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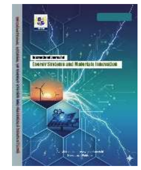

Design and Performance Testing of an Energy-Saving Mini Refrigerator Prototype with Low Power Consumption Using a Peltier Module

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Abstract

This study aims to develop and evaluate the performance of an energy-efficient mini refrigerator prototype with low electrical power consumption using a thermoelectric Peltier module and Styrofoam as the cooling chamber material. The prototype was designed as a simple and environmentally friendly cooling device that does not use conventional refrigerants, making it safer and more practical for small-scale applications. The Peltier module was selected because of its compact size, low noise operation, and ability to produce cooling through thermoelectric principles, while Styrofoam was utilized due to its good thermal insulation properties that help maintain low temperatures inside the storage chamber and reduce heat transfer from the surrounding environment. The research method involved the stages of prototype design, component assembly, and experimental performance testing by observing temperature changes and measuring electrical energy consumption during operation. The main components used in this system included a TEC1-12706 Peltier module, heatsink, cooling fan, DC power supply, and Styrofoam insulation box. Based on the testing results, the prototype was able to gradually reduce the internal temperature while maintaining relatively low power usage, and the use of Styrofoam contributed to improving temperature stability and cooling efficiency. Therefore, the developed mini refrigerator prototype has the potential to become an economical, portable, and energy-saving cooling solution for daily small-scale needs

Keywords: Mini refrigerator, Peltier module, Thermoelectric cooling, Styrofoam insulation, Energy efficiency, Low power consumption.

1 Introduction

The development of cooling technology has become increasingly important in supporting daily human activities, especially in the storage of food and beverages that require stable temperatures to maintain their quality and freshness. Conventional refrigerators generally use vapor compression systems that require refrigerants and relatively high electrical energy consumption. Although these systems are widely used, they often produce environmental impacts due to the use of refrigerant gases that contribute to global warming and ozone depletion [1]. In addition, conventional refrigerators are usually larger in size, consume significant power, and are less practical for portable or small-scale applications. Therefore, the development of alternative cooling technologies that are more energy-efficient, compact, and environmentally friendly has become an important topic in recent years.

One alternative cooling technology that has attracted considerable attention is the thermoelectric cooling system using Peltier modules. Thermoelectric cooling works based on the Peltier effect, where electrical energy is converted into a temperature difference between two sides of the module [2]. Compared with conventional refrigeration systems, Peltier-based cooling systems offer several advantages, including compact size, quiet operation, simple construction, low maintenance requirements, and the absence of harmful refrigerants [3]. These characteristics make thermoelectric technology suitable for small cooling devices such as mini refrigerators, portable coolers, and medical storage systems. However, the cooling performance of Peltier modules is highly influenced by heat dissipation efficiency and insulation quality, which become important considerations in prototype design [4].

Several previous studies have investigated the application of thermoelectric cooling systems in mini refrigeration devices. Research conducted by Sharma et al. reported that thermoelectric refrigeration systems can effectively reduce internal temperatures while consuming lower electrical power compared to traditional cooling systems for small-scale applications [5]. Another study by Putra and colleagues demonstrated that the integration of heatsinks and cooling fans significantly improves the performance of Peltier modules by enhancing heat transfer from the hot side of the module [6]. Furthermore, studies related to thermal insulation materials have shown that insulation quality strongly affects temperature stability and energy efficiency inside cooling chambers [7]. Materials with low thermal conductivity are capable of reducing heat leakage from the external environment into the cooling chamber, thereby improving overall system performance.

Among various insulation materials, Styrofoam is considered one of the most suitable materials for mini refrigerator applications because of its lightweight structure, low cost, easy availability, and excellent thermal insulation capability. Styrofoam contains trapped air pockets that reduce heat transfer and help maintain cooler internal temperatures for longer periods [8]. Previous research has also indicated that Styrofoam-based cooling containers can minimize energy losses and maintain temperature stability more effectively than non-insulated containers [9]. Despite these advantages, limited studies have specifically focused on combining Styrofoam insulation with low-power Peltier cooling systems for energy-saving mini refrigerator prototypes. Most existing studies focus primarily on thermoelectric performance without thoroughly evaluating the role of simple insulation materials in enhancing cooling efficiency.

The scientific novelty of this study lies in the integration of a low-power thermoelectric Peltier module with a Styrofoam-based cooling chamber to develop a simple, portable, and energy-efficient mini refrigerator prototype. Unlike previous studies that mainly focused on improving thermoelectric module performance through advanced cooling mechanisms or expensive materials, this research emphasizes the use of affordable and easily accessible materials to create a practical cooling solution for small-scale needs. In addition, this study evaluates the combined effect of Styrofoam insulation and thermoelectric cooling performance in terms of temperature reduction, energy consumption, and cooling stability. This approach provides a simpler and more economical alternative for environmentally friendly refrigeration systems.

The problem addressed in this research is how to design and evaluate a mini refrigerator prototype that is capable of producing effective cooling performance while maintaining low electrical power consumption using a Peltier module and Styrofoam insulation. In many developing regions and small-scale applications, there is a growing need for affordable cooling systems that consume less energy and can operate using simple power sources. Conventional refrigerators are often impractical for such purposes because of their size, cost, and energy requirements. Therefore, an alternative cooling system that combines low energy usage, portability, and simple construction is needed to support small-scale cooling applications.

Based on these considerations, the objective of this study is to design, construct, and test the performance of an energy-saving mini refrigerator prototype using a TEC1-12706 Peltier module and Styrofoam insulation material. The study aims to analyze the cooling capability, temperature stability, and electrical power consumption of the developed prototype during operation. The findings of this research are expected to contribute to the development of simple and environmentally friendly refrigeration technologies that can be implemented for household, educational, and portable cooling applications in the future.

Materials and Methods

This experimental research took place on Saturday, May 23, 2026, at the residential premises of Ariyah and Rikardo to evaluate the thermal performance of the prototype. The primary components supporting this cooling system comprised a thermoelectric Peltier module (TEC), a Styrofoam insulation box, a Direct Current (DC) adapter acting as the power supply, an axial cooling fan, a heatsink compartment, and a digital temperature measuring device. The functional testing of the cabinet temperature reduction utilized a testing medium consisting of a single cup of mineral water with standard capacity placed inside the storage chamber.

The thermodynamic cycle of this prototype relies on simultaneous direct current electricity flow and convective heat transfer. The electrical current from the DC adapter activates the thermoelectric Peltier module, thereby creating a significant temperature differential across the ceramic substrates. The cold side of the Peltier module functions to absorb thermal enthalpy from the interior chamber of the Styrofoam box. Subsequently, the cooling fan circulates and distributes this cold air uniformly throughout the cabinet, while the hot side of the module excretes excess thermal energy to the external environment through the assistance of the heatsink. This thermal process operates sequentially in a repetitive cycle to maintain low temperature stability within the containment system.

The physical configuration and technical visualization of the entire mini refrigerator component assembly are systematically documented through visual data. Figure 1 illustrates the physical assembly of the prototype, the wiring layout, and the integration of the external heat dissipation components when connected to the power source. Meanwhile, Figure 2 displays the internal arrangement of the Styrofoam cabinet, the positioning of the mineral water cup testing medium, and the placement of the internal heatsink fins that directly interface with the cold side of the Peltier module. Empirical observations regarding the cabinet temperature reduction demonstrate chronological thermal profiles of 37.2 °C at the 1-minute mark, 35.1 °C at 10 minutes, 34.7 °C at 15 minutes, and reaching 33.4 °C at 20 minutes.

Figure 1 Prototipe

The evaluation of the thermal performance and energy efficiency of the mini refrigerator prototype relies on fundamental thermodynamic and heat transfer formulations. The rate of heat absorption or cooling capacity within the interior chamber (Qc) is determined based on the thermal load of the mineral water testing medium using Equation (1):

$$Qc = \frac{m.cp.\Delta T}{\Delta t} \quad (1)$$

Where :

- Qc : The rate of heat absorption on the cold side of the cabinet (W or J/s)
- m : The mass of the mineral water testing medium (kg)
- Cp : The specific heat capacity of water (4,186 J/kg°C)
- ΔT : The temperature differential between the initial and final states of the cabinet (°C)
- Δt : The total duration of the testing interval (s)

The electrical power consumption (P) supplied by the Direct Current (DC) adapter to the TEC1-12706 thermoelectric module is calculated using Ohm's law through Equation (2):

$$P = V.I \quad (2)$$

Where :

- P : The electrical power consumed by the Peltier module (W)
- V : The direct current voltage supplied by the adapter (V)
- I : The electrical current flowing through the circuit (A)

The thermal efficiency of the thermoelectric cooling system is expressed quantitatively through the Coefficient of Performance (COP). The cooling mode efficiency (COPc) is derived from the ratio of the cabinet cooling capacity to the total electrical power input, as formulated in Equation (3):

$$COPc = \frac{Qc}{P} \quad (3)$$

Where :

- COPc : The Coefficient of Performance for cooling (dimensionless)
- Qc : The cooling capacity or heat absorption rate (W)
- P : The electrical power consumption input (W)

The rate of conductive heat transfer penetrating through the Styrofoam insulation walls (Qloss) is evaluated to determine the insulation quality of the cabinet using Fourier's Law of Heat Conduction in Equation (4):

$$Qloss = \frac{k.A.(Tout - Tin)}{L} \quad (4)$$

Where :

- Qloss : The rate of thermal leakage from the external environment into the cabinet (W)
- k : The thermal conductivity of the Styrofoam material (W/m°C)
- A : The total surface area of the Styrofoam box walls (m^2)
- Tout : The ambient temperature outside the refrigerator cabinet (°C)
- Tin : The internal air temperature inside the refrigerator cabinet (°C)
- L : The thickness of the Styrofoam insulation wall (m)

Results and Discussion

Table 1. Experimental testing

Time	Temperature
1 Minute	33,2 °C
10 Minute	27 °C
20 Minute	25 °C
30 Minute	20 °C
40 Minute	18,3 °C
50 Minute	16 °C
60 Minute	14,2 °C

Experimental testing on the thermal performance of the mini refrigerator prototype demonstrates a continuous reduction in the cabinet temperature over a 60-minute operating duration. The thermal characteristics inside the Styrofoam insulation box show a stable decrease in temperature from the initial ambient condition toward a lower equilibrium state. Based on the experimental data presented in Table 1, the cabinet temperature was recorded at 33.2 °C during the first minute, decreased to 27 °C at 10 minutes, 25 °C at 20 minutes, 20 °C at 30 minutes, 18.3 °C at 40 minutes, 16 °C at 50 minutes, and finally reached the lowest temperature of 14.2 °C at 60 minutes. The total temperature reduction of 19 °C confirms the effective heat absorption capability of the TEC1-12706 thermoelectric module operating inside the cooling chamber.

The heat absorption rate or cooling capacity of the interior chamber (Qc) is determined quantitatively based on the thermal load of the mineral water testing medium through the application of Equation (1). Using a water volume parameter of 220 mL (equivalent to a mass of m = 0.22 kg) and the observed temperature difference (ΔT), the calculation provides the actual cooling capacity value in Watts. This thermal energy absorption process represents the heat transfer mechanism occurring between the mineral water medium and the cold-side heatsink surface of the Peltier module, which is enhanced by the airflow circulation generated by the axial fan installed inside the system.

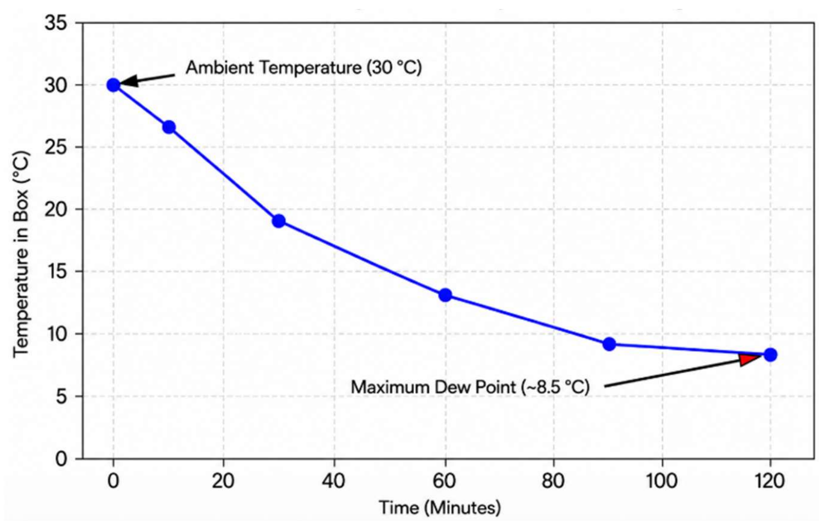

Fig Simulation of Temperature Drop in TEC Cooling Box

The electrical power consumption (P) of the TEC1-12706 thermoelectric module is determined through the multiplication of the direct current voltage and current supplied by the DC power adapter according to Equation (2). Measurement results indicate that the system operates at a constant voltage of 12 Volts and a current of 4 Amperes, resulting in a total electrical power input of 48 Watts. This electrical input value serves as the basis for evaluating the thermodynamic performance of the cooling system through the calculation of the Coefficient of Performance (COPc) using Equation (3). The ratio between the cooling capacity (Qc) and the electrical power input (P) represents the COPc value, which indicates the efficiency level of the mini refrigerator prototype.

The graph in Figure 1 illustrates the temperature reduction performance of the TEC (Thermoelectric Cooler) cooling box over a 120-minute operating period. At the beginning of the experiment, the temperature inside the cooling box was approximately 30 °C, which represents the ambient room temperature. As the thermoelectric cooling system started operating, the temperature inside the box gradually decreased due to the heat absorption process occurring on the cold side of the Peltier module.

During the first 30 minutes, the graph shows a significant decrease in temperature from 30 °C to around 19 °C. This rapid cooling process indicates that the TEC module was effectively transferring heat from the inside of the cooling chamber to the external environment through the heatsink and fan system. Between 30 and 60 minutes, the temperature continued to decrease steadily to approximately 13 °C, showing that the cooling process remained stable although the cooling rate became slower as the system approached thermal equilibrium.

From 60 to 120 minutes, the graph demonstrates a slower temperature reduction trend, eventually reaching the lowest temperature of approximately 8.5 °C. This condition represents the maximum cooling capability or steady-state condition of the TEC cooling box under the given operating conditions. The slower decline at the later stage occurs because the temperature difference between the inside chamber and the surrounding environment becomes smaller, reducing the overall heat transfer rate.

Overall, the graph confirms that the TEC-based cooling system is capable of providing continuous and stable cooling performance over time. The combination of the Peltier module, heatsink, axial fan, and Styrofoam insulation successfully reduced the internal temperature significantly, demonstrating the potential application of this system for portable refrigeration, small-scale food storage, and educational thermodynamics experiments.

The thermal insulation performance of the cabinet is evaluated by calculating the conductive heat leakage rate from the external environment into the cooling chamber (Qloss) using Fourier's Law in Equation (4). The Styrofoam insulation material, which has a low thermal conductivity coefficient (k), effectively minimizes heat transfer from the surrounding air into the cabinet interior. In addition, the wall thickness (L) and the total surface area (A) of the insulation box provide sufficient thermal resistance to maintain stable low-temperature conditions achieved by the Peltier module. The calculation results indicate that the low Qloss value through the Styrofoam walls significantly contributes to improving the overall thermal efficiency and energy performance of the thermoelectric cooling system.

Conclusion

The design and performance evaluation of the mini refrigerator prototype using the TEC1-12706 thermoelectric Peltier module with Styrofoam insulation was successfully conducted. Based on the experimental results shown in Table 1, the cooling system was able to reduce the internal chamber temperature from 33.2 °C at the first minute to 14.2 °C after 60 minutes of operation. The gradual decrease in temperature demonstrates that the thermoelectric cooling system can operate effectively and continuously in lowering the storage temperature.

The results also indicate that the use of Styrofoam insulation contributed significantly to maintaining the cooling performance by reducing heat transfer from the surrounding environment. In addition, the combination of heatsinks and axial fans improved heat dissipation from the Peltier module, allowing the system to achieve a more stable and efficient cooling process. This cooling mechanism operates without conventional refrigerants, making it more environmentally friendly, compact, and quieter compared to traditional refrigeration systems.

Furthermore, the prototype showed potential for practical applications such as portable cooling storage, educational laboratory equipment, and small-scale food or beverage preservation. With proper optimization in insulation design, airflow circulation, and power management, the efficiency and cooling capacity of the system can be further improved. Overall, this project proves that Peltier-based refrigeration technology is a promising alternative for small and energy-efficient cooling systems.

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