Feasibility study of Thermal Electric Generator Configurations as Renewable Energy Sources

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Abstract. Thermoelectric Generator is a solid state device that able to convert thermal energy into electrical energy via temperature differences. The technology is based on Seebeck effect that was discovered in year 1821, however till now there is no real application to exploit this capability in mass scale. This research will report the performance analysis of TEG module in controlled environment of lab scale model. National Instrument equipment and Labview software has been choosen and developed to measure the TEG module in various configurations. Based on the experiment result, an additional passive cooling effort has produced a better ∆T by 7°C. The optimal electrical loading of single TEG is recorded at 200Ω. As for circuit connections, series connection has shown superior power output when compared to parallel connection or single TEG. A series connection of two TEGs has produced power output of 416.82µW when compared to other type connections that only produced around 100µW.

1. Introduction

Renewable energy has been a focal point of research in the recent years. Various renewable energy sources ranging from solar [1], wind [2], hydro energy [3] was used to generate electricity in large scale. These energy sources were important due to the advantages towards clean environment and sustainability issues. As the world preparing to reduce dependence on coal based energy generator, various methods of renewable energy have been developed and implemented.

Apart from the renewable energy source mentioned above, there are a lot of research activities in harvesting energy at lower level which is using different physics phenomenon such as piezoelectric[4], vibration [5], acoustic noise, radio frequency (RF) [6] and thermoelectric[7]. Table 1 shows comparison between harvesting technology with respect to power density [8].

Thermoelectric generator or TEG is a device that able to convert thermal energy to electrical energy. It requires temperature differences at the junction in order to create electrical current. High reliability is one of the advantages since there are solid state device with no mechanical moving parts unlike MEMS based energy harvester that may requires additional self-x system to ensure system functionality [9]. TEG can be small in size and easily to be scaled depends on applications. However,
there are some drawbacks in this technology such as low in energy conversion efficiency and requires relatively constant heat source. These drawbacks lead to limited application and implementation in mass market.

| Harvesting technology         | Power density |
|------------------------------|--------------|
| Solar cells (outdoors at noon) | 15 mW/cm²    |
| Piezoelectric (shoe inserts)  | 330µW/cm³    |
| Vibration (small microwave oven) | 116µW/cm³ |
| Thermoelectric (10°C gradient) | 40µW/cm³     |
| Acoustic noise (100dB)        | 960nW/cm³    |

In a country like Malaysia, in which received a lot of sunshine throughout the year and thus make source of thermal energy come in abundance. The availability of thermal energy makes a good appeal for implementation of TEG to become one of renewable energy source. This research is focusing on evaluating and analyzing TEG modules in various configurations.

2. Experimental Setup

The evaluation of TEG module is done by using a commercial Peltier module TEC1-12706. It has the size of 40x40x3.5 mm. The device has a total 127 couples of PN junction interconnected as shown in Fig. 1.

In this research, the measurement of output produced by TEG is controlled by using NI-CRIO 9014 real-time controller from National Instrument. For temperature measurement, NI-9211 module is used to allow direct connections with thermocouple. This module can handle up to 4-channel of thermocouple measurement simultaneously. In all temperature measurement points, type K thermocouples were used. In performing current measurement, NI-9203 module was used. While in performing voltage measurement, NI-9201 is selected. The overall setup of the experiment is shown in Fig. 2 where as the wiring diagram is shown in Fig. 3.
In order to record the measurement data, LabView software was used to develop a data acquisition programme. In this programme, 2 points of thermocouple measurements and 1 point each for current and voltage measurement was recorded simultaneously. The output measurement is recorded with the interval of 1 second. The measurement data is then processed to calculate the value of $\Delta T$ and instantaneous output power. The block diagram of the software is shown in Fig. 4. The red box is referred to the block area where the raw data are acquired from the sensor module. The blue box represents the block area where the data acquired from the sensor are processed to calculate the value of $\Delta T$ and output power. The green box area shows the block area for storing measured and calculated value in csv file.

Several sets of experiment were done to evaluate the performance of the TEG. In the first part, the performance of TEG will be compared between modules with and without additional cooling. Passive cooling technique in the form of heat sink will be used in this experiment. The second part of experiment will try to determine the optimum electrical loading value. While in the final part, the performance will be compared between single, series and parallel connections.

Fig. 2: Experimental setup of the TEG measurement.

Fig. 3: Wiring layout of the TEG measurement
3. Result And Discussion

3.1 Performance Analysis of TEG with and without Heat Sink

In the first set of experiment, the differences in performance of TEG between with and without heat sink were investigated. In this experiment, the load resistance is set to $100\,\Omega$. The heat sink which has size of 40x40mm covers the hot plate area. Fig. 5 shows the box plot of data acquired during measurement.

From the results in the Table 2: Box plot parameter of performance analysis of TEG with and without heat sinkTable 2, the median data of $\Delta T$ is $23.45^\circ C$ for TEG without heat sink and $30.13^\circ C$ for TEG with heat sink. The temperature difference is larger by $7^\circ C$ when the TEG is equipped with additional heat sink. The bigger $\Delta T$ produced the bigger electricity output. From the experiment the power output produced from TEG without heat sink is $22.7\mu W$ while the output of $62.3\mu W$ is produced by TEG with heat sink. This is a significant improvement which up to 3 times from without heat sink power output value.

![Fig. 4 Block diagram of data acquisition programme used in the experiment](image)

![Fig. 5: Box plot of temperature difference of TEG with and without heat sink](image)
Table 2: Box plot parameter of performance analysis of TEG with and without heat sink

| Parameter       | Lower Quartile, $Q_1$ | Median, $Q_2$ | Upper Quartile, $Q_3$ |
|-----------------|-----------------------|---------------|-----------------------|
| $\Delta T \,[^\circ C]$ | Without heat sink   | 23.15         | 23.45                 | 23.71                   |
|                 | With heat sink       | 29.78         | 30.13                 | 30.63                   |
| Voltage [V]     | Without heat sink   | 0.106         | 0.106                 | 0.111                   |
|                 | With heat sink       | 0.178         | 0.178                 | 0.183                   |
| Current [mA]    | Without heat sink   | 0.204         | 0.210                 | 0.214                   |
|                 | With heat sink       | 0.341         | 0.346                 | 0.350                   |
| Power [µW]      | Without heat sink   | 21.225        | 22.7                  | 23.875                  |
|                 | With heat sink       | 60.5          | 62.3                  | 63.8                    |

3.2 Performance Analysis of TEG with Varied Load Resistance

The next experiment is to define the optimum load resistance range of a single TEG. Using the similar setup, the TEG is equipped with heat sink and the similar heat source. The load resistance is tested ranging from 0.2$\Omega$ to 500$\Omega$. The measurement period were taken for 5 minutes which resulted to 300 instantaneous data points for each load resistance.

In this experiment, a median $\Delta T$ of 31.5°C has been recorded during all load resistances testing. At 0.2$\Omega$, a median value of instantaneous current of 1.469mA has been recorded. This is the highest value when compared to the other load resistance value. The output instantaneous current showed a reduction as it load resistance increases. At 500$\Omega$, the instantaneous current is recorded at 0.346mA.

The measurements of instantaneous voltage have shown opposite trend. At 0.2$\Omega$, a very low value of 0.003V was recorded. As the load increases, the voltages are also increase respectively. In order to see the optimum instantaneous power, the data need to be calculated using the equation of $P=IV$. Fig. 6 showed the graph of box plot for current, voltage and power output. Based on this figure, the optimum power for single TEG module can be obtained for the load of 200$\Omega$. This is because at this point, 96.1µW has been produced. As we increased the load resistance, the output power produce has been reduced. Even though at high load resistance, the output voltage were continuously increased, but the output current also decreasing significantly. Thus, the instantaneous power output after 200$\Omega$ of load was also reduced.

![Boxplot of voltage and current of TEG with varied load resistance](image-url)
Fig. 7: Boxplot of voltage and current of TEG with varied load resistance

Table 3. Median value of parameter of performance analysis of TEG with varied load resistance

| Measurement Parameter | Load Resistance |
|-----------------------|-----------------|
|                       | 0.2Ω  | 100Ω  | 200Ω  | 300Ω  | 400Ω  | 500Ω  |
| Voltage [V]           | 0.003 | 0.091 | 0.137 | 0.158 | 0.173 | 0.178 |
| Current [mA]          | 1.469 | 0.905 | 0.690 | 0.527 | 0.426 | 0.346 |
| Power [µW]            | 4.71  | 81.35 | 96.1  | 83.4  | 72.8  | 62.3  |

3.3 Performance Analysis of Multiple TEG with Varied Configuration

In this final part of analysis, the experiment was done to determine the TEG instantaneous performance in various connection configurations. In the previous part, the experiment only used single TEG module. In this part, series and parallel connection are being tested to see the effect towards the TEGs output.

In this experiment, the measurements were done with the median value of ΔT recorded at 33.05°C. The comparisons of performance were compared between single, parallel and series connections. For instantaneous voltage measurement, the parallel connection recorded a median value of 0.122V which is similar with single TEG measurement. The series connection produced 0.250V median value which is double from the single TEG module. These results are in line with the classical electrical law in which the total voltage supply in series is equal to the sum of the voltage across it.

As for output current measurement, the single and parallel connections record ed median values of 0.834mA and 0.824mA respectively. A stark contrast in result can be seen when compared to the median value of series connection which produced 1.671mA which is double the value from other types of connection. The same trend can be determined when the output power is being calculated. The single connection recorded 102.85µW while the parallel connection also recorded about the same value at 101.14µW. The series connection produced significantly higher output which is at 416.26µW.

From these results as shown in Table 4, it is clear that a series connection of TEG module will produce a higher output power generation when compared to parallel connections.
Fig. 8: Boxplot of voltage of multiple TEG with varied configuration

Table 4. Boxplot parameter of performance analysis of multiple TEG with varied configuration

| Output Parameter | Type of connections |
|------------------|---------------------|
| Voltage (V)      | Single Parallel Series |
| 0.122            | 0.122 0.250         |
| Current (mA)     | Single Parallel Series |
| 0.834            | 0.824 1.671         |
| Power (µW)       | Single Parallel Series |
| 102.85           | 101.14 416.26       |

4. Conclusion
From these experiments, the performance and characteristics of TEG has been confirmed. The TEG will produce a better performance when additional cooling effort is done in the cold part of TEG. In the experiment, passive cooling method has been implemented and a temperature difference of around 7°C has been achieved. This gives a significant improvement in power output produced by TEG. In terms of optimum electrical loading, results shows that a single TEG will produce maximum power output when applied to resistance loading of 200Ω. As for circuit configuration, a series connection will give a boost to not only instantaneous voltage but also current. This connection gives the power output of 416.26µW from two TEGs in series where as a single and parallel connections will give a merely 100µW of output power. These results give a better understanding in terms of scalability of TEG in order to build better energy harvester system.

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