# Optimization Analysis of Thermoelectric Generator Characteristics in The Conversion of Heat Energy to Electrical Energy

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**ABSTRACT**
This study analyzes the optimization of thermoelectric generator (TEG) characteristics type TEC1-12706 to convert heat energy into electrical energy. The study focuses on measuring the open voltage (Voc) and current (I) generated by thermoelectric in various configurations (single, two series, and two parallel) with variations in temperature difference (ΔT). The test results show a linear relationship between ΔT and thermoelectric output characteristics. In a single configuration, the approximate equations are Voc = 0.0275ΔT - 0.036 and I = 0.0046ΔT + 0.0017. In a two series configuration, the approximate equations are Voc = 0.0513ΔT - 0.046 and I = 0.0054ΔT + 0.0043. Meanwhile, for the two parallel configuration, the approximate equation Voc = 0.0253ΔT - 0.0203 and I = 0.0057ΔT + 0.0039. This test shows that the two series configuration produces the highest voltage, while the two parallel configuration provides a larger current. Thus, these results can be a reference in the design and development of optimal thermoelectric generators for applications converting heat energy into electrical energy.

***Keywords:*** Thermoelectric Generator, Energy Conversion, Temperature Difference, Characteristic Optimization.

## Introduction

Renewable energy has become a major focus in efforts to reduce dependence on limited and environmentally unfriendly fossil fuel sources. One promising form of renewable energy is the utilization of abundant heat energy, both from natural sources such as the sun and from waste heat produced by various industrial activities. In converting heat energy into electrical energy, thermoelectric generator (TEG) technology offers great potential as an efficient and environmentally friendly solution. This technology works based on the principle of the Seebeck effect, where the temperature difference between two sides of the thermoelectric material produces an electrical voltage.

Thermoelectric generators have advantages, including the absence of moving parts, the ability to operate in a variety of environments, and a relatively simple design. This makes TEGs an ideal technology for utilizing previously untapped heat energy, such as waste heat from industry, transportation, and households. However, the energy conversion efficiency of TEGs remains a major challenge, mainly due to limitations in the thermoelectric materials used and suboptimal system design.

The efficiency of thermal energy conversion into electrical energy in TEG is greatly influenced by various characteristics, such as Seebeck coefficient, thermal conductivity, electrical conductivity, and internal resistance. In addition, environmental factors, such as the temperature difference between the hot and cold sides and the stability of the thermoelectric material under operational conditions, also play an important role in the performance of TEG. To improve efficiency, an integrated approach is needed in understanding and optimizing the characteristics of TEG through in-depth research.

This study aims to analyze and optimize the characteristics of TEG in converting heat energy into electrical energy. The focus of the study includes the influence of thermoelectric materials, physical design of the generator, and operational conditions on conversion efficiency. With this approach, it is expected to obtain a better understanding of the factors that affect TEG performance and strategies to improve efficiency.

The results of this study are expected to not only provide scientific contributions to the development of TEG technology, but also support efforts to manage thermal energy more efficiently and sustainably. Furthermore, this study can provide guidance for developers and manufacturers in creating more reliable and efficient TEG devices, as well as encourage the application of this technology in various sectors.

Formulation of the problem:

1) What are the characteristics of a thermoelectric generator that affect the efficiency of converting heat energy into electrical energy?
2) Are there other factors outside the thermoelectric characteristics of the generator that affect the results of converting heat energy into electrical energy?
3) How to optimize the performance of thermoelectric generators in generating electrical energy from heat energy sources?

## Literature Review

### 1. Thermoelectric Generator (TEG) Technology

Thermoelectric generator (TEG) is a device that converts temperature differences into electrical energy using the principle of the Seebeck effect. The Seebeck effect is a phenomenon in which two conductors or semiconductors with different temperatures will produce a potential difference that can be used to generate electric current. This technology is very interesting because it does not require moving components, thus reducing mechanical wear and increasing the durability of the device. TEG can be used in various applications, ranging from the utilization of industrial waste heat, transportation, to household applications.

### 2. Thermoelectric Materials

The main characteristic that determines the efficiency of TEG is the selection of thermoelectric materials. Good thermoelectric materials should have a high Seebeck coefficient, high electrical conductivity, and low thermal conductivity. Materials with these characteristics can improve the energy conversion from heat to electricity. Materials commonly used in TEGs include *bismuth telluride (Bi2Te3), lead telluride (PbTe), and silicon-germanium (SiGe)*, each of which has advantages in a certain temperature range. In addition, recent research is also directed at the development of nanostructure-based thermoelectric materials, such as nanocomposites and graphene-based materials, to improve energy conversion efficiency.

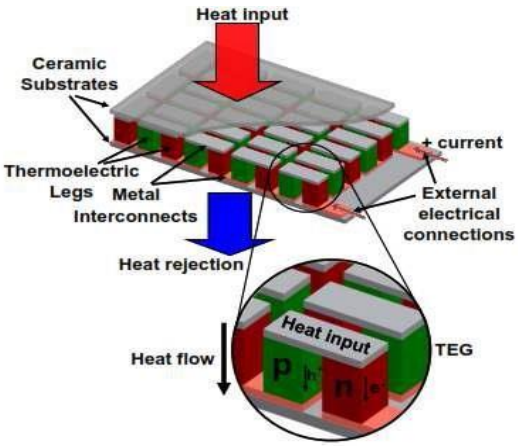


**Figure 1.** Thermoelectric building blocks

## 3. Principle of Seebeck and Peltier Effects

The Seebeck and Peltier effects are two phenomena that play a role in the TEG system. The Seebeck effect converts temperature differences directly into electrical voltage, while the Peltier effect is related to the heating or cooling that occurs when an electric current flows through the junction of two different thermoelectric materials (Goldsmid, 2010). Both complement each other in TEG operation, where a maintained temperature difference between the two sides of the system produces an electric current, while the Peltier junction can modulate the temperature between the sides to maintain the temperature difference.

## 4. Thermoelectric Generator Efficiency

The energy conversion efficiency of TEG is greatly influenced by the thermal and electrical characteristics of the materials used. One of the key parameters in TEG efficiency is *the figure of merit (ZT),* which describes the performance of thermoelectric materials. ZT is calculated using the equation:

$$ZT = \frac{S2\sigma T}{\kappa}$$

Where S is the Seebeck coefficient, \sigmaσ is the electrical conductivity, T is the absolute temperature, and κ\kappaκ is the thermal conductivity. Materials with high ZT values will be more efficient in converting heat into electricity. Therefore, efforts to increase the ZT of materials through material engineering and nanotechnology are very important in improving the efficiency of TEG.

## 5. Design and Operational Factors of TEG

The physical design and configuration of TEGs also play an important role in determining the energy conversion efficiency. Factors such as the size and orientation of the thermoelectric module, as well as the temperature difference between the hot and cold sides, have a direct impact on the performance of TEGs. Design modifications such as the use of different material alloys, the arrangement of the module positions, and the use of effective cooling systems can improve the efficiency of TEGs. In addition, environmental factors also play a role, such as ambient temperature conditions and the long-term stability of thermoelectric materials.

## 6. Thermoelectric Generator Applications

TEG has a wide range of applications, especially in the utilization of waste heat energy. In the industrial sector, many processes produce heat as waste, such as in the metallurgy industry, power generation, and chemical industry. By using TEG, this heat energy can be reused to generate electricity, which can reduce external energy consumption and improve overall energy efficiency. In addition, TEG is also widely applied in energy recovery systems in vehicles, as well as in remote areas that are not reached by the main power grid.

**7. Research Challenges and Prospects**

Although TEG technology has great potential, several challenges still exist, especially related to the relatively low conversion efficiency when compared to other energy conversion technologies. Several strategies that are being developed to overcome this problem include thermoelectric material engineering, increasing *the figure of merit (ZT)*, and innovation in the design and configuration of TEG systems. In addition, the development of cheaper and more sustainable thermoelectric materials is also a focus of research. Further research in this area is expected to produce more efficient TEG systems that can be widely implemented in various applications. A deep understanding of the characteristics of thermoelectric materials and TEG design is essential to optimize the conversion of heat energy into electricity. Efforts to improve TEG efficiency through the development of better materials and system designs will open up great opportunities in the utilization of renewable energy and more efficient waste heat management. Further research in this area will contribute to the development of more effective, efficient, and widely applicable TEG technologies in various sectors.

## Research Method

1) Literature Review: The first stage in the research is to conduct a literature review to understand the basic concepts and theories related to thermoelectric generators (TEG). At this stage, researchers collect references and previous research results regarding the working principles of TEG, thermoelectric materials used, energy conversion efficiency, and TEG applications in various industrial sectors and others. The purpose of this stage is to gain a strong understanding of the topic to be studied and identify gaps or opportunities for further research.
2) Preparation of Materials and Tools: At this stage, researchers prepare the materials and tools needed for the experiment or making the tool. The materials needed include thermoelectric materials that will be used in making thermoelectric generators, as well as other components such as heatsinks, thermometers, and other supporting devices. The tools used can be equipment for assembling the TEG system, temperature gauges, and electrical measuring equipment such as voltmeters and ammeters.
3) Tool Making: At this stage, the tool that will be used for the experiment is made or assembled. This process involves selecting and installing thermoelectric materials that meet the desired specifications. The tool that is made must be able to produce a temperature difference sufficient to activate the Seebeck effect and generate electricity. The manufacturing process also includes the installation of a cooling and heating system to maintain the required temperature difference in the TEG.
4) Equipment Inspection: After the equipment is assembled, an inspection is performed to ensure that the equipment is functioning properly and according to the desired specifications. This inspection involves checking all components of the equipment, ensuring that there are no defective or damaged parts, and checking that the cooling and heating systems are working effectively.

5) Characteristic Measurement: At this stage, measurements are made to observe the thermoelectric characteristics of the generator. The measurements carried out include measuring the temperature on both sides of the thermoelectric material, the voltage generated by the TEG, and the electric current generated. This measurement aims to obtain the data needed for the analysis of the efficiency and performance of the TEG in converting heat energy into electrical energy.
6) Measurement Success: After the measurement is performed, this step indicates whether the measurement was successful and the data obtained can be used for further analysis. If the measurement is successful, the data obtained can be processed and analyzed to determine the factors that affect the performance of the TEG.
7) Data Processing and Analysis: Data that has been collected from the measurements will be processed and analyzed. This analysis process aims to identify the thermoelectric characteristics of the generator and evaluate its efficiency in converting heat energy into electrical energy. At this stage, researchers will use statistical methods or mathematical models to analyze the data obtained, such as calculating energy conversion efficiency, figure of merit (ZT), and other factors that affect TEG performance.
8) Conclusion: After the data analysis is complete, the final stage is to draw conclusions from the research results. This conclusion will provide an understanding of the optimization of the thermoelectric characteristics of the generator, factors affecting the efficiency of heat energy conversion, and recommendations for improving the design and operation of the TEG. This conclusion will also contribute to the development of more efficient thermoelectric generator technology. Done.

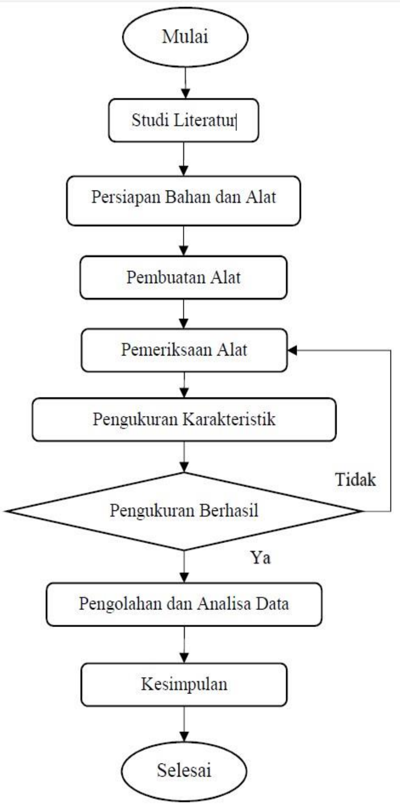


**Figure 2.** Flowchart

## Results and Discussion

### 1. Single Configuration Thermoelectric Open Voltage Testing

Open circuit voltage testing on single configuration thermoelectrics aims to measure the voltage produced by the thermoelectric when no load is connected to its output. This test is very important because it can provide an overview of the electrical potential that can be produced by the thermoelectric system under ideal conditions, namely when no current flows (open load). This open voltage occurs due to the difference in temperature that creates a temperature gradient between the two sides of the thermoelectric material, resulting in the Seebeck effect.

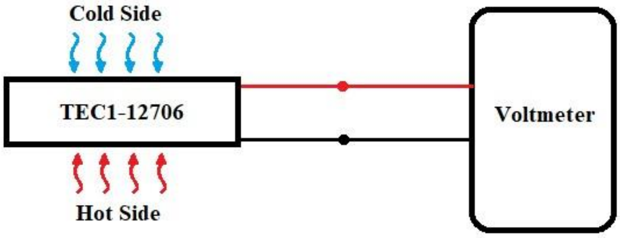


**Figure 3.** Single Configuration Open Voltage Test Schematic

a. Thermoelectric Open Voltage Testing of Two Series Configurations

In this test, the main objective is to measure the open circuit voltage generated by two thermoelectrics connected in series. This series configuration is different from the single configuration which only uses one thermoelectric. In the series configuration, the voltage generated by each thermoelectric will be added up, provided that the two thermoelectrics have sufficient temperature difference.

b. Testing Process

In a two-series configuration, two thermoelectrics, each with a hot side and a cold side, are connected in a series circuit. The output cables of the two thermoelectrics are then connected directly to a DC voltmeter to measure the voltage produced. As in the test with a single configuration, the test is carried out by maintaining a temperature difference between the hot and cold sides, which triggers the Seebeck effect in the two thermoelectrics. In a series configuration, the voltage produced by the two thermoelectrics will accumulate. For example, if each thermoelectric produces a certain voltage based on the applied temperature difference, then the total voltage measured at the output of the series circuit is the sum of the voltages of each thermoelectric.

c. Test Results

**Table 1.** Results of open voltage testing on the configuration of two thermoelectrics in series.

| Tc (°C) | Th (°C) | ΔT (°C) | Voc (Volt) |
|---|---|---|---|
| 28 | 31 | 3 | 0.06 |
| 28 | 34 | 6 | 0.13 |
| 28 | 37 | 9 | 0.2 |
| 28 | 40 | 12 | 0.29 |
| 28 | 43 | 15 | 0.37 |

The test results show that as the temperature difference (ΔT) increases, the resulting open voltage (Voc) also increases. However, it is important to note that these measurements show the open voltage at no-load (open circuit) conditions, meaning no current is flowing in the system.

This test shows that the series configuration can increase the voltage generated compared to a single configuration, because the voltages from each thermoelectric are added together. For example, if we look at the test results at a temperature difference of 15°C (Tc = 28°C, Th = 43°C), where the Voc generated is 0.37 Volts, we can compare it to the test results on a single configuration that may produce a lower voltage under the same conditions. Basically, the voltage generated by each thermoelectric in a series configuration will depend on the magnitude of the temperature difference (ΔT). The larger the ΔT, the greater the voltage generated by the thermoelectric. In this case, the effect of temperature on the open voltage is very significant, and increasing the number of thermoelectrics in series allows for higher voltages to be achieved.

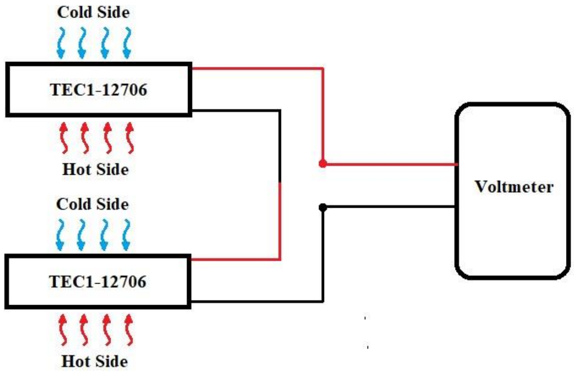


**Figure 4.** Two Series Configuration Open Voltage Test Schematic

**Table 2.** Open Voltage Test Data for Two Series Configurations

| Tc (°C) | Th (°C) | ΔT (°C) | Voc (Volt) |
|---|---|---|---|
| 28 | 31 | 3 | 0.11 |
| 28 | 34 | 6 | 0.29 |
| 28 | 37 | 9 | 0.46 |
| 28 | 40 | 12 | 0.61 |
| 28 | 43 | 15 | 0.74 |

2. Single Configuration Thermoelectric Current Testing with 1 Ω Load

This test is conducted to determine the value of the electric current flowing through a load with a resistance of 1 Ω connected to the thermoelectric in a single configuration. The testing process involves connecting the thermoelectric directly to a DC ammeter and a load with a resistance of 1 Ω, as shown in Figure 5. The results of this test are recorded and used to analyze the performance of the thermoelectric under load conditions.

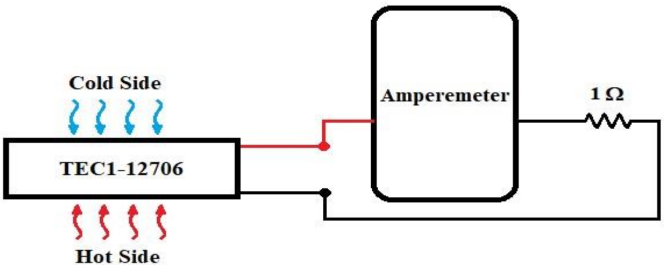


**Figure 5.** Single Configuration Open Current Test Schematic with 1Ω Load

**Table 3.** Single Configuration Thermoelectric Current Test Data with 1 Ω Load

| Tc (°C) | Th (°C) | ΔT (°C) | I (Ampere) |
|---|---|---|---|
| 28 | 31 | 3 | 0.01 |

| | | | |
|---|---|---|---|
| 28 | 34 | 6 | 0.02 |
| 28 | 37 | 9 | 0.04 |
| 28 | 40 | 12 | 0.05 |
| 28 | 43 | 15 | 0.07 |

From the test results, it can be seen that the current flowing through a 1 Ω load increases with increasing ΔT (temperature difference between the hot and cold sides). This shows a linear relationship between the temperature difference and the resulting current value. At a ΔT of 3°C, the current flowing is only 0.01 A. However, when ΔT increases to 15°C, the resulting current reaches 0.07 A. This condition is in accordance with the principle of the Seebeck effect, where increasing ΔT produces a higher voltage, which ultimately produces a higher current through the load. However, the current generated in a single configuration is still relatively small, indicating that thermoelectrics with this configuration may be more suitable for applications with low power requirements. To produce greater power, more complex thermoelectric configurations, such as series or parallel, may be required. These test results provide initial insight into the performance of thermoelectrics in a single configuration, as well as a reference for further optimization of design and operational conditions.

## Conclusion

Based on the research results on the Thermoelectric type TEC1-12706 which was tested as a generator by utilizing the temperature difference (ΔT), several conclusions were obtained. The relationship between open voltage (Voc) and ΔT in a single configuration is formulated by the equation $V_{oc} = 0.0275\Delta T - 0.036$, in a two-series configuration with the equation $V_{oc} = 0.0513\Delta T - 0.046$, and in a two-parallel configuration with the equation $V_{oc} = 0.0253\Delta T - 0.0203$. The open voltage increases as the temperature difference increases, with the two-series configuration producing the largest voltage compared to other configurations.

In addition, the relationship between current (I) and ΔT at a 1 Ω load shows that a single configuration has a current with the equation $I = 0.0046\Delta T + 0.0017$, a two-series configuration with the equation $I = 0.0054\Delta T + 0.0043$, and a two-parallel configuration with the equation $I = 0.0057\Delta T + 0.0039$. The resulting current increases linearly with the temperature difference, with the two-parallel configuration producing the highest current.

From the results, the two-series configuration is superior in producing open voltage (Voc), while the two-parallel configuration is more efficient in producing current (I), especially for applications that require higher power at a given load. Thus, the selection of thermoelectric configuration is highly dependent on the application needs. For high voltage needs, the two-series configuration is more recommended, while for high current needs, the two-parallel configuration is more appropriate. This study provides important insights to optimize the design and application of thermoelectrics as generators, especially in utilizing heat sources for more efficient electrical energy conversion.

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