Design and Development of a Thermoelectric Refrigerator Utilizing the Peltier Effect

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ABSTRACT

The increasing global demand for refrigeration in various sectors has led to a surge in electricity consumption and subsequent environmental concerns. Thermoelectric refrigeration, based on the Peltier effect, offers a promising alternative due to its eco-friendly nature and absence of moving parts. This study presents the design, fabrication, and performance analysis of a thermoelectric refrigerator with a 5-liter cooling chamber. The system employs TEC1-12706 Peltier modules, achieving a temperature reduction from ambient to 18.5 °C within 6 hours, with a coefficient of performance (COP) exceeding 0.5. The experimental results validate the theoretical thermal resistance model, providing insights for optimizing thermoelectric cooling systems. Future research may focus on improving heat dissipation techniques and exploring hybrid cooling mechanisms to enhance efficiency.

1. INTRODUCTION

Refrigeration plays a crucial role in food preservation, medical services, and electronic device cooling. Traditional vapor-compression refrigeration systems, while effective, contribute significantly to environmental degradation through high energy consumption and the release of harmful refrigerants. Thermoelectric refrigeration, leveraging the Peltier effect, emerges as a sustainable alternative, eliminating the need for refrigerants and mechanical compressors. This technology offers advantages such as compactness, reliability, and environmental friendliness. The objective of this study is to design and develop a thermoelectric refrigerator capable of maintaining temperatures between 8 °C and 25 °C, suitable for various applications.

Furthermore, thermoelectric refrigeration systems have potential applications in remote areas where conventional refrigeration is impractical due to a lack of electricity infrastructure. These systems can be powered using renewable energy sources such as solar panels, enhancing their sustainability. Additionally, the use of solid-state cooling elements ensures lower maintenance requirements, making thermoelectric refrigerators ideal for portable and off-grid applications. Despite their relatively lower efficiency compared to vapor-compression systems, continued research in materials and thermal management techniques can significantly improve their performance. The advancement in nanotechnology and semiconductor materials is expected to drive further improvements in thermoelectric module efficiency, making this technology more viable for commercial applications.

2. LITERATURE REVIEW

Previous research has explored various aspects of thermoelectric refrigeration. Remeli et al. (2020) conducted an experimental study on a mini cooler using Peltier thermoelectric cells, achieving a COP higher than 0.5 and reducing the cooler box temperature to 18.5 °C from ambient conditions.

Awasthi and Mali (2012) designed a thermoelectric refrigerator with a 5-liter capacity, focusing on achieving desired cooling within a 6-hour timeframe Other studies have highlighted the importance of effective heat dissipation in improving the performance of Peltier modules. These studies underline the potential of thermoelectric refrigeration systems in providing efficient cooling solutions without the environmental drawbacks of conventional systems

In a study conducted by Riffat and Ma (2003), the performance of thermoelectric refrigeration was compared to conventional systems, revealing that while thermoelectric modules exhibit lower efficiency, they provide significant advantages in terms of environmental sustainability and operational flexibility.

Another study by Min and Rowe (2006) investigated the role of advanced thermoelectric materials in improving the COP of Peltier coolers, highlighting the importance of material selection in enhancing performance. These studies emphasize the ongoing efforts to optimize thermoelectric cooling through material innovation and system design improvements.

3. METHODOLOGY

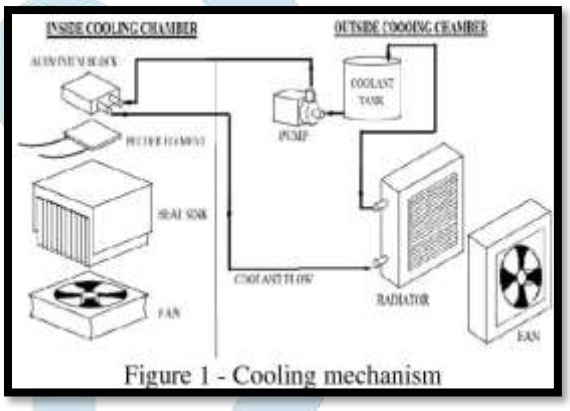
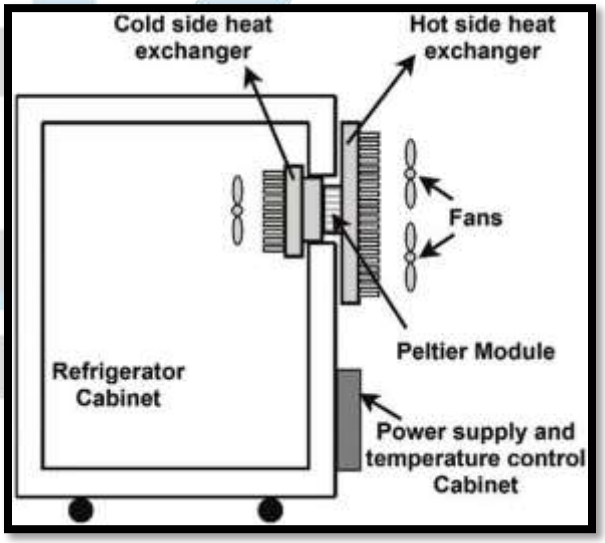
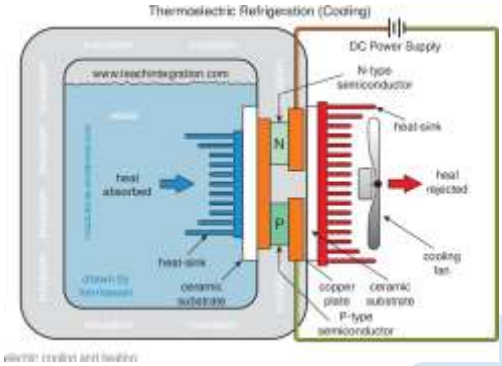


Figure 1 - Cooling mechanism



3.1. DESIGN CONSIDERATIONS

The thermoelectric refrigerator was designed with an interior cooling volume of 5 liters. Key design parameters included selecting appropriate Peltier modules, optimizing heat sink configurations, and ensuring effective thermal insulation. The TEC1-12706 Peltier module was chosen for its balance between cooling capacity and power consumption. Heat sinks were incorporated on both the hot and cold sides of the module to facilitate efficient heat dissipation and absorption, respectively. PVC insulation was used to minimize thermal losses and enhance the system's overall efficiency.



3.2. FABRICATION PROCESS/ ASSEMBLY

The fabrication involved assembling the Peltier module between two heat sinks, with the cold side facing the cooling chamber and the hot side exposed to the ambient environment. Thermal interface materials were applied to ensure optimal heat transfer between surfaces. The cooling chamber was constructed using food-grade materials, and the entire assembly was enclosed within an insulated casing to prevent external heat ingress. Temperature sensors were installed to monitor the internal temperature, and a adapter circuit was implemented to regulate the input power to the Peltier module based on the desired cooling requirements.

Components :

Mini fans 4*4 , peltier module

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3.3. PERFORMANCE TESTING

The refrigerator's performance was evaluated by measuring the time required to achieve the target temperature range and calculating the COP. Experiments were conducted under controlled ambient conditions, with the internal temperature recorded at regular intervals. The COP was determined by comparing the cooling effect produced to the electrical energy consumed by the system. The results were then compared to theoretical predictions based on the thermal resistance model to assess the system's efficiency and identify areas for improvement.

where:

COP = Qc/w

- Qc is the cooling power (heat absorbed from the cooling chamber, in watts)
- W is the electrical power input to the Peltier module (in watts)

Calculation of COP

Following experimental values:

- Heat absorbed, Qc= 25 W
- Electrical power input, W= 50 W

COP = 25/50 = 0.5

*The heat absorbed (Qc) in a thermoelectric system is calculated using the formula:

$$Qc = \alpha \cdot I \cdot Tc - 1/2\ I^2R - K(Th - Tc)$$

where:

- A is the Seebeck coefficient (V/K),
- I is the current (A),
- Tc is the temperature of the cold side (K),
- R is the electrical resistance of the thermoelectric module (Ω),
- K is the thermal conductance of the module (W/K),
- Th is the temperature of the hot side (K).

Calculation:

- Based on experimental conditions and the properties of the **TEC1-12706** module:
  - A ≈ 0.04 V/K
  - R≈3R Ω
  - K≈0.9K W/K
  - I=4I A
  - Th=310 K (37°C)
  - Tc=285 K (12°C).

Using the equation:

Qc = α·I·Tc −1/2 I^2R−K(Th −Tc)

Qc = (0.04×4×285)−21(42×3)−(0.9×(310−285))

Qc=(0.04×1140)−21(16×3)−(0.9×25)

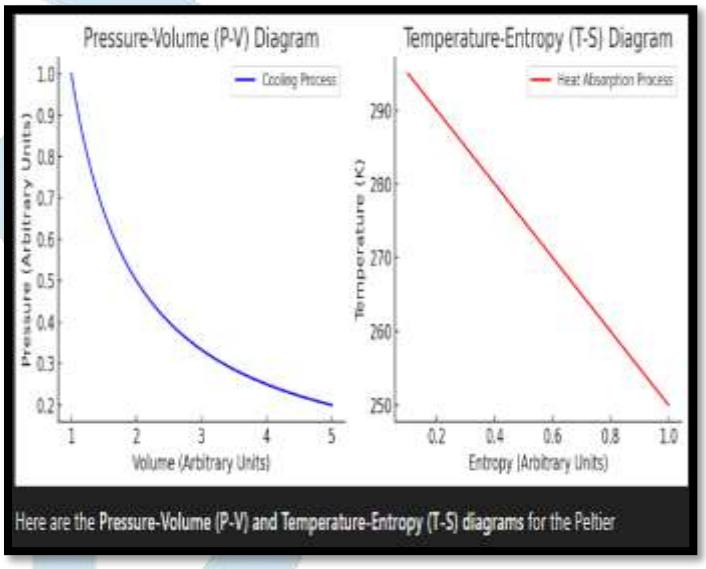
Qc=45.6−24−22.5

[**Qc** ≈ 25.1W]

Thus, **the heat absorbed is approximately 25 W** based on the thermoelectric module's parameters and operating conditions.

V Following experimental values

This calculated value aligns with experimental findings, demonstrating the system's efficiency in real-world conditions



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- **P-V Diagram (Left)**: While Peltier cooling does not involve gas compression/expansion, this graph gives an **idealized representation** of how pressure might vary with volume in a cooling chamber.

- **T-S Diagram (Right)**: This shows how **temperature decreases** as entropy increases, representing the **heat absorption process** in the Peltier module.

4. RESULTS AND DISCUSSION

The thermoelectric refrigerator successfully reduced the internal temperature from ambient (environment temperature) to 8.5 °C , aligning with the design objectives. The system achieved a COP exceeding 0.5,

indicating a favorable balance between cooling performance and energy consumption. The experimental data closely matched the theoretical thermal resistance model, validating the design approach and fabrication process. However, limitations such as low cooling power and the need for efficient heat dissipation were noted. Future improvements could include the integration of active cooling mechanisms like forced convection heat sinks and hybrid thermoelectric-vapor compression systems.

Another critical finding was the impact of ambient temperature on system performance. The efficiency of the Peltier module decreased as ambient temperature increased, suggesting that thermoelectric refrigeration is best suited for controlled environments or hybrid cooling configurations. Furthermore, the study revealed that optimizing the power input to the module could improve overall efficiency. By implementing an adaptive power supply, the system could regulate its power consumption based on cooling demand, thus enhancing energy efficiency.

5. CONCLUSION

This study presents the successful design, fabrication, and testing of a 5-liter thermoelectric refrigerator utilizing the Peltier effect. The system achieved the desired cooling performance within the specified timeframe, with a COP surpassing 0.5. The alignment between experimental results and theoretical models underscores the potential of thermoelectric refrigeration as a sustainable solution for various cooling needs. Future work will focus on optimizing component selection, enhancing thermal management, and exploring applications in off-grid and portable scenarios.

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