration ratio, $C_F=1100$ and height ratio of two TE stages $\tau=0.98$, the maximal efficiency $\eta_{\text{top stage}}$ can reach to 5%.

Fig. 5(b) shows the efficiency of bottom TE stage is affected by height ratio of two TE stages $\tau$. On the contrary, the efficiency of bottom TE stage $\eta_{\text{bottom stage}}$ decreases as $\tau$ increase and decrease ratio becomes increasingly when $C_F$ comes to 700-1100. This result is because of that height of bottom TE stage $H_t$ decrease with the increase of the height ratio $\tau$, so the temperature difference of bottom TE stage $(T_m - T_l)$ decrease. So the output power and efficiency of the bottom TE stage descend. Under the conditions of optical concentration ratio $C_F=1100$ and height ratio of two TE stages $\tau=0.05$, the maximal efficiency $\eta_{\text{top stage}}$ can reach to 6.7%.

Fig. 5(c) shows that total efficiency of TE stages $\eta_{\text{TE stages}}$ is affected by height ratio of two TE stages $\tau$. The total efficiency of two TE stages decrease with the height ratio of two TE stages $\tau$ when $C_F=100-500$, the incoming solar energy is inadequate, which cause the hot-junction temperature and temperature difference keeps in a low condition. Decreased curves without optimal points reveal that the height of top TE stage should be occupied in a low proportion, because the bottom TE stage of low-temperature materials performances better than the top TE stage of middle-temperature materials relatively in low-temperature conditions. However, this total efficiency increase with $\tau$ when $C_F$ comes to 700-1100, reaching its maximum point within $\tau$ and then falling down. These curves
increase firstly is the result that the top TE stage of middle-temperature materials has a better performance as temperature increases. However, when $H_b$ has a large proportion, part of low-temperature difference can’t be used adequately, so the total efficiency of two TE stages falls down. These curves also prove that two cascaded TE stages efficiency has an optimal value in the wide temperature range, as compared to single TE stage ($\tau=1$ or $\tau=0$). And optimal height ratio is 0.4 and 0.6 when optical concentration ratio is 900 and 1100 respectively.

4.2. Effects of the ratio of the optical concentration
When wavelength splitter works at an optimized value of cutoff wavelength, the performance of the photovoltaic unit and the thermoelectric unit will significantly vary with the concentration ratio of the optical system. To investigate the effects of $C_F$ on temperatures, we let the value of $C_F$ vary from 100 to 1100 under a specific condition of other parameters (DNI=1000W/m2, $\tau=0.6$ for the optimal result), and we calculated the efficiency of the hybrid system according to the concentration ratio.

![Fig. 5. The efficiency of TE stages varies with a height ratio of TE stages(DNI=1000). (a) top TE stage efficiency; (b) bottom TE stage efficiency; (c) two TE stages efficiency](image)

Fig. 6. shows that how the temperature of TE stages increases as the ratio of optical concentration varies from 100 to 1100. The hot-junction temperature $T_h$ can reach 628 K and middle temperature $T_0$ can reach to 425 K when $C_F$ increases, as a result of the increase of heat flux. While the cold side temperature has a limited change and keeps at 300 K when $C_F$ increases proving that parallel heatsink perform satisfactorily in TE module. Obviously, the temperature difference between hot side and cold side increase significantly as $C_F$ increases. Fig. 7. shows that the temperature of the solar cell $T_{cell}$ can reach 327 K and increases linearly with optical concentration ratio $C_F$, as a result of the limited performance of heat sink when heat flux increase. Yet, the temperature 327 K of the solar cell is still less than its operating temperature 353 K.

Fig. 8. shows the efficiency-$C_F$ curves. The TE subsystem efficiency $\eta_{TE}$ increases linearly with
As a result of the increase of energy density, the PV subsystem efficiency $\eta_{PV}$ increases according to optical concentration ratio $C_r$, reaching its maximum point within optical concentration ration and then falling down. The reduction of the PV subsystem efficiency at high optical concentration ratio is because of the rising temperature of solar cell and the series resistance of solar cell, the maximum efficiency of hybrid system $\eta_{PV}$ is about 46%. So the hybrid system efficiency $\eta_{PV-TE}$ increases firstly according to optical concentration ratio $C_r$. However, when the reduction rate of PV subsystem efficiency is coincident to increase rate of TE subsystem efficiency, the total efficiency then becomes constant, so the optimal optical concentration ratio can be confirmed at 1000, and the $\eta_{PV-TE}$, $\eta_{PV}$, $\eta_{TE}$ are 35%, 44%, 8% respectively. Therefore, the optical concentration ratio has a positive effect on this hybrid system.

4.3. Effects of the direct normal irradiation on a hybrid system

To investigate the effects of DNI on temperatures, we let the value of DNI vary from 1 to 1000 (W/m$^2$) under a specific condition of other parameters($C_r$=1000, $\tau$=0.6 for optimal result), and we calculated temperature efficiency of the hybrid system according to the DNI. The temperature of solar cell and TE stages are both increase with direct normal irradiation due to the effects of optical concentration ratio. The solar temperature can reach to 325 $K$, and increase linearly with DNI showed in Fig. 10. Fig. 9, shows that how the temperature of TE stages increase as DNI varies from 1 to 1000 (W/m$^2$). The hot-junction temperature $T_h$ can reach to 600 $K$ and middle temperature $T_m$ can reach to 420 $K$, while the cold side temperature also has a limited change when DNI increases and keeps at 300 $K$. And the temperature difference between hot side and cold side increase significantly as DNI increases.
We also calculated efficiency of the hybrid system according to the DNI showed in Fig. 11. Obviously, the increasing DNI means more incoming solar energy, so the TE subsystem efficiency increases as the results of increasing temperature difference and output power. And the PV subsystem efficiency increases with DNI is due to the increase of illumination intensity. So, the hybrid system efficiency increases with DNI, that is why most solar power station are placed in favorable direct normal irradiation areas. When DNI=1000 W/m², the TE subsystem efficiency $\eta_{\text{TE}}$, the PV subsystem efficiency $\eta_{\text{PV}}$ and hybrid system $\eta_{\text{PV-TE}}$ are 8%, 46% and 35% respectively.

In addition, we obtained the influences of DNI to this hybrid system under experimental conditions, and the variation trend of temperatures are approximately consistent with simulated analysis. Fig. 12. shows that the hot-junction temperature $T_h$ can reach 525 K and middle temperature $T_m$ can reach to 425 K, and the cold-junction temperature is higher than 300 K. The hot-junction temperature is 12.5% lower, the middle temperature is 1.2% higher, and cold-junction is 6.7% higher than that of optimized simulation result respectively, as a result of limited performances of thermal insulator and heat sink. Fig. 13. shows the solar cell temperature can reach 335 K, which is 3.1% higher than optimized simulation result.
Fig. 14. The experimental output power of PV unit varies with DNI

Besides, the output power of the PV subsystem and TE subsystem are obtained from experimental research, but the direct normal irradiation just can reach to 880 W/m² because of the area conditions. The output power of PV subsystem increases with DNI and can reach to 22 W showed in Fig. 14. The TE subsystem output power also increases with DNI and can reach to 1.9 W showed in Fig. 15. Generated power of the hybrid system working under cutoff wavelength $\lambda_c=900$ nm is highly depended on the PV subsystem, because this subsystem converts the larger portion of solar energy and has a higher conversion efficiency.

5. Conclusions
Photovoltaic/cascaded thermoelectric generators hybrid system is presented in this paper, and a numerical model is established for parameters evaluation. The model is used to analyze the thermal and electrical performance of the hybrid system with solar cell and two individual TE stages which are CoSb₃ middle-temperature materials and Bi₂Te₃ low-temperature materials. This hybrid system shows several privileges proved by experimental research. From this work, we can conclude that:

(1) Due to the different materials of two TE generators, the height of top stage and height of bottom stage has an optimized ratio for different height ratio of TE stages, especially in the wide temperature range.

(2) The hybrid system could reach the highest efficiency as the ratio of optical concentration varies, and the optimized concentration ratio corresponds to a maximal output power of the whole system.

(3) The DNI can affect the solar cell efficiency because of increasing temperature, yet the total increase with DNI, which proves that this hybrid system has its advantage.

(4) Due to the different materials of two TE generators, the height of top stage and height of bottom stage has an optimized ratio for different height ratio of TE stages, especially in the wide temperature range.

(5) When direct normal irradiation DNI=1000 W/m², optical concentration ratio $C_P=1000$, optimized height ratio of two TE stages $\tau=0.6$. The TE subsystem efficiency $\eta_{TE}$ can reach to 8%; the PV subsystem efficiency $\eta_{PV}$ can reach to 44%, and total hybrid system efficiency $\eta_{PV-TE}$ can reach to 35%.

(6) Under the experimental condition that DNI=880 W/m², the output power of PV subsystem and TE subsystem are 22 W and 1.9 W respectively.

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