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Investigation of Electrical Voltage Influence on Thermoelectric Cooler (TEC) Performance in a Stacked Cooling Enclosure

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Abstract
The Thermoelectric Cooler (TEC) is an environmentally friendly solid-state cooling technology with wide application potential. This study aims to analyze the effect of voltage variation on the thermal performance of a TEC-based cooling system applied to a prototype cooling box. The methodology involved designing a system with eight symmetrically installed TEC units, tested at five voltage levels: 16 V, 18 V, 20 V, 22 V, and 24 V. Evaluated parameters included cold and hot side temperatures, heat absorbed (Qc), and Coefficient of Performance (COP). Experimental results revealed that increasing voltage up to 22 V significantly enhanced system efficiency, with the highest COP of 0.25 and maximum Qc of 5.24 W. However, at 24 V, performance declined due to excessive heat accumulation on the hot side of the TEC, exceeding heat dissipation capacity. In conclusion, an optimal input voltage of 22 V was identified to yield the most efficient cooling performance. These findings support the applicability of TEC technology for compact and sustainable cooling systems.

Keywords: Thermoelectric Cooler, electrical voltage, thermal performance, Coefficient of Performance

1. Introduction

One promising technology addressing environmental challenges and future opportunities for mitigating greenhouse gas emissions is the thermoelectric cooler (TEC). This system is considered an ideal solution due to its unique characteristics: it operates without noise, working fluids, or chemical reactions [1]. These advantages position TEC as an attractive alternative to conventional vapor-compression refrigeration systems, which often require harmful refrigerants and generate sound pollution[2].

A TEC component is a solid-state device that operates on the Peltier effect, a physical phenomenon where heat is absorbed or released at the junction of two dissimilar materials when an electric current flows through them. This phenomenon enables the direct conversion of electrical energy into cooling without the need for moving parts, making it highly reliable and maintenance-free [3]. This solid-state design also contributes to its compact size, allowing for integration into applications with strict space constraints [4].

TEC development is currently being extensively pursued due to its broad range of potential applications. Significant applications that have been and are being developed include cooling 5G communication chips to maintain high-speed device performance [5], cooling medical devices requiring precise temperature control for biological sample stability [6], and cooling microchips in modern electronic systems to prevent overheating and extend device lifespan [7]. This versatility demonstrates TEC's adaptability to diverse industrial and scientific needs.

In addition to their varied applications, TEC devices also offer numerous substantial advantages over conventional cooling methods. These benefits include noise-free operation, minimal vibration, and maintenance-free performance due to the absence of moving parts. Furthermore, they do not require liquid media such as refrigerants, which pose risks of leakage or environmental contamination [7]. This combination of characteristics positions TEC as a highly relevant and strategic technology in the global endeavor to develop more efficient, environmentally friendly, and sustainable cooling systems for the future [8].

2. Methods

This research was conducted through the design and testing of an experimental cooling chamber prototype integrating TEC modules as the primary cooling components. The system configuration consists of a cooling chamber equipped with eight TEC units, with four units each mounted on opposing right and left sides of the chamber. This TEC arrangement was engineered to maximize cooling distribution within the chamber volume. Figure 1 presents a schematic overview of the developed TEC-based cooling chamber experimental setup. To investigate the effect of input power variations on cooling performance, five discrete voltage levels—ranging from 16 V to 24 V—were applied to the TEC modules.

Optimal heat transfer efficiency is achieved by arranging TEC units in a series-parallel configuration and carefully mounting them to ensure proper thermal interfacing. The cold side of each TEC makes direct contact with the internal aluminum wall of the cooling enclosure, facilitating heat absorption from the cooled space. On the other hand, a heatsink is affixed to the hot side of the TEC to effectively dissipate heat to the surrounding atmosphere. To improve the heat transfer coefficient from the heatsink and induce forced convective cooling, a fan is utilized to blow ambient air over the heatsink fins. For precise temperature monitoring, thermocouples are strategically placed at three key locations: the TEC cold face, the TEC hot face, and within the interior of the cooling compartment.

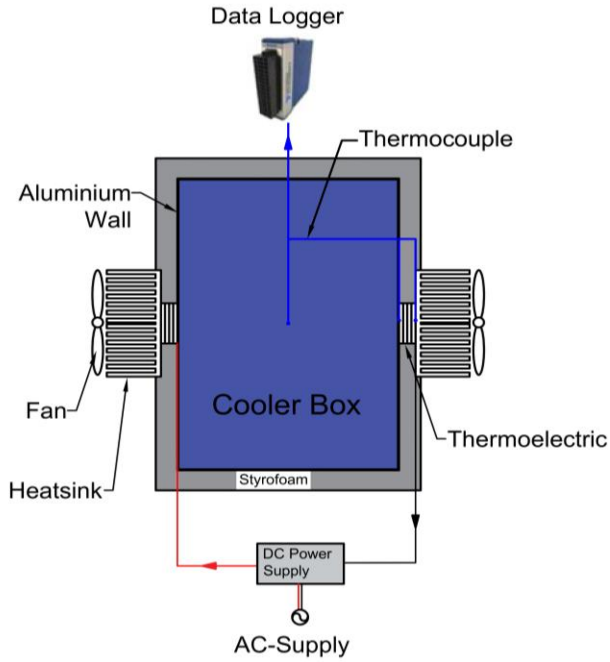

Figure 1. Data acquisition scheme

Temperature data from thermocouples were automatically recorded using a data logger, which subsequently transmitted the data to a computer for further processing. Data acquisition was performed over a two-hour duration after activating the TEC system and fans for each voltage variation. This timeframe was selected to ensure the system reached thermal steady-state conditions, guaranteeing that the recorded data represent the cooling chamber's stable performance. The collected data will be analyzed to evaluate key thermal performance parameters, including internal temperature drop, temperature differential across the TEC (between cold and hot sides), and cooling efficiency at various input voltage levels.

Comprehensive analysis of the experimental results will be conducted to determine the

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relationship between input voltage fluctuations and the thermal performance of the cooling unit. The collected temperature data will be presented graphically to show the cooling characteristics and how the system responds to changes in power input. This analysis will involve calculating the coefficient of performance (COP) and the net heat transfer rate under several operating conditions. Interpreting this data should yield a thorough understanding of the system's energy efficiency and its peak cooling capacity.

$$COP = \frac{Qc}{P_{in}} \quad (1)$$

$$Qc = \alpha.Tc.I - \frac{I^2R}{2} - k.\Delta T \quad (2)$$

$$P_{in} = Qh - Qc \quad (3)$$

The Coefficient of Performance (COP) is calculated using Equation (1), where each parameter is determined through Equations (2) and (3). In these equations, Qc represents the heat absorbed at the TEC's cold side, while P_{in} denotes the input power required to operate the TEC. In Equation (2), α signifies the Seebeck coefficient, Tc is the cold-side temperature of the TEC, and k represents the thermal conductance.

3. Results and Discussions

This section details the experimental findings derived from the performance evaluation of a Thermoelectric Cooler (TEC) integrated into a cooling enclosure under varied electrical voltage inputs. The presented data encompasses the temperature profiles of both the cold and hot sides of the thermoelectric device throughout the cooling cycle, along with the established correlation between input voltage and the absorbed heat flux, as well as the system's Coefficient of Performance (COP). The objective of this data analysis is to ascertain the optimal operational parameters and the thermal attributes of the developed cooling box prototype.

3.1 Profile Temperature Cold Side TEC

Figure 2 displays the cold-side temperature (*T*c) profiles of the TEC module under five applied voltage variations. At the experiment's initiation (t = 0 min), all curves exhibit relatively high initial temperatures, followed by significant decreases during the first 0-20 minutes interval. This rapid temperature reduction indicates the cooling transient phase where the system approaches steady-state conditions. Beyond approximately 20 minutes, the cooling rate progressively diminishes, and between the 40-120 minutes of the interval, temperatures stabilize, confirming achievement of thermal steady-state.

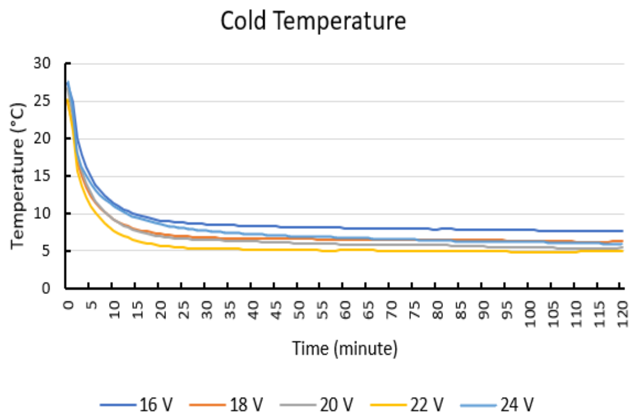

Figure 2. Cold side temperature

Further observation of Figure 2 reveals that input voltage variations have a clear impact on the TEC cold side temperature. Under conditions Tc1 to Tc4, higher applied electrical voltage results in a lower achievable cold side temperature once the system reaches steady-state. For instance, curve Tc4 shows the lowest temperature at approximately 5.01°C, while curve Tc1 is around 7.71°C. This aligns with the TEC's operating principle, where an increase in current (due to increased voltage) enhances the Peltier effect, thereby increasing the temperature difference between its cold and hot sides. However, it's important to note that despite the temperature differences across voltage variations, the TEC cold side temperature tends to increase under certain voltage conditions, indicating a limitation in optimal cooling performance.

3.2 Profile Temperature Hot Side TEC

Figure 3 presents the temperature profile graph on the hot side of the TEC (Th), also for five variations of the applied electrical voltage. Similar to the cold side, at the beginning of the experiment (t = 0 minutes), the hot side temperature is relatively low and then rises sharply during the initial period before eventually reaching a steady-

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state condition. This rapid temperature increase on the hot side indicates the heat dissipation generated by the Seebeck effect and the heat pumped from the cold side of the thermoelectric device. After approximately 10-15 minutes, the hot side temperature begins to stabilize, demonstrating a balance between the heat generated and the heat released to the environment through the heatsink via forced convection.

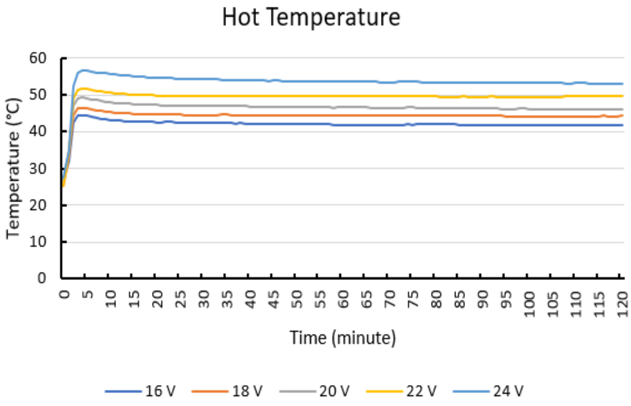

Figure 3. Hot side temperature

Figure 3 clearly demonstrates that increased electrical voltage to the TEC module directly correlates with elevated hot-side temperatures under steady-state conditions. The Th 5 curve (highest voltage) achieves the maximum hot-side temperature of 53.11°C, while Th 1 (lowest voltage) remains around 41.88°C. This hot-side temperature rise can be attributed to greater electrical input power generating increased Joule heating, alongside enhanced heat pumping rates from the cold side. Although higher hot-side temperatures facilitate heat rejection to the environment, excessive temperatures may reduce overall thermoelectric efficiency, as smaller temperature gradients limit cooling capacity.

3.3 Caloric Response at Cold Side

Figure 4 graphically represents the dependence of the cold-side absorbed heat rate (Qc) of the thermoelectric module on the applied electrical voltage. The findings reveal a tendency for Qc to increase proportionally with the escalation of electrical voltage within the range of 16 V to 22 V. Specifically, the absorbed heat rate measured approximately 4.54 W at 16 V, continuously ascending to a peak value of approximately 5.24 W at 22 V. This augmentation in Qc directly correlates with an enhanced thermoelectric cooling capability driven by increased input power, which is in full agreement with the operational principles of the Peltier effect.

Interestingly, at 24 V, a slight decrease in the heat absorption rate is observed, dropping to approximately 5.16 W. This phenomenon indicates the existence of an optimal point in the applied electrical voltage, beyond which further voltage increase can lead to a decline in cooling performance. This reduction is caused by excessive heat within the thermoelectric device, which diminishes the heat pumping efficiency, or by limitations in the hot side heat dissipation system (heatsink and fan) that can no longer accommodate the increased heat generation rate.

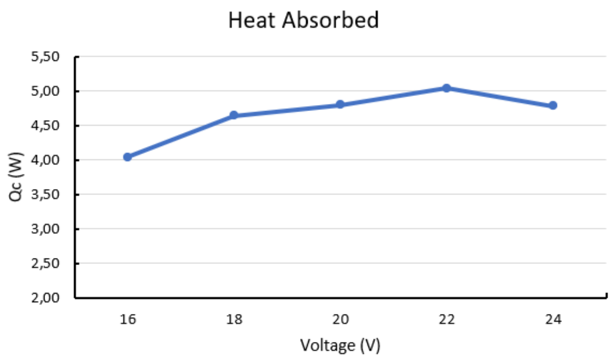

Figure 4. Heat absorbed

3.4 Coefficient of Performance (COP)

In Figure 5, the Coefficient of Performance (COP) of the TEC in the cooling box system is plotted as a function of electrical voltage variations. COP serves as a critical performance metric, quantifying cooling system efficiency as the ratio of absorbed cold-side heat (Qc) to the thermoelectric module's electrical power consumption. Analysis of the graph reveals a discernable increase in COP correlating with an escalation in electrical voltage from 16 V to 22 V. At an input of 16 V, the system's COP measured approximately 0.21, subsequently achieving a peak value of around 0.25 at 22 V. This observed improvement in COP within the specified range signifies a more efficient conversion of electrical energy into a cooling effect with increasing input power, up to an inflection point.

Similar to the absorbed heat trend, the COP value shows a slight decrease when electrical voltage increases from 22 V to 24 V, though not statistically significant. At 24 V, COP marginally declines to approximately 0.24. This pattern reinforces prior observations of an optimal

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operating voltage around 22 V for this thermoelectric cooling system. The COP reduction at higher voltages stems from a disproportionate increase in electrical power consumption relative to Q_c enhancement. That is, while absorbed heat remains substantial, the power required to achieve it becomes less efficient.

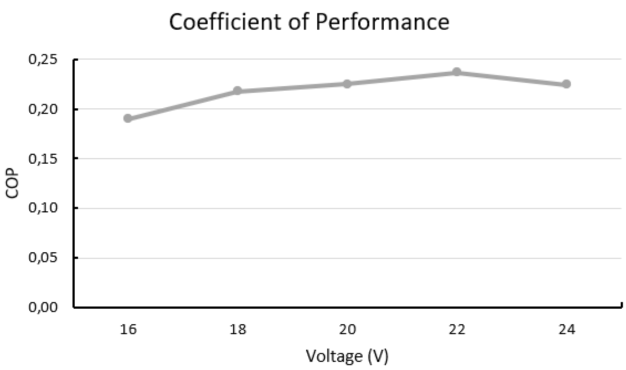

Figure 5. Coefficient of Performance

4. Conclusion

This investigation effectively analyzed the influence of electrical voltage variations on the operational characteristics of a Thermoelectric Cooler (TEC)-based cooling system integrated into a cooling box prototype. Employing five distinct voltage inputs ranging from 16 V to 24 V, we determined that the system's thermal efficacy demonstrated a substantial improvement with increasing voltage, reaching an optimal inflection point at 22 V. This is substantiated by a reduction in TEC cold side temperature, an augmentation in the absorbed heat rate (Qc), and an optimized Coefficient of Performance (COP), peaking at 0.25 at the aforementioned voltage. Beyond this optimum, specifically at 24 V, a decline in performance was observed, marked by diminished Qc and COP values. This phenomenon suggests the presence of a thermal efficiency saturation point attributable to excessive heat accumulation on the TEC's hot junction. Ergo, the results of this study underscore the existence of an optimal voltage input for achieving peak cooling performance in TEC systems.

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