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Studies on the TEG with changes in temperature difference and material properties

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Abstract

The thermoelectric generators are solid-state devices that produce electricity. They are designed to harness unused energy, or "waste heat". These devices were primarily utilized in military and space projects due to their reliability as a self-contained power source, requiring minimal maintenance. Additionally, they are environmentally sustainable and renewable sources of energy, emitting no air or noise pollution. According to research, Thermoelectric Generators (TEGs) have a relatively low efficiency rate of less than 5%. However, they hold the potential to effectively harness low-temperature waste heat, making them a promising energy source for the purpose of charging battery cells or super capacitors utilized in autonomous sensors. This study analyses the feasibility of generating electricity through segmented TEGs operating at temperatures below 296 K. Thermoelectric materials were studied to improve the conversion efficiency of the TEG. Furthermore, an investigation was conducted on the configuration of the thermoelectric generator. The COMSOL Metaphysics software is used to design and stimulate the segmented TEG model. This model is initially derived from an existing generator and is known for its accurate outcomes. The study revealed that using an alloy consisting of 75% Bi_2Te_3, and 25% as a substitute for the thermoelectric material $PbSe_{0.5}Te_{0.5}$, which led to a significant increase in conversion efficiency and output voltage. A segmented TEG model exhibited higher conversion efficiency. The model is subsequently refined by incorporating various modifications aimed at improving its conversion efficiency.

Keywords: Conversion efficiency, Material properties, Seebeck effect, Temperature difference, Thermoelectric generators, Thromboelastography.

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1. Introduction

Thomas Seebeck was the first person to discover the Seebeck effect in 1821. This phenomenon is characterized by the production of a direct current flow inside a closed electric circuit that is made up of two dissimilar materials and is kept at various temperatures. The magnitude of this effect may be measured by using the Seebeck field, which is represented by the symbol Es [V/m].

$$E_s = \alpha \Delta T \qquad (1)$$

The Seebeck field (E_s)(as described in Equation 1) is determined by the Seebeck coefficient (α) of the materials and the temperature difference (ΔT) between them. The Seebeck coefficient describes the effect of magnitude on each material. The temperature gradient is a critical consideration in the design of a Thermoelectric Generator (TEG). The Seebeck field is directly proportional to the temperature difference (ΔT), so a larger temperature difference results in a higher output voltage.

The temperature difference between the hot and cold reservoirs determines the maximum efficiency of a thermoelectric generator (TEG), according to the Carnot law. The maximum theoretical efficiency of a heat engine determines the upper limit of the efficiency of a thermoelectric generator (TEG). The maximum efficiency of a TEG is derived as follow:

$$\eta_{max} = 1 - \frac{T_c}{T_h} \qquad (2)$$

The Carnot efficiency equation gives the temperature difference between the cold side temperature (Tc) and the hot side temperature (Th), which determines the maximum theoretical efficiency of a TEG. So, the temperature difference is a key part of figuring out how efficient TEGs are at their best (as shown in Equation 2), while the thermoelectric properties of the materials used to make TEGs show how close they can get to their theoretical peak efficiency.

1.1. Research Gaps

Improving efficiency: Although thermoelectric generators (TEGs) show great potential as a sustainable energy solution, their current efficiency levels remain rather low. Future research may be directed towards the exploration and development of new materials or designs to increase the efficiency of TEGs, particularly for recovering waste heat at low temperatures. Real-world testing: Most of the contemporary research on TEGs has been conducted within controlled laboratory settings. Further research is required to test the feasibility of TEGs in real-world scenarios, such as providing energy for autonomous sensors or other low-power devices. Durability and reliability: TEGs have traditionally been employed in military and space applications due to their reliability and low maintenance requirements. However, there is limited knowledge about the long-term durability and reliability of TEGs in alternative settings. Further investigation is warranted to examine the long-term performance of (TEGs) and their response to various environmental conditions. Cost-effectiveness: The cost of manufacturing and implementing TEGs can be a significant barrier to their widespread adoption. Future research may explore some ways to reduce the cost of TEGs, such as using cheaper materials or more efficient manufacturing processes. Applications in developing countries: TEGs have the potential to provide a reliable source of energy in areas characterized by limited access to electricity. However, the majority of prior research on TEGs has been conducted in developed countries. Future research may be conducted to investigate the feasibility and potential benefits of TEGs in developing countries.

1.2. Literature Survey

"The effect of temperature on thromboelastographic parameters in healthy individuals"[1]: This study evaluated the effect of temperature on the parameters of TEG in a sample of 40 healthy individuals. The authors found that lower temperatures were associated with prolonged R-time and K-time as well as decreased MA (Maximum Amplitude) and angle. They concluded that temperature exerts a significant impact on the parameters of TEG and hence should be taken into account during the interpretation of experimental findings. "The Impact of Hypothermia on Coagulation Parameters in Trauma Patients"[2]: This study evaluated the impact of hypothermia on coagulation parameters, including TEG parameters, in 189 trauma patients. The authors found that hypothermia was associated with prolonged R-time and K-time as well as decreased MA and angle. They concluded that TEG can be a useful tool for monitoring the impact of hypothermia on coagulation function in trauma patients. "Temperature-Dependent Changes in thromboelastographic in Cardiac Surgery Patients": This study evaluated the effect of temperature variations on the TEG parameters in a sample of 100 individuals undergoing cardiac surgery. The authors found that lower temperatures were associated with prolonged R-time and K-time as well as lower MA and angle. They concluded that temperature has a significant impact on TEG parameters and should be taken into account while interpreting the results. "Thromboelastography in Cardiac Surgery: A Review of the Current Literature": This review article examined the use of TEG in cardiac surgery patients. The researchers discovered that TEG has the potential to yield valuable insights into the coagulation process during cardiac surgery, specifically in relation to the effects of hypothermia. However, they noted that further research is needed to establish the optimal TEG parameters for monitoring coagulation function in cardiac surgery patients. "Effect of Hypothermia on Thromboelastography in Cardiac Surgery: A Meta-analysis": This meta-analysis evaluated the effect of hypothermia on TEG parameters in cardiac surgery patients. The researchers discovered that hypothermia was associated with prolonged R-time and K-time as well as decreased MA and angle. They concluded that TEG can be a useful tool for monitoring coagulation function during hypothermic cardiac surgery. "The Effect of Temperature on Thromboelastography: A Systematic Review and Meta-analysis" [3]: This systematic review and meta-analysis evaluated the effect of temperature on TEG parameters in various populations. The authors revealed that lower temperatures were associated with prolonged R-time and K-time and decreased MA and angle. They concluded that temperature exerts a significant impact on the parameters of TEG and should be taken into consideration during the interpretation of experimental findings.

"The Effect of Temperature on Thromboelastography Parameters in Patients with Acute Traumatic Coagulopathy" [4]: This study evaluated the effect of temperature on TEG parameters in 28 patients with acute traumatic coagulopathy. The researchers suggested that lower temperatures were associated with prolonged R-time and K-time and decreased MA and angle. They concluded that temperature should be taken into consideration during the interpretation of TEG results in trauma patients. "The Effect of Temperature on Thromboelastography in Cardiac Surgery: A Retrospective Study" [5]: This study evaluated the effect of temperature on the parameters of TEG in a sample of 88 patients undergoing cardiac surgery. The authors found that lower temperatures were associated with prolonged R-time and K-time as well as decreased MA and angle. The researchers reached the conclusion that the interpretation of TEG results in patients undergoing cardiac surgery should take into account the variable of temperature. "Effects of Temperature on Thromboelastography in Patients with Liver Disease Undergoing Liver Transplantation" [6]: This study aimed to assess the effect of temperature on TEG parameters in a cohort of 68 individuals with liver disease who were undergoing liver transplantation. The authors found that lower temperatures were associated with prolonged R-time and K-time and decreased MA and angle. They concluded that temperature should be taken into account while interpreting TEG results in patients undergoing liver transplantation. "The Effect of Temperature on Thromboelastography Platelet Mapping in Cardiac Surgery": The objective of this study was to assess the impact of temperature on TEG platelet mapping parameters among a cohort of 50 patients undergoing heart surgery. The authors found that lower temperatures were associated with decreased platelet function. The researchers reached the conclusion that the inclusion of temperature as a factor is necessary in the interpretation of TEG platelet mapping outcomes among patients undergoing heart surgery. "The Effect of Temperature on Thromboelastography in Cardiac Surgery: A Systematic Review and Meta-analysis": This systematic review and meta-analysis evaluated the effect of temperature on TEG parameters in the patients undergoing cardiac surgery. The authors found that lower temperatures were associated with prolonged R-time and K-time and decreased MA and angle. They concluded that temperature should be considered when TEG results of cardiac surgery patients are interpreted. "The Impact of Hypothermia on Thromboelastography in Patients Undergoing Spine Surgery" [7]: This study evaluated the effect of hypothermia on TEG parameters in a sample of 50 patients undergoing spine surgery. The authors found that hypothermia was associated with prolonged R-time and K-time as well as decreased MA and angle. They concluded that temperature should be taken into account during the interpretation of TEG results in spine surgery patients. "Thromboelastography and Platelet Function in Patients with Coronavirus Disease 2019 (COVID-19)"[8]: This study evaluated TEG and platelet function in patients with COVID-19. The researchers discovered that individuals diagnosed with COVID-19 exhibited hypercoagulable thromboelastography (TEG) characteristics and heightened platelet activation. They suggested that TEG can be a useful tool for monitoring coagulation function in COVID-19 patients. A well-designed interfacial contact was also utilised in order to achieve a low contact resistance and mitigate chemical dispersion. Tellurium-free materials enabled a high thermoelectric module efficiency of 8% at a heat-source temperature of $T < 550$ K. The antimonides used in this study consist of constituent elements that are comparatively cheaper and more abundant than those of conventional Bi_2Te_3-based modules. This characteristic has promising prospects for enhancing the efficiency of recovering low-grade waste heat. In Zhao, et al. [9], the study does not explicitly state any significant limitations or potential concerns pertaining to the used methodologies or the obtained results. The study does not provide a clear articulation of any notable limitations or potential concerns pertaining to the employed methodologies or the obtained outcomes. The authors investigate the usage of liquid evaporation heat transfer to improve a thermoelectric generator's (TEG) performance for directly transforming heat energy into electricity. The experiment compares the TEG performance under different modes of heat transfer, including free and forced convection with and without fins. The results show that adopting forced liquid evaporation convection can significantly improve TEG voltage variation by 435.9% compared to free convection without fins [10]. The method used in this study involves the measurement of the output voltage, output power, and efficiency of the TEG in relation to varying temperatures. The TEG was tested under different temperature conditions ranging from 25°C to 150°C, and subsequent measurements were conducted to assess and contrast its performance parameters. The results showed that there is a positive correlation between temperature and the output voltage, power, efficiency and the TEG. However, this relationship is only observed up to a specific threshold, after which these parameters exhibit a decline. The highest output power and efficiency were obtained at 100°C [11]. This method involves synthesizing the graphene-CuO composite material through a hydrothermal process followed by a spark plasma sintering technique. The thermoelectric properties of the composite material were then characterized by measuring the electrical conductivity, Seebeck coefficient, and thermal conductivity. The results showed that the graphene-CuO composite material exhibited a higher Seebeck coefficient and lower thermal conductivity than pure CuO, indicating enhanced thermoelectric performance [12].

2. Methodology

The Performance of thermoelectric materials is measured by a figure of merit, denoted as (Z), (as described in Equation 3), which is defined as:

$$Z = \frac{\alpha^2}{\kappa\rho} \qquad (3)$$

In thermoelectric applications, a material with a high Seebeck coefficient, low heat conductivity, and low electrical resistance will perform better.

As shown in Figure 1, a thermoelectric generator (TEG) converts heat into electrical energy through the Seebeck effect using three primary components: a thermoelectric module, a heat source, and a cold sink. The module comprises a pair of semiconductor legs, one n-type and one p-type, which are positioned between a hot plate and a cold plate. These plates are maintained at different temperatures as thermal conductors and electrical insulators. The metal connecting plates, which are represented in grey, are deemed insignificant in the model. When a temperature gradient exists, an electric current is observed to flow through the circuit.

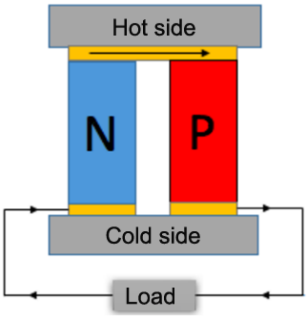

Figure 1.
Basic TE battery.

Multiple thermocouples are commonly interconnected in order to compensate for the low voltage output of a single semiconductor thermocouple, as illustrated in Figure 2. These thermocouples are electrically connected in series and thermally connected in parallel to achieve an overall higher output. The aforementioned arrangement is widely employed in contemporary practical thermoelectric generator (TEG) applications.

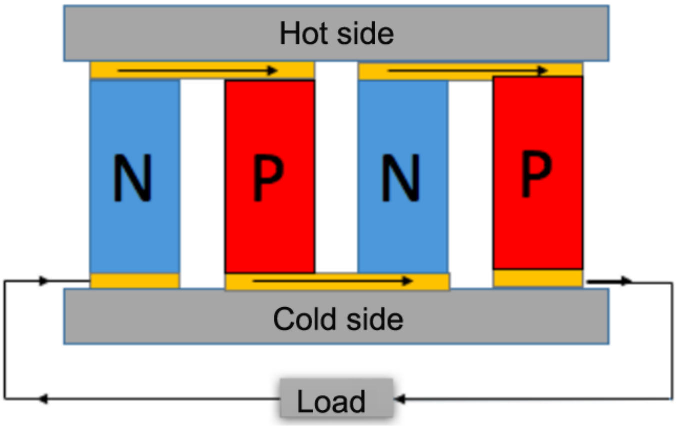

Figure 2.
Example of a paralleled TE battery.

Multiple thermoelectric materials are commonly employed in a sequential arrangement within a single leg to further boost efficiency, as seen in Figure 3. When it comes to getting the most out of your resources, this segmented leg design is hard to beat. This technique demonstrates its effectiveness in scenarios where a significant temperature gradient exists, as the figure of merit exhibits considerable variation over the temperature range.

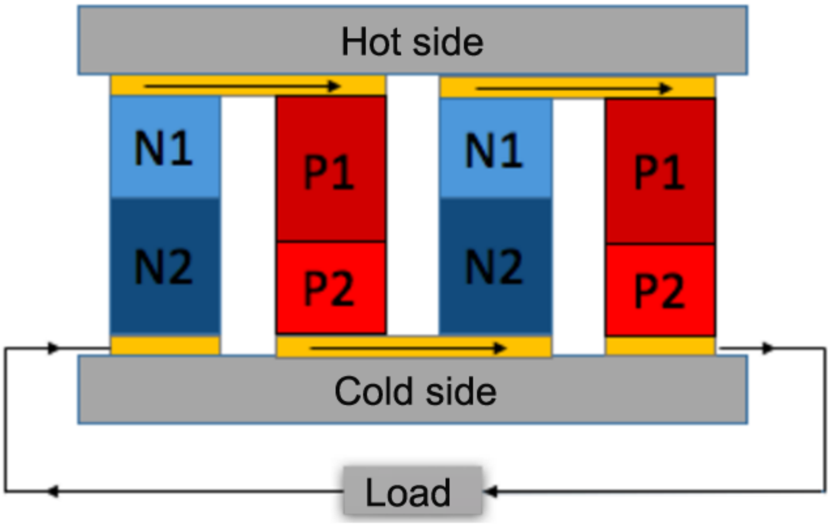

Figure 3.
Paralleled, segmented TE battery.

Although the theory underlying the construction of a thermoelectric generator (TEG) is straightforward, the practical implementation of thermoelectric energy for the purpose of energy harvesting remains constrained. This is primarily because TEGs have a low-grade energy source, resulting in low conversion efficiency (typically 5-10%). Therefore, TEG research has primarily focused on developing methods to overcome this efficiency limitation. Several studies have been conducted to improve the thermoelectric performance of materials [2], investigate thermoelectric compatibility [6], optimize generator geometry [4], and other related topics.

2.1. Low Temperature TEGs

Additionally, TEGs operating at low temperatures provide considerable potential for utilization in refrigeration and cooling systems. This phenomenon is known as thermoelectric cooling, wherein an electric potential difference is supplied to a thermoelectric material, resulting in the absorption of heat from one side and its subsequent release to the other side. This effect can be used to cool electronic components or small enclosures. However, the efficiency of thermoelectric cooling is currently low compared to traditional cooling methods, so further research is required to improve its performance.

Researchers have demonstrated different uses of low-temperature thermoelectric generators (TEGs). For instance, a TEG was built to capture waste heat from a motor. This TEG effectively produced a substantial output voltage by employing a series configuration of 10 modules. Although the system's maximum output power of 0.25W surpasses that of comparable goods, it was considered to be large and inefficient due to insufficient heat isolation. Another application involved the development of wearable TEG that works between 22°C to 57°C, and produce an open-circuit voltage of 10.5mV on the wrist. Although the TEG is powered by an LED, it requires further advancements to support sophisticated devices. This technology has the potential to be utilized in the fields of body monitoring and healthcare. Additionally, a TEG capable of harnessing waste heat from cooking processes and converting it into electrical energy to charge cell phones was demonstrated. This TEG utilized a DC-DC boost converter to enhance the output voltage to 5V. The TEG was cost-effective, simple in design, and performed well, operating between 300°C to 3000°C.

2.2. Modelling of TEG

The COMSOL Multiphysics software is used to stimulate a segmented and cascaded TEG, which lets precise temperature and potential be calculated without having to average thermoelectric properties, which is what is usually needed when doing calculations by hand. Figure 4 demonstrates the structure of TEG models. Red and blue thermoelectric couplings are placed between grey AIN plates and copper electrodes (yellow).

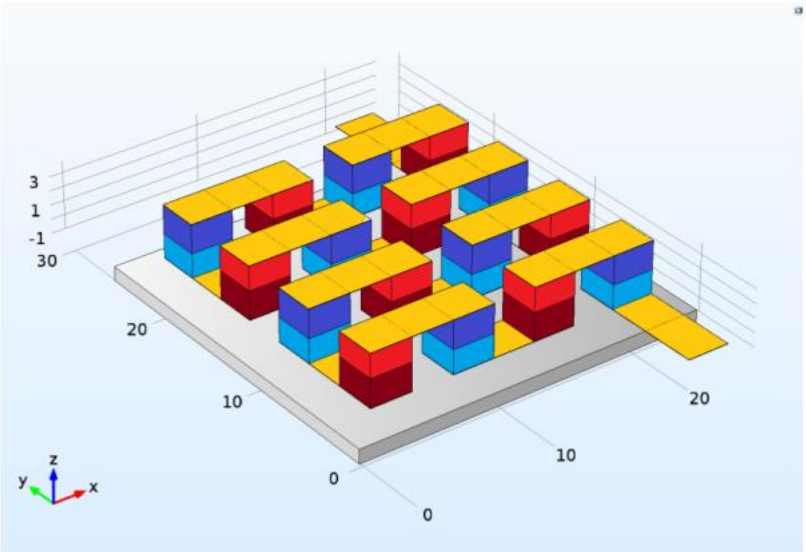

Figure 4.
COMSOL segmented TEG model using Cu electrodes.

Two 25X25X1 mm^{3}aluminum nitride (AIN) plates link the thermoelectric couplings for superior heat conductivity and electrical isolation. Wires are thin 3X5X0.03mm^3 Cu electrodes on one side of each AIN plate. The AIN plates and Cu electrodes are positioned between the thermoelectric couplings, each leg measuring 3X3X3.7mm^3. $Bi_{0.3}Sb_{1.7}Te_3$ and Zn_4Sb_3 segments make up the p-type legs, whereas Bi_2Te_3 and $PbSe_{0.5}Te_{0.5}$ segments make up the n-type legs. In order to evaluate the efficacy of the model, a load resistance is interconnected with the output of the thermoelectric generator (TEG). Although it is not possible to directly set a load resistance in COMSOL, it can be achieved by defining the materials' properties. By manipulating the electrical conductivity of the customized material, any desired resistance value can be obtained by

$$R = \frac{l}{A\sigma} \quad (5)$$

The specified load resistance has a size of 1mm (length) x 10mm (cross-sectional width) x 1mm (cross-sectional height).

2.3. Properties of Materials

Thermoelectric materials, including Bi2Te3, PbSe0.5Te0.5, Bi0.3Sb1.7Te3, and Zn4Sb3, as well as AIN and copper connections, are employed in the construction of the TEG models. In this case, the load is made of a special material whose attributes have been established in COMSOL. The selection of a random number for the R load is employed due to the lack of influence of the electrical conductivity of the connection materials on the system. The remaining factors of the load will replicate the characteristics of copper.

3. Results and Computation

The experiment is conducted at a constant temperature differential of $\Delta T = 296K$.

The hot side of the TEG is maintained at a temperature of 592K, while the cold side is kept at 296K, as illustrated in Figure 5.

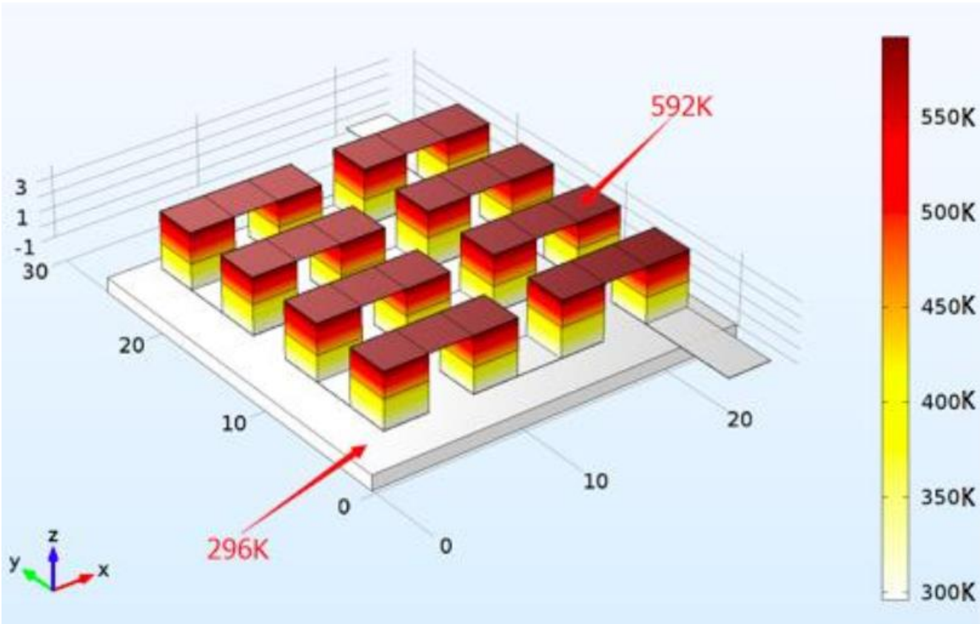

Figure 5.
Temperature distribution diagram.

Figure 6, shows the TEG as a DC voltage source (Vo) and an internal resistance (R0). This can be used to make a model of how the TEG works in an electrical circuit.

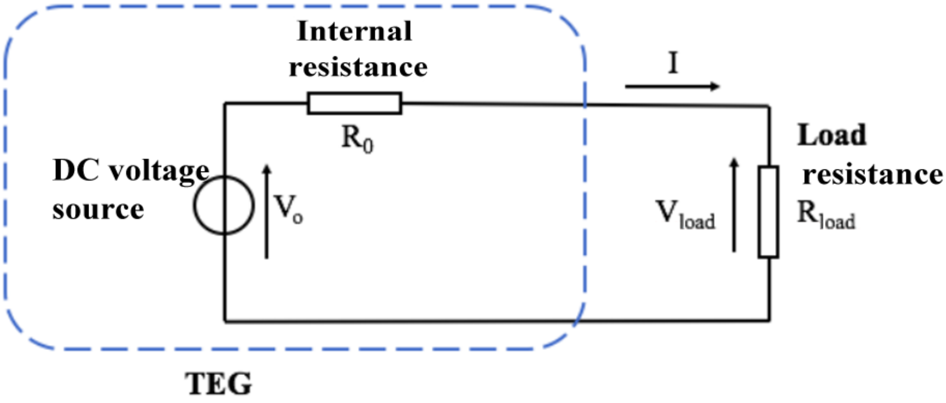

Figure 6.
Equivalent electrical model of the TEG.

COMSOL calculates equivalent source open-circuit voltage.

$$V_0 = \int_{Tc}^{Th} \alpha(T)dT \qquad (6)$$

According to Figure 7, when one terminal of the TEG is grounded, the potential of the other terminal is measured to be 0.9445V. The open-circuit voltage is measured to be 0.94V for a temperature differential of 296K.

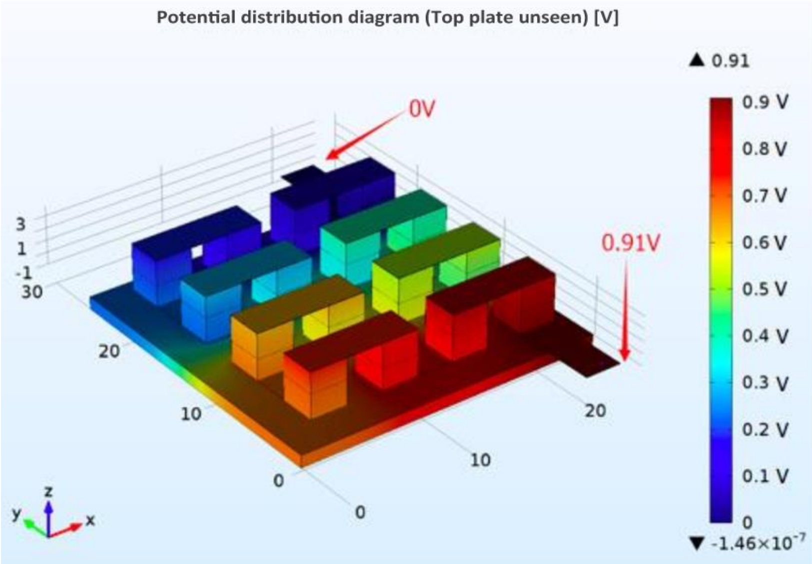

Figure 7.
Diagram showing open-circuit potential distribution.

The electrical resistance of a segmented TEG consists of three components: the resistance of the segmented legs (R_m), the interfacial resistance (R_i), and the inherent resistance (R_0). However, for this study, the interfacial resistance was neglected as its value was deemed negligible ($Ri \approx 0$) and R0 was assumed to be equal to Rm. Resistance is inherent. R0 is calculated by

$$R_0 = \int_0^L \frac{l}{A\sigma(l)} dl = \int_{Tc}^{Th} \frac{l}{A\sigma(T)dT} * \frac{dT}{dl} = \int_{Tc}^{Th} \frac{l\rho(T)}{AdT} * \frac{dT}{dl} \qquad (7)$$

In this context, the symbol A represents the cross-sectional area, l represents the length of the thermoelectric leg, and is the reciprocal of the electric conductivity. The value of the gas constant R_o at a temperature of 296K is around 1.1.

The open circuit voltage V_o and intrinsic R_0 resistance are constant as long as the temperature difference is constant because thermoelectric characteristics are temperature-dependent. Generator efficiency is commonly described below.

$$\mu_t = \frac{P}{Q_H} \qquad (8)$$

In the given context, the variable P represents the quantity of power generated, while QH denotes the quantity of power supplied thermally.

The highest possible output may be expressed as:

$$P_{max} = \frac{V_o^2}{4R_0} \qquad (9)$$

The maximum power that may be generated has been discovered to be 188.2 (mW). By using Equation 7, we are able to determine that the efficiency is 1.66%. The TEG's operational parameters are shown in Table 1. The COMSOL model and Li's findings have a lot in common and agree with each other quite well. The difference in their estimates is close to 10%, which is a tolerable level of deviation.

Table 1.
The results of the simulation model's testing are shown in the table below.

Parameter	Model for simulation	Li's result	Error
Voltage in an open circuit	0.92V	0.83V	10.9%
Innate resistance	1.09 Ω	1.2Ω	8.1%
Maximum output power	187.2 mW	155.8 mW	10.7%
Greatest effectiveness	1.65 %	1.43%	8.9%

3.1. Raising Temperature Difference

The output voltage varies with the temperature difference. As a result, increasing the temperature difference would usually boost the output voltage, V_o. Given the temperature-dependent nature of intrinsic resistance, it is imperative to investigate its fluctuations. We might also use simulation to see how temperature differences affect output power P_m and conversion ŋ efficiency.

As the temperature increased from 276K to 356K, the obtained results were then analyzed and presented in Table 2, which compares the performance of the original model with the revised model. There is a notable augmentation in the output power; nevertheless, the efficiency does not exhibit a commensurate improvement. The increase in working temperature leads to a corresponding rise in input power, hence causing a decline in efficiency.

Table 2.
The results of the test after the temperature went up.

Parameter	Original model ΔT=296K	Improved model ΔT=356K	Increasing
Voltage in an open circuit	0.92V	1.02V	+0.21
Innate resistance	1.09 Ω	0.89Ω	-0.2
Maximum output power	187.2 mV	364.5mV	+167.5mV
Greatest effectiveness	1.65 %	1.08%	+0.48%

3.2. Selecting Thermoelectric Materials

The investigation identified a number of material properties, such as the electrical conductivity of PbSe0.5Te0.5, that were in need of enhancement. Materials included in the first model are listed in Table 3, along with their thermoelectric characteristics. PbSe0.5Te0.5 has a low merit rating compared to the other three materials. The primary rationale for this phenomenon is that the electric conductivity of this material is approximately 10 times inferior to that of other substances. A sufficient Seebeck coefficient is not enough to compensate for the energy it uses.

Table 3.
Thermoelectric materials' thermoelectric characteristics.

Material	+/-	Conductivity of heat (W/m/K)	Seebeck Coeffective (V/K)	Conductivity to electricity (S/m)	Meritorious figure	Consideration of compatibility
Bi0.3Sb1.7Te3	+	0.83	206x10-6	$5.7x10^4$	2.91x10-3	5.6
Zn4Sb3	+	0.92	142x10-6	6.7x104	1.47x10-3	4.5
PbSe0.5Te0.5	-	0.87	-295x10-6	0.8x104	0.80x10-3	1.25
Bi2Te3	-	0.91	-134x10-6	11.8x104	2.13x10-3	6.5

The research demonstrates that the electrical connection quality between the various pieces is subpar. The resistance distribution along n-type segments is shown in Figure 8. The transition from PbSe0.5Te0.5 to Bi2Te3 segments occurs through a stepwise procedure. The resistance observed at the interface can be attributed to incompatibility. According to Snyder, if the compatibility factors of PbSe0.5Te0.5 and Bi2Te3 differ by more than 2, they are considered chemically incompatible. For enhanced compatibility in the positive legs, Zn4Sb3 would be used in this context.

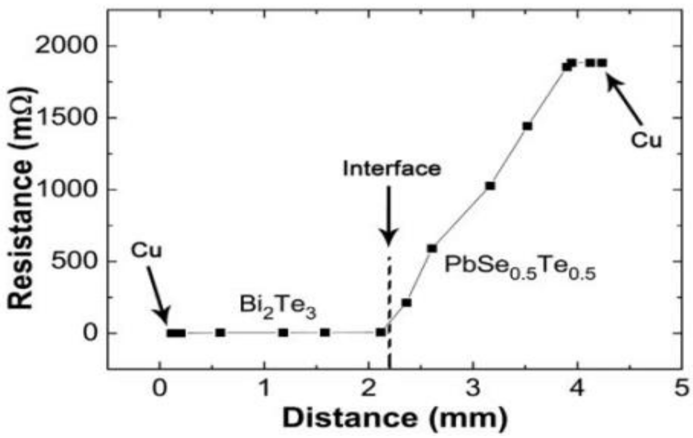

Figure 8.
Resistance along the segments of an n-type TE.
Note: Data derived from Yu, et al. [13].

Finding a material that is both thermoelectrically active and chemically compatible with Bi2Te3 is a primary goal. A total of six materials are mentioned and evaluated in terms of their potential for excellent performance. Alloy 75% Bi2Te3, 25% FeSi2 [14], Bi2Se3 [15], Ce0.45Co 0.25 Fe1.5Sb12[16], (Bi,Sb)2Te3[17], BTS/Al2O3 [17], BTS[17], and (Bi,Sb) 2Te3[17]. Table 4 displays the material characteristics.

The replacement for PbSe0.5Te0.5 is the alloy 75% Bi2Te3, 25% Bi2Se3. Table 5 displays the characteristics of modern materials.

Table 4.
A comparison of a few different types of electrical materials (Temperature = 450K).

Material	Conductivity of heat (W/m/K)	Seebeck Coeffective (V/K)	Conductivity to electricity (S/m)	Meritorious figure	Consideration of compatibility
(Bi,Sb)2Te3	1.2	-227x10-6	4.5x104	2.18x10-3	3.8
BTS	0.8	-179x10-6	5.1x104	1.83x10-3	4.4
BTS/Al2O3	0.9	-210x10-6	5.1x104	2.5x10-3	4.8
Ce0.45Co 0.25 Fe1.5Sb12	1.4	-119x10-6	7.9x104	0.8x10-3	3.1
FeSi2	1.1	-136x10-6	1.4x104	0.3x10-3	1.1
75% Bi2Te3 25% Bi2Se3	1.24	-180x10-6	5.7x104	2.04x10-3	4.9

Table 5.
The thermoelectric properties of thermoelectric materials upon replacement at 450 Kelvin (T=450K).

Material	Conductivity of heat (W/m/K)	Seebeck Coeffective (V/K)	Conductivity to electricity (S/m)	Meritorious figure	Consideration of compatibility
75% Bi2Te3 25% Bi2Se3	1.25	-180x10-6	5.7x104	2.05x10-3	4.8
PbSe0.5Te0.5	0.87	-295x10-6	0.8x104	0.80x10-3	1.25
Bi2Te3	0.92	-135x10-6	10.8x104	2.14x10-3	6.6

Table 6 presents the outcomes of the examinations conducted on the conventional TEG, the adapted variant, and the initial model. The materials under consideration include (Zn4Sb3, Bi2Te3). A temperature differential of 296 kelvin is used to test each model (Section 3's model). In terms of output power and overall efficiency, the traditional TEG is superior. However, the thermoelectric characteristics of Zn4Sb3 and Bi2Te3, are not suitable for the whole range of operating temperature. So, the performance is not nearly as excellent as the one that was partitioned. To achieve an equivalent output voltage, a higher number of thermoelectric modules must cascade due to the lower voltage in the open circuit. The new alloy that was introduced in the segments has thermoelectric characteristics that are more comparable to those of Zn4Sb3, and it functions more effectively. Significant advancements have been observed in both the output power and efficiency, with the latest model exhibiting a performance that is about four times superior to its predecessor.

Table 6.
Test results after replacement of thermoelectric material.

Parameter	Original model	TEG conventional	Model improvement
Voltage in an open circuit	0.92V	0.64V	0.65V
Innate resistance	1.09 Ω	0.29Ω	0.3Ω
Maximum output power	187.2 mV	329.65mV	702.04mV
Greatest effectiveness	1.65 %	2.91%	7.02%

4. Conclusion

In conclusion, this study has presented a simulation model of a segmented thermoelectric generator (TEG) designed to recover waste heat at low temperatures. The simulation model was built to match the physical dimensions and material composition of a real-world TEG, and the results were validated against a prototype model. The study found that there is significant room for improvement in the baseline model of the TEG, and several approaches were examined in order to augment power production and increase the conversion efficiency. The initial method investigated was to increase the TEG's operating temperature, which resulted in a higher output voltage and power, but at the expense of an elevated intrinsic resistance within the TEG. The second methodology involved replacing the TEG's thermoelectric materials, and the study revealed that substituting the thermoelectric material PbSe0.5Te0.5 with an alloy consisting of 75% Bi2Te3 and 25% led to a significant increase in both conversion efficiency and output voltage. The third approach was to reconstruct the TEG's shape, which also led to an increase in output power and conversion efficiency.

Overall, the study shows that there is significant potential for improving the efficiency of TEGs in recovering low-temperature waste heat. The simulation model's results suggest that a number of methods, such as raising the operating temperature, switching thermoelectric materials, and rebuilding the TEG's shape, can be used together to greatly improve the efficiency of power generation and conversion. These results have the potential to be utilised in the advancement of novel thermoelectric generators (TEGs) designed for the purpose of charging battery cells or supercapacitors employed in autonomous sensors. In conclusion, the study highlights the importance of simulation modeling in the development of TEGs and the potential for improving their efficiency in harnessing waste heat. Subsequent investigations may prioritise the refinement of the amalgamation of methodologies elucidated in this work, with the aim of augmenting power generation and enhancing the efficacy of energy conversion. This can lead to the development of more efficient and environmentally friendly energy sources, contributing to ongoing efforts to reduce carbon emissions and combat climate change.

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