



EXPERIMENTAL STUDY ON THE SYNERGISTIC EFFECTS OF COOLING METHODS AND HEAT SINK DESIGN ON THERMOELECTRIC GENERATOR PERFORMANCE

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Abstract

Thermoelectric generators (TEGs) are a promising option for recovering waste heat into electricity, particularly in low-power applications. However, their performance is often limited by poor heat management, inefficient cooling at the cold side, and substandard material choices. This paper investigates the performance of different heat sink configurations which are the, High-Density Fin Aluminum Alloy (HDFA) and Extruded Aluminum Fin Alloy (EAFA), on a thermoelectric generator (TEG) module and tested under different temperature differences and cooling options such as the ice cooling and fan cooling. The study analyzes the impact of temperature difference on voltage, current, and power output of the thermoelectric generator to determine the most effective heat sink configuration and cooling technique for optimizing thermoelectricity generation. Experimental results showed that the HDFA consistently performed better than the EAFA across all trials which demonstrates higher voltage, current, and power output. Additionally, ice cooling was more effective than fan cooling which generates more power by maintaining higher temperature difference. Results also indicated a direct correlation between power output and temperature difference, further validating how important heat management is in thermoelectric energy conversion. Despite these promising results, some limitations were found such as, controlled laboratory conditions that was used in the experiments that may not fully represent real-world applications. Further research should explore alternative thermoelectric materials, hybrid cooling techniques, and dynamic environmental conditions. These results contribute to the advancements of thermoelectric generators (TEGs) modules, while further supporting their applications into renewable energy systems. Finally, selecting better heat sink materials and cooling techniques would help accelerate the technologies for waste heat recovery and renewable energy systems.

Keywords: Thermoelectric Generator (TEG), Heat Sinks, Fan cooling, Ice cooling, Temperature difference.

Nomenclatures

ΔT	Temperature difference across the module in K or °C
T_h	Hot-side temperature measured in K or °C
T_c	Cold-side temperature measured in K or °C
Q	Heat flow across the TEG module measured in W
A	Surface area of the module measured in m^2
d	Thickness of the module measured in meters
k	Thermal conductivity in W/m·K
σ	Electrical conductivity, S/m

Greek Symbols

α	Seebeck coefficient, V/K
η	Heat-to-electricity conversion efficiency

Abbreviations

TEG	Thermoelectric Generator
H DFA	High-Density Fin Aluminum Extruded Aluminum Fin Alloy
EAFA	

Introduction

Across every industrial sector, energy is being lost as waste heat globally. A significant portion between 15% and 50% of their primary energy is being lost to the environment and 70% of the household energy consumption are being wasted to the ambient surroundings (Holyk, 2023). This energy loss leaves a critical gap with the urgent need for efficient waste heat recovery systems in order to be able to run energy sustainability. Waste heat recovery is not only about conserving energy but also reducing greenhouse gas emissions in the environment (Energy Tech Review, 2024; Globe Newswire, 2024).

Thermoelectric generators (TEGs) can address this energy crisis by converting the waste heat energy directly into electricity through the Principle of Seebeck effect (Talebjedi, Khosravi and El Haj Assad, 2023). Seebeck effect explains why an electric potential difference can be generated when a temperature difference exists across two dissimilar thermoelectric materials (Ali, Ishak and Ghazali, 2023; Nourdanesh and Kantzas, 2023). TEG modules typically consist of p-type and n-type semiconductors, whereby the heat flows from the hot side to the cold side, which enables it to drive charge carriers and produce usable electricity. (Liu et al., 2023).

One particular feature of TEGs are their solid-state structure, which means they do not have any moving parts which makes it less costly to maintain, can operate silently, and they are of high durability which makes them suitable for off-grid and remote low power applications (Jaldurgam and Ahmad, 2022; Hsu et al., 2011; Coherent Market Insights, 2025). In addition, their compact nature allows for easy scalability in different systems, from industrial heat recovery units to small household appliances (Coherent Market Insights, 2025; Iversen, 2021). Despite their promising features, the efficiency of TEGs remains challenging.

Most of the available TEGs in the market have a conversion efficiency of only about 6–7% under practical conditions and that is far lower than other green energy alternatives like solar or wind energy (Bos, 2012). This inefficiency is as a result of several factors, one of which is the limitation in achieving high figure of merit (ZT) values which correspond to the efficiency of thermoelectric generators. Thermoelectric materials with high thermal conductivity tend to dissipate heat rather than convert it into electricity, while those with high electrical conductivity may still suffer from excessive heat loss which would reduce the overall power output of the TEGs.

In practical applications, poor heat contact, substandard heat sinks designs, and poor cooling techniques have also affected the efficiencies of the TEGs (Kumari, Singh and Dasgupta, 2025). Moreover, TEG performance heavily relies on the thermal properties of the materials being used which are very expensive and scarcely available (Chen *et al.*, 2024). Given these limitations, maximizing the readily available TEG modules by improving the heat sink configurations and cooling techniques is very crucial in order to enhance the power output making the TEGs more viable for real-world applications. A key factor influencing TEG performance is the temperature difference (ΔT) across the module, as voltage output is directly proportional to the differential between the hot and cold sides (Singh, 2023). Efficient heat management, through better heat sinks and cooling techniques, plays a crucial role in maximizing this temperature difference in order to boost conversion efficiency.

Therefore, this paper investigates the thermoelectric performance of a single TEG module (HZ-14HV) sourced from Hi-Z Technologies, an American company that was tested under various conditions (Hi-Z Technology, 2025). we compared the voltage, current, and power output generated using two different heat sink materials—High-Density Fin Aluminum Alloy (HDFA) and Extruded Aluminum Fin Alloy (EAFA), and evaluated the impact of cooling mechanisms, specifically ice and fan cooling, on the temperature difference and overall TEG performance. The paper further provides supporting evidence between temperature difference and power output to identify the best heat management techniques for efficient thermoelectric energy harvesting. Finally, this research contributes to the advancement of TEG technology by demonstrating how material selection, cooling techniques, and heat sink design can enhance waste heat recovery and support the integration of TEGs into sustainable energy systems (Agoundedemba, Kim and Kim, 2023; Zoui *et al.*, 2020).

Materials and Methods

This research used a single thermoelectric generator module (HZ-14HV) which contains 49 Bismuth Telluride-based thermocouples arranged electrically in series and thermally in parallel. The module, gotten from Hi-Z Technologies, can run continuously up to 250°C and intermittently up to 400°C (Hi-Z Technology, 2025).

Two heat sink materials were tested: a High-Density Fin Aluminum alloy (HDFA) obtained from a Biolite Camp Stove (BioLite, 2025), and an Extruded Aluminum Fin alloy (EAFA) sourced locally. These were evaluated using two cooling mechanisms: Ice cooling to achieve wider temperature difference, and Fan cooling for a more stable heat removal continuously. All tests were conducted under controlled heating conditions with measured voltage, current, and temperature difference.

High-Density Fin Aluminum Alloy (HDFA) Heat Sink

The first heat sink used in this research is a high-performance aluminum alloy (Al-Mg-Si) heat sink which has a dense fin structure that was originally designed for the Biolite cook stove. The heat sink also features a semi-cylindrical fin arrangement, which maximizes convective heat dissipation by increasing surface area exposure to airflow. The nature of the heat sink material allows for better heat conductivity, improving efficient heat transfer from the hot side of the thermoelectric generator (TEG) to the surrounding environment. The fins are closely spaced to dissipate heat while maintaining a compact form factor. HDFA sinks are ideal for applications that demands maximum heat dissipation and can handle high-power electronic devices but are costlier and require more complex manufacturing. Figure 1 shows the HDFA heat sink, and Table 1 show the result of the element content of the HDFA heat sink carried out at the Engineering Material Development Institute (EMDI) in Akure, Nigeria.



Figure 1: High-Density Fin Aluminum Alloy (HDFA) Heat sink

Table 1: Element Content of HDFA Heat Sink

Element	Intensity	Content
Mg	0.0328	6.8782
Al	1.0000	85.4918
Si	0.0964	5.6885
Ti	0.0000	0.0000
Cr	0.0000	0.0073
Mn	0.0000	0.0355
Fe	0.0063	0.5330
Ni	0.0004	0.0572
Cu	0.0040	0.0731
Zn	0.0105	0.2458
Sr	0.0024	0.0016
Pb	0.0000	0.0000
Sn	0.0141	0.4190
Sb	0.0168	0.5590

Extruded Aluminum Fin Alloy (EAFA) Heat sink

The Extruded Aluminum Fin Alloy (EAFA) Heat sink is a passive cooling component designed to dissipate heat from electronic and electrical devices. This type of heat sink is manufactured through the extrusion process, which ensures uniform fin structures with high thermal conductivity. The parallel fin arrangement increases the surface area available for heat dissipation, enhancing natural or forced convection efficiency. Due to its lightweight

and corrosion-resistant properties, the EAFA is widely used in heat sink applications and it's commonly found in the West African markets. It offers cost- effective, durable, and reliable cooling, especially for passive cooling applications, but their heat efficiency is limited compared to the HDFA heat sinks. Figure 2 shows the EAFA heat sink and Table 2 shows the element content of the EAFA Heat sink.



Table 2: Element Content of EAFA Heat Sink

Element	Intensity	Content
Mg	0.0388	8.6705
Al	1.0000	89.5204
Si	0.0301	0.0000
Ti	0.0000	0.0000
Cr	0.0000	0.0077
Mn	0.0000	0.0371
Fe	0.0047	0.4492
Ni	0.0004	0.0599
Cu	0.0040	0.0545
Zn	0.0033	0.1602
Sr	0.0040	0.0000
Pb	0.0000	0.0000
Sn	0.0128	0.3941
Sb	0.0182	0.6364

Figure 2: Extruded Aluminum Fin Alloy (EAFA) Heat Sink

Thermoelectric Generator (TEG) Module (HZ-14HV)

The HZ-14HV Thermoelectric Generator (TEG) module is a high-performance heat-to-electricity conversion device. According to the Seebeck effect, this module can efficiently convert waste heat into usable electricity which makes it suitable for waste heat recovery applications. The HZ-14HV model is specifically designed for high-

temperature applications, which features robust semiconductor materials and better junctions to ensure stable performance under extreme conditions. Figure 3 shows the HZ-14HV TEG module and Table 3 shows the data sheet of this TEG module.

Figure 3: Thermoelectric Generator (TEG) HZ-14HV Module

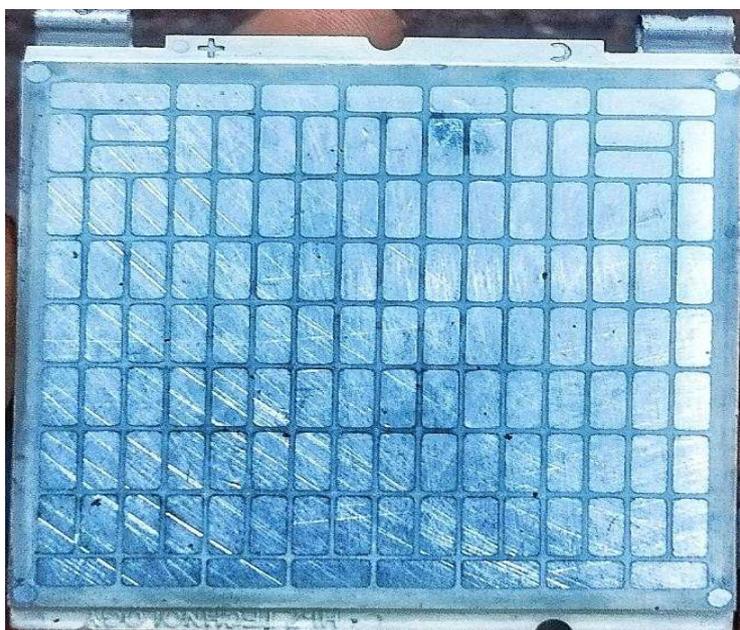


Table 3: HZ-14HV TEG Module Data Sheet

Parameter	Temperature Gradient	Minimum	Typical	Maximum
Power	200°C	14W	15W	16W
Open Circuit Voltage	200°C	2.8V	3.0V	3.2V
Matched load Voltage	200°C	1.4V	1.5V	1.6V
Current	200°C	8A	9A	10A
Mass		48g	49g	50g

Other materials and instruments used

For accurate heat and electrical measurements during the experiment, the following instruments were used:

- a). **Electric Hotplate:** This is the main source of heat supply and the temperature can be adjusted up to 400°C providing a stable heat source for the thermoelectric generator (TEG) module.
- b). **Thermal Interface Materials (TIMs):**
 - i. **Aluminum Wafers:** These were placed on both sides of the TEG module to smoothen the heat distribution and ensure uniform contact.
 - ii. **Thermal Grease:** This is a high-conductivity silicone-based thermal paste which was applied to minimize heat resistance and improve the conduction efficiency.
- c). **Measurement Instruments**
 - i. **Multimeter:** FNIRSI 2C23T 3-in-1 Digital Oscilloscope Multimeter was used. It has auto-ranging capability that can measure precise voltage and current values.
 - ii. **Thermocouples:** Type K thermocouples (temperature range up to 800°C) were used to monitor the hot and cold side temperatures of the TEG module.
 - iii. **Non-Contact Infrared Thermometer Gun:** This was used to measure the hot and cold side of the TEG without touching any hot surfaces. It can measure over 600°C

Experimental Design

This research investigates the optimization of thermoelectric generator (TEG) performance by analyzing the effects of different heat sink materials and cooling techniques on the voltage that can be generated from the waste heat. The primary objective was to assess the power output of the TEG module (HZ-14HV) under varying heat conditions. This offered various insights into its applicability for waste heat recovery. The experiment involved four different modes:

- a) **Mode 1:** The TEG module was placed between the hotplate (heat source) and the High-Density Fin Aluminum Alloy (HDFA) heat sink, with a 5V DC fan that was positioned behind the heat sink for cooling.
- b) **Mode 2:** The TEG module was placed between the hotplate and the HDFA heat sink, with a container of ice water placed behind the heat sink for cooling.
- c) **Mode 3:** The TEG module was placed between the hotplate and the Extruded Aluminum Fin Alloy (EAFA) heat sink, with a 5V fan for cooling.
- d) **Mode 4:** The TEG module was placed between the hotplate and the EAFA heat sink, with a container of ice water placed behind the heat sink for cooling.

Figures 4 and 5 show the setup for the four different modes

Figure 4: Experimental setup of the TEEG Placed between the hot plate and the HDFA heat sinks. (a) Mode 1 and (b) Mode 2



Figure 5: Experimental setup of the TEG placed between the hot plate and the EAFA heat sinks. (a) Mode 3 and (b) Mode 4



The voltage and current readings were taken at 3-minute intervals over a 60-minute duration using an FNIRSI 2C23T 3-in-1 Digital Oscilloscope Multimeter. The 3-minute interval was chosen in order to capture different variations in power output without introducing excessive data redundancy, while the 60-minute duration allowed the system to reach and maintain heat equilibrium under each mode. This duration also allows for the observation of performance stability over time.

The experiment systematically explored how transfer efficiency and cooling techniques can influence the voltage output in order to ensure more reliable and repeatable results. To simulate real-world conditions, the hotplate was heated gradually from 200°C to 400°C over a duration of 60 minutes. In the first cooling mode (Figure 4(a) and 5(a)), a bottle filled with ice water was placed on the aluminum alloy heat sink to facilitate water convection cooling.

In the second mode (Figure 4(b) and 5(b)), a 5V blower fan was placed adjacent to the heat sink to improve cooling efficiency. These cooling techniques were tested with both HDFA and EAFA heat sinks, leading to four distinct experimental conditions as shown in Figure 4 and 5.

Mathematical Assessment of TEG Performance

The performance of the thermoelectric generator (TEG) module used in this research can be mathematically determined using fundamental principles of thermoelectricity and heat transfer. The Seebeck effect, which governs the basic operation of a TEG module, states that a voltage is generated across a thermoelectric material when a temperature difference exists between its two ends. This relationship is given by:

$$V = \alpha \cdot \Delta T \tag{1}$$

Where **V** is the output voltage, **α** is the Seebeck coefficient, and **ΔT** is the temperature difference across the module. In the case of the HZ-14HV module, the maximum voltage measured was 2.5V with a temperature difference of 200°C (400°C hot side and 200°C cold side). Using this data, we can calculate the total Seebeck coefficient across the module as:

$$\alpha = \frac{V}{\Delta T} = \frac{2.5}{200} = 0.0125 \frac{V}{K} = 12500 \frac{\mu V}{K} \tag{2}$$

This value represents the cumulative Seebeck coefficient of all the thermocouples connected in series within the TEG module. To evaluate the electrical performance, the output power **P** is calculated as the product of the output voltage and current:

$$P = VI = 2.5 \times 4.6 = 11.5 W \tag{3}$$

Similarly, for HDFA with fan-assisted cooling (2.2 V, 4.1 A), the output power is:

$$P = 2.2 \times 4.1 = 9.02 W \tag{4}$$

These calculations are similar to the results gotten from the experiments and further establishes the influence of cooling techniques on electrical performance of TEG Modules.

The heat transferred through the TEG module can be estimated using the Fourier’s Law of heat conduction:

$$Q = k \cdot A \cdot \frac{\Delta T}{d} \tag{5}$$

Assuming, a thermal conductivity, **k** of 1.5 W/m·K (typical for Bi₂Te₃), TEG surface area **A** of

62 mm × 62 mm = 0.003844 m², Thickness **d** = 0.00508m and **ΔT** = 200 K;

$$Q = \frac{1.5 \times 0.003844 \times 200}{0.00508} = 227.02W \tag{6}$$

Hence, about 227 W of heat energy enters the module under stable conditions. Finally, the heat-to-electricity conversion efficiency **η** of the module is calculated from the ratio of power output to heat input.

$$\eta = \frac{P}{Q} \times 100\% \tag{7}$$

Given: P = 11.5W, Q = 120W

$$\eta = \frac{11.5}{227.02} \times 100 = 5.07\% \tag{8}$$

This is very close to the expected efficiency range of commercial TEG modules, typically between 4-6% under practical conditions (Attar et al., 2017).

Results and Discussion

Comparative Analysis of the Voltage and current Outputs gotten under Different Cooling Methods

Figure 6 and 7 shows the plot of the TEG performance under ice and fan cooling conditions using EAFA and HDFA heat sinks. The plots showed critical insights into improving the temperature difference that contributes to the overall conversion efficiency. It is observed that as the temperature difference (**ΔT**) increases, voltage and current outputs increase due to the Seebeck effect. However, the magnitude of these outputs significantly depends on the cooling technique used.

Ice cooling consistently performed better than fan cooling thereby maintaining a lower cold-side temperature which leads to a sharper temperature difference and better efficiency. The current output, in particular, shows a sharper increase than voltage, which highlights its greater sensitivity to the temperature variations.

Ice cooling performed better than fan cooling by maintaining a significantly lower cold-side temperature, thereby maximizing the temperature difference (ΔT) and improving the power output. While fan cooling effectively dissipates heat, it does not sustain as high a temperature difference which leads to comparatively lower voltage and

current output. The fan cooling method gives a more linear increase in output, whereas ice cooling shows a sharper rise, particularly at higher ΔT values. This establishes the critical role of the optimized cooling techniques in maximizing thermoelectric generation efficiency.

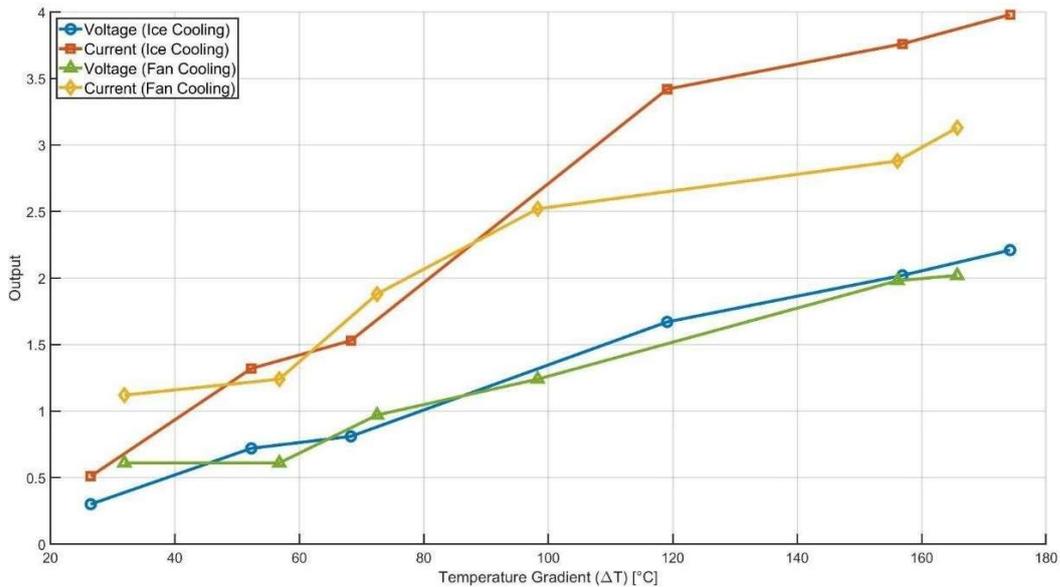


Figure 6: Voltage and Current plotted against temperature difference for Extruded Aluminum Fin Alloy (EAFA)

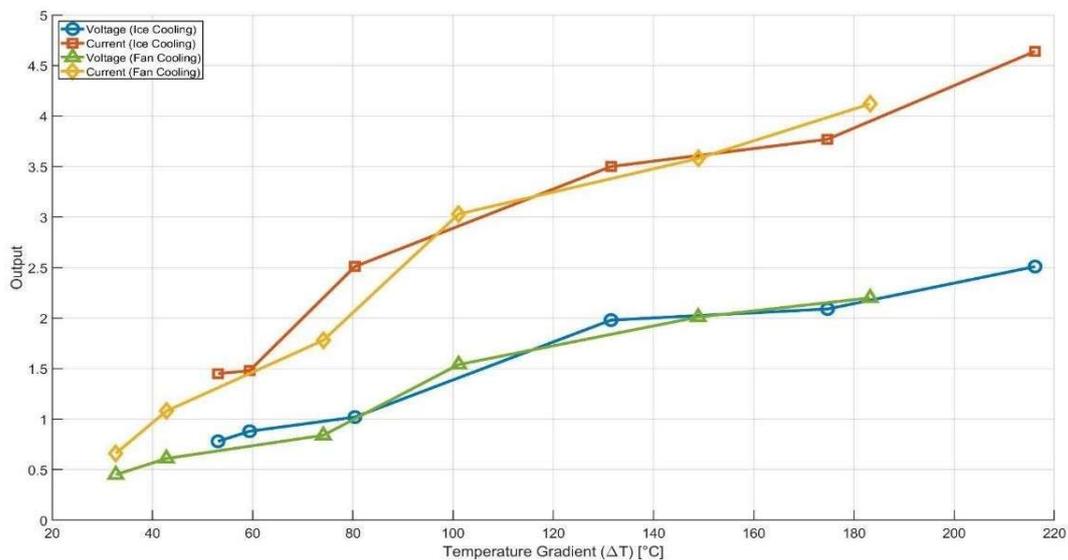


Figure 7: Voltage and Current plotted against Temperature Difference or High-Density Fin Aluminum Alloy (HDFA)

The Comparative Performance Analysis of HDFA and EAFA Under Ice and Fan Cooling

The performance comparison of HDFA and EAFA under both ice and fan cooling shows important insights into thermoelectric generation efficiency. In both cases, voltage and current increase with temperature difference (ΔT), but the rate of increase is significantly different based on the cooling

technique. Ice cooling, which maintains a lower cold-side temperature, results in a sharper rise in voltage and current which maximizes the temperature difference and leads to more output. Fan cooling, while effective in dissipating heat, produces a more gradual increase due to its limited ability to sustain an extreme temperature difference ΔT . Figure 8 and 9 shows the plot of this investigation.

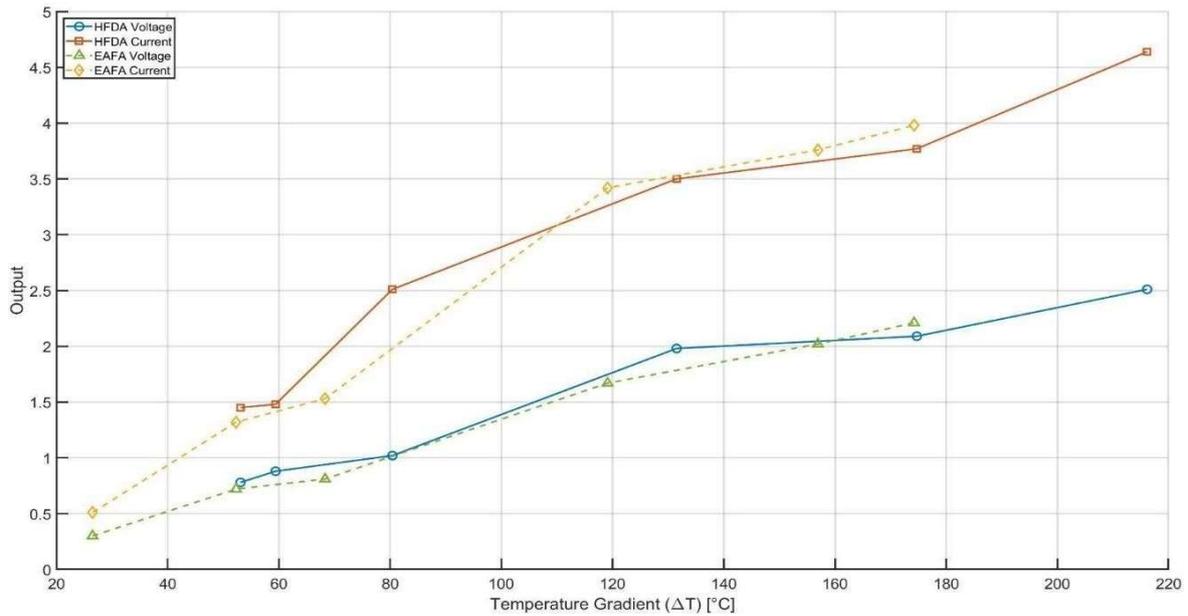


Figure 8: Voltage and Current Performance Comparison of HDFA and EAFA under Ice Cooling

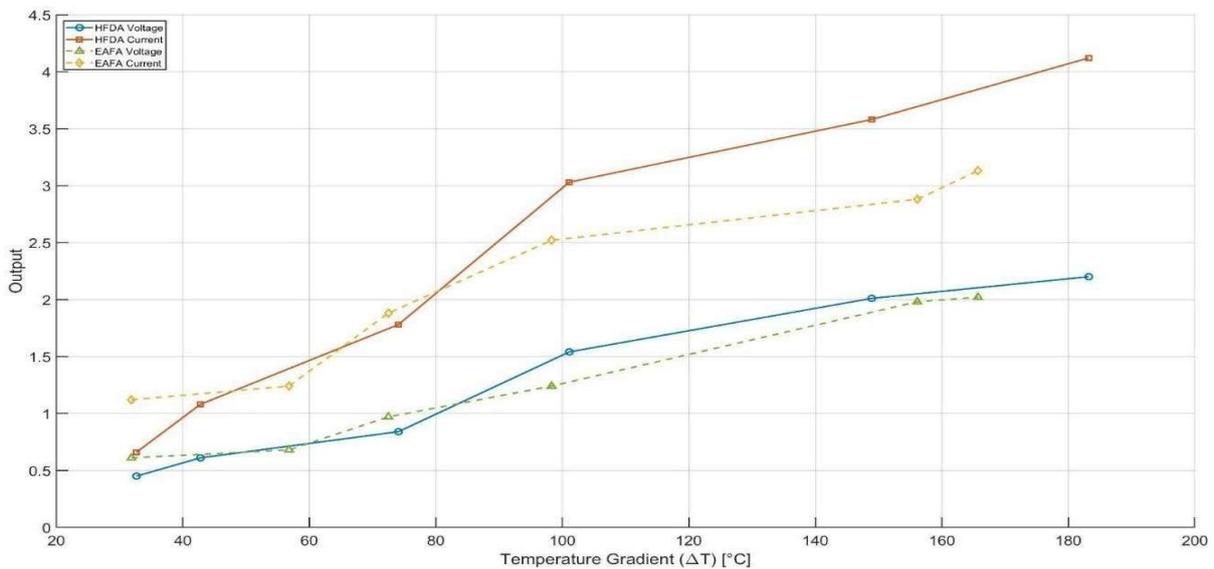


Figure 9 Voltage and Current Performance Comparison of HDFA and EAFA Under Fan Cooling

In both cooling techniques, HDFA consistently performed better than EAFA in the current output across all conditions, indicating better electrical conductivity or thermoelectric generation efficiency. However, EAFA shows a comparable voltage output at lower ΔT values. Under ice cooling, the sharper output increase highlights the importance of aggressive cooling techniques in improving thermoelectric performance.

With fan cooling, the performance trend remains similar, but the voltage and current increase is more linear, suggesting a steady but less pronounced improvement when compared to ice cooling. The temperature difference reduces and that results in lower overall output values. This analysis establishes that maximizing the cooling technique is

crucial for increasing the efficiency of thermoelectric generation systems, where maintaining a high temperature difference directly affects power generation.

Comparison of Power Output in HDFA and EAFA Under Ice and Fan Cooling

The power output of HDFA and EAFA was analyzed under two cooling conditions: ice cooling and fan cooling. In both cases, power output increased with the temperature difference (ΔT), confirming the direct relationship between thermoelectric performance and ΔT . Figure 10 and 11 shows the plot of this investigation.

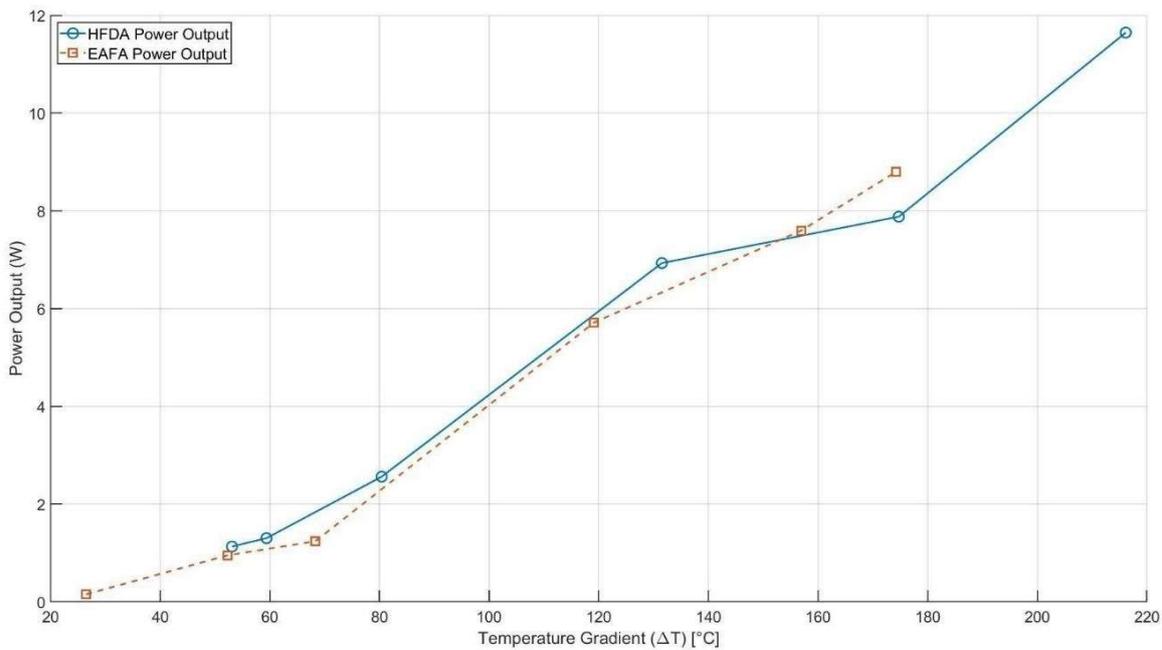


Figure 10: Power Output of HDFA and EAFA under Ice-Assisted Cooling

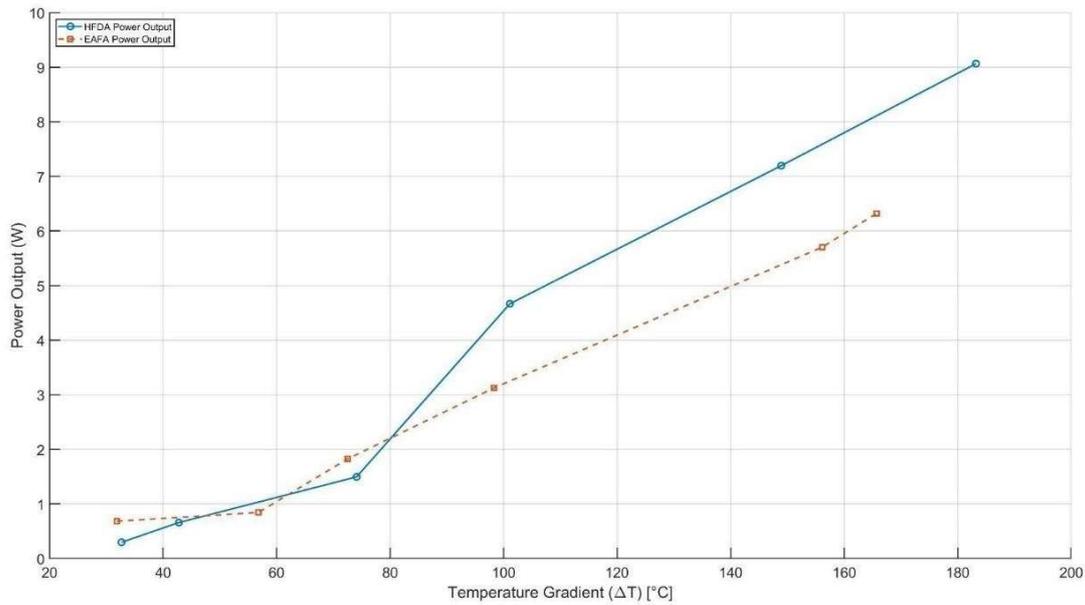


Figure 11: Power Output of HDFA and EAFA under fan-assisted Cooling

HDFA consistently performed better than EAFA, giving higher power output across all temperature difference. Under ice cooling, the power output was significantly higher compared to fan cooling, particularly at higher ΔT values. This highlights the effectiveness of ice cooling in maintaining a larger temperature difference, which improves the conversion efficiency. In contrast, fan cooling gave a more gradual power output increase, indicating its lower efficiency in sustaining the required heat difference.

Conclusion and Recommendations

This paper indicated that HDFA consistently performed better than EAFA across all tested conditions. Both materials showed a direct correlation between power output and temperature difference, with ice cooling gave higher power generation compared to fan cooling. The implications of this research extend to the development of more effective thermoelectric generators (TEGs) for energy harvesting applications. By improving material selection and cooling techniques, it is possible to improve energy conversion efficiency, making TEGs more viable for real-world applications, such as waste heat recovery and renewable energy systems.

However, Future research should focus on expanding the range of materials tested, incorporating dynamic environmental conditions, and exploring advanced cooling techniques such as phase-change materials or hybrid cooling systems. Additionally, integrating machine learning for predictive modeling of thermoelectric performance could further enhance efficiency optimization.

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