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Experimental Study of a Peltier-Based Thermoelectric Refrigerator with Waste Heat Utilization

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Abstract: - This paper investigates thermoelectric refrigeration as a promising alternative to traditional refrigeration systems. The primary objective is to explore the use of the Peltier effect, where a temperature difference between two dissimilar conductors generates an electromotive force, opposite to the Seebeck effect. Three Peltier modules were used, each consisting of p-type and n-type semiconductor elements sandwiched between ceramic plates. Three test cases were experimented focusing on the activation of 1,2, and 3 modules respectively. When a DC voltage is applied, heat is absorbed on one side of the module and released on the other. The thermoelectric refrigeration system was designed with heat sinks and fans to dissipate heat from the cooling chamber to the external environment efficiently. The chamber was constructed with a dual-layer design, featuring polystyrene insulation on the interior and acrylic on the exterior, ensuring effective retention of cooling. Additionally, the excess heat generated by the thermoelectric refrigerator was repurposed for secondary applications, such as heating food products in an adjacent cabin, thus minimizing waste output. For each of the three cases, the temperature variations over time for both hot and cold cabin were recorded, and the coefficient of performance (COP) was calculated and compared.

Keywords: Thermoelectric, Peltier Effect, coefficient of performance (COP), Refrigeration.

I. INTRODUCTION

Thermoelectric refrigerators, an innovative alternative to conventional vapor-compression refrigeration systems, use the Peltier effect to create a heat flux between the junction of two materials. Conventional refrigeration systems are characterized by heavy moving parts and high energy consumption. These systems commonly use chlorofluorocarbons (CFCs) as refrigerants, which are not environmentally friendly. Conventional refrigerators are immobile, which limits their use in outdoor settings such as picnics or workplaces where portability is essential for storing perishable items like food, beverages, and vaccines [1],[2]. They are also designed with specific power requirements, often requiring a stable electrical source to operate effectively.

In contrast, thermoelectric refrigeration offers a versatile solution. Thermoelectric refrigeration utilizes electrical energy to generate cooling through a solid-state process. The core component of this system is the thermoelectric module, which is typically made of semiconductor materials. The thermoelectric module comprises P-type and N-type semiconductors. When a voltage is applied across the thermoelectric module, electrons in the N-type material move from a state of high energy to a state of low energy, releasing energy in the form of heat at one junction, resulting in cooling at that junction. Conversely, when electrons move from a region of lower energy to higher energy within the P-type material, they absorb energy from the surrounding environment, further enhancing the cooling effect [3]. Since a single thermoelectric couple cannot create a significant temperature gradient, multiple thermoelectric couples are connected in series electrically and in parallel thermally to amplify the temperature difference enabling effective cooling. By connecting thermoelectric elements in this manner, the system can produce a considerable cooling effect, making it suitable for various applications [4]. Thermoelectric refrigerators offer precise temperature control which is crucial for applications requiring stable temperatures, such as in medical and scientific storage [5]

The efficiency of thermoelectric devices is primarily determined by the thermoelectric figure of merit (ZT), which is a function of the material's electrical conductivity, thermal conductivity, and Seebeck coefficient. Historically, bismuth telluride (Bi2Te3) has been the material of choice due to its relatively high ZT at room temperature. Reference [3] discusses the development and optimization of Bi_2Te_3-based alloys, which have shown significant improvements in thermoelectric performance. Reference [4] provides a comprehensive overview of the design principles and fabrication techniques for thermoelectric modules. The study emphasizes the importance of optimizing the electrical and thermal connections within the module to minimize losses and improve overall

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efficiency. Studies by [5] have explored innovative module designs that incorporate advanced heat sinks and heat spreaders to improve thermal management. Reference [6] highlights the environmental issues caused by conventional refrigeration technologies and the possibility of integration of solar energy into thermoelectric systems.

Current thermoelectric refrigerators face significant challenges in achieving high marketability due to their low coefficient of performance (COP) compared to conventional refrigeration systems. This low efficiency limits their competitiveness, despite their advantages such as portability, compact size, and environmental benefits. The marketability of thermoelectric refrigerators is hindered primarily by their limited efficiency, which is a critical factor for broader adoption and practical applications. [7]

To address this issue, our research focuses on developing a thermoelectric refrigeration system with an enhanced COP. By utilizing waste heat, we aim to improve the overall efficiency of the system. Specifically, our project involves designing a system that not only cools but also uses the waste heat to preserve food products that need to be stored hot. This dual functionality can significantly enhance the system's energy efficiency and make thermoelectric refrigeration more competitive in the market.

In our experimental setup, we will analyze the COP for different configurations of the thermoelectric modules based on the new approach of utilizing the waste heat. This approach will provide valuable insights into the potential of thermoelectric refrigeration systems to achieve higher performance levels and broader market acceptance.

The research aims to fill the gap by demonstrating a practical and efficient application of thermoelectric technology, thereby enhancing its viability as a sustainable and competitive alternative to traditional refrigeration methods.

II. COMPONENTS

The thermoelectric refrigeration system comprises several key components, each playing a crucial role in its operation and efficiency. The primary components include the Peltier module, Styrofoam box, acrylic sheet, cooling fan, and heat sink. The Peltier module, based on the Peltier effect, is the core component of the system. Fig.1 shows the thermoelectric module used in the experiment. The performance specification of the Peltier module is shown in Table 1. In this study, three Peltier modules (TEC1-12706) are used. These modules create a temperature gradient by transferring heat from one side to the other when an electric current is applied. The modules consist of p-type and n-type semiconductor materials made from bismuth telluride (Bi_2Te_3), known for its high thermoelectric figure of merit (ZT) at room temperature. The structure of the refrigerator is built using a Styrofoam box, chosen for its excellent thermal insulation properties. This box is divided into two compartments by a wall with three apertures arranged vertically, matching the dimensions of the Peltier modules. This design ensures that the modules are securely fixed in place. Polystyrene boxes are attached to polymer sheets that have been laser-cut to the required exterior dimensions, enhancing the robustness and insulation of the enclosure. To manage heat dissipation, cooling fans and heat sinks are essential. Heat sinks or fins are attached to both sides of each Peltier module to facilitate the transfer of heat away from the module. Cooling fans are also used to increase the heat transfer rate through forced convection. To prevent thermal exchange through any gaps, thermal silicon sealer is applied around the Peltier modules once they are placed in the apertures. This sealing process is crucial to maintaining the thermal integrity of the system and preventing unwanted heat transfer between the compartments. Each Peltier module is provided with a separate electrical connection, allowing for precise control and efficiency. The electric current required to power the Peltier modules is supplied through an AC-to-DC converter, ensuring a stable and consistent power supply to each module. Additionally, a secondary cabin, similar in structure to the main refrigeration compartment but with different measurements, is used to capture and utilize the heat rejected from the primary cabin. This setup ensures efficient heat management and maintains the desired cooling effect in the primary cabin and heating effect in the secondary cabin. This innovative design not only improves energy efficiency but also provides a dual-function capability, enabling the system to heat food using the waste heat from the cooling process.

Figure 1. The thermoelectric module used in the experiment, TEC1-12706.

III. EXPERIMENT

Fig.2 illustrates the final setup of the thermoelectric refrigeration system. The experimental configuration is meticulously designed to assess the performance of the system under various conditions. The final arrangement includes three thermoelectric cooler modules that, when electrically connected, produce a cooling effect on one side and a heating effect on the other.

The TEC modules are strategically positioned in the central wall, which separates the two compartments. The cold sides of the modules face the cold cabin, while the hot sides face the hot cabin. Upon the application of electrical power, the cold cabin's temperature decreases progressively, whereas the temperature in the hot cabin increases correspondingly.

To measure temperatures accurately, we used three thermocouples: one for measuring the temperature of the cold cabin, another for the hot cabin, and a third for measuring the ambient temperature as time varies. The thermocouples ensure precise monitoring of the temperature changes in each compartment.

The experiment was conducted in three different cases to observe the variation in temperature over time for each cabin:

1. **Case 1**: Only one TEC module is activated.
2. **Case 2**: Two TEC modules are activated.
3. **Case 3**: All three TEC modules are activated.

Table 1. Performance Specification of TEC module

Description	Min	Max
I_{max} (Amp)	6.4	6.4
Hot side Temperature (°C)	25	50
Q_{max} (Watt)	50	57
Delta T_{max}(°C)	66	75
V_{max} (Volts)	14.4	16.4
Module Resistance (Ohm)	1.98	2.30

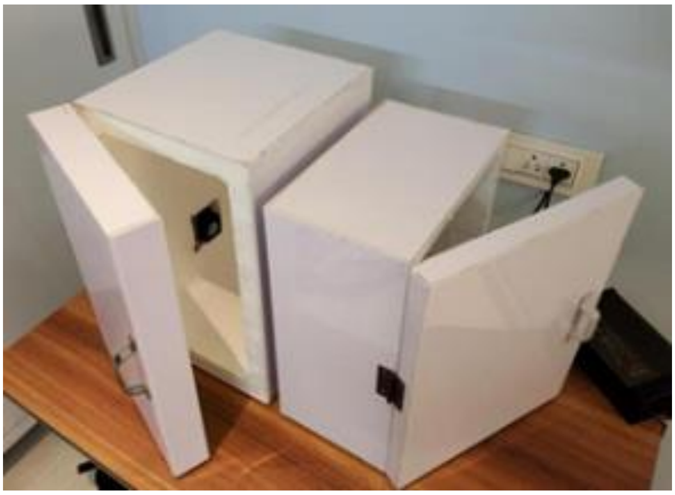

Figure 2. The final setup

In each case, the temperature of the cold cabin decreases as time progresses, while the temperature of the hot cabin increases. These observations were recorded and plotted to analyze the performance of the thermoelectric refrigeration system under configurations.

The power supply for the TEC modules is provided by an AC-to-DC converter with a power rating of 12V and 33.34A. To enhance the thermal management of the system, we incorporated two sets of cooling fans: one set for the cold side and another for the hot side. For the cold side, we used smaller cooling fans, each rated at 12V and 0.1A. The choice of smaller fans for the cold side is due to the lower heat load, which requires less airflow for effective cooling. In total, three small fans were used, one for each cold side of the TEC modules.

For the hot side, larger cooling fans were employed, each rated at 12V and 0.2A. The larger fans are necessary to dissipate the higher heat load on the hot side, ensuring efficient thermal management. Three large fans were utilized, one for each hot side of the TEC modules.

The variations in temperature for both the cold and hot cabins across different test cases are illustrated in Figures 3, 4, and 5. Figure 3 indicates that a minimum temperature of 17°C can be achieved in the cold cabin, while a maximum temperature of 48°C can be reached in the hot cabin when all three thermoelectric modules are activated.

The internal dimensions are crucial for understanding the volume of air being cooled or heated, while the external dimensions are important for considering insulation and spatial constraints. The internal volume cold cabin is 14 liters (calculated as 20cmx20cmx35cm) and the internal volume of the hot cabin is 11.08 liters (calculated as 24cmx14cmx33cm). These measurements provide a clear understanding of the scale and capacity of each compartment.

By knowing the volume of each compartment, we can better understand the thermal dynamics and efficiency of the system. The larger the volume, the greater the amount of energy required to achieve the desired temperature changes. The thickness of the polystyrene used is 3cm and 2 cm for the hot cabin and the thickness of the acrylic sheet used is 0.2 cm. Table 2 shows the list of materials used in the development of the setup.

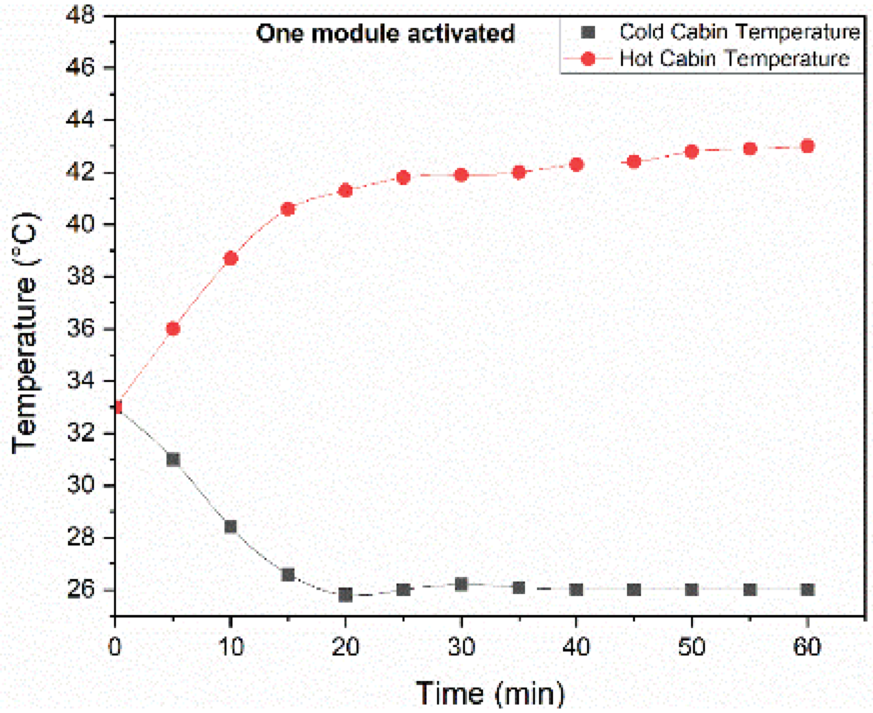

Figure 3. Temperature vs. time when only one module is activated

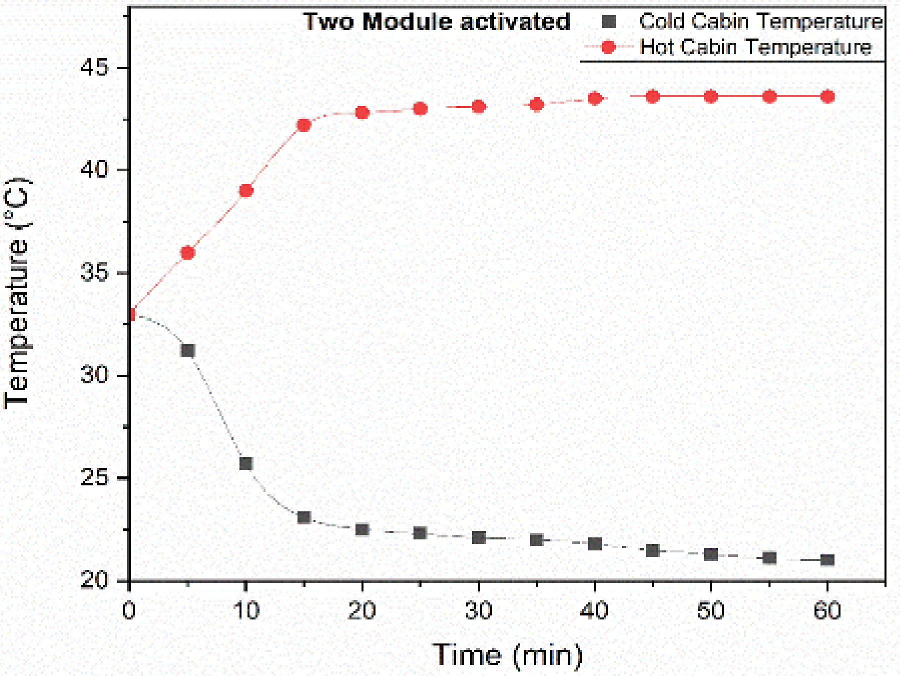

Figure 4. Temperature vs. time when two modules are activated

Governing Equations and performance parameters

Seebeck Coefficient of Thermoelectric Refrigeration (TER)

The Seebeck coefficient, also known as thermoelectric power, quantifies the voltage generated per unit temperature difference across a thermoelectric material. It reflects the material's ability to convert a temperature gradient into an electric potential. This coefficient is critical for assessing the thermoelectric efficiency of the system as it directly influences electrical power generation or consumption. Mathematically, it is expressed as:

$$\alpha_m = \frac{V_{max}}{T_h}$$

where α_m represents the Seebeck coefficient, V_{max} denotes the maximum voltage output, and T_h is the temperature of the hot side.

Thermal Resistance of Thermoelectric Refrigeration (TER)

Thermal resistance plays a pivotal role in thermoelectric refrigeration by governing heat transfer across the system. It measures the resistance to heat flow between the hot and cold sides of the thermoelectric module. Lower thermal resistance enhances heat transfer efficiency and improves cooling performance. The thermal resistance θ_m is determined by the module’s materials and geometry, and is given by:

$$\theta_m = \frac{2T_h \times \Delta T_{max}}{V_{max} \times I_{\max} \left(T_h - \Delta T_{max}\right)}$$

where ΔT_{max} is the maximum temperature difference across the module, I_{max} is the maximum current, and other variables retain their previous definitions.

Electrical Resistance of Thermoelectric Refrigeration (TER)

Electrical resistance is crucial for calculating the Coefficient of Performance (COP). It characterizes the opposition to electrical current flow within the thermoelectric module. Higher electrical resistance results in greater power dissipation, reducing overall system efficiency. Minimizing electrical resistance is essential for optimizing performance and energy efficiency. The electrical resistance R_m is defined as:

$$R_m = \frac{V_{max}(T_h - \Delta T_{max})}{I_{max} \times T_h}$$

where R_m represents the electrical resistance, V_{max} is the maximum voltage output, T_h is the temperature of the hot side, and ΔT_{max} is the maximum temperature difference across the module.

Cooling Power

Cooling power measured in watts(W), indicates the rate at which heat is extracted from the cold compartment by the thermoelectric system. It is a fundamental parameter for

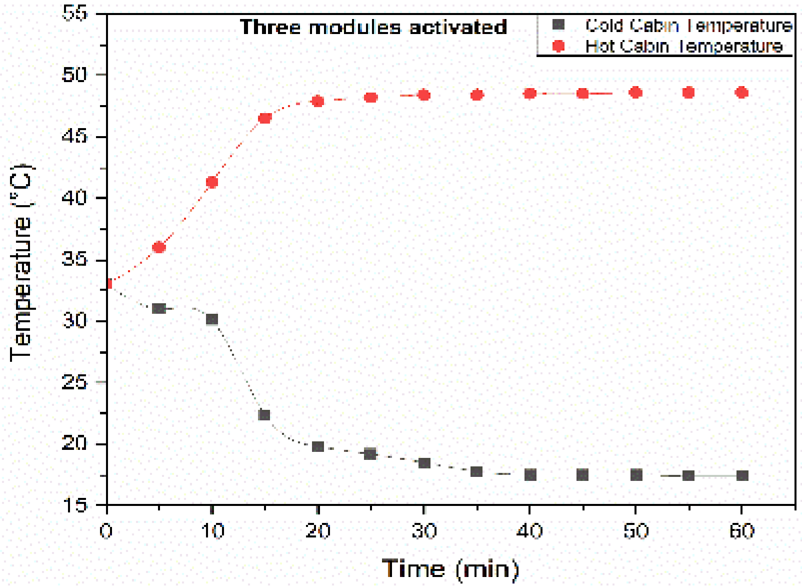

Figure 5. Temperature vs time when three modules are activate evaluating the performance of the refrigeration system. The cooling power can be expressed as:

$$Q_c = \alpha_m \times T_c \times 1 - \frac{\Delta T}{K_m} - I^2 \times \frac{R_m}{2}$$

Here, Q_c represents the cooling power, T_c is the temperature of the cold side, and the other variables are defined as previously explained.

Heating Power

In addition to cooling, the thermoelectric module also generates heat on the hot side. Heating power quantifies the amount of heat added to the hot compartment. This parameter is crucial for a complete performance evaluation of the thermoelectric system. The heating power is calculated as:

$$Q_h = \alpha_m \times T_h \times 1 - \frac{\Delta T}{K_m} + I_2 \times \frac{R_m}{2}$$

In this equation, Q_h denotes the heating power T_h is the temperature of the hot side, and the other parameters are as previously described.

IV. RESULTS AND DISCUSSION

The ambient temperature at the time of the experiment was 33℃. To calculate the performance of the thermo-electric system, a combined Coefficient of performance of heating and the cooling effect is considered for each of the three test cases.

$$Combined\ COP = \frac{Q_c + Q_h}{P}$$

WhereQ_c is the cooling power, Q_h is the heating power and P is the power input of the system. COP can be expressed as:

$$COP = \frac{\alpha_m T_c I + \alpha_m T_h I - \frac{2\Delta T}{K_m}}{I \times V}$$

Fig 6, 7, and 8 depict the variation of COP with respect to time for configuration with 1, 2, and 3 active thermoelectric modules.

Table 2. Materials used in the experiment

1	Cold & Hot Cabins	Styrofoam
2	Outer Material for Cabins	Acrylic
3	Peltier Module	3x (TEC1-12706)
4	Heat Sinks for cold side	3x Aluminum Fins With Copper Base (Small)
6	Cooling Fans (Big)	3x 0.2A 12V Fans
7	Cooling Fans (small)	3x 0.1A 12V Fans
8	Thermal Paste	Silicon Compound
9	Power Source For Peltier & fans	AC to DC Converter - 12V, 33.34A
10	Temperature Measurement	3xMini LCD digital thermometer sensors
11	Sealant	Thermal Silicon Sealant
12	Electrical Wires	For Electrical Connection

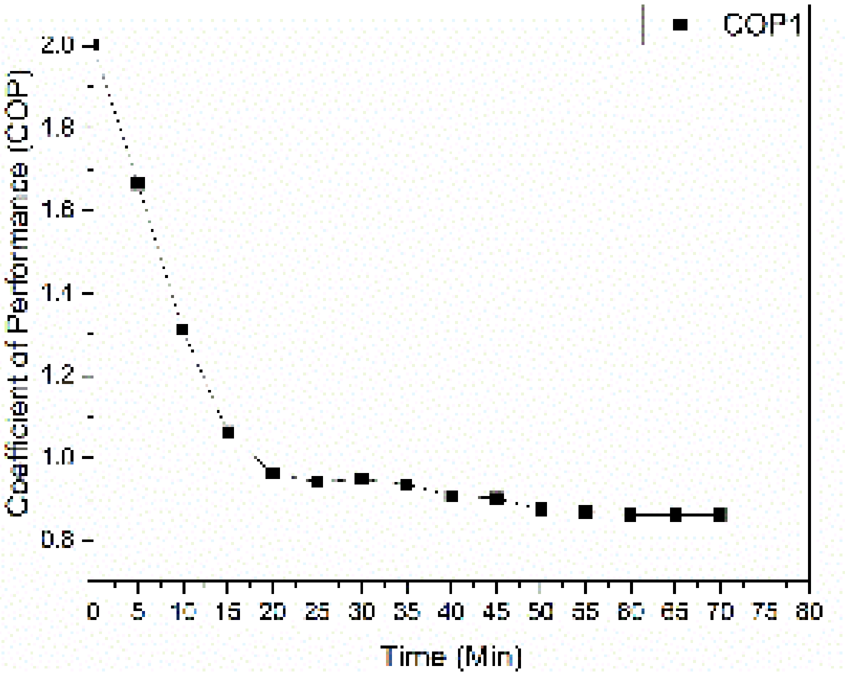

Figure 6. COP vs time when only one module is activated

Under testing, it was observed that the temperature of the cold cabin decreased from 33°C to 17.4°C in 50 min, whereas the temperature of the hot cabin increased from 33°C to 48.6°C at the same time when all three modules were activated. On comparing the COP of the three test cases, as shown in the graph, the COP initially decreases rapidly in all three configurations and achieves stabilization over time. The system with three active modules exhibits the highest COP throughout the experiment, reaching a steady-state value faster than the other configurations. This suggests that increasing the number of active modules enhances the system’s ability to efficiently manage thermal loads. The system's peak efficiency is observed in the three-module configuration, where the COP stabilizes at a higher value compared to the one and two-module setups. This indicates that the additional modules contribute positively to the overall performance, offering a better balance between cooling and heating. However, power consumption also increases, which must be considered when designing systems for specific applications.

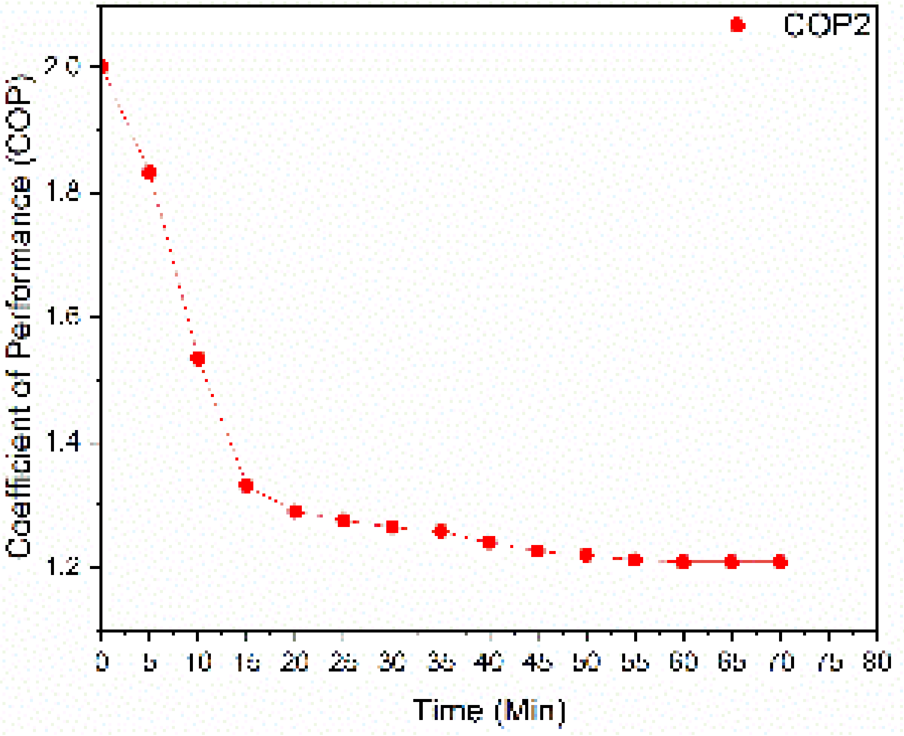

Figure 7. COP vs Time when two modules are activated

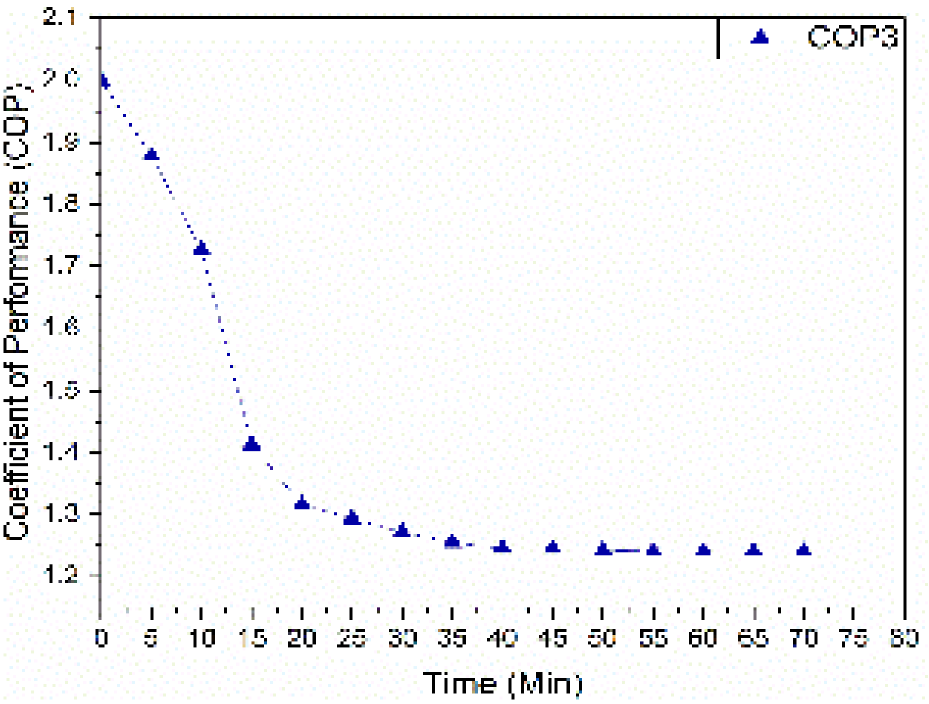

Figure 8.COP vs Time when all three modules are activated

Table 3. Parameters for Calculation

$\mathbf{T_h}$	TEC Hot Side Temperature
$\mathbf{T_c}$	TEC Cold Side Temperature
$\mathbf{I_{max}}$	Current that produces ΔT_{max}
$\mathbf{V_{max}}$	Voltage at ΔT_{max} Condition
$\mathbf{\Delta T_{max}}$	Maximum achievable ΔT(Th-Tc) at no heat load
I	Operating Current
V	Operating Voltage
P	Input Power
$\mathbf{T_a}$	Ambient Temperature
$\mathbf{Q_c}$	Heat Pumped at the Cold Side of TEC(Cooling capacity)
$\mathbf{Q_h}$	Heat Pumped at the hot side of TEC
$\boldsymbol{\alpha_m}$	Seeback Coefficient of TEC
$\boldsymbol{\theta_m}$	Thermal Resistance of TEC
$\mathbf{R_m}$	Electrical Resistance of TEC
Z	Figure of Merit of TEC
COP	Coefficient of Perfomance of TEC
$\boldsymbol{\theta_{ha}}$	Heat Sink to Ambient Thermal Resistance

V. CONCLUSION

In this work, a portable thermoelectric refrigerator unit was made and tested with the aim of achieving the maximum efficiency possible. In order to improve the efficiency of the system a hot cabin has been incorporated effectively utilizing the waste heat. The research presented in this study demonstrates the performance of a thermoelectric refrigeration system under varying configurations, with a focus on understanding the impact of the number of active thermoelectric modules on system efficiency, as measured by the Coefficient of Performance (COP). The results indicated that the system was able to reduce the temperature of cold cabin from 33℃ to 17.4℃ and obtain a COP of 1.24 in 50 minutes when all three modules were activated. This setup was able to obtain a higher COP that the other setups when the system attains equilibrium. The cold side of the module was utilized for the refrigeration process whereas the hot side was utilized for heating of the food products.

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