Preliminary experiment on a novel photovoltaic-thermoelectric system in summer

Guiqiang Li[a, *]

Guiqiang.Li@hull.ac.uk

Samson Shittu[a]

Kai zhou[b]

Xudong Zhao[a, **]

xudong.zhao@hull.ac.uk

Xiaoli Ma[a]

[a]School of Engineering, University of Hull, Hull, HU6 7RX, UK

[b]Department of Mechanical Science and Technology, University of Illinois at Urbana Champaign, 1206 W Green Street Urbana, 61801, Illinois, USA

*Corresponding author.

**Corresponding author.

Abstract

Compared with the PV electricity generation, the hybrid Photovoltaic-thermoelectric (PV-TE) can generate more electricity due to its ability to utilize a wider solar spectrum than the PV. The PV-TE employing micro-channel heat pipe array is a novel PV-TE-MCHP system which is capable of providing high cost performance compared to the traditional PV-TE due to the use of the micro-channel heat pipe array. In this paper, the experimental investigation of this new system in summer in Hefei city, China is presented for the first time. The comparison between this system and PV alone is made, and the details are presented. The power output, PV temperature, and the hot and cold sides temperatures of the TE are all tested. The results show that the novel system has a higher electrical output than the PV alone. The electrical efficiencies of this system during the test are all higher than 14.0% and the PV temperatures are about 20 °C higher than the ambient temperature. Based on this experiment, the results also verify the feasibility of the new system, which will give a valuable reference for the PV-TE design.

Keywords: Photovoltaic-thermoelectric; Micro-channel heat pipe; Experimental investigation; Power output

1 Introduction

Rapid economic and industrial development within the past decades has led to an increased consumption of non-renewable and polluting fossil fuels. Therefore, it is of utmost importance to explore renewable energy sources to meet the increased demand for energy [1,2]. In addition, issues such as: scarcity of conventional energy sources, hike in fuel prices and environmental pollution has made the generation of power from conventional energy sources to be unsustainable and unviable [3]. The sun is one of the most potent energy sources as its contribution to the world's energy demand is substantial and its availability greatly exceeds any conceivable future energy demands [4]. Solar energy is therefore one of the most widely abundant and used renewable energy source. The most common method to utilize solar energy is to convert it into two easily harnessed forms which are; electrical and thermal energy [5]. Solar photovoltaic (PV) systems can be used to convert solar radiations directly into electricity via the Photovoltaic effect. It is considered as one of the most viable solution to meet the electrical energy demand and demand for clean energy as it can achieve noiseless operation, needs low maintenance and has zero pollution [6]. However, the major issues hindering the widespread application of the PV are: limited conversion efficiency, elevated temperature and dust accumulation [7].

A thermoelectric generator (TEG) is a device which can convert waste heat directly into electrical energy via the Seebeck effect and it has attracted substantial interest recently because of its advantages such as: silent operation and compactness [8]. A hybrid device can be obtained by integrating a thermoelectric generator into a photovoltaic module to compensate for the disadvantages of the photovoltaic (elevated temperature) by using the thermoelectric generator for waste heat recovery. In fact, it has been reported that the integration of thermoelectric generators into solar panels can provide an additional energy of 2–10% depending on the thermoelectric material, connection and configuration [9]. Combining Photovoltaic (PV) and thermoelectric (TE) will be a good choice for solar applications because the resulting hybrid system can utilize a wider solar spectrum to produce electricity [10]. This is because, the photovoltaic mainly converts the ultra-violet (UV) and visible regions of the solar spectrum while the thermoelectric utilizes the infrared (IR) region of the solar spectrum [11].

Several scholars have proved the feasibility of the hybrid Photovoltaic-thermoelectric (PV-TE) system. Van Sark [12] performed a feasibility study of a PV-TE system using an idealized model. The author developed a simple model to determine the efficiency of a combined photovoltaic and thermoelectric, and the results showed that adding a TE converter to the back side of a PV module can lead to an efficiency increase of 8–23%, depending on the type of module integration [4]. Similarly, Rezania et al. [13] performed a feasibility and parametric study of hybrid concentrated PV-TE system over a wide range of solar concentrations and different types of heat sinks. They found that the concentrated PV-TE system is more efficient than the concentrated PV only system when a thermoelectric material with figure of merit $(ZT \approx 1)$ is used. Furthermore, Attivissimo et al. [14] presented another feasibility study of hybrid PV-TE systems and the main conclusion from their study is that the PV-TE system performs better when operated in locations with high radiance and low ambient temperature.

In order to achieve a higher electrical output from the PV-TE, many simulation and optimization efforts have been made in the recent years. Babu et al. [15] performed a theoretical analysis of a hybrid PV-TE system using MATLAB/Simulink. They found that the hybrid system provided an increased overall efficiency of 6% under standard conditions. Similarly, Lamba et al. [16] analysed the performance of a concentrated hybrid PV-TE system using MATLAB and found that the maximum power output and efficiency of the hybrid system increased by 5% compared to the conventional PV only system. Lin et al. [17] investigated the performance of a hybrid PV-TE system using a thermodynamic method. In addition, the optimal problems relating to load matching in the hybrid system design were discussed and the results obtained showed that the hybrid PV-TE system provided an increased efficiency and electrical power compared to the conventional PV system. Hajji et al. [18] theoretically investigated the energetic efficiency of an indirectly coupled PV-TE system in which the concentrator was placed between the PV and the TE without any physical contact between the three components. The authors argued that the indirect coupling significantly improved the overall efficiency. Yang et al. [19] investigated the performance of a spectrum splitting concentrated PV-TE system and an analytical expression for the system efficiency was derived. They argued that spectrum splitting PV-TE system can efficiently harvest the full solar spectrum compared to the single PV cell especially when low solar concentration factors are used. Similarly, Yin et al. [20] presented a novel optimal design method for concentrating spectrum splitting hybrid PV-TE system and found that when the cut-off wavelength increases, the thermoelectric efficiency can be increased through optimization.

Finite element method (FEM) has also been employed to numerically study the performance of hybrid PV-TE systems. Shittu et al. [21,22] performed a detailed comparison and optimization of thermoelectric element geometry in a hybrid PV-TE system using FEM and found that the optimum geometry for a TE in a hybrid PV-TE system is dependent on the PV cell characteristics used thus, it could be different from the optimum geometry in a TE only system. Li et al. [23] argued that the geometry optimization of thermoelectric elements in a hybrid PV-TE is essential to achieve optimum performance from the hybrid system. Furthermore, Kohan et al. [24] used a three-dimensional numerical model to study the performance of a hybrid PV-TE system and found that the hybrid system can generate more electrical power compared to the conventional PV only system under certain environmental conditions. Makki et al. [25] performed a numerical investigation of a heat pipe based hybrid PV-TE system and found that the hybrid system provided an increased performance compared to the conventional PV system even at high ambient temperature and low wind speed conditions. Similarly, Li et al. [26] presented the conceptual development of a novel PV-TE which employed a micro-channel heat pipe array and the results obtained via the numerical study showed that the novel system offered a good economic advantage compared to the conventional PV only system.

Currently, in addition to the simulations, there are many experimental researches that have verified the feasibility and advantages of the PV-TE system. Daud et al. [27] experimentally studied the performance of a hybrid PV-TE system and performed a cost analysis. The authors found that the hybrid PV-TE provided an enhanced efficiency compared to the conventional PV only system. Beeri et al. [28] presented an experimental study of a concentrated PV-TE using multi-junction PV cell and a thermoelectric generator. The results obtained showed that the hybrid PV-TE system has a potential to achieve an overall efficiency that is greater than 50% when advanced PV cells are used. Kossyvakis et al. [29] experimentally studied the performance of a hybrid PV-TE system using polycrystalline silicon and dye-sensitized solar cells. They found that the use of thermoelectric generators with shorter thermoelectric legs results in improved output power. Cotfas et al. [30] investigated the performance of a hybrid PV-TE system experimentally and an economic analysis was also presented. The authors argued that the hybrid system can become attractive when the price of the thermoelectric device decreases substantially and its efficiency increases. Kil et al. [31] presented a concentrating hybrid PV-TE system using a single-junction, GaAs-based solar cell and observed an efficiency increase of ~3% compared to the conventional concentrated PV only system at solar concentration of 50 suns. Furthermore, Cui et al. [32] investigated a novel PV-PCM-TE system in which the phase change material (PCM) was used to ensure the system operated at an ideal working temperature for a long time. An experimental study was performed by the authors and they found that compared to the PV only system, the novel hybrid system had a higher conversion efficiency. Soltani et al. [33] performed an experimental investigation of hybrid PV-TE system using a new nanofluid-based cooling method. They found that SiO_2/water nanofluid cooling provided the highest power and efficiency improvement of 54.29% and 3.35% respectively. Sweet et al. [34] experimentally studied a hybrid II-V concentrator PV-TE receiver under primary and secondary optimal elements. The authors found that the high combined primary and secondary optical intensity gain coefficient was 0.92. Recently, Zhang et al. [35] performed an experimental study of a hybrid PV-TE system in which the ceramic plates of the commercial thermoelectric modules were eliminated to enhance heat transfer and reduce thermal resistance. The authors observed an increase in PV-TE efficiency caused by the V-type groove which was used.

For the PV-TE, the significance of the experiment is particularly important. The simulation is often operated in an ideal state, and the experimental results can truly reflect the possibility that the PV-TE performance is better than the PV performance, and can provide accurate model parameters for the further system optimization. However, as shown from the detailed literature review above, the current overwhelming experiment of PV-TE is based on the existing pair-arrangement between the PV and TE modules. But for the new PV-TE employing micro-channel heat pipe array system (PV-TE-MCHP), its performance has not be verified by experiment. Therefore, the aim of this paper is to preliminarily experimentally study the performance of the novel PV-TE-MCHP.

In this work, the experimental platform of PV-TE-MCHP is set up for the first time. The comparison between the PV-TE with MCHP and PV alone is conducted in the summer in Hefei city, China. The details of the electrical output, PV temperature, and the TE hot side and cold side temperatures during the test 1 - test 10 are also illustrated. The experimental results show that the PV-TE-MCHP can obtain higher power output than PV alone, which verifies the feasibility of this system.

2 An experimental set-up

The schematic diagram of the PV-TE-MCHP is shown in Fig. 1. It can be seen that the PV modules are attached to the upper surface of the MCHP while the thermoelectric modules are attached to the lower surface of the condenser. Solar energy is impinged on the PV surface during operation and the waste heat (thermal energy) from the PV is conveyed to the MCHP's condenser via evaporation of the working fluid within the MCHP. Furthermore, heat is released via condensation of the MCHP's working fluid in the condenser and this heat is transferred to the attached thermoelectric modules. This operation creates a temperature difference across the thermoelectric module which results in conversion of thermal energy to electrical energy via the ‘Seebeck effect’. In addition, the thermoelectric generator is cooled via air cooling and the cooling structure, ambient temperature and wind speed affects the cooling effectiveness.

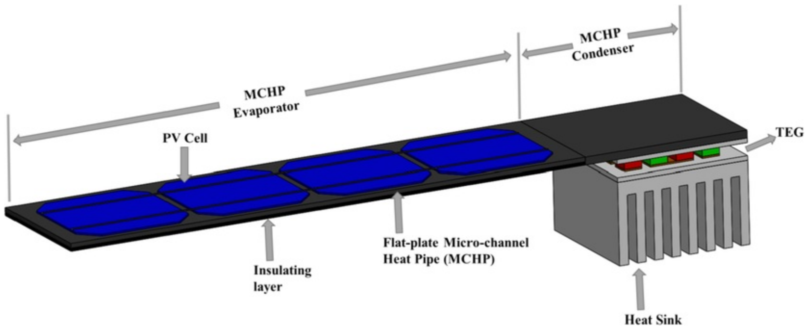

Fig. 1 Schematic diagram of PV-TE-MCHP.

alt-text: Fig. 1

The experimental setup of the PV-TE-MCHP is shown in Fig. 2. A crystalline silicon (c-Si) is used in this system and it is attached to the top surface of the MCHP. The efficiency of the PV cell in the standard test condition is about 16%. The solar cells are embedded into the ethylene-vinyl acetate (EVA) layers while the glass layer is the topmost layer which prevents dust accumulation and a transparent tedlar-polyester-tedlar (TPT) layer is the lowest layer. The TPT is used due to its very good electrical insulation while the EVA is an adhesive material. In addition, the thermoelectric modules with dimensions of 40*40 mm are placed on the MCHP's condenser surface and the material of the thermoelectric module is Bi_2Te_3 which is the common commercial thermoelectric module [36]. The size of the MCHP is 60*650 mm. The top surface of the MCHP not covered by the PV is the thermal absorber layer while the bottom surface of the MCHP is covered with insulating materials. The micro-channel heat pipe (MCHP) is a flat aluminum plate heat pipe which has multiple parallel micro-channel heat pipes. Furthermore, the thickness of the MCHP is 3 mm and each MCHP has several inner microgrooves also known as micro-fins which enhance the transfer of heat by repeated evaporation and condensation of the inner working fluid. The detailed components of the PV-TE-MCHP are shown in Table 1.

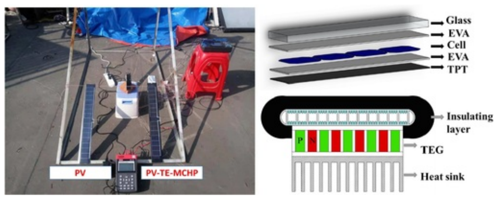

Fig. 2 Experimental rig of PV-TE-MCHP.

alt-text: Fig. 2

Table 1 Components of the PV-TE-MCHP system.

alt-text: Table 1

Components		Size
PV	Crystalline silicon	$6.0*6.5*10^{-3}m^2$
	Coverage ratio	0.85
MCHP	Length of the heat pipe	$6.5*10^{-1}m$
	Width of the heat pipe	$6*10^{-2}$ m
TEG	Bi_2Te_3	$4.0*4.0*10^{-4}m^2$
	Numbers of P or N junction nteg	241
	Length of leg	$3.4*10^{-3}m$
Heat sink	Height of the heat sink H	$1*10^{-2}m$
	Length of the heat sink L	$5*10^{-2}m$
	Cross section area of the heat sink	$1.2*10^{-4}$ m^2
	Total area of the fins	$1.46*10^{-2}m^2$

The main goal of this research is to study the feasibility of applying the PV-TE -MCHP to produce more electricity, therefore, the PV-TE-MCHP is studied experimentally and compared to a PV only system with the same area. The TEGs are externally loaded with the resistor to obtain the maximum power output. PV electrical parameters are measured by a solar module analyser. The specifications of test components are shown in Table 2.

Table 2 The specification of test components.

alt-text: Table 2

Test equipment	Specification	Accuracy	Production site	Quantity	Position
Solar Module Analyser	ISM 490	±1%	RS Components Ltd	1	Near experimental rig
Thermocouple	0.2 mm copper-constantan	±0.5 K	homemade	5	PV surface; TEG hot and cold sides; heat sink surface;
Pyranometer	TBQ-2	2%	Jinzhou, China (Sun Co.)	1	Near experimental rig with the same surface of the experiment set up
Multimeter	Pocket Digital Multimeter	±1.0%	Neoteck	2	Near experimental rig
Ambient monitor	JZH-1	±0.5 K	Jinzhou, China (Sun Co.)	1	Near experimental rig

Others: Data Acquisition Instrument: Agilent 34970A(USA), test computer, electrical wires, etc.

3 Experimental procedure and error analysis

The two types of systems including PV-TE-MCHP and PV alone are tested during this study. The thermoelectric devices are connected in series and when the TEGs are in a closed circuit, both voltage and current are recorded. The TEGs are externally loaded with the resistor and the parameters are measured by the standard multimeter. The system is equipped with several thermocouples placed at strategic positions to accurately measure the temperature at the different positions in the system. The temperature of PV surface, TEG hot and cold sides, and heat sink surface are all test by the thermocouples, which are all fixed to the surface of the corresponding part. At the same time, the electrical performances of PV and TEG are also tested using the solar module analyser and multimeters respectively. By changing the external electrical resistance, different TEG outputs are obtained to determine the maximum value.

The electrical efficiency of the PV-TE-MCHP can be expressed as

$$\eta = \frac{P_{pv} + P_{te}}{\mathrm{G} \cdot \mathrm{A}} \quad (1)$$

where P_{pv} is the PV output, P_{te} is the TE output.

According to the theory of error propagation, the relative error (RE) of the dependent variable y can be calculated as follows [37,38]:

$$RE = \frac{dy}{y} = \frac{\partial f}{\partial x_1}\frac{dx_1}{y} + \frac{\partial f}{\partial x_2}\frac{dx_2}{y} + \cdots + \frac{\partial f}{\partial x_n}\frac{dx_n}{y} \quad (2)$$

$$y = f\left(x_1, x_2 \cdots x_n\right) \quad (3)$$

where $x_{i,}$ ($i = 1$, ...,n) is the variable of the dependent variable y. f/x is the error transferring coefficient of the variables.

The experimental relative mean error (RME) during the test period can be expressed as:

$$RME = \frac{\sum_1^N |RE|}{N} \quad (4)$$

According to Eq. (2) to Eq. (4), the RMEs of all variables were calculated and the results were given in Table 3.

Table 3 The experimental RME of the variables.

alt-text: Table 3

Variable	T	G	I	U	P	η_{power}
RME	0.33%	2.0%	±1.0%	±1.0%	2.0%	4.0%

4 Results and discussion

This study is to compare the electrical outputs between the PV-TE-MCHP system and PV alone. Ten test cases are made and the details of temperatures of the systems are also indicated.

The series of tests are conducted in summer (June) in Hefei city, China. The ambient conditions are shown in Fig. 3. The solar radiations are between 880 and 960 Wm^{-2}. And the ambient temperatures are between 32.0 and 34.5 °C. The wind speed is between 2.35 and 2.70 m/s.

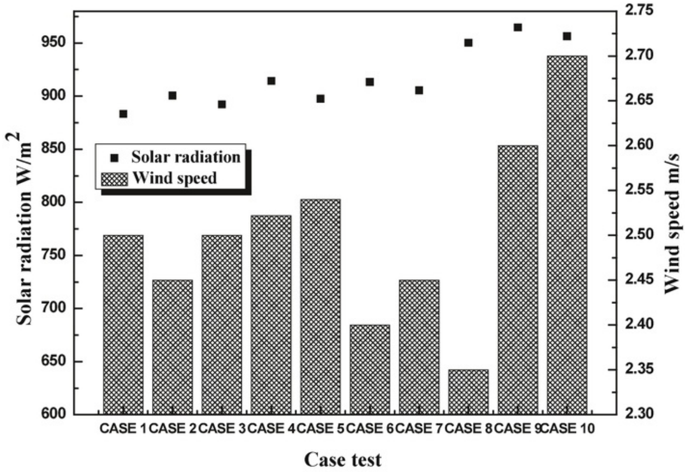

Fig. 3 Ambient conditions of tests.

alt-text: Fig. 3

The biggest challenge for the combination of PV and TE is whether the system has higher electrical performance compared to the PV alone. The comparison experiments show that the PV-TE-MCHP has higher electrical outputs during the case 1 – case 10 tests, which means that the design of the PV-TE-MCHP is feasible and TE can help the system obtain more electricity. In addition, it is clear that for the PV-TE-MCHP, the PV output is lower than that of PV alone, since the thermal energy cannot be transferred into the ambient environment in time which leads to a decrease in PV efficiency (Fig. 4). It can also be seen that in summer, the PV-TE-MCHP system can keep the electrical efficiency at approximately 14.0%. And the maximum electrical efficiency of the PV-TE-MCHP is about 14.3%, but that of PV alone is about 13.6%. In fact, from the previous study [26,36], it can be seen that the electrical efficiency of the PV-TE-MCHP is usually lower than that of the common PV-TE, since the thermal resistance between the PV and TE for the PV-TE-MCHP increases due to the addition of heat pipe. However, the PV-TE-MCHP system saves a lot of expensive TE devices comparison with the common PV-TE system, so it still has a high cost effective.

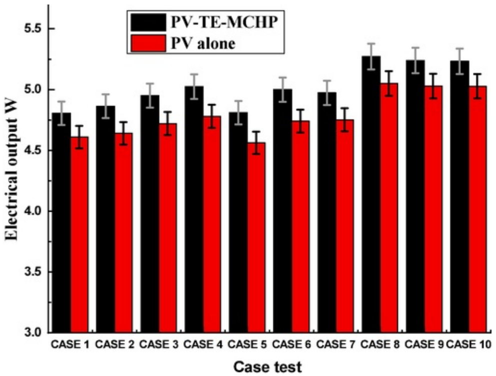

Fig. 4 Electrical output comparison between PV-TE-MCHP and PV alone.

alt-text: Fig. 4

For PV-TE system, it is important to note that the TE will increase the thermal resistant between the PV and the ambient environment, so it is hard to decrease the PV temperature. From Fig. 5, it can be seen that the PV temperatures are all about 50 °C, but the ambient temperatures are all below 35 °C, and during the testing, the temperature of PV alone are all about 40 °C. Therefore, for PV in PV-TE system, the PV output will be lower than that of PV alone, which is the disadvantage of the PV in PV-TE. However, due to the further power production from the TE, the total electrical output will be increased.

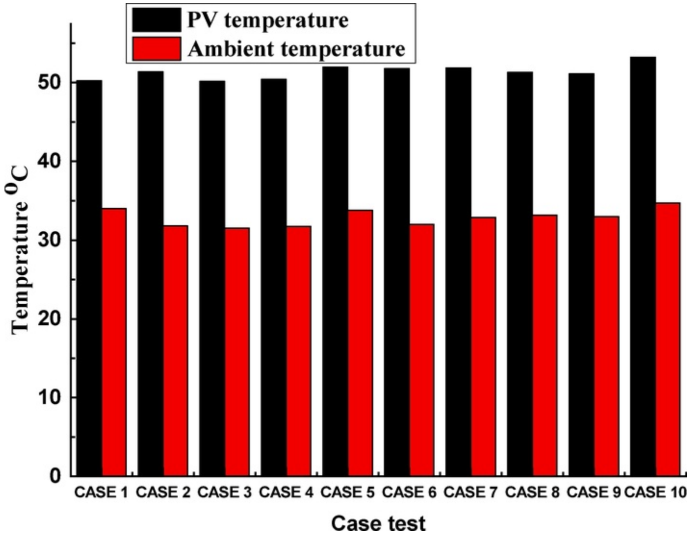

Fig. 5 PV temperature in PV-TE-MCHP.

alt-text: Fig. 5

As a result of the good heat transfer capacity of the MCHP, the solar thermal energy can be obtained by TE which is attached to the condenser side of the MCHP. Therefore, based on the principle of Seebeck effect, the TE can produce electrical power as long as there exist a temperature difference between the hot side and cold side. Fig. 6 shows the temperature differences between the hot and cold sides of the thermoelectric generator.

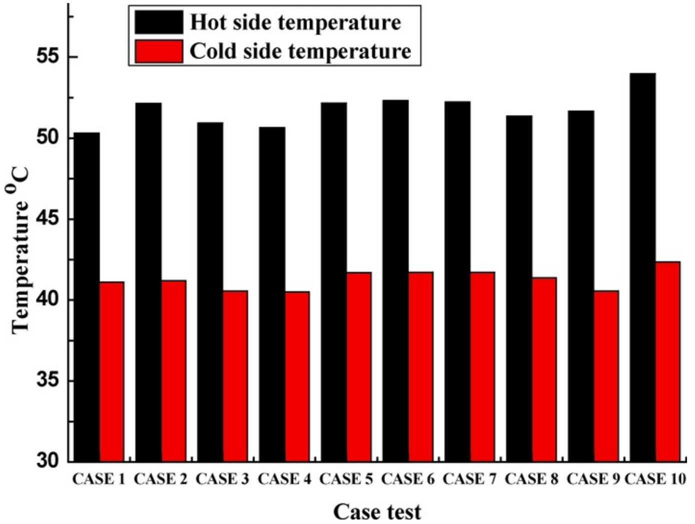

Fig. 6 Hot side and cold side temperatures of TE in PV-TE-MCHP.

alt-text: Fig. 6

5 Conclusion

This paper presented the experimental investigation of a PV-TE-MCHP system for the first time. The testing was conducted in summer (June) in Hefei city, China. An experimental platform for the PV-TE-MCHP and the PV alone was set up to compare their performance. The results obtained are shown below:

- The PV-TE-MCHP has a higher electrical output than PV alone, and the TE can effectively use the heat transferred by the micro-channel heat pipe to produce more electrical power.
- Since the micro-channel heat pipe reduces the heat transfer area between the PV panel and the ambient, the PV temperature had a significant rise, which was about 20 °C higher than the ambient temperature. But for PV alone, the temperature between PV and the ambient is within 10 °C.
- The temperature difference between the TE hot and cold sides are more than about 10 °C. Due to the high ambient temperature, the temperature difference between the thermoelectric hot and cold sides are not large, therefore, further solutions such as increasing the solar radiation, enlarging the PV area and utilizing efficient cooling technology may help to raise the temperature difference.

In order to get a higher electrical output, further optimization of the PV-TE-MCHP design needs to be done, and this needs to consider the matching of the PV panel and the TE. From this preliminary experiment of the PV-TE-MCHP carried out, the feasibility of this system is shown and its advantage can also be seen compared to the PV only system. This study will therefore provide a valuable reference for future PV-TE design. In the future, the optimization of the components and the system will be carried out to achieve the higher power generation, and the long time testing will be completed.

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Nomenclature

$\boldsymbol{G}$: solar radiation

$\boldsymbol{I}$: electric current

$\boldsymbol{U}$: electric voltage

T: temperature

P: output power

P_{pv} : PV output

P_{te} : TE output

Greek symbols

$\boldsymbol{\eta}$: electrical efficiency

Highlights

- Experiment on a novel Photovoltaic-thermoelectric system in summer was made.
- The comparison between the PV-TE system and PV alone was indicated.
- The PV temperature in PV-TE was about 20 °C higher than the ambient temperature.
- The maximum electrical efficiency of the PV-TE WAS about 14.3%.
- The PV-TE has a higher electrical output than the PV alone.

Queries and Answers

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