

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

Ding Liang¹, Qi Luo^{2*}, Peng Li^{1*}, Yayu Fu¹, Lanlan Cai¹, Pengchen Zhai²

¹Wuhan University of Technology, School of Mechanical and Electronic Engineering, Wuhan 430070, China

²Wuhan University of Technology, School of Science, Wuhan 430070, China

*Corresponding Author: lp1968@whut.edu.cn; luoqi871062@gmail.com

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 η_{TE} can reach to 8%, the PV subsystem efficiency η_{PV} can reach to 44%, and total hybrid system efficiency η_{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

A	area (m ²)	V_{OC}	open circuit voltage of the solar cell (V)
C_F	geometrical concentration ratio	<i>Greek letters</i>	
E_{in}	incident solar radiation (W/m ²)	ε	emissivity
E_{PV}	solar energy directed to PV unit (W)	α	Seebeck coefficient of TE materials (V/
E_{TEG}	solar energy directed to TE unit (W)		

FF	solar cell fill factor (%)	K	
n	quantity of finite elements of TE module	α_{PV}	absorptivity of the solar cell
		α_{TA}	absorptivity of a thermal absorber
$F(\lambda)$	AM1.5D spectral irradiance ($W/m^2 K$)	η	efficiency (%)
h_{sink}	heat transfer coefficient of heat sink ($W/m^2 K$)	κ	Thermal conductivity of TE material ($W/m \cdot K$)
h_{nc}	natural convection heat transfer coefficient ($W/m^2 K$)	λ	wavelength of photons (nm)
I_{SC}	short circuit current of the solar cell (A)	λ_k	cutoff wavelength (nm)
I	the current of TE module (A)	σ	electrical conductivity of TE material (S / m)
K	thermal conductivity ($W/m \cdot K$)	σ_{SB}	Stefan-Boltzmann constant ($W / m^2 K^4$)
L	length of TE model legs (m)	<i>Subscripts</i>	
P	generated power (W)	AIR	ambient air
Q_{conv}	convective heat loss (W)		
Q_{cool}	heat removed by the heat sink (W)	HS	heat sink
Q_{rad}	radiative heat loss (W)	TA	thermal absorber
R	electricity resistance (Ω)	PV	photovoltaic solar cell
T	temperature (K)	TE	thermoelectric generator

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. Bjørk^[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^[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^[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^[14, 15]. Besides, almost most previous works about two-stage TE generators hadn't combined with PV system^[12, 16, 17], or they just used one TE generator^[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.

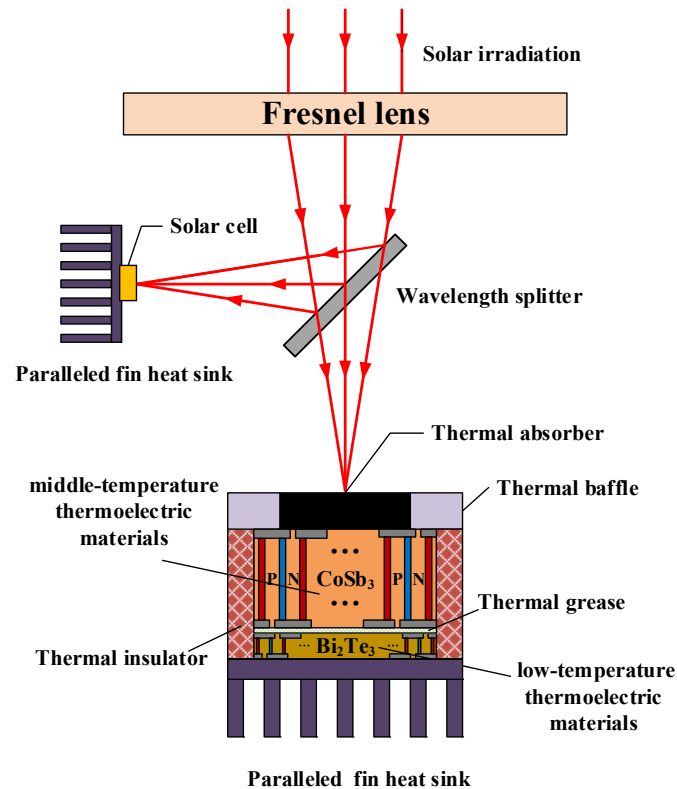


Fig. 1. The schematic photograph of concentrating photovoltaic/cascaded thermoelectric generators hybrid system

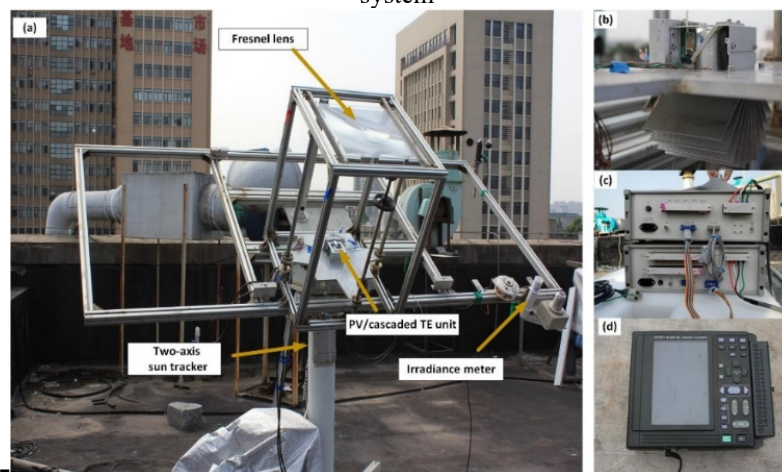


Fig. 2. The photographs of the experimental setup (a), PV/cascaded TE unit (b) and test equipment(c-d).

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 CoSb_3 TE generator and hot side of Bi_2Te_3 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 λ_k is the cutoff wavelength decided by wavelength splitter; E_{TE} is the solar energy separated to the TE unit (from λ_k to 4000 nm), E_{PV} is the another part of solar energy separated to the PV unit (from 280nm to λ_k); η_{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.

$$E_{TE} = \int_{\lambda_k}^{4000nm} \eta_{opt} A_{TA} C_F F(\lambda) d\lambda \quad (1)$$

$$E_{PV} = \int_{280nm}^{\lambda_k} \eta_{opt} A_{PV} C_F F(\lambda) d\lambda \quad (2)$$

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,

$$Q_{rad,TE} = \varepsilon_{TA} A_{TA} \sigma_{SB} (T_{TA}^4 - T_{AIR}^4) \quad (3)$$

$$Q_{conv,TE} = h_{nc} A_{TA} (T_{TA} - T_{AIR}) \quad (4)$$

where ε_{TA} is the emissivity of the thermal absorber, σ_{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,

$$Q_{cool,TE} = h_{sink} A_{HS} (T_c - T_{sink}) \quad (5)$$

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,

$$Q_{h,TE} = \alpha_{TA} E_{TE} - Q_{rad,TA} - Q_{conv,TE} \quad (6)$$

where α_{TA} is the absorptivity of the thermal absorber surface,

Hence, the generated power of the TE unit is,

$$P_{TE} = Q_{h,TE} - Q_{cool,TE} \quad (7)$$

And the conversion efficiency of the TE unit is,

$$\eta_{TE} = P_{TE} / (A_{TA} \cdot E_{TE}) \quad (8)$$

Analogously,

$$Q_{rad,PV} = \varepsilon_{PV} A_{PV} \sigma_{SB} (T_{PV}^4 - T_{AIR}^4) \quad (9)$$

$$Q_{cool,PV} = h_{hc} A_{PV} (T_{PV} - T_{AIR}) \quad (10)$$

$$Q_{cool,PV} = h_{cool} A_{HS} (T_{PV} - T_{sink}) \quad (11)$$

$$P_{PV} = \alpha_{PV} E_{PV} - Q_{rad,PV} - Q_{conv,PV} - Q_{cool,PV} \quad (12)$$

$$\eta_{PV} = P_{PV} / (A_{PV} \cdot E_{PV}) \quad (13)$$

where ε_{PV} is the emissivity of the solar cell surface, T_{PV} is the average temperature of the solar cell, and α_{PV} is the absorptivity of the solar cell.

And the total conversion efficiency of this hybrid system is,

$$\eta_{total} = (P_{TE} + P_{PV}) / (A_F \cdot E_{in}) \quad (14)$$

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 m pairs of thermoelectric elements and a bottom stage with n pairs of thermoelectric elements, their heights are H_h and H_l 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,

$$Q_{h,TE} = m[\alpha_h IT_h - \frac{1}{2} I^2 R_h + K_h (T_h - T_m)] \quad (15)$$

$$Q_{m,TE} = m[\alpha_h IT_m + \frac{1}{2} I^2 R_h + K_h (T_h - T_m)] \quad (16)$$

$$Q_{m,TE} = n[\alpha_l IT_m - \frac{1}{2} I^2 R_l + K_l (T_m - T_l)] \quad (17)$$

$$Q_{cool,TE} = n[\alpha_l IT_l + \frac{1}{2} I^2 R_l + K_l (T_m - T_l)] \quad (18)$$

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,

$$R_h = \frac{\rho_{P,h} H_h}{A_h} + \frac{\rho_{N,h} H_h}{A_h}, \quad R_l = \frac{\rho_{P,l} H_l}{A_l} + \frac{\rho_{N,l} H_l}{A_l} \quad (19)$$

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,

$$K_h = \frac{\kappa_{P,h} A_h}{H_h} + \frac{\kappa_{N,h} A_h}{H_h}, \quad K_l = \frac{\kappa_{P,l} A_l}{H_l} + \frac{\kappa_{N,l} A_l}{H_l} \quad (20)$$

The Seebeck coefficient of a pair of thermoelectric elements for top stage and bottom stage are α_h and α_l respectively, can be obtained as,

$$\alpha_h = \alpha_{P,h} + \alpha_{N,h}, \quad \alpha_l = \alpha_{P,l} + \alpha_{N,l} \quad (21)$$

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.

$$Q_{h,TE} = m\left\{\alpha_h IT_h - \frac{1}{2} I^2 R_h + K_h T_h + \frac{[\frac{1}{2} m I^2 R_h + \frac{1}{2} n I^2 R_l + m K T_h + n K T_l] K_h}{m \alpha_h I - n \alpha_l I - m K_h - n K_l}\right\} \quad (22)$$

$$Q_{cool,TE} = n\left\{\alpha_l IT_l + \frac{1}{2} I^2 R_l - K_l T_l - \frac{[\frac{1}{2} m I^2 R_h + \frac{1}{2} n I^2 R_l + m K T_h + n K T_l] K_l}{m \alpha_h I - n \alpha_l I - m K_h - n K_l}\right\} \quad (23)$$

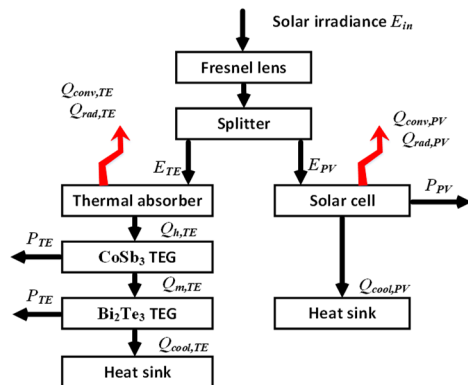


Fig. 3. Energy flow chart of the photovoltaic/cascaded thermoelectric generators hybrid system

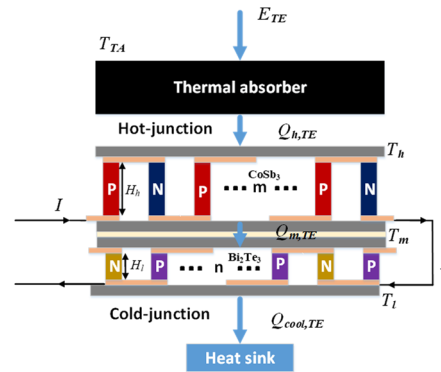


Fig. 4. Schematic diagrams of two-stage TEG in electricity series configuration

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 τ . 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, $L = H_h + H_l = 0.0145$ m, $\tau = H_h/L$.

Fig. 5(a) shows the efficiency of top TE stage is affected by height ratio of two TE stages τ . When optical concentration ratio C_F increases, the growth rate of top TE stage efficiency $\eta_{top\ stage}$ increases. Because of the height of top TE stage H_h increase with the increase of the height ratio τ , 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 $\eta_{top\ stage}$ can reach to 5%.

Fig. 5(b) shows the efficiency of bottom TE stage is affected by height ratio of two TE stages τ . On the contrary, the efficiency of bottom TE stage $\eta_{bottom\ stage}$ decreases as τ 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_l decrease with the increase of the height ratio τ , 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 $\eta_{top\ stage}$ can reach to 6.7%.

Fig. 5(c) shows that total efficiency of TE stages $\eta_{TE\ stages}$ is affected by height ratio of two TE stages τ . The total efficiency of two TE stages decrease with the height ratio of two TE stages τ 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 τ when C_F comes to 700-1100, reaching its maximum point within τ 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_h 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 ($\text{DNI}=1000\text{W/m}^2$, $\tau=0.6$ for the optimal result), and we calculated the efficiency of the hybrid system according to the concentration ratio.

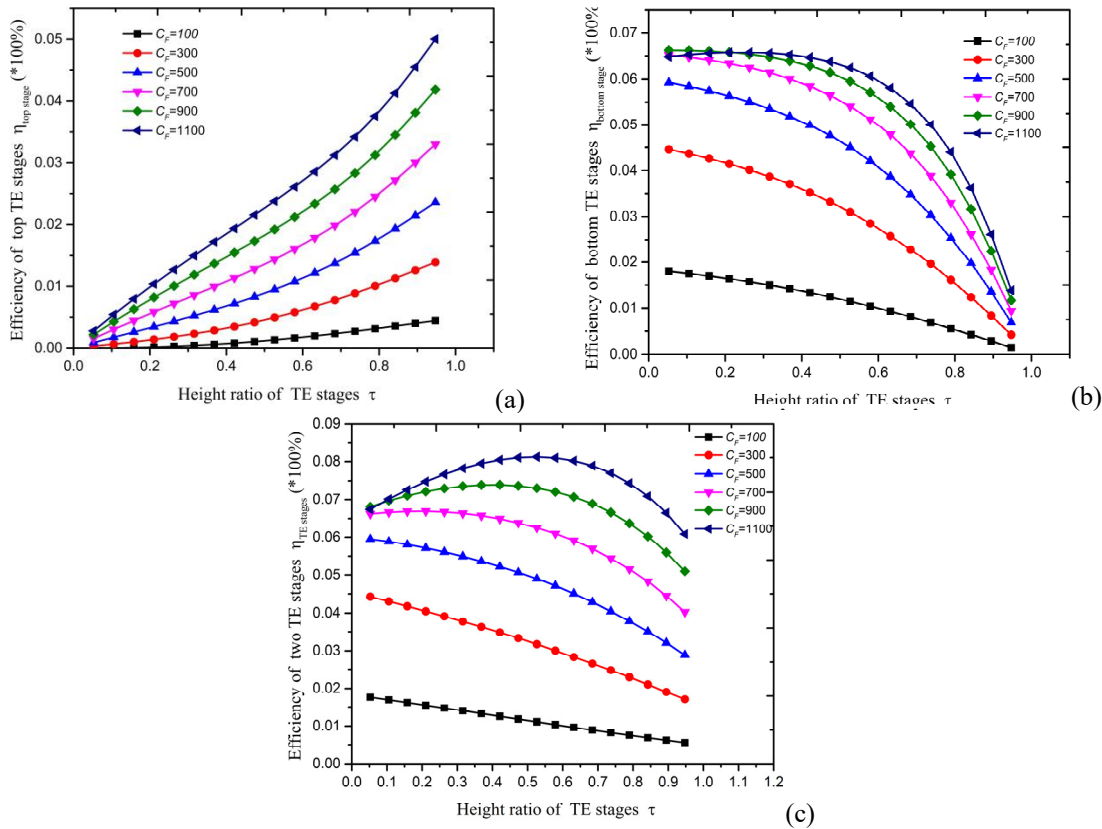


Fig. 5. The efficiency of TE stages varies with a height ratio of TE stages ($\text{DNI}=1000$). (a) top TE stage efficiency; (b) bottom TE stage efficiency; (c) two TE stages efficiency

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_m 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 η_{TE} increases linearly with

C_F , as a result of the increase of energy density. And the PV subsystem efficiency η_{PV} increases according to optical concentration ratio C_F , reaching its maximum point within optical concentration ratio 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 η_{PV} is about 46%. So the hybrid system efficiency η_{PV-TE} increases firstly according to optical concentration ratio C_F . 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 η_{PV-TE} , η_{PV} , η_{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 ($C_F=1000$, $\tau=0.6$ 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.

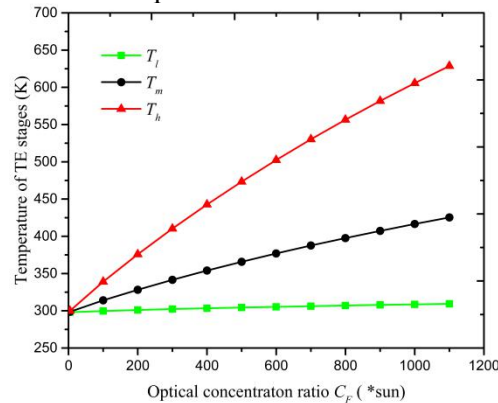


Fig. 6. Effect of optical concentration ratio on temperature on TE stages (DNI=1000W/m², $\tau=0.6$)

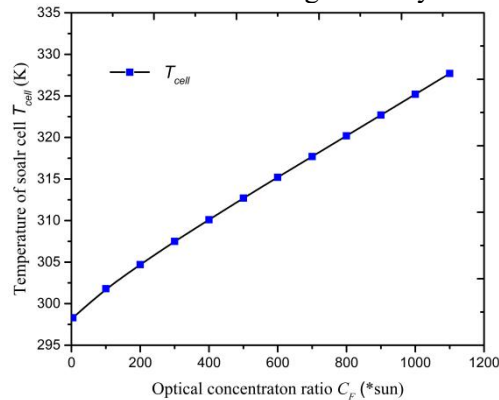


Fig. 7. Effect of optical concentration ratio on temperature on solar cell (DNI=1000W/m², $\tau=0.6$)

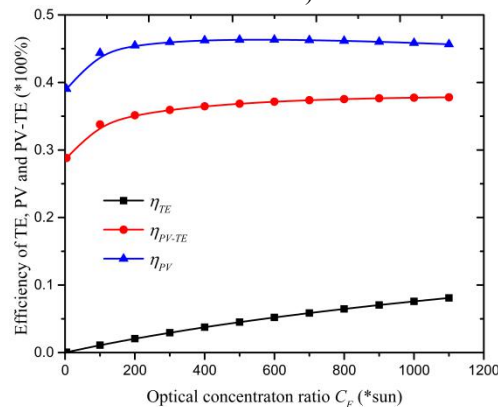


Fig. 8. Effect of optical concentration ratio on efficiency (DNI=1000W/m², $\tau=0.6$)

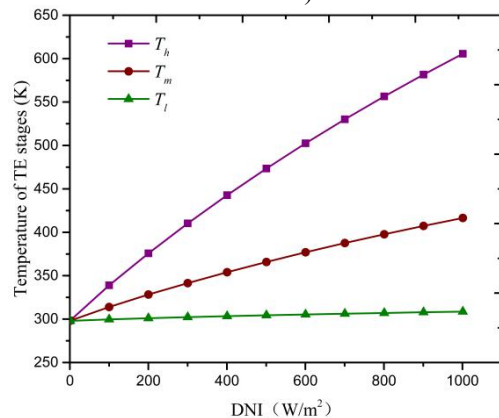


Fig. 9. The temperature of TE stages varies with DNI ($C_F=1000$, $\tau=0.6$)

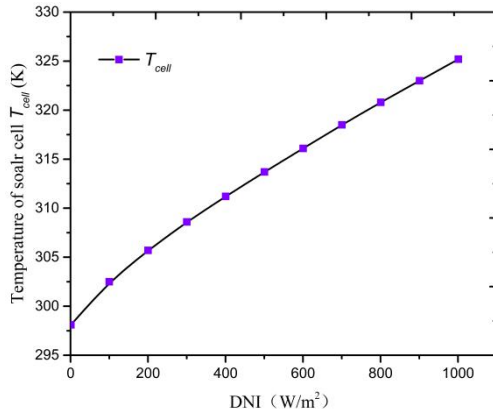


Fig. 10. The temperature of the solar cell varies with DNI ($C_F=1000$, $\tau=0.6$)

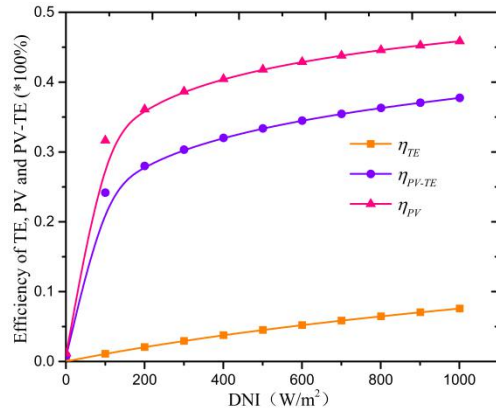


Fig. 11. Efficiency of TE, PV, and PV-TE vary with DNI ($C_F=1000$, $\tau=0.6$)

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 $DNI=1000 \text{ W/m}^2$, the TE subsystem efficiency η_{TE} , the PV subsystem efficiency η_{PV} and hybrid system η_{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.

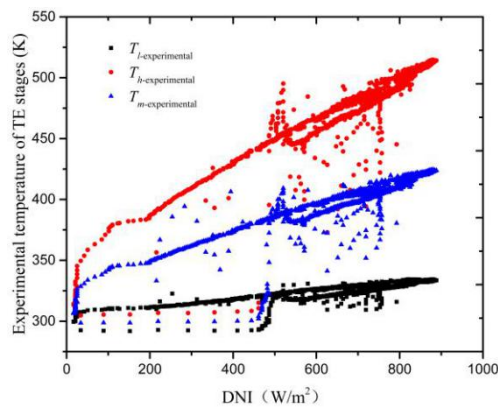


Fig. 12. The experimental temperature of TE stages varies with DNI

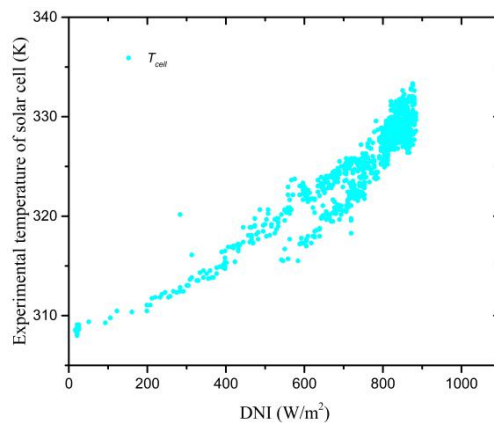


Fig. 13. The experimental temperature of solar cell varies with DNI

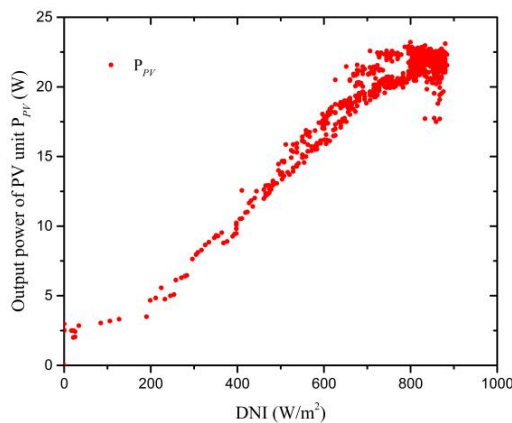


Fig. 14. The experimental output power of PV unit varies with DNI

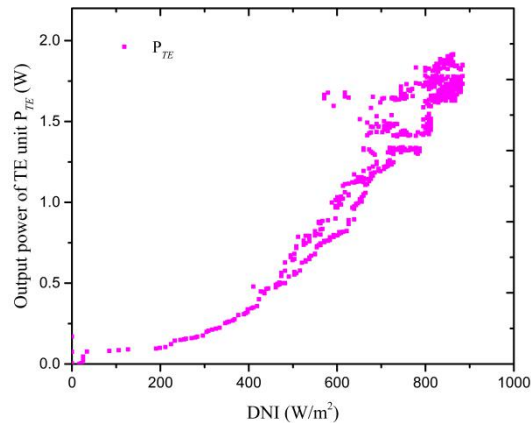


Fig. 15. The experimental output power of TE unit varies with DNI

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/m^2 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 $\lambda_k=900 \text{ nm}$ 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 CoSb_3 middle-temperature materials and Bi_2Te_3 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 $\text{DNI}=1000 \text{ W/m}^2$, optical concentration ratio $C_F=1000$, optimized height ratio of two TE stages $\tau=0.6$. The TE subsystem efficiency η_{TE} can reach to 8%; the PV subsystem efficiency η_{PV} can reach to 44%, and total hybrid system efficiency η_{PV-TE} can reach to 35%.
- (6) Under the experimental condition that $\text{DNI}=880 \text{ W/m}^2$, the output power of PV subsystem and TE subsystem are 22 W and 1.9 W respectively.

Acknowledgments

This work was financially supported by National Natural Science Foundation of China (No. 51272198, No. 51402224 and No. 51772231), the International S&T Cooperation Program of China (2014DFA63070), and Supported by the Excellent Dissertation Cultivation Funds of Wuhan

University of Technology (2016-YS-035).

References

- [1] Sha W E I, Choy W C H, Wu Y, et al. Optical and electrical study of organic solar cells with a 2D grating anode[J]. *Optics Express*, 2012,20(3):2572-2580.
- [2] Mojiri A, Taylor R, Thomsen E, et al. Spectral beam splitting for efficient conversion of solar energy—A review[J]. *Renewable and Sustainable Energy Reviews*, 2013,28:654-663.
- [3] Sakurai T, Uehigashi H, Islam M M, et al. Temperature dependence of photocapacitance spectrum of CIGS thin-film solar cell[J]. *Thin Solid Films*, 2009,517(7):2403-2406.
- [4] He W, Zhang G, Zhang X, et al. Recent development and application of thermoelectric generator and cooler[J]. *Applied Energy*, 2015,143:1-25.
- [5] He W, Zhang G, Zhang X, et al. Recent development and application of thermoelectric generator and cooler[J]. *Applied Energy*, 2015,143:1-25.
- [6] Zhao D, Tan G. A review of thermoelectric cooling: Materials, modeling and applications[J]. *Applied Thermal Engineering*, 2014,66(1-2):15-24.
- [7] SudhanshuSharma, Dwivedi V K, Pandit S N. A Review of Thermoelectric Devices for Cooling Applications[J]. *International Journal of Green Energy*, 2014,11(9):899-909.
- [8] R. Bjørk, and K. K. Nielsen, The Performance of a Combined Solar Photovoltaic (PV) and Thermoelectric Generator (TEG) System [J]. *Solar Energy*, 2015,120:187-94.
- [9] Cui T, Xuan Y, Yin E, et al. Experimental investigation on potential of a concentrated photovoltaic-thermoelectric system with phase change materials[J]. *Energy*, 2017,122:94-102.
- [10] Mizoshiri M, Mikami M, Ozaki K. Thermal-Photovoltaic Hybrid Solar Generator Using Thin-Film Thermoelectric Modules[J]. *Japanese Journal of Applied Physics*, 2012,51(6):6F-7F.
- [11] Ju X, Wang Z, Flamant G, et al. Numerical analysis and optimization of a spectrum splitting concentration photovoltaic-thermoelectric hybrid system[J]. *Solar Energy*, 2012,86(6):1941-1954.
- [12] Arora R, Kaushik S C, Arora R. Thermodynamic modeling and multi-objective optimization of two stage thermoelectric generator in electrically series and parallel configuration[J]. *Applied Thermal Engineering*, 2016,103:1312-1323.
- [13] Meng F, Chen L, Sun F. Performance optimization for two-stage thermoelectric refrigerator system driven by two-stage thermoelectric generator[J]. *Cryogenics*, 2009,49(2):57-65.
- [14] Snyder G J, Toberer E S. Complex thermoelectric materials[J]. *Nature Materials*, 2008,7:105.
- [15] Sootsman J, Chung D, Kanatzidis M. New and Old Concepts in Thermoelectric Materials[J]. *Angewandte Chemie International Edition*, 2009,48(46):8616-8639.
- [16] McEnaney K, Kraemer D, Ren Z, et al. Modeling of concentrating solar thermoelectric generators[J]. *Journal of Applied Physics*, 2011. 110(7): p. 074502.
- [17] Snyder G J. Application of the compatibility factor to the design of segmented and cascaded thermoelectric generators[J]. *Applied Physics Letters*, 2004. 84(13): p. 2436-2438.
- [18] Lin W, Shih T, Zheng J, et al. Coupling of temperatures and power outputs in hybrid photovoltaic and thermoelectric modules[J]. *International Journal of Heat and Mass Transfer*, 2014,74:121-127.
- [19] Wu Y, Wu S, Xiao L. Performance analysis of photovoltaic-thermoelectric hybrid system with and without glass cover[J]. *Energy Conversion and Management*, 2015,93:151-159.
- [20] Lin J, Liao T, Lin B. Performance analysis and load matching of a photovoltaic-thermoelectric hybrid system[J]. *Energy Conversion and Management*, 2015,105:891-899.
- [21] Kossyvakis D N, Voutsinas G D, Hristoforou E V. Experimental analysis and performance evaluation of a tandem photovoltaic-thermoelectric hybrid system[J]. *Energy Conversion and Management*, 2016,117:490-500.