Power Generation using Thermoelectric Power Generator with Parabolic Solar Dish Concentrator

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Abstract. Solar Thermoelectric Generator (STEG), a hybridization system of thermoelectric generator (TEG) with a heat exchanger have been thoroughly explored because of its ability to produce both electricity and heat simultaneously. In this research, two tests were conducted: single TEG characterization test and STEG application. A theoretical modelling was developed based on the characterization test. For the STEG application, a solar parabolic dish concentrator and a single TEG were used to produce both heat and electricity simultaneously. An absorber plate placed on the focal point of the dish was used to facilitate the heat transfer of the reflected solar radiation to the TEG through the plate. The effects of various temperature difference were investigated. The absorber plate thickness was 1 mm and made up from copper to ensure high heat transfer rate and was well insulated so as to ensure minimal heat loss. To evaluate the performance of the TEG under the various temperatures, water-cooled cooling method (with water cooling jacket) and air-cooled cooling method (with finned heat sink and USB powered fan) were employed. Results showed that water-cooled cooling method was able to enhance the performance of STEG for higher power generation than air-cooled cooling method.

1.0 Introduction

Fossil fuels are hydrocarbons consists of carbon, hydrogen, sulphur, nitrogen, oxygen, and mineral matter. Fossil fuels are usually coal, oil, and natural gas. Fossil fuels generates energy and when extracted, the energy is used for heating and power generation. Fossil fuels are well established due to vast exploration, production and utilization; hence, it is much cheaper and more convenient compared to other alternative energy sources, such as wind energy, solar energy, biomass, etc. [1].

However, the usage of fossil fuel degrades our environment and cause major environmental issues such as global warming and green house effects. Also, fossil fuels will deplete over time and are not finite. To ensure the sustainability of our future, an alternative to fossil fuels must be explored.

Using renewable energy such as Solar Energy as an alternative to fossil fuels is a great option. Solar energy is completely free and infinite. Also, solar energy is the most abundant and available in both direct and indirect radiation. Solar energy is harnessed from the sun and converted into thermal or electrical energy [2]. It is a clean energy source derived from the sun, used to generate electricity [3]. There are two ways to convert the solar energy into electricity: solar thermal and solar photovoltaic (PV) systems. Solar thermal systems use collectors such as Solar Parabolic Dish Concentrator to recover heat energy from solar radiation, simply said, involving the sun as a source of heat. The
concentrated heat is then used to drive a heat engine which may be a traditional steam turbine, gas turbine, or a sterling engine. On the other hand, solar PV systems uses photovoltaic effect to turn solar radiation into electricity. In contrast with solar PV, solar thermal systems are much more compact and does not need much space for operation [4].

As one of the many types of solar collectors available, Solar Parabolic Dish Concentrator is a unique heat exchanger system because it can achieve very high concentration ratios. In this research, a thermoelectric generator (TEG) is used with solar parabolic dish concentrator to convert the thermal energy from the sun into electrical energy directly [5]. TEG is a solid-state device that is compact, robust, have no moving parts, relatively simple and environmentally friendly [6].

The hybridization of the TEG and the solar parabolic dish concentrator is then referred to as Solar Thermoelectric Generator (STEG). STEG is an exciting system because it can produce both electricity and heat simultaneously. Wide application of STEG system includes recovery of different types of waste heat, including photovoltaic [7], [8], automobile exhaust [9], light emitting diode [10], and industrial waste heat [11].

The purpose of this research is to test and characterize both thermal and electrical characteristics of thermoelectric cell and to evaluate the performance of single TEG for different heating conditions with two cooling methods for best power. For this, a TEG characterization test is performed with water-cooled cooling method (with water heat sink) and air-cooled (forced convection) cooling method with finned heat sink. To validate the characterization test, a mathematical modelling is developed. The TEG is also tested under STEG applications with the same cooling method.

2.0 TEG Fundamentals and Applications
The father of thermoelectrics, Thomas Johann Seebeck is an Estonian-German physicist, chemist and physician born in 1770 in Tallinn, Estonia. Thomas Johann Seebeck discovered the Seebeck effect in 1821. While conducting an experiment, he observed that a magnetic compass needle was deflected when the junctions in a closed loop between two dissimilar metals or semiconductors were at different temperatures [12].

Initially, Seebeck believed this phenomenon was due to magnetism induced by the temperature differences. However, Seebeck realized that it was an induced electrical current, which by Ampere’s law deflects the magnet. In short, an electrical potential (voltage) is produced due to the temperature difference, which can drive an electric current in a closed circuit. As for today, this is known as the Seebeck effect. The Seebeck effect can be mathematically expressed as:

$$\alpha = \frac{V}{\Delta T}$$  \hspace{1cm} (1)

where V is the potential difference in V.
\(\Delta T\) is the temperature difference in K.

A thermoelectric (TE) module comprises of n-type and p-type semiconducting materials connected electrically in series and thermally in parallel (see Figure 1). Several tens to hundreds of pairs of TE couples are embedded in each TE modules. This will then allow a part of the thermal energy that passes through them convert directly into electricity. The figure of merit ZT defines the material performance. It depends on the thermoelectric material properties Seebeck coefficient S, electrical conductivity \(\sigma\), and thermal conductivity \(k\), and \(ZT = S^2\sigma T/k\) where \(T\) is the temperature of the material [13]. The benefits of TEG are summarised as follows [14]–[18]:

- Simple, robust, and extremely reliable (typically exceed 100,000 hours of steady-state operation).
- Silent in operation since they have no mechanical moving parts.
- Require considerably less maintenance.
- Have very small size and virtually weightless.
- Capable of operating at elevated temperatures.
• Suited for small scale and remote applications typical of rural power supply, where there is limited or no electricity.
• They are environmentally friendly.

A mathematical model was developed based on theoretical analysis. The following assumptions were made:

1. Assume steady-state conditions (Seebeck coefficient, thermal conductivity, and electrical resistivity of TEG assumed constant throughout the experiment).
2. No contact resistances between the couples within the modules.
3. Thomson effect are negligible.
4. All heat transfer is occurring through the elements of the module (no convection or radiation losses).

The net heat transfer rate at TEG hot side, $Q_h$ and TEG cold side, $Q_c$ are defined as [19]:

$$Q_h = \alpha I T_h - \frac{1}{2} I^2 R + K(T_h - T_c)$$

$$Q_c = \alpha I T_c + \frac{1}{2} I^2 R + K(T_h - T_c)$$

where $\alpha$ is the Seebeck Coefficient, $I$ is the TEG current, $R$ is the TEG internal resistance, $K$ is the TEG thermal conductance, $T_h$ is the TEG hot side temperature and $T_c$ is the TEG cold side temperature.

Based on the first law of thermodynamics, which states the internal energy is equal to the difference of the heat transfer (denoted as positive) and the work done by the system (denoted as negative), the power output $\dot{W}$ is expressed by

$$\dot{W} = Q_h - Q_c = \alpha I(T_h - T_c) - I^2 R$$

By referring to the load resistance, the power output $\dot{W}$ can also be expressed as

$$\dot{W} = I^2 R_L = VI$$

where $V$ is the voltage across the load resistor and $R_L$ is the load resistance of TEG. Alternately, $V$ can also be expressed by referring to Ohm’s Law and the Seebeck voltage
\[ V = IR_L = \frac{W}{I} = \alpha(T_h - T_c) - IR \] (6)

Conclusively, the current in the circuit equals to

\[ I = \frac{\alpha(T_h - T_c)}{R_L + R} \] (7)

The Seebeck Coefficient is determined experimentally and it is equal to 0.0438 V/K. When TEG \( P_{\text{out}} \) is maximum, the internal load resistance \( R \) will match with the external load resistance \( R_L \). \( R \) can be identified from I-V curve by taking an inverse of the slope.

The TEG used in this research is manufactured by Beijing Huimao Cooling Equipment Co., Ltd. Below is the information sheet of the TEG used in this research [20]:

| Couples | Maximum output current \( I_{\text{max}} \) (A) | Maximum output voltage \( V_{\text{out}} \) (V) | Maximum net heat transfer rate at cold side \( Q_{\text{max}} \) (W) | Maximum temperature difference \( \Delta T_{\text{TEG}} \) (°C) | Dimensions | Resistance (Ω) | Weight (g) |
|---------|---------------------|------------------|-----------------|-----------------|------------|-------------|-----------|
|         |                     |                  |                 |                 | Length, L (mm) | Width, W (mm) | Thickness, H (mm) |
| 127     | 6                   | 15.2             | 56.5 (at \( T_h = 27°C \)) | 65 (at \( T_h = 27°C \)) | 40         | 40          | 3.9       |

**3.0 STEG**

The parabolic dish used in this research was made up from a recycled satellite dish with a diameter (major axis) of 0.65 m and was covered with small segments of mirrors to reflect the incoming solar irradiation. A single TEG unit was placed onto the focal point of the dish using an absorber plate made up from copper.

A mathematical analysis is conducted to determine the theoretical sun temperature and efficiency [21]:

Table 2: Parabolic Dish Specifications.

| Parameter               | Value     |
|-------------------------|-----------|
| Diameter of aperture, D (m) | 0.65      |
| Focal point, F (m)      | 1.69      |
| Depth (m)               | 0.015625  |
| Receiver width (m)      | 0.006     |
| Receiver height (m)     | 0.001     |

The diameter of aperture \( D \) and the maximum angle, \( \phi \) is expressed as

\[ \phi = 2\tan^{-1}\left(\frac{D}{4F}\right) = 10.985° \] (8)

The edge of radius, \( r_r \), also known as the maximum distance values existing between the focal point and the parabolic extreme is expressed as,
The area of the aperture, \( A_a \) is expressed as
\[
A_a = \frac{\pi D^2}{4} = 0.3318 \text{ m}^2
\] (10)

The area of the receiver \( A_r \) is calculated as
\[
A_r = 6 \times 10^{-5} \text{ m}^2
\] (11)

The collector concentration \( C \) is defined as the ratio of aperture area and area of the receiver
\[
C = \frac{A_a}{A_r} = 5530
\] (12)

The calculated concentration ratio corresponds to the maximum concentration ratio obtained from a parabolic concentrator with a flat receptor [22].

After determining the theoretical values of the parabolic dish, a thermal and optical analysis was then performed. The optical efficiency \( \eta_o \) can be evaluated by using Equation 13 based on the parameters in Table 3.
\[
\eta_o = \rho_c \tau_v \rho S = 48\%
\] (13)

Table 3: Parameters Used to Determine the Optical Efficiency of Parabolic Dish Concentrator.

| Parameter                        | Value |
|----------------------------------|-------|
| Receptor absorptance \( \rho_c \) | 0.850 |
| Transmittance of glass coating \( \tau_v \) | 1.000 |
| Reflectivity of the concentrator \( \rho \) | 0.572 |
| Shape factor, \( S \) | 0.995 |

Assuming the receiver efficiency \( \eta \) equals 0.5, the receiver emissivity \( \varepsilon \) equals 0.5, approximate temperature of the sun \( T_{\text{sun}} \) equals 5726.84°C, and the ambient temperature \( T_{\text{amb}} \) equals 30°C, the maximum temperature of the receiver \( T_r \) can be calculated as:
\[
T_r = \frac{T_{\text{amb}} + T_{\text{sun}}}{2} \left( 1 - \eta \right) \left[ \frac{\eta_o C}{46311} \times \varepsilon \right] = 179.122^\circ\text{C}
\] (14)

To find the optical energy in which the receiver absorbs energy, \( Q_{op} \), with the assumption of solar radiation in Malaysia \( I_s \) is 750 W/m\(^2\),
\[
Q_{op} = A_a \rho_c T_r \rho S I_s = 120.3859 \text{ W}
\] (15)

Therefore, the energy loss to the environment by the receiver, \( Q_{loss} \) can be calculated as:
\[
Q_{loss} = A_r U_L (T_r - T_{\text{amb}}) = 1.0817 \text{ W}
\] (16)

where \( U_L \) is the total heat loss coefficient of the collector, which equals to 120.8971 W/(m\(^2\)K).

The net power collected by the collector \( Q_{net} \) is computed as:
\[ Q_{\text{net}} = Q_{\text{op}} - Q_{\text{loss}} = 119.3042 \text{ W} \]  

(17)

Hence, the theoretical efficiency of the collector system \( \eta_{\text{th}} \) is computed as:

\[ \eta_{\text{th}} = \frac{Q_{\text{net}}}{A_{\text{a}}I_{\text{s}}} = 47.94\% \]  

(18)

This efficiency value is expected since it falls within the range of 40 to 60\% [22]–[25].

4.0 Methodology

TEG electrical characterization test was conducted first in this research. TEG electrical characterization test was done by sandwiching a single TEG between a cooling system and an aluminium block. To reduce thermal contact resistance between the contact surfaces, a thermal paste was applied. Heater cartridges were placed inside the aluminium block to heat the block uniformly. A variable AC transformer was connected to the heater cartridges so that it can step down the voltage input from the grid. This way the heat intensity of the heater cartridges can be manipulated accordingly.

Four small protrusions were made on the top surface of the aluminium block to ensure that the TEG was placed firmly onto the block. This was also to avoid any gap between the TEG and the aluminium block that can cause thermal contact resistance. Also, the aluminium block was insulated with wood to ensure minimal heat loss. Based on Figure 2 (a) and (b), the TEG was connected to a DC electronic load to allow for power generation. This way the open-circuit voltages and currents and short-circuit voltages and currents were able to be measured. Using the DC electronic load, the load resistance was varied from 0 \( \Omega \) to 234.3 \( \Omega \).

The TEG characterization tests were evaluated with water-cooled cooling method (see Figure 2 (a)) with a water-cooling jacket and air-cooled cooling method (see Figure 2 (b)) with finned heat sink attached with a 12V fan. Figure 3 shows the detailed experimental setup. According to [26], water flow rate had an impact on the TEG power output. Hence, water flow rate variation test was conducted first to determine the best flow rate. The flow rates were evaluated based on the results from output power against output voltage (P-V) graph and output current against output voltage (I-V) graph. Based on these graphs, the flow rate that results in the highest TEG output power will be chosen and used throughout this research.

Figure 2: (a) Schematic Diagram of Characterization Test Bench with Water-Cooled Cooling Method.  
(b) Schematic Diagram of Characterization Test Bench with Air-Cooled (Forced Convection) Cooling Method.
Prepare the set-up
Heat up the aluminum block
Set Thot to 40°C
Take all required temperatures
Plot V-I curve & P-I curve
Repeat experiment with different sets of T_hot temperature
Measure output voltage & output current at loaded with resistance varied
Measure output voltage & output current at no load

Figure 4: Experimental Procedures for Flow Rate Variation Test.

Four flow rate variation were tested: 15%, 45%, 75% and 100%. The flow rate was adjusted by adjusting the water tap opening. At 100% flow rate, the water tap opening was fully opened. The water flowrate was determined by considering the volume of water filled in a measuring beaker within 3 seconds. To get accurate results, the process was repeated for 5 times. Table 4 below shows the water flow rate measurements.

Table 4: Water Flowrate Calculation.

| Valve Opening (%) | Average water volume measured in 3 seconds (ml) | Water flowrate (ml/s) |
|-------------------|-----------------------------------------------|-----------------------|
| 15.0              | 60.0                                          | 20.0                  |
| 45.0              | 180.0                                         | 60.0                  |
| 75.0              | 300.0                                         | 100.0                 |
| 100%              | 400.0                                         | 133.3                 |

Each of the flow rate had the same methodology. The summarization of the steps taken can be referred to Figure 4. The hot side of TEG, T_hot was set to be at 40°C by heating it up using the heater cartridges. The TEG was connected to a DC electronic load. By using the electronic load, load resistance was varied from 0 Ω to 234.3 Ω.
The measured parameters were: ambient temperature $T_{\text{amb}}$, hot side temperature $T_{\text{hot}}$, cold side temperature $T_{\text{cold}}$, water in temperature $T_{\text{water,in}}$ and water out temperature $T_{\text{water,out}}$ for water-cooled cooling method setup. All these temperatures were measured by using thermocouples that were connected to a data logger. From this, the TEG output voltage and output current were measured according to the load resistance applied.

Based on the collected data, a P-V and I-V curve were plotted. From these graphs, the best flow rate was identified (see Results and Discussion). After the best flow rate was identified, the experiment was further conducted by varying the hot side temperature of TEG $T_{\text{hot}}$. The experimental procedure for $T_{\text{hot}}$ variation was similar with the flow rate variation test. After the $T_{\text{hot}}$ variation test was done for water-cooled cooling method, air-cooled (forced convection) $T_{\text{hot}}$ variation test was then carried out.

Next, an outdoor weather-based experiment was conducted. The outdoor experiment was conducted at the rooftop of Tower 1 (Level 21), Kompleks Kejuruteraan Mekanikal, UiTM Shah Alam, Malaysia. The parameters measured for this experiment were TEG hot side temperature $T_{\text{hot}}$, TEG cold side temperature $T_{\text{cold}}$, ambient temperature $T_{\text{amb}}$, solar irradiation, TEG output voltage $V_{\text{out}}$, TEG output current $I_{\text{out}}$, water-in temperature $T_{\text{in}}$, and water-out temperature $T_{\text{out}}$. Table 5 below shows the equipment used to take the readings:

| Equipment                  | Description                                                                 |
|----------------------------|-----------------------------------------------------------------------------|
| Electronic DC Load         | To measure TEG output voltage and output current                              |
| Solar Power Meter          | To measure solar radiation                                                   |
| 10 channel data logger     | To measure temperature of all the temperature parameters                     |

To ensure optimum concentration, the axis of the reflector was set to be parallel with the incoming radiation. This was to focus the solar ray’s incidents to the concentrated area. To achieve this, the parabolic concentrator was manually adjusted 5 minutes before each intervals of 30 minutes so that maximum solar radiation was reflected onto the TEG. The adjustments were based on two-axis tracking mechanism. At each intervals, the parameters mentioned above were taken and tabulated. The experiment was conducted for 4 hours, from 11.00 a.m. until 3.00 p.m.

For efficient data collection period, both water-cooled cooling method and air-cooled cooling method (forced convection) were conducted concurrently. Both set up were placed side by side (see Figure 5). Two days of data collection period was arranged (21/11/2019 and 22/11/2019).

Figure 5: STEG setup for both cooling methods.
5.0 Results and Discussion

As mentioned previously, flow rate variation test was conducted first to determine the best flow rate to be used throughout the experiment. From Figure 6, it clearly shows that a 100% valve opening, or 133.33 ml/s corresponds to the highest power generation, hence, this water flow rate will be used throughout the experiment.

![Figure 6: Flow Rate Variation Test.](image)

Figure 7 shows P-V and I-V curve for water-cooled cooling method for $T_{hot} = 40^\circ C$ to $T_{hot} = 120^\circ C$. Similarly, Figure 8 shows P-V and I-V curve for air-cooled (Forced Convection) cooling method for $T_{hot} = 40^\circ C$ to $T_{hot} = 120^\circ C$. From these figures, it can be deduced that as temperature difference $\Delta T_{TEG}$ increases across the two sides of TEG, the output current $V_{out}$ and output power $P_{out}$ produced by the TEG increases. Also, from these figures, the slope of I-V was almost similar, which means that the TEG internal resistance remains constant with different values of TEG hot side temperature and load resistance.

![Figure 7: P-V and I-V curves for Water-Cooled Cooling Method (Characterization Test) for $T_{hot} = 40^\circ C$ to $T_{hot} = 120^\circ C$.](image)

Figure 8: P-V and I-V curves for Air-Cooled (Forced Convection) Cooling Method (Characterization Test) for $T_{hot} = 40^\circ C$ to $T_{hot} = 120^\circ C$.

Figure 9 shows the comparison data between experimental and theoretical values of the characterization test with water-cooled cooling method at $T_{hot} = 120^\circ C$ while Figure 10 shows the comparison data between experimental and theoretical values of the characterization test with air-cooled cooling method at $T_{hot} = 120^\circ C$.

As mentioned previously, the Seebeck Coefficient was determined experimentally to be 0.0438 V/K. After determining the value of the TEG internal resistance and the Seebeck Coefficient of TEG, Equation 4 can be used to obtain the theoretical power output. From both Figure 9 and Figure...
10, both experimental and theoretical curves were almost similar. Hence, the deviation of experimental values and theoretical values were minimal. Heat loss to the surrounding may have contributed to this deviation.

Figure 9: P-V and I-V curve with Experimental and Theoretical Values Deviation for Characterization Test with Water-Cooled Cooling Method at \(T_{\text{hot}} = 120^\circ\text{C}\).

Figure 10: P-V and I-V curve with Experimental and Theoretical Values Deviation for Characterization Test with Air-Cooled Cooling Method at \(T_{\text{hot}} = 120^\circ\text{C}\).

Figure 11 (a) shows the outdoor weather-based experiment’s result for Water-Cooled Cooling Method whereas Figure 11 (b) shows the outdoor weather-based experiment for Air-Cooled (Forced Convection) Cooling Method for data taken on 21/11/2019. Both graphs show the P-V curve. From these graphs, the peak solar irradiation was at noon 12 pm (1295 W/m\(^2\)), hence power generated by the TEG was the highest at this time. For water-cooled cooling method, 709 mW was the highest power being generated whereas for air-cooled (forced convection) cooling method, 460 mW was the highest power being generated.

Figure 11 (a) shows the outdoor weather-based experiment for Water-Cooled Cooling Method whereas Figure 11 (b) shows the outdoor weather-based experiment for Air-Cooled (Forced Convection) Cooling Method for data taken on 22/11/2019. However, the data collection period on 22/11/2019 was until 1.00 pm only after which the weather was not suitable for data collection. Nevertheless, the data taken was sufficient to show that power can still be generated. For water-cooled cooling method, 1148 mW was the highest power being generated whereas for air-cooled (forced convection) cooling method, 784 mW was the highest power being generated. The highest solar irradiation recorded was at 12.00 pm (1550 W/m\(^2\)).
Figure 12: (a) STEG P-V Curve for Air-Cooled (Forced Convection) Cooling Method (22/11/2019).
(b) STEG P-V Curve for Water-Cooled Cooling Method (22/11/2019).

Figure 13 shows the comparison of TEG temperature difference value and the solar irradiation value for both cooling methods for both experimental days. As expected, water-cooled cooling method were able to cool the TEG more efficiently. A larger temperature gradient was established, hence a higher power output was generated.

Figure 14 shows the comparison of the maximum power generated and the solar irradiation value for both cooling methods for both experimental days. The highest power generated among the introduced cooling methods was consistent with water-cooled cooling method. It is no doubt that water-cooled cooling method was able to enhance the performance of the TEG for maximum power generation possible.

6.0 Conclusion
The experiment was carried out in two categories: indoor characterization test and outdoor weather-based experiment. The indoor characterization test was done by characterizing a single TEG electrically and thermally with two cooling methods introduced: Water-Cooled and Air-Cooled (Forced Convection). The same cooling methods were used in the outdoor weather-based experiment (STEG). In the characterization test, the experimental model was indeed validated with the theoretical model, having a maximum difference of 13.07% for water-cooled cooling method and 13.26% for air-cooled cooling method. These differences were due to heat loss to the surroundings. Next, a theoretical
model of STEG was also defined. The STEG experiment was conducted for two days. The highest power generated for water-cooled cooling method was 1148 mW whereas the highest power generated for air-cooled cooling method was 784 mW for solar irradiation of 1550 W/m² with TEG temperature difference of 92°C and 70°C. All results showed TEG power output increases as TEG temperature difference increases.

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