Experimental Investigation of a Thermoelectric Power Generation System for Low Temperature Waste Heat Recovery Applications

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Abstract - Alternative energy and systems have become increasingly popular to create energy sustainably. Thermoelectric generators (TEGs) can provide a helpful solution, by converting waste heat into usable energy. The experiment aims to utilize TEG modules between a heat source and cooling system. This allows electrical energy to be produced from the temperature difference, creating direct thermoelectric power. This experiment investigated the effects of varying temperature differences on the power produced. Using cooling systems helped the modules achieve larger temperature differences. This increased the thermal efficiency and therefore allowed more heat energy to be converted into electrical energy. This was shown to have a clear effect on the voltage output of the device, depending on the temperature difference. All the electrical energy produced can be stored within a rechargeable battery. This energy can be used to power low powered devices such as LED lighting, wireless sensors or even charge electronic devices such as smartphones. The system for the thermoelectric generation is simple, clean, quiet and reliable however will require maintenance. Overall, it provides an opportunity to recover wasted heat in areas which produce a large amount of unused thermal energy, making it a promising option for energy in many applicable situations.

Key Words: Thermoelectric Generator, Waste Heat Recovery, Seebeck Effect, Sustainable Energy, Energy Harvesting, Electrical Power Generation.

1.INTRODUCTION

Due to the increasing worldwide demand of energy and the negative impact of burning fossil fuels, there has been an increase in research into sustainable and energy efficient technologies. A large amount of energy is wasted within these various sectors (industry, electricity generation, automobiles and heating). By recovering this wasted energy, the overall energy efficiency can be improved and will reduce the emission of greenhouse gasses. Thermoelectric power generation is a great example of recovering this wasted thermal energy. This type of generator uses the Seeback principle to generate electrical energy. As there is a temperature difference across the TEG module (Thermoelectric Generator), an electrical voltage is generated with no moving parts or working fluids. Due to the compact size, silent operation, high reliability and low maintenance needed, TEGs have caused huge interest in sustainable power generation applications. [1-2]

Thermoelectric generators are found to be beneficial in recovering waste heat from industrial processes, automotive exhaust systems, heating appliances, remote power supplies and wearable/electronic/wireless sensors. The ability of the TEG to convert low-grade waste heat into an electrical energy source makes them a desirable option for improving energy efficiency, as well as reducing the need for fossil fuels. The performance of TEG systems is also affected by the temperature differential across the TEG, thermal contact resistance, distribution of cooling and how the TEG operates under certain operating conditions. Therefore, experimental research on TEG systems is necessary to determine their practical performance and to develop ways that will increase their output power.

This study is focused on conducting an experimental study to measure the output of a thermoelectric power generation system using a commercially available TEG module placed between a controlled heat source and heat sink. The TEG will be used in combination with a DC-DC converter to increase the output of the TEG's thermal gradient, and to store power into an energy-stored battery for practical use. Performance will be

evaluated under different thermal gradients by testing the output voltage, output current and output power. Performance of the TEG will also be evaluated using various thermally efficient cooling methods to determine if the application of thermal-efficient cooling will assist in maintaining an increase in temperature gradient across the TEG and improve the electrical performance of the TEG.[3]

The findings show that the voltage, current and power output increases with the increase of temperature gradient within the thermoelectric module. This system can be applied to low power electronic devices showing the feasibility of using thermoelectric generators to recover waste heat.

It was found that different power outputs were produced by the gas to liquid thermoelectric generator in relation to the waste heat recovery [4]. In the experiment, a number of variables were altered. This included the inlet gas temperatures (150° C to 300° C, centigrade), mass flow rate, a number of different types of turbulence and their effects on the heat transfer performance and different electrical connections. It was found that there wasn't an even temperature gradient throughout the heat exchanger for the inlet gas. This caused a reduction in the electrical output of the TEG system.

[5] demonstrated how a thermoelectric generator can be used to retrieve waste heat from a combustion chamber. The prototype was able to produce a maximum net power of 21.56 W. It was shown that an increase in net power of 43% was achieved through the use of heat pipes to cool down the system compared to finned heatsinks. This demonstrates how important it is to have efficient thermal management in order to improve the performance of TEGs.

[6] investigated simulation and experimental methods to understand how the power output of a thermoelectric generator will behave due to the geometrical design. It was found that the optimal height for the thermoelectric generator was 1.1mm. This shows how important it is to optimize the geometry of the module to produce maximum power output, whilst still keeping the material cost to a minimum.

A thermoelectric generator with PCM was integrated to provide steady electricity generation from fluctuating heat sources [7] (Yulong Zhao et al. 2025). However, this caused the total power output and average efficiency to decrease by 23.4% and 23.2%. This study showed how the relative position of the TEG was important to the phase change characteristics and electricity generation of PCM-TEGs. Therefore it is important to consider the configuration of the TEG system to generate useful amounts of electricity.

An innovative thermoelectric generator system was developed to be integrated into highway pavements to capture solar heat [8] (Seyed Amid Tahami et al(2019)). Through the use of a phase change heat sink within the optimized system, an average power output of 29 mW was produced. This shows how the waste heat from the pavement can be captured and used as an energy source for powering wireless sensors installed beside roads and low energy communication devices requiring less than 1 watt of continuous power.

A 5 layer modular TEG system containing 90 modules was researched to overcome the issue of large scale thermoelectric power generation [9] (Kewen et al (2020)). Experimental research was performed to see how the different temperature gradients and cooling water flow rates would affect the voltage, electricity generation and efficiency of the system. It was shown that a maximum electricity production of 45.7 watts could be produced at 72.2°C. This shows that modular designs are a viable option for increasing the scale of TEG systems to capture waste heat from commercial applications.

The performance of a 1kW TEG was improved through optimization of the mechanical design and electrical connections [10] (Jinlong Chen). It was found through experimentation that a 34.6% increase in the power output was achieved. A maximum conversion efficiency of 6.5 % was achieved instantaneously with a temperature gradient of approximately 120°C. It was concluded that the efficiency of TEG systems can be greatly improved through optimization of the mechanical and electrical structures. This is especially beneficial when using low temperature waste heat or geothermal recovery.

A Thermoelectric generator (TEG) using Phase Change Material (PCM) as the cooling medium was analyzed to understand how it would perform when using solar radiations [11] (Maciej Jaworski et al. 2015). Voltage, current and temperature were recorded at different points in the heat flux and circuit. It was shown that the PCM was very effective at regulating the temperature of the cold side of the TEG.

The work done by Menkeli et al.2025[12] looked at the effect of using radiating heater inserts within heat exchangers of flue gases to treat industrial waste gases. This showed that an increased flue gas temperature

resulted in an increased overall heat transfer rate. Using radiating heater inserts was shown to provide a better heat transfer within the system.

This investigation looked at an experimental based system to generate thermoelectric power. A commercial thermoelectric generator module was used between a controllable heating source and aluminum heat sink. This generated electrical energy as there was a temperature gradient, this was increased using a DC-DC converter and then stored into a rechargeable battery. The system was looked at with different temperature differences to show how it would perform. It was proven that having larger temperature differences will result in a better performance from the thermoelectric module with increased voltage, current and power. This shows the ability to convert waste heat energy into electrical energy.

2. Experimental setup

This test rig was designed to allow testing of the electric power production of the thermoelectric generator under various thermal conditions. The test rig contains the following components: commercially available thermoelectric module, controllable electrical heating element, aluminum heat sink, DC cooling fan, DC-DC boost converter, voltage regulator, 12 volt rechargeable battery and load resistance. The test rig was designed to give a consistent and stable thermal gradient across the TEG so that accurate measurements could be taken of the electric power produced. To do this the thermoelectric module was placed between the heating element and the aluminium heat sink. Thermal paste was used between the surfaces to provide a low thermal resistance between the 2 surfaces and help increase the heat transfer between them. The module was also clamped using a mechanical system to keep even pressure across the surface of the module without causing any damage. To create convection currents and remove heat from the TEG module on the cold side (Aluminium heat sink side) a DC cooling fan was attached to the Aluminium heat sink. The whole setup can be seen in Figure 1.

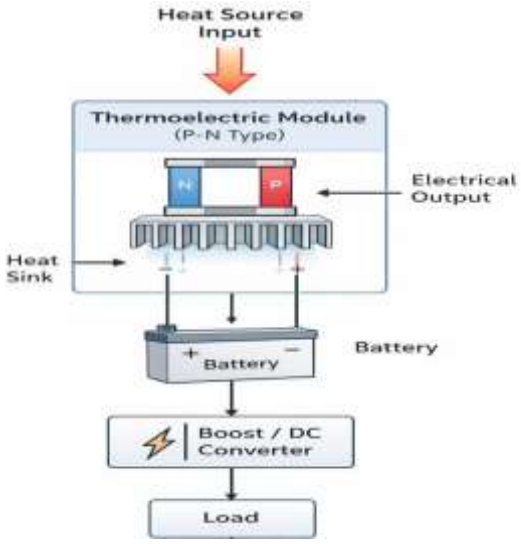


Fig -1: Figure

The thermoelectric generator (TEG) consists of the following components: the TEG itself, heat dissipation, converter and loading. The TEG uses materials with both p-type and n-type semiconducting properties. They are then connected together in series for electrical connectivity and parallel for thermal connectivity. When there is a temperature gradient between the hot and cold sides, there is an increase of charge carrier movement from one end to the other resulting in a DC voltage being produced. To aid in increasing the temperature gradient between each end, an aluminium heat sink was used to cool the cold side of the TEG. As the TEG has low levels of electrical energy, and the voltage output depends on temperature gradient, it was decided to include a DC-DC converter and voltage regulator to stabilize the voltage. The energy can then be stored in a 12 volt rechargeable battery or used to provide an electrical current to the loading. The TEG electrical performance was carried out by using a variable resistive load. This allowed for the voltage and current to be recorded under different conditions. The resistors were chosen carefully to provide the best power output possible from the TEG.

2.1 Experimental Approach

The TEG was assembled between the heat source and heat sink with TIMs. The TIMs reduce the thermal resistances of attaching the TEG to the heat source and heat sink. Fig 2 Once the heat source reached steady state the heat could flow into the hot side of the TEG. From the TEG the cold side of the TEG is constantly cooled down by the cooling fan. A temperature difference is created across the TEG which creates an

electrical voltage from the DC voltage as shown in the Seebeck Effect. The temperatures at the hot and cold sides of the TEG were measured using calibrated temperature sensors and the electrical voltage was measured using a digital multimeter (DMM) and the current was measured using a digital multimeter. [13] Yunan Wang et al 2025

The data obtained from the experiment was analyzed to find out how the TEG performed electrically over a range of temperature differences and in naturally and forced convective thermal management systems. The electrical power generated by the TEG was calculated using P=VI. Where P is the output electrical power (W), V is the output electrical voltage (V) and I is the output electrical current (A).

There were three repeats done so the data can be averaged to give accurate results for the next two experiments. A graph was created showing the performance of the TEG over varying temperature differences and the voltage, current and power outputs from the previous experiment. Then the results from the experiments were analyzed further to find out what conditions are needed to improve the efficiency of thermoelectric power generation.

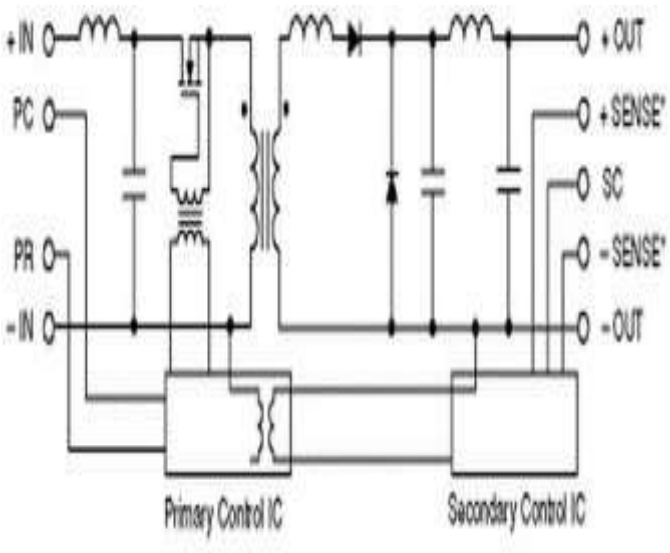


Fig 2 Experimental setup approach

Temperature Difference (°C)	Output Voltage (V)	Output Current (mA)	Output Power (mW)
10	0.30	20	6.0
20	0.70	45	31.5
30	1.20	70	84.0
40	1.80	95	171.0

Table -1: Experimental output characteristics of the thermoelectric generator under different temperature differences

3. Results and Discussion

The thermoelectric generator was run at a range of temperatures (10˚C, 20˚C, 30˚C, 40˚C and 50˚C). Table 1 shows that the output voltage, current and power all increased as the temperature increased. This is due to the Seebeck effect, where the increase in thermal gradient increases the EMF generated in the semiconductor junctions.

When the temperature was varied to 10˚C the TEG output 0.30 volts, with a 20mA current giving an output power of 6mW. When the temperature was increased to 20˚C, this gave an increase in output voltage and current to 0.70 volts and 45mA. This created an increase in output power to 31.5mW. An increase in temperature to 30˚C gave a higher output of 1.20V and 70mA. This resulted in the power of 84mW. Finally increasing the temperature to 40˚C increased the output voltage to 1.80V and the current to 95mA, giving a power of 171mW.

Increasing the temperature difference between the hot side and cold side to 50°C produced a higher output from the thermoelectric generator. It had an output voltage of 2.50V and a current of 120mA. This gave a maximum output power of 300mW. This is almost 50 times higher than the output power at 10°C. This shows how greatly the temperature difference affects the performance of the thermoelectric generator. Figure 3 and 4 shows variation in temperature difference with voltage and power. The results show that by increasing temperature difference you can improve the amount of output power produced. The thermoelectric generators ability to create power depends on how efficiently the heat is used. Efficient heat transfer is needed to heat up the hot side and cool down the cold side of the TEG. The results show that by using efficient heating and cooling methods you can create a much greater temperature

Temperature Difference (°C)	Output Voltage (V)	Voltage Increase (%)	Output Current (mA)	Current Increase (%)	Output Power (mW)	Power Increase (%)
10	0.30	–	20	–	6.0	–
20	0.70	133.3	45	125.0	31.5	425.0
30	1.20	300.0	70	250.0	84.0	1300.0
40	1.80	500.0	95	375.0	171.0	2750.0
50	2.50	733.3	120	500.0	300.0	4900.0

Table 2 Temperature difference with respect to output voltage and current and percentage increase in values

difference between this and another method of increasing the temperature differences in the generator are that it provides a more efficient thermoelectric generator based on the electricity produced. Increasing the thermal gradient will cause an increase in electromotive force within the generator due to the Seebeck Effect. This will result in larger currents being produced resulting in a higher power output. In order to achieve the best performance from a thermoelectric generator, an efficient thermal management system must be implemented. This can be achieved by using an optimized heat sink.

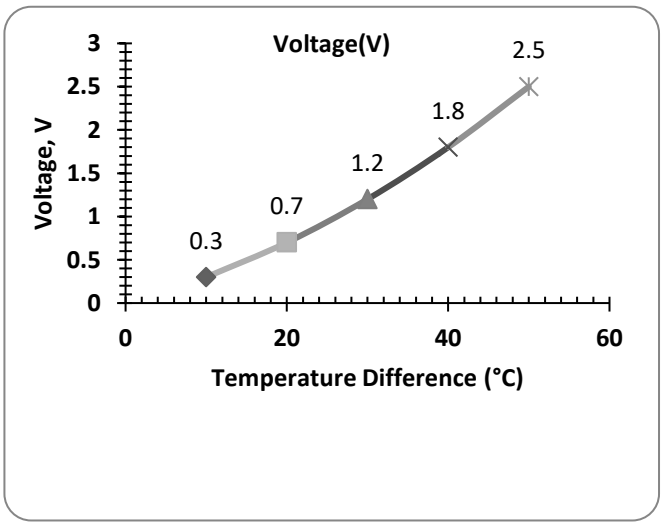


Fig.3

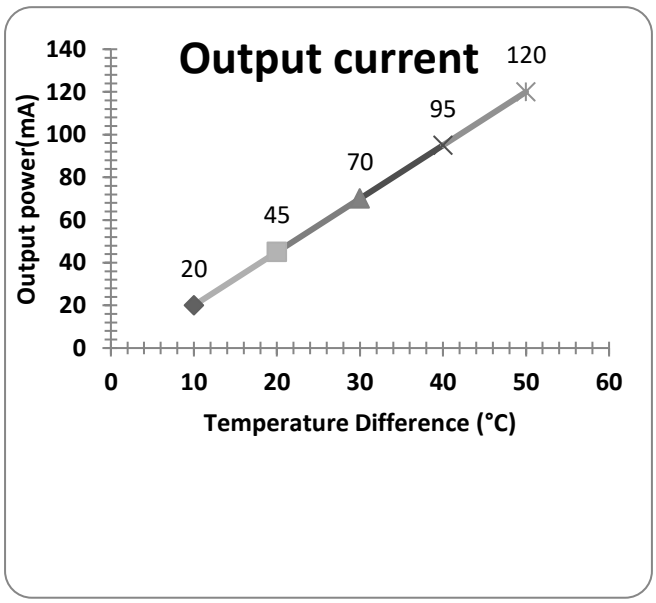


Fig.4

Fig. 3 and 4 variation of temperature difference with voltage and output power

The electrical output of the thermoelectric generator was measured across a range of temperature differentials (from 10°C to 50°C). Output voltage, output current, and power output were all measured. The TEG had an output voltage of 0.30 V, an output current of 20 mA, and an output power of 6.0 mW at a 10°C temperature differential. These values were the minimum electrical performance

3. CONCLUSIONS

This research investigated how effective a thermo electrical generator would be in converting low grade waste heat into electrical energy. It was found that by increasing the temperature gradient across the device, more electrical characteristics were produced such as higher voltages, currents and power outputs. This shows why it is important to have a large temperature gradient to produce the best conversion of energy. The highest results were achieved when there was a 50 °C temperature gradient. The results achieved were 2.50V, 120mA and 300mW.

Having an aluminium heat sink and a DC cooling fan improved the cooling efficiency of the system. This enabled the cold side of the TEG to dissipate more heat. Adding a DC to DC boost converter and voltage regulator allowed the electricity produced to charge batteries and carry out other tasks using low power electrical devices. The proposed thermoelectric power

generation system provides a simple solution for converting low grade raw heat from industrial, automotive and domestic sources in an easy, efficient and ecological way.

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Data availability statement

All data produced during the current study included in this article.

Competing Interests

The study was conducted without any impact of commercial or personal interests.

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