International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-8 Issue-4, November 2019

Optimum Design Consideration for Photovoltaic-Thermoelectric Hybrid Generator

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***Abstract:** This study focuses on the development of a hybrid generator from the combination of thermoelectric module (TEM) and solar cell. The attention is on the design of the heat sink for thermoelectric power generation (TEPG) through simulation and experiment. The impact of surface ratio between TEM and heat sink as well as the effect of various fin heights is investigated at different temperatures by using ANSYS software, while a number of experiments is carried out to study the output characteristics of TEM. This paper shows how the hot side temperature affects the output performance of TEM. Finally, the data from the simulation and the experiment yields the prototype with 256 cm^2 heat sink capable of producing 1-4.5 W at 200 °C from TEMs, and 2.3 W from 128 cm^2 crystalline silicon solar cell under the global AM1.5 spectra (1000 W/m^2).*

***Keywords:** Power generation; photovoltaic-thermoelectric; hybrid generators; passive cooling units; heat sink.*

Manuscript published on November 30, 2019.
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I. INTRODUCTION

A solid-state thermoelectric module (TEM) is defined as a machine that lacks movable parts and changes temperature gradient (ΔT) into electricity. It is composed of elements with different Seebeck coefficients (p-doped and n-doped semiconductors) connected electrically in series to increase the operating voltage and thermally in parallel to increase the thermal conductivity. The modules are relatively small in size and weight, and can be mounted in any orientation [1]. An output performance (essentially, the power) of TEMs can be attained by thermoelectric power generation (TEPG) systems either by intentionally supplying heat sources or by recycling wasted heat sources. Many efforts have been expanded into the development of advanced TEMs that possesses excellent conversion efficiency [2]. However, the thermal performance of TEMs in the context of power generation remains quite poor, with the maximum efficiency recorded in the neighborhood of<5% [3]. This implies that 95% of the energy from the heat source is rejected. It is believed that TEPG systems have a potential future towards commercialization by 1) enhancing the TEPG systems' design 2) improving the independent developments in TEM [4]. Currently, almost 90% of commercial TEMs are manufactured from bismuth telluride, which works at temperature below 230 °C [5].

The opposing side of TEMs is solar photovoltaic (PV), a fast growing market. Its compound annual growth rate (CAGR) of installations was 24% between year 2010 to 2017. The PV effect describes the phenomena of converting sunlight energy into electricity. The PV cell or solar cell is mainly composed of two different types of semiconductors (p- and n-type) that are metallurgically joined together to create a p-n junction. In 2017, silicon-wafer based PV technology accounted for ~95% of the total production while the market shares of all thin film technologies amounted to ~5% [6]. Malaysia has incredible potential to use solar energy for both thermal and PV applications [7, 8].

In this study, a hybrid generator prototype is developed using combined photovoltaic and thermoelectric systems. This project focuses on the TEPG, which includes software simulation and experiment. The impact of surface ratio between TEM and passive heat sink as well as the fin's height of heat sink are investigated in various temperatures by ANSYS software, while a number of experiments is carried out to study the output characteristic of TEM.

The final prototype of this project is proposed with a proper number of TEM and an improved passivating cooling system along with the solar cell.

II. RESPONSE SURFACE METHODOLOGY

At first, various geometries for heat sink were designed by using Solid works Software. We assumed that a 4 cm × 4 cm TEM was sandwiched between a fixed heat source and various heat sinks with different surface areas (16, 36, 64, and 100 cm^2) and fins height (1, 2, and 3 cm). Overall 12 designs were imported in to ANSYS software in order to analyze the heat transfer from the hot side to the cold side as Figure 1 depicts. Materials for each part of TEPG was selected accordingly. Aluminum was selected for the heat source stabilizer and heat sink, aluminum nitrate was selected for the outer block of TEM, copper for the connector between n-p semiconductors, and finally bismuth telluride as the n-p semiconductor. Each geometry was placed in ~~a~~ steady-state thermal condition.

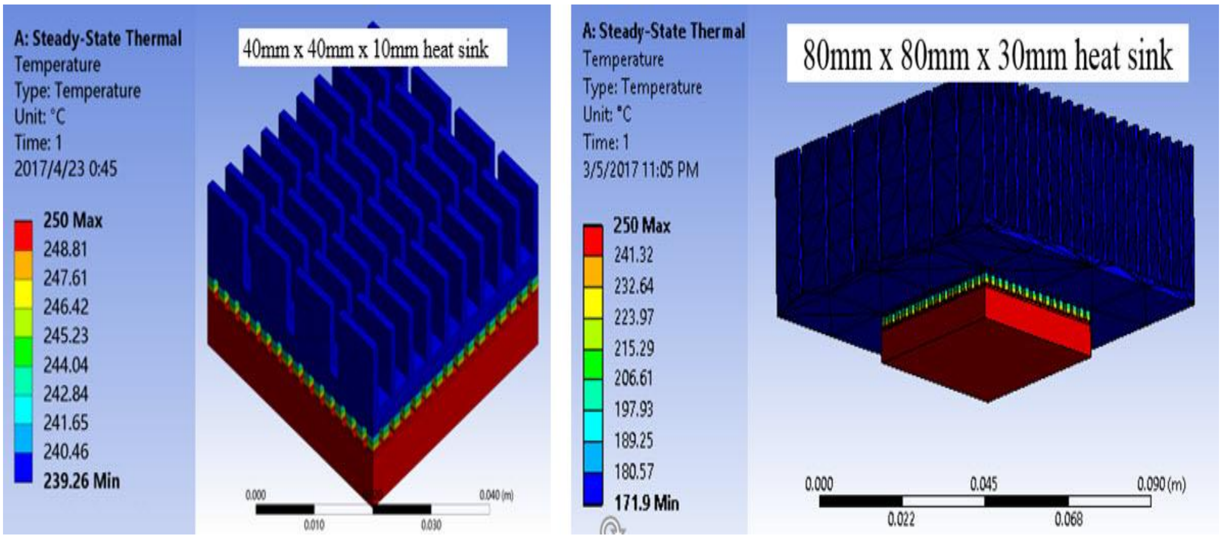

Fig. 1 40 mm × 40 mm × 10 mm versus 80 mm × 80 mm × 30 mm heat sinks for TEPG system

In the second part, the output characteristics of the cheapest and most available TEM in the market (4 cm × 4 cm SP1848) were investigated in imbalanced pressure conditions as well as using different sizes of heat sink. The comparison between TEPG without and with screw mounted heat sink of size 4 cm × 4 cm was made prior to the use of 8 cm × 4 cm heat sink. The 4 cm × 4 cm and 8 cm × 4 cm heat sinks were 2.6 and 3 cm in height, respectively, and both were made of aluminum. A thermal Grease HY710 (3.17 W/(m-K)) was applied to all sides of the TEM to reduce the interfacial thermal resistance. Finally, the output voltage and current for each TEPG were recorded at different temperatures as shown in Figure 2. The generated power was calculated by using formula P=VI. A heater was used to apply specific hot side temperature to the stabilizer and the cold side temperature was measured by infrared thermometer. Various external resistors from 2 to 50 Ω were selected in order to obtain the maximum output power.

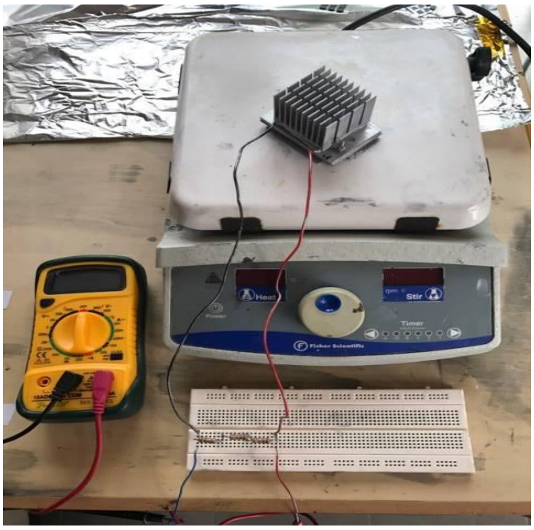

Fig. 2 Experimental set up of TEPG

III. RESULTS AND DISCUSSIONS

Figure 3 shows the contour graph of obtained ΔT produced by four different sizes of heat sink. As shown, the ΔT is low at 50 °C for all designs. The trend is similar in all designs as well, and the ΔT increases as the size and height of heat sink increase. The height of heat sink does not have any effect on the ΔT at low temperature, however, its significance increases at higher temperature with respect to the heat sink's area.

At 250 °C, the fin's height of 1, 2, 3 cm yields the ΔT of 10.29, 18.76, and 27.24 °C for 16 cm^2; 20.78, 36.42, and 48.97 °C for 36 cm^2; 42.48, 50.97, and 66.53 °C for 64 cm^2, and 44.59, 67.08, and 88.31 °C for 100 cm^2, respectively. The 64 cm^2heat sink acts as a better cooling system compared to the 16 and 36 cm^2. Even at 10 mm height, it creates 42.48 °C ΔT, which is double of the 36 cm^2. It is observed that if the heat sink surface area increases further, the ΔT would not increase as same as 16 and 36 cm^2. This issue emphasizes that the surface ratio of 0.25 might be the turning point to get the maximum performance in TEPG systems. Based on the literature, the conversion efficiency of heat passivation is proportional to the fin height, and the optimal fin height can be determined for the corresponding maximum net thermal power density [9-11], which is in accordance with our results.

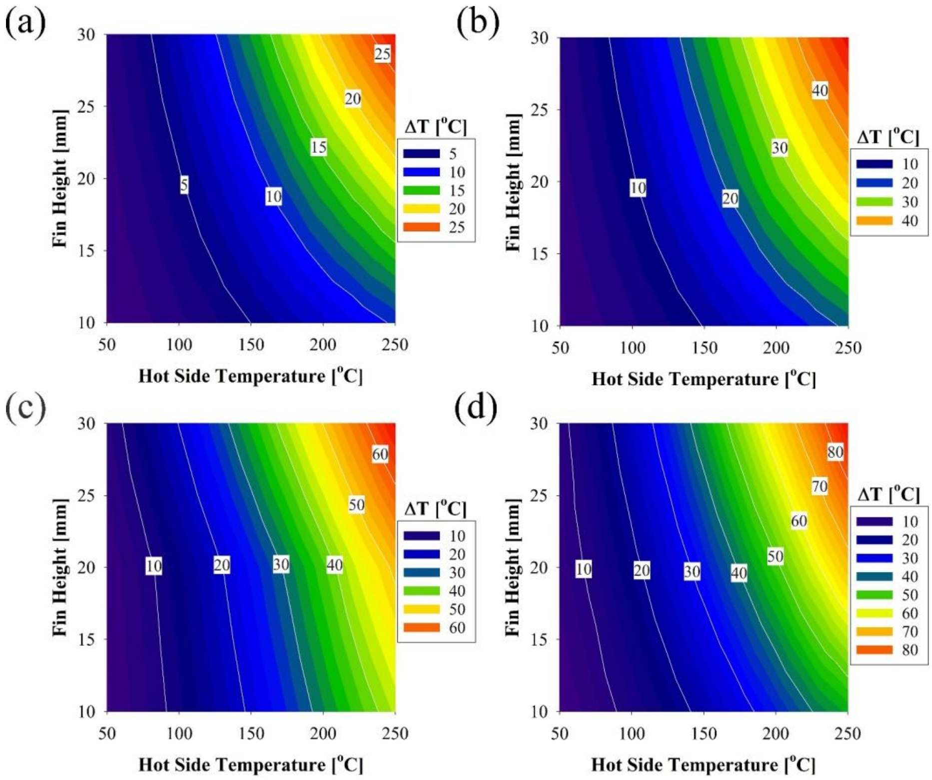

Fig. 3 Contour graph of obtained ΔT in four different sizes of heat sink in various hot side temperatures and fin heights: (a) heat sink area of 40 × 40 mm^2 or surface ratio of1, (b) heat sink area of 60 × 60 mm^2 or surface ratio of 0.44, (c) heat sink area of 80 × 80 mm^2 or surface ratio of 0.25, (d) heat sink area of 100 × 100 mm^2 or surface ratio of 0.16.

Table 1, 2 and 3 show output characteristics of TEM with different set up of TEPG. As shown in Table 1, for TEM with screw mounted heat sink, the highest output voltage and current are 0.715 V and 143 mA, respectively at 5 Ω external load, and consequently 0.102 W output power. The increase in hot side temperature especially at above 200 °C increases the output power. When the hot side temperature increases, the ΔT increases as well. Interestingly, using screw mounted heat sink in our setup did not change the output characteristics as shown in Table 2. Therefore, screwing at the side of heat sink and stabilizer does not improve the output performance due to bowing effect in agreement with Frederick A. Leavitt et al. [12]. In Table 3, we found that the output characteristics of the TEM with 32 cm^2 unscrewed heat sink is the highest as expected from simulation. With the bigger heat sink, the heat on the TEM is easier to be conveyed to the surrounding. The highest power of 0.00187, 0.0333, 0.1022, 0.1992 W is obtained with unscrewed heat sink at hot side temperature of 50, 100, 150, 200, and 225°C, respectively.

Table. 1 Output characteristics of TEM with screw mounted 16 cm^2 heat sink

Hot Side Temperature (°C)	Cold Side Temperature (°C)	Temperature Difference (°C)	Power Generation (W)
50	46	4	0.0011
100	88	12	0.0193
150	132	18	0.0572
200	171	29	0.0911
225	192	33	0.102

Retrieval Number: D5133118419/2019©BEIESP
DOI:10.35940/ijrte.D5133.118419
Journal Website: www.ijrte.org

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Blue Eyes Intelligence Engineering
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Table. 2 Output characteristics of TEM without screw mounted 16 cm^2 heat sink

Hot Side Temperature (^{o}C)	Cold Side Temperature (^{o}C)	Temperature Difference (^{o}C)	Power Generation (W)
50	43	7	0.0014
100	88	12	0.0178
150	133	17	0.052
200	176	24	0.0895
225	195	30	0.104

Table. 3 Output characteristics of TEM without screw mounted 32 cm^2 heat sink

Hot Side Temperature (^{o}C)	Cold Side Temperature (^{o}C)	Temperature Difference (^{o}C)	Power Generation (W)
50	33	17	0.0018
100	67	33	0.0333
150	109	41	0.1022
200	149	51	0.1992
225	168	57	0.2554

By considering the results obtained in simulation and experiment. A final prototype is designed as shown in Figure 4. For the cooling system of the prototype, a 256 cm^2 surface area heat sink with 35 mm fins height was used. This cooling system is attached to the cold side of the 4 TEMs, which all are supported by an aluminum sheet as a stabilizer. All elements of TEPG can be held in place by a clamp that applies pressure from the center as learnt from our experimental study. All TEMs are connected in series to form a square shape of 64 cm^2 surface area. From the simulation, we found that to achieve a temperature difference more than 60 ^{o}C, the ratio of TEM to heat sink has to be less than 0.25. Thus, 4 TEMs with a total size of 64 cm^2 need a heat sink of at least 256 cm^2 in order to obtain the ΔT more than 60 ^{o}C at 250 ^{o}C.

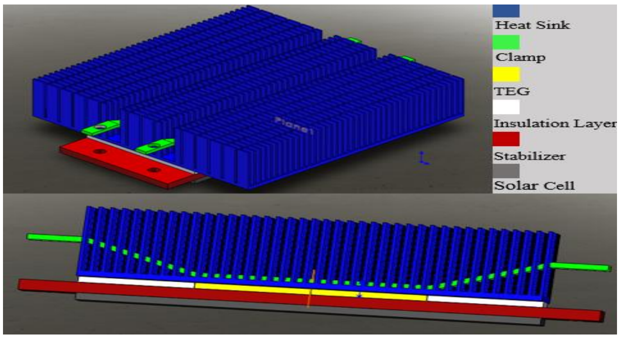

Fig. 4 Proposed hybrid prototype: a battery charger using photovoltaic-thermoelectric

According to experimental results, at 225^{o}C the output power generated by a single TEM is 0.2554 W. However, in our experiment there were a few factors, which might affect the output performance. The effects of pressure and insulation are not considered in the experiment, thus the 0.2554 W power generated by TEM is not the maximum power. In the final prototype, the pressure is exerted from the center of TEM by using a clamp that is screwed to the stabilizer. The clamp is slightly bent in structure and touches the heat sink at the center. By compressing the TEM using clamp, the pressure can be made perpetually in the strongest mode to maximize the effective heat transfers between interfaces. With all these factors, the prototype can produce at least 1 W at the ΔT of 60 ^{o}C. According to the data sheet provided by the manufacturer, with 60 ^{o}C ΔT, one single TEM can produce 2.4 V and 469 mA and generate power of 1.125 W. In this case, four TEMs that are connected in series can generate the maximum power around 4.5 W.

In order to combine solar cell and thermoelectric generator in the final prototype, a 128 cm^2 magnetic crystalline silicon solar cell is proposed to fit at the bottom of the stabilizer. According to solar cell worldwide datasheet, the minimum efficiency of crystalline silicon solar cell is 18% [13]. Therefore, with 128 cm^2 size of solar cell, 2.3 W power can be generated. With higher output power generation in future study, this prototype can be applied to various electronic gadgets available in the market. Lastly, a suitable size of battery storage can also be installed to this prototype. It allows the battery charger to store energy when there is sunlight or heat sources. This stored energy can be used to charge up devices when there is no sunlight or heat sources.

IV. CONCLUSIONS

A working prototype of photovoltaic–thermoelectric hybrid generator was proposed based on our simulation and experimental guidelines. This system is believed to provide more stable output power. It had the heat sink with 256 cm^2 surface area and 35 mm of fins height as the cooling system. By using this heat sink, the TEM could achieve more than 60 °C of ΔT. In this prototype, four TEMs were proposed to be connected in series, the maximum power generated by thermoelectric generator was expected about 4.5 W. A 128 cm^{2}solar cell with a magnetic base was also attached to the stabilizer of TEPG system. By considering the lowest efficiency of crystalline silicon solar cell around 18%, a solar cell with dimension of 128 cm^2 could generate at least 2.3W of electrical power.

ACKNOWLEDGMENTS

Authors would like to acknowledge the Universiti Kebangsaan Malaysia (UKM). Appreciations are also extended to Institute of Sustainable Energy (ISE) of Universiti Tenaga Nasional (@The National Energy University) for the cordial support through BOLD2025 Program.

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