DESIGN AND DEVELOPMENT OF AN AUTOMATED THERMOELECTRIC REFRIGERATION SYSTEM BASED ON THE PELTIER EFFECT FOR ECO-FRIENDLY AND PORTABLE COOLING APPLICATIONS



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APPROVAL

This is to certify that the project on " Design and Development of an Automated Thermoelectric Refrigeration System Based on the Peltier Effect for Eco-Friendly and Portable Cooling Applications" by Sadi Md. Emon (ID No: ME2201026170), Md. Jahid (ID No: ME2201026152), Sarowar Hosen (ID No: ME2201026155), Ahasanulla Sourav (ID No: ME2201026096), Md. Ismail Hossain (ID No: ME2201026336) has been carried out under our supervision. The project has been carried out in partial fulfillment of the requirements of the degree of Bachelor of Science (B.Sc.) in Mechanical Engineering of the year 2025 and has been approved as to its style and contents.

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DECLARATION

We, the undersigned, do hereby solemnly declare that the work presented in this project report is the outcome of our own sincere effort, research, and investigation. To the best of our knowledge, this report has not been previously submitted, either in part or in full, to any university, academic institution, or organization for the award of any degree, diploma, or certificate. We further confirm that all sources of information and data used in the preparation of this report have been duly acknowledged and cited, and that this work does not violate any existing copyright laws or intellectual property rights. Moreover, we accept full responsibility for the content of this report and undertake to indemnify the university or any other concerned authority against any claims, losses, or damages that may arise as a result of a breach of the aforementioned declarations.

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ABSTRACT

This thesis presents the design and development of a compact, energy-efficient thermoelectric refrigeration system as a sustainable alternative to conventional vapor compression technology. The system utilizes a TEC-12706 Peltier module as the primary cooling element, with an Arduino Uno microcontroller enabling automated control for precise operation. A DS18B20 digital temperature sensor provides accurate real-time monitoring, while a relay module regulates the switching of the Peltier device to maintain the desired setpoint, and a digital display allows direct observation of the chamber temperature. To enhance performance, aluminum heat sinks and DC fans are integrated on both sides of the Peltier module to improve heat transfer and sustain the required thermal gradient. The entire unit is powered by a 12V DC SMPS, ensuring stable operation. Experimental tests within an insulated chamber demonstrate effective temperature reduction and maintenance, making the system suitable for applications such as portable mini-refrigerators, medical sample storage, and vaccine transport. By combining microcontroller-based automation with solid-state thermoelectric cooling, this work highlights the potential of eco-friendly, compact, and energy-efficient refrigeration systems for portable and versatile applications.

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CHAPTER 1

INTRODUCTION

1.1 Overview

This thesis presents the design, development, and performance evaluation of a thermoelectric refrigeration system utilizing a Peltier module controlled by an Arduino Uno. The aim of the project is to provide a compact, eco-friendly, and energy-efficient cooling solution suitable for small-scale applications. Unlike conventional vapor-compression refrigeration systems, this design uses the Peltier effect, a solid-state method of heat transfer that eliminates the need for refrigerants or mechanical compressors.

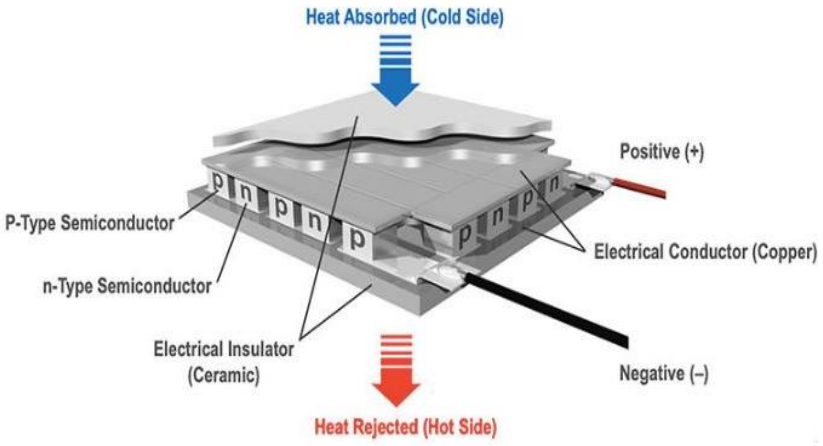


Fig 1.1: Peltier System [16].

The central component of the system is the TEC-12706 Peltier module, which creates a temperature differential when powered by a DC current. The cold side absorbs heat from the insulated chamber, while the hot side must be efficiently cooled using aluminum heat sinks and DC fans to maintain system performance. To enable automated operation and temperature regulation, an Arduino Uno microcontroller is employed. It receives real-time temperature data from a DS18B20 temperature sensor and controls the power to the Peltier module via a relay module. The system includes a display for live temperature monitoring, improving the user interface and usability.

The entire unit is powered by a 12V DC SMPS, ensuring stable operation for both the Peltier and the control components. All parts are selected based on affordability, compactness, and ease of integration, making the system ideal for academic, experimental, and low-power commercial uses.

Through controlled testing, the prototype demonstrates its ability to reduce temperature effectively within a small, insulated chamber. It provides sufficient cooling for sensitive applications such as portable mini-refrigerators, medicine carriers (e.g., for vaccines or insulin), laboratory samples, or personal food storage. The performance of the system is evaluated in terms of temperature drop, energy efficiency, response time, and reliability.

This project also highlights the potential of microcontroller-based control systems in enhancing the functionality of thermoelectric devices. By integrating automation, temperature sensing, and digital display into a single platform, the system not only becomes more efficient but also easier to operate and monitor. The use of clean, noiseless, and low-maintenance solid-state.

Overall, this thesis demonstrates that a Peltier-based thermoelectric cooling system can be a practical and effective solution for portable and energy-sensitive refrigeration needs. It lays the groundwork for further development, including advanced control techniques (e.g., PID control), solar power integration, and IoT-enabled temperature monitoring in future versions.

1.2 Problem Statement

Conventional refrigeration systems, though widely used and efficient, have several limitations. They are typically large, consume significant amounts of electrical energy, generate noise, and require complex mechanical components such as compressors and condensers. Additionally, they rely on refrigerants that are often harmful to the environment, contributing to ozone depletion and global warming.

In many parts of the world—especially in remote, rural, or resource-constrained areas—access to reliable and environmentally safe refrigeration is limited. This becomes a critical issue for applications such as vaccine storage, portable medical coolers, small-scale food preservation, or personal refrigeration, where compactness, energy efficiency, and environmental safety are essential.

To address these challenges, this project explores the use of thermoelectric cooling technology, based on the Peltier effect, which allows for solid-state, compact, and chemical-free cooling. Although thermoelectric systems generally have lower efficiency than traditional refrigeration, they offer significant advantages in terms of size, simplicity, and eco-friendliness.

The integration of Arduino Uno as a control system enables intelligent temperature monitoring and automation using a temperature sensor and relay module, making the system responsive, efficient, and easy to operate.

1.3 Objectives

- To design and construct a compact refrigeration unit based on Peltier modules.
- To evaluate system performance by measuring cooling capacity, power consumption, and coefficient of performance (COP).
- To investigate the potential applications of thermoelectric refrigeration in domestic cooling, portable coolers and medical storage cooling.
- To develop a green eco-friendly refrigeration system.

CHAPTER 2

LITERATURE REVIEW

2.1 Literature Review

Alves, J. and Costa, P. (2019) [1], Implementation of PID and PWM Control in Thermoelectric Coolers, Alves and Costa explore advanced control strategies for thermoelectric systems. They integrate Proportional-Integral-Derivative (PID) controllers with Pulse Width Modulation (PWM) to finely regulate the power delivered to the Peltier module. Their experiments demonstrate improved temperature stability and reduced power consumption compared to simple on/off control. This work underscores the value of sophisticated control algorithms in enhancing thermoelectric refrigeration performance.

Chen, L., Wang, H., and Liu, S. (2016) [2], Performance Analysis of DS18B20 Temperature Sensors in Embedded Systems, this research evaluates the DS18B20 sensor's suitability for real-time temperature monitoring in control systems. Chen et al. show that the DS18B20 offers high accuracy, linear output voltage proportional to temperature, and quick response times, making it ideal for closed-loop control in thermoelectric refrigeration. The study also discusses sensor calibration and noise reduction techniques, ensuring reliable operation in embedded applications.

Goldsmid, H.J. (2010) [3], Thermoelectric Refrigeration. Goldsmid's text focuses extensively on the physics of thermoelectric materials and device performance. He introduces the figure of merit (ZT), a crucial parameter representing the efficiency of thermoelectric materials. Goldsmid argues that the primary bottleneck in thermoelectric refrigeration lies in the limited ZT values of existing materials. His work also outlines the critical role of thermal conductivity, electrical conductivity, and Seebeck coefficient in optimizing device efficiency. The study advocates for the development of advanced semiconductor materials to enhance cooling capacity and energy efficiency.

Johnson, R. and Lee, M. (2018) [4], Relay Modules for Switching High Power Loads in Thermoelectric Applications, Johnson and Lee analyze the integration of relay modules in controlling high-current Peltier devices. Their study focuses on electrical isolation, protection against voltage spikes, and minimizing relay switching noise. They demonstrate that properly

implemented relay control ensures safe and reliable operation of thermoelectric cooling systems while prolonging component lifespan. Their recommendations are widely adopted in embedded thermoelectric system designs.

Kumar, R., Sharma, P., and Gupta, S. (2017) [5], Environmental Impact Assessment of Thermoelectric Refrigeration, this paper reviews the environmental advantages of thermoelectric refrigeration compared to conventional systems. Kumar et al. discuss the elimination of refrigerants, lower noise pollution, and reduced maintenance waste. The study also addresses the challenges of improving system efficiency to reduce electricity consumption. It advocates the wider adoption of thermoelectric cooling in sectors seeking sustainable alternatives.

Kusakana, K. and Vermaak, H. (2015) [6], Design and Optimization of Thermoelectric Cooling Devices, Kusakana and Vermaak explore the thermal design challenges in thermoelectric refrigeration systems. Their research highlights the critical importance of optimizing heat sinks and insulation to reduce unwanted heat flow and maximize the temperature difference created by the Peltier module. They propose several design methodologies to improve heat dissipation on the hot side, including forced convection techniques and advanced heat sink geometries. Their work provides valuable insights into improving the overall system efficiency and operational stability.

Lee, S., Kim, J., and Park, H. (2018) [7], Comparative Study of Vapor Compression and Thermoelectric Refrigeration Systems, Lee and colleagues provide a comprehensive comparison between traditional vapor compression and thermoelectric refrigeration. They analyze cooling capacity, noise levels, maintenance, environmental impact, and energy efficiency. The study concludes that while vapor compression remains superior for large-scale refrigeration, thermoelectric devices offer significant advantages in small-scale, portable, and noise-sensitive applications, supporting their use in specialized markets.

Patel, R. and Shah, D. (2021) [8], IoT-Enabled Arduino Control for Smart Thermoelectric Refrigerators, this recent research integrates Internet of Things (IoT) technology with Arduino-controlled thermoelectric coolers. Patel and Shah demonstrate remote temperature monitoring, control, and alert systems via smartphone applications. Their system enables real-time data logging and fault diagnosis, offering increased reliability and user convenience. This work exemplifies the trend toward connected smart appliances in refrigeration.

Patel, S. and Kumar, V. (2019) [9], Thermal Management Strategies for Peltier-Based Cooling Systems, this study investigates effective thermal management techniques to improve Peltier device performance. Patel and Kumar analyze various heat sink materials, fin designs, and fan configurations. Their experimental results show that maximizing airflow over the hot side and minimizing thermal resistance are critical to maintaining efficient heat dissipation. They also explore passive and active cooling combinations and stress the importance of system-level thermal integration for optimal refrigeration performance.

Rowe, D.M. (2006) [10], Thermoelectric: An Environmentally-Friendly Cooling Technology. Rowe's seminal work provides a comprehensive overview of thermoelectric cooling based on the Peltier effect. He describes how thermoelectric devices operate as solid-state heat pumps with no moving parts, enabling silent, reliable, and maintenance-free refrigeration. Rowe highlights the environmental benefits of thermoelectric cooling, emphasizing its potential to replace vapor-compression systems that rely on harmful refrigerants. His research stresses the challenges related to thermoelectric efficiency and encourages the exploration of new materials and design improvements to increase practical applications.

Singh, P., Verma, A., and Sharma, R. (2018) [11], Power Supply Optimization for Thermoelectric Cooling Systems, Singh et al. address the challenges of powering thermoelectric modules efficiently. They advocate the use of switched-mode power supplies (SMPS) due to their high efficiency, small footprint, and ability to provide stable DC output. Their research shows that consistent voltage and current supply reduces thermal fluctuations, improving the reliability and efficiency of thermoelectric refrigerators. They also compare different power supply topologies suitable for portable applications.

Smith, J., Patel, R., and Nguyen, T. (2017) [12], Arduino-Based Temperature Control for Thermoelectric Refrigerators, Smith and colleagues demonstrate a practical implementation of Arduino microcontrollers for precise temperature control in thermoelectric refrigeration. Their study details how the Arduino can process input from temperature sensors and actuate cooling elements using relay modules. They emphasize the benefits of using such low-cost embedded systems for automation, including flexibility in control algorithms, ease of programming, and user-friendly interfaces. This work provides a strong foundation for integrating microcontrollers in smart cooling applications.

Vineis, C.J., Shakouri, A., Majumdar, A., and Kanatzidis, M.G. (2010) [13], Nanostructured Thermoelectric: Enhancing Performance, this influential paper investigates the impact of nano structuring on thermoelectric materials. The authors demonstrate that introducing nanoscale features into thermoelectric materials can reduce lattice thermal conductivity without adversely affecting electrical transport. This leads to a significant increase in the figure of merit, which directly translates to improved cooling efficiency. Their findings underline the importance of material science advancements in overcoming traditional limitations of thermoelectric cooling systems, making them more viable for real-world applications such as refrigeration.

Zhang, Y., Li, Q., and Chen, J. (2020) [14], Development of Portable Thermoelectric Refrigerators for Vaccine Storage, Zhang and colleagues present a prototype of a portable thermoelectric cooler designed specifically for vaccine transport in areas with limited refrigeration infrastructure. Their system integrates a Peltier module with a battery power supply and Arduino-based control for maintaining precise temperature ranges critical for vaccine efficacy. The study evaluates cooling performance, battery life, and insulation effectiveness, concluding that thermoelectric coolers are a promising solution for medical logistics in remote regions.

Zhao, L., He, J., and Wang, Y. (2022) [15], Advances in Thermoelectric Materials and Device Performance, Zhao et al. review the latest advancements in thermoelectric materials, focusing on nanostructured bismuth telluride alloys and novel composites. They report significant improvements in the figure of merit (ZT), leading to better cooling efficiencies and wider application potential. The paper discusses material synthesis techniques, scalability, and integration challenges, providing a roadmap for next-generation thermoelectric refrigeration technologies.

CHAPTER 3

METHODOLOGY

3.1 Methodology

- The project begins with system planning, where objectives were defined and a block diagram was created to outline the working process.
- Appropriate components such as the Peltier module, Arduino Uno, DS18B20 temperature sensor, relay module, display, cooling fans, and a 12V SMPS were carefully selected.
- All the components were connected as per the designed circuit diagram to form the complete hardware setup.
- The Arduino Uno was programmed to read data from the DS18B20 sensor, control the relay based on the temperature range, and show the real-time values on the display.
- A small insulated cooling chamber was built to house the Peltier module and ensure a stable internal environment for testing.
- The system was powered and tested to check its cooling performance, including temperature drop, relay operation, and fan functionality.
- Performance data was recorded and analyzed, and necessary adjustments were made to improve overall system efficiency and stability.

3.2 Block Diagram

The block diagram illustrates the working of the thermoelectric refrigerator. The Arduino Uno serves as the main controller, receiving temperature input from the DS18B20 sensor and displaying it. Based on the readings, it controls the Peltier module via a relay. A DC fan with a heat sink removes heat from the hot side, and the system is powered by a 12V SMPS.

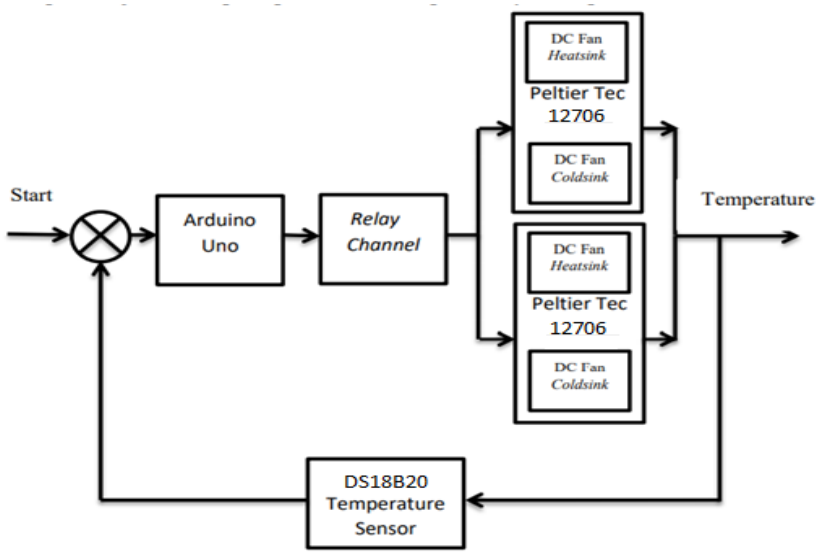


Fig 3.1: Block diagram of Thermoelectric Refrigeration System [16].

3.3 Circuit Diagram

In this part we show our project circuit design and connect out instrument through standard wire

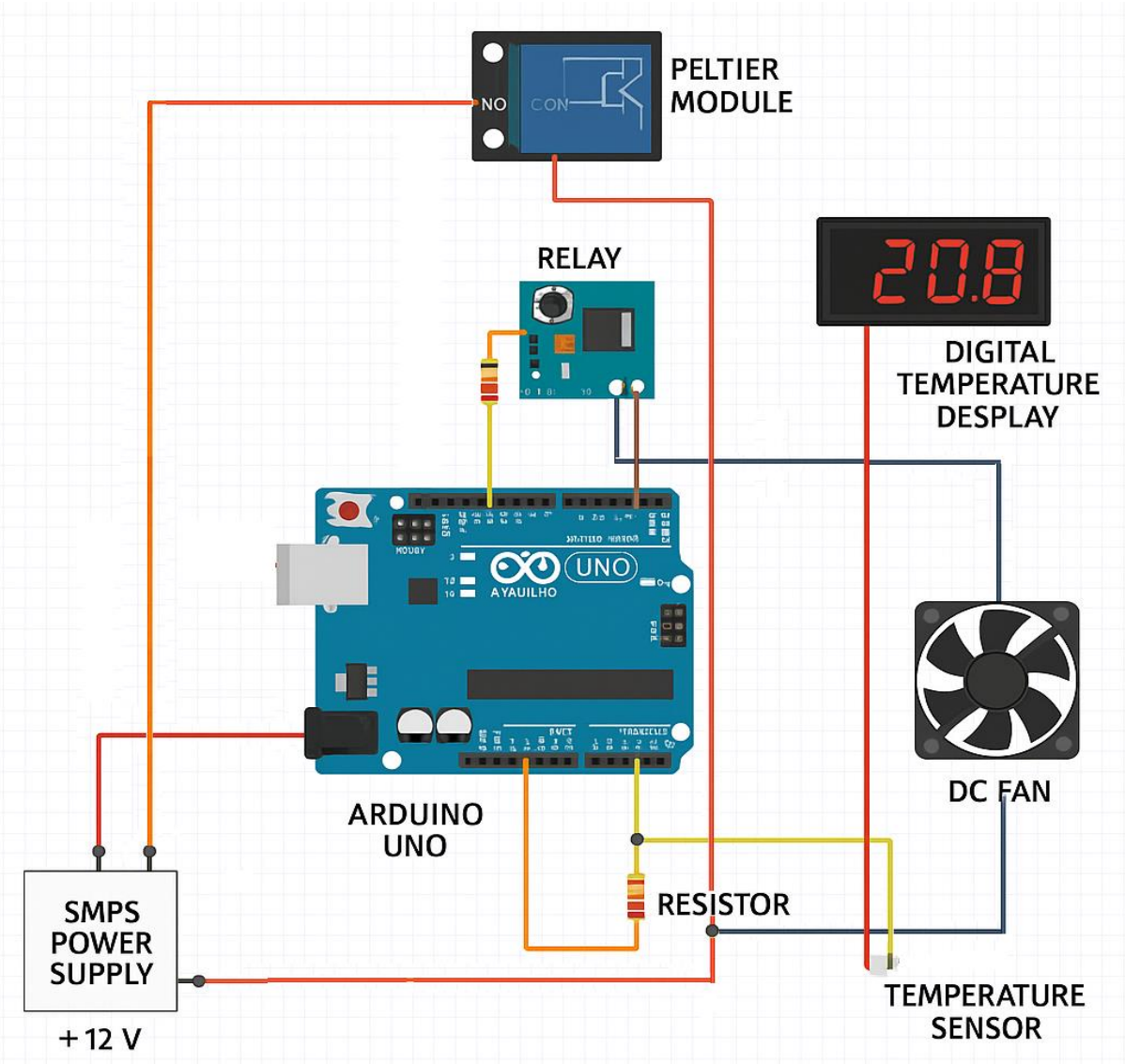


Fig 3.2: Circuit diagram of Thermoelectric Refrigeration System

3.4 Isometric Model

In this part we show our project Isometric model with all the necessary dimensions

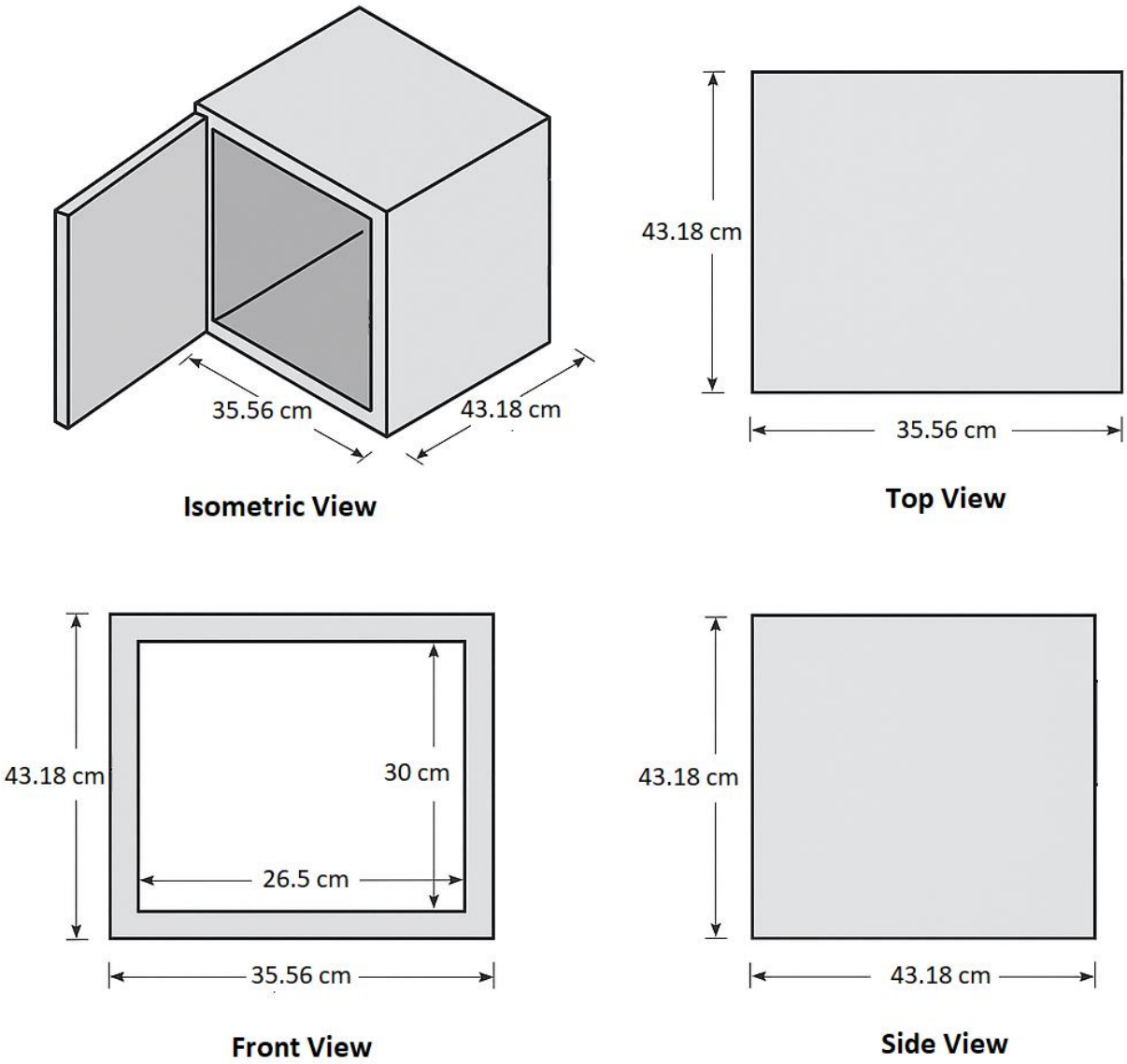


Fig 3.3: Isometric Model of Thermoelectric Refrigeration System

3.5 Working principle

The thermoelectric refrigerator operates based on the Peltier effect, which creates a temperature difference when an electric current flow through two dissimilar semiconductor materials. In this system, a Peltier module (TEC-12706) is used to generate cooling on one side and heat on the other.

At the heart of the system is the Arduino Uno, which serves as the main controller. It receives real-time temperature input from the DS18B20 temperature sensor placed inside the insulated cooling chamber. The DS18B20 converts temperature into an analog voltage, which is read by the Arduino through its analog input pin.

The Arduino is programmed to compare the sensor's temperature readings with a predefined threshold. If the measured temperature exceeds the desired limit, the Arduino sends a signal to the relay module, which acts as an electronic switch to turn ON the Peltier module. When the temperature falls below the set limit, the relay switches the Peltier module OFF to prevent overcooling and save energy.

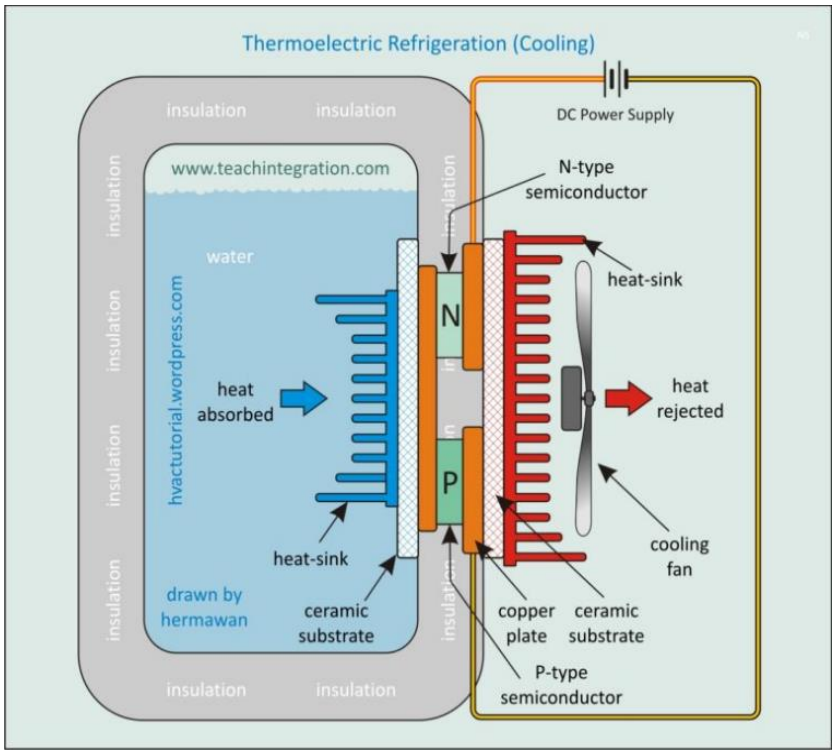


Fig 3.4: Working Principle of Thermoelectric Refrigeration System [16].

During operation, the cold side of the Peltier module cools the inner chamber, while the hot side generates heat. To maintain efficient performance, a heat sink and DC fan are mounted on the hot side to dissipate excess heat. This thermal management is crucial, as overheating can reduce the effectiveness of the Peltier module.

A display is connected to the Arduino to show real-time temperature values inside the cooling chamber, allowing users to monitor the system's operation. The entire system is powered by a 12V SMPS (Switched Mode Power Supply), which provides stable voltage and current to all components, including the Peltier module, Arduino, fan, and relay.

3.6 Final Project

A compact, energy-efficient thermoelectric refrigerator designed and fabricated utilizing the Peltier effect, with Arduino-based control for accurate temperature regulation. The silent operation, portability, and eco-friendly features ensure suitability for small-scale needs and medical refrigeration applications.



Fig 3.5: Design and Fabrication of Thermoelectric Refrigerator System

3.7 Cost Analysis

Table 1: List of Component with Price

Sl.no	Particulars	Specification	Qty.	Unit Price (Taka)	Total Price (Taka)
1	Peltier Module	TEC-12706	2	350	700
2	Arduino Uno	R3	1	1000	1000
3	G. I Sheet	12x3 Feet		2500	2500
4	Heat Sink	12x3.5x1.1 inch	3	600	1800
5	Relay Module	5V	1	150	150
6	12V DC Fan	90x90x25mm	9	150	1350
7	12V DC Fan	30x30x10mm	3	120	360
8	SMPS	12V	1	800	800
9	Digital Temp. Display	HTC-2	1	500	500
10	Temperature Sensor	DS18B20	1	200	200
11	PU Foam	750 ml	1	400	400
12	Aluminum Foil Paper	7.62m x 45.7cm	1	150	150
13	Resistor	4.7k ohm		50	50
14	Thermal Paste	10 g	1	100	100
15	PVC Sticker	12x3 Feet		300	300
16	Others				2000
				Total	10,560/=

CHAPTER 4

HARDWARE ANALYSIS

4.1 Hardware

Hardware

- Peltier Module
- Arduino Uno
- G. I Sheet
- Heat Sink
- Relay Module
- 12V DC Fan
- SMPS
- Digital Temp. Display
- Temperature Sensor
- PU Foam
- Aluminum Foil Paper
- Resistor
- Thermal Paste
- PVC Sticker

4.2 Peltier Module (TEC-12706)

The Peltier Module is a thermoelectric device that plays a central role in modern solid-state cooling applications. It utilizes the Peltier effect—a phenomenon discovered in the 19th century by Jean Charles Athanase Peltier—which enables heat transfer across the junctions of two dissimilar conductors when a direct current (DC) is applied. In simple terms, the module has two sides: when powered, one side becomes cold (heat is absorbed), and the opposite side becomes hot (heat is expelled). This characteristic allows the module to be used in miniature refrigeration systems without relying on compressors, refrigerants, or moving mechanical parts.

In this project, the TEC-12706 module has been selected due to its availability, affordability, and reliability for small-scale refrigeration. This module typically operates at 12V and draws a current of up to 6A, delivering up to 60W of cooling power. It is composed of multiple p-type

and n-type semiconductor pellets connected electrically in series and thermally in parallel, sandwiched between two ceramic plates. The Peltier module's small size, silent operation, and absence of chemical refrigerants make it environmentally friendly and perfect for compact cooling systems.

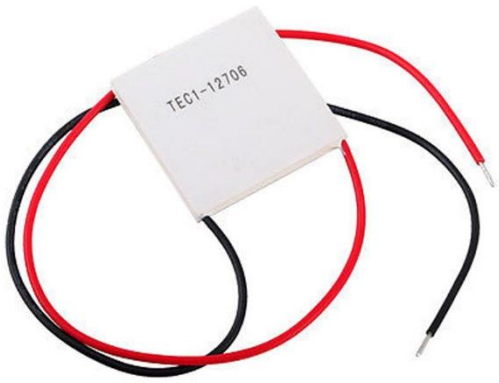


Fig 4.1: Peltier Module [17].

However, a key drawback is its low coefficient of performance (COP)—only a small portion of the electrical energy is converted into effective cooling. To enhance performance, it is critical to ensure that heat is removed efficiently from the hot side. Without proper dissipation, the heat will build up and significantly reduce the temperature differential, potentially damaging the module. Therefore, in this system, a heat sink and fan are coupled with the hot side, and insulation is used around the cold side to maximize cooling performance. The correct application of a thermal interface material like thermal paste further improves the thermal contact between the module and the heat sink. The Peltier module’s effectiveness is tightly coupled with proper heat management, electrical control, and environmental insulation.

4.3 Arduino Uno

The Arduino Uno is a microcontroller development board designed for beginners and professionals to create embedded electronic systems with ease. Based on the ATmega328P microcontroller, the board offers 14 digital input/output pins, 6 analog inputs, a USB connection, and a power jack. Its open-source nature, easy programming through Arduino IDE, and massive community support have made it one of the most widely adopted platforms in electronics, automation, and Internet of Things (IoT) applications.

In this thermoelectric refrigeration system, Arduino Uno serves as the main control unit or "brain." It is responsible for monitoring the internal temperature through a connected sensor

(such as LM35 or DS18B20), processing the data, and making intelligent decisions about when to turn the Peltier module on or off. This decision-making is accomplished by sending signals to a relay module, which acts as an electrical switch. The Arduino is programmed using a simplified version of C/C++ language, allowing for efficient implementation of conditional logic, delays, hysteresis control, and even more advanced functions such as pulse-width modulation (PWM) or sensor averaging.



Fig 4.2: Arduino Uno [17].

Arduino not only automates the operation but also enhances the interactivity of the system. It can drive displays to show real-time temperature data. Additionally, the system can be expanded to include alarms, remote monitoring, or logging capabilities. The versatility of Arduino also allows future upgrades—for example, adding a real-time clock (RTC) for time-based control, SD card module for data storage, or Wi-Fi/Bluetooth module for wireless communication.

One major advantage of using Arduino is its low power consumption and ability to interface with both analog and digital components. Its compatibility with thousands of sensors and modules makes it scalable for industrial and educational applications alike. As a programmable controller, it turns a passive cooling circuit into an intelligent system, improving energy efficiency, usability, and safety. Therefore, the Arduino Uno acts as the critical interface between the physical world and logical automation within the refrigeration project.

4.4 G. I Sheet (Galvanized Iron Sheet)

In this project, the Galvanized Iron (G.I) sheet serves as the external casing for the thermoelectric refrigerator. It is made from cold-rolled steel coated with zinc, providing excellent resistance to corrosion, weathering, and mechanical wear—ideal for outdoor and industrial applications.



Fig 4.3: G. I Sheet [18].

The G.I sheet offers strong structural support, securely housing internal components like the Peltier module, heat sink, power supply, and insulation. It is easy to fabricate—cutting, bending, and drilling can be done with basic tools—making it suitable for custom-built enclosures.

Although metal conducts heat, the G.I sheet’s zinc coating and thin profile limit heat transfer. Internal insulation with PU foam and aluminum foil further reduces thermal loss. The sheet is also flame-retardant, chemically stable, and resistant to moisture, pests, and mold.

Mechanically, it protects against deformation and vibration, while its conductive surface can be grounded to prevent electrostatic discharge. For aesthetics, the surface can be laminated with PVC film for branding or a polished finish.

Overall, the G.I sheet enhances the refrigerator's strength, safety, and thermal performance, playing a vital role in both function and appearance.

4.5 Heat Sink

The heat sink is a crucial thermal management component used to draw heat away from the hot side of the Peltier module, ensuring a stable temperature difference essential for effective cooling. Typically made of aluminum for its high thermal conductivity and light weight, it features a finned structure that increases surface area for better heat dissipation, especially when aided by a DC fan.

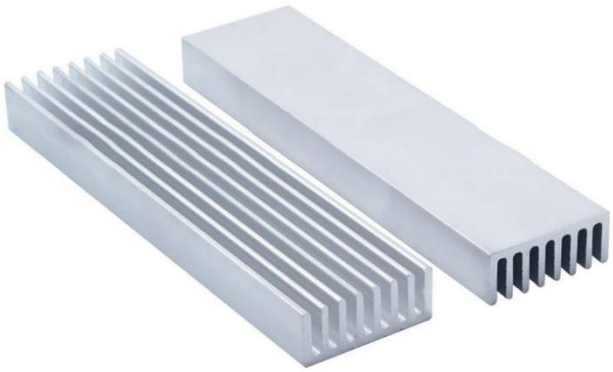


Fig 4.4: Heat Sink [17].

It works through conduction (absorbing heat), convection (releasing heat into the air), and sometimes radiation. A layer of thermal paste is applied between the Peltier and heat sink to fill microscopic air gaps and reduce thermal resistance, enhancing heat transfer efficiency.

In this project, the heat sink is selected based on the Peltier module's power rating (60W–72W) and is mounted securely to ensure proper airflow through its fins. Without it, the hot side would overheat, reducing cooling performance and potentially damaging the module.

Overall, the heat sink is essential for maintaining thermal balance, protecting components, and ensuring reliable operation of the refrigeration system.

4.6 Relay Module

The relay module is an electromechanical switching device that acts as a bridge between low-voltage control systems and high-voltage or high-current loads. In this refrigeration system, it plays a pivotal role in enabling the Arduino Uno—which operates on 5V digital logic—to control the 12V Peltier module and possibly the cooling fans, both of which draw relatively high current. The relay ensures that the microcontroller can safely manage these components without being damaged by overcurrent or voltage surges.

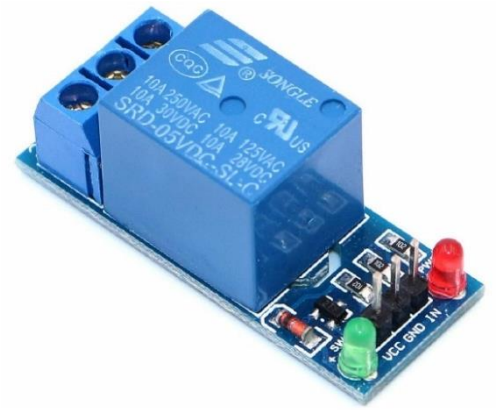


Fig 4.5: Relay Module [17].

Each relay consists of a coil, a magnetic core, and a set of contacts. When the coil is energized by a small voltage (from the Arduino), it creates a magnetic field that pulls the contacts together, completing the circuit and allowing high current to flow to the connected load. Most modern relay modules also include an opto-isolator (opto-coupler), which provides electrical isolation between the control circuit (low voltage) and the load circuit (high voltage), adding a layer of protection against voltage spikes.

The relay module used here is typically a single-channel 5V relay with an output rating of 10A at 250VAC or 30VDC, which is sufficient to handle the current drawn by one or two Peltier modules. It includes indicator LEDs that help in debugging by showing the ON/OFF state of the relay. When the Arduino senses that the internal temperature has crossed a threshold (e.g., above 10°C), it sends a signal to the relay, which in turn powers the Peltier. When the temperature drops below the set limit, the relay disconnects the circuit, stopping power to the Peltier.

4.7 12V DC Fan



Fig 4.6: 12V DC Fan [17].

The 12V DC fan is essential for active heat dissipation in thermoelectric cooling systems. While the Peltier module creates cooling on one side, its hot side generates significant heat that must be removed to maintain performance.

The fan enhances airflow over the heat sink, increasing convective heat transfer and preventing thermal buildup. Operating on the same 12V supply as the Peltier, the fan typically draws 0.1–0.3A, making it energy-efficient. Usually of the axial type, it is mounted directly onto or near the heat sink to expel hot air and draw in cooler ambient air. In some cases, a second fan on the cold side helps circulate chilled air inside the chamber for uniform cooling.

Fans may run continuously or be controlled via Arduino, depending on the system design. By preventing overheating, they protect the Peltier module, improve system efficiency, and extend component lifespan. Compact and low-noise, a 3"–4" fan is ideal for this application, turning a passive heat sink into an active thermal solution.

4.8 SMPS (Switched Mode Power Supply)

The Switched Mode Power Supply (SMPS) is a modern, compact, and highly efficient power supply unit that converts 220V AC mains input into 12V DC output, which is required to operate the Peltier module, cooling fans, and sometimes even the Arduino. Unlike traditional linear regulators, SMPS uses high-frequency switching and energy storage elements (like inductors and capacitors) to regulate output voltage with minimal power loss.



Fig 4.7: SMPS (Switched Mode Power Supply) [17].

One of the key advantages of SMPS is its efficiency, often above 80–90%, meaning less energy is wasted as heat. This becomes particularly important when dealing with high-power devices like the Peltier module, which may draw up to 6A or more. An SMPS with a 12V output and 10A current capacity is commonly used in such systems, ensuring sufficient and stable power delivery.

The SMPS unit includes various protective features such as:

- **Over-current protection (OCP)** – prevents damage from excessive current draw.
- **Over-voltage protection (OVP)** – stops voltage spikes from reaching connected components.
- **Short-circuit protection (SCP)** – shuts down power in case of wiring faults.

Mechanically, the SMPS is housed in a ventilated metal enclosure and includes screw terminals for easy wiring. Some models include a cooling fan for self-regulation. It is mounted securely within the G.I sheet structure and is grounded to avoid electrical hazards.

In the context of this project, the SMPS ensures uninterrupted and regulated power for the entire system. It also eliminates the need for multiple adapters or transformers, simplifying the circuit design. Without a reliable power source like SMPS, the system could suffer from unstable performance, erratic temperature control, or even component failure.

4.9 Digital Temperature Display



Fig 4.8: Digital Temperature Display [17].

The Digital Temperature Display is a crucial interface in the thermoelectric refrigeration system. It shows the real-time internal temperature, allowing users to monitor the system's performance and verify cooling efficiency. Common display types include HTC-2, 7-segment, or OLED displays, often connected to the Arduino Uno.

In this project, a HTC-2with I2C interface is used for its ease of wiring and readability. It displays the temperature value received from the sensor (e.g., LM35 or DS18B20) and can also show system status such as "Cooling ON" or "Threshold Reached." This feedback helps during testing, debugging, and real-time use.

The display runs on 5V power from the Arduino and updates temperature readings every few seconds. By giving users clear, real-time data, the digital temperature display greatly enhances usability, diagnostics, and system transparency.

4.10 Temperature Sensor (DS18B20)

The temperature sensor provides real-time feedback for monitoring and controlling internal temperature. This project uses either the DS18B20 digital sensor. The DS18B20 outputs voltage linearly proportional to temperature (10mV/°C) and is easy to interface with Arduino. The DS18B20 offers higher accuracy (±0.5°C) and uses a one-wire digital protocol, ideal for more precise or networked systems.



Fig 4.9: Temperature Sensor (DS18B20) [17].

The sensor is placed inside the cooling chamber or near the Peltier’s cold side to track temperature. Arduino compares this reading with a setpoint (e.g., 14°C) and activates or deactivates the Peltier via relay accordingly, forming a basic feedback control loop.

Sensors may also be used to display temperature on an LCD. For advanced setups, multiple sensors can monitor hot, cold, and ambient conditions. Overall, the temperature sensor is critical for maintaining stable and efficient cooling in the system.

4.11 PU Foam (Polyurethane Foam)

PU (Polyurethane) Foam is a highly effective insulation material used in this refrigeration system to reduce heat exchange between the internal chamber and the external environment. With a closed-cell structure and low thermal conductivity (0.02–0.03 W/m·K), it significantly limits heat gain, helping maintain low internal temperatures and improving overall system efficiency.



Fig 4.10: PU Foam (Polyurethane Foam) [18].

In this project, PU foam lines the walls, ceiling, and base of the chamber, preventing heat entry and retaining cold air produced by the Peltier module. This reduces the cooling load, conserves energy, and extends component lifespan. It can be applied by spraying, injecting into wall cavities, or using pre-cut panels for easier assembly.

Beyond thermal insulation, PU foam also offers acoustic dampening and resistance to mold, moisture, and pests. For added protection and a clean finish, it is typically covered with aluminum foil or a plastic liner. Overall, PU foam plays a crucial, behind-the-scenes role in ensuring efficient, durable, and reliable refrigeration performance.

4.12 Aluminum Foil Paper

Aluminum foil paper, laminated with paper or plastic, is used as an inner lining over PU foam in refrigeration systems. It plays a vital role in thermal insulation, hygiene, and structural protection.



Fig 4.11: Aluminum Foil Paper [17].

Thermally, it acts as a radiant barrier—reflecting up to 97% of heat radiation—reducing external heat gain and helping maintain internal cooling by bouncing cold radiation back into the chamber. This improves overall energy efficiency and temperature consistency.

Structurally, the foil protects PU foam from physical damage, moisture, and chemical degradation. It also creates a smooth, non-toxic, corrosion-resistant surface that's easy to clean, making it suitable for food or medical use.

In this project, aluminum foil is carefully glued to the chamber's interior, fitted to the G.I structure, and folded at edges for full coverage. Aesthetically, it gives a clean, metallic finish, enhancing the unit's professional look.

Overall, aluminum foil paper strengthens the insulation system, improves durability, and boosts thermal performance, making it an essential component in the refrigerator's construction.

4.13 Resistor



Fig 4.12: Resistor [17].

Resistors are fundamental passive components used to control the flow of electrical current in a circuit. In this thermoelectric refrigeration project, resistors are used in sensor circuits, LED indicators, displays, and possibly for fan speed control or logic-level interfacing.

By limiting current and reducing voltage, resistors help protect sensitive components like sensors and microcontroller input pins. For example, with the LM35 temperature sensor, resistors may be used in voltage divider circuits or to limit analog input current to ensure accurate readings. They are also used with LEDs on relays or displays to prevent overcurrent, which could damage or burn out the components.

Resistors operate by converting excess electrical energy into heat, thereby regulating current flow. They are selected based on their resistance value (in ohms), power rating (in watts), and tolerance. Common resistor values in such systems include 220Ω for LEDs, 1kΩ–10kΩ for sensor signal conditioning, and pull-up or pull-down configurations.

4.14 Thermal Paste

Thermal paste, also called thermal compound or grease, is a heat-conductive material applied between two surfaces to improve heat transfer by filling microscopic air gaps. In this project, it is applied between the Peltier module and the heat sink to enhance thermal conductivity. Even though the surfaces appear flat, tiny imperfections trap air that reduces heat flow. Thermal paste fills these voids, ensuring better contact and efficient heat transfer from the Peltier's hot side to the heat sink. This lowers thermal resistance, improves temperature regulation, and boosts overall system performance.



Fig 4.13: Thermal Paste [18].

Typically made of silicone mixed with ceramic, metal, or carbon particles, thermal paste has a conductivity of about 1 to 10 W/m·K depending on the type. Applying a thin, even layer is crucial—too little leaves gaps; too much acts as an insulator.

Without thermal paste, heat sinks cannot perform optimally, causing overheating and reduced cooling efficiency. In precise systems like this thermoelectric refrigerator, thermal paste is a simple, low-cost but essential component for effective thermal management.

4.15 PVC Sticker

PVC stickers, made from durable Polyvinyl Chloride, are used in this project for aesthetic finishing, surface protection, and informative labeling on the G.I. sheet casing. They are waterproof, flexible, and resistant to scratches, dust, and UV exposure, making them ideal for improving both the appearance and durability of the unit.



Fig 4.14: PVC Sticker [18].

Applied over metallic surfaces, PVC stickers give a clean, smooth, and professional look, while protecting against fingerprints and oxidation. They can display important details such as temperature ranges, branding, control instructions, or power ratings, enhancing user-friendliness and presentation value.

Available in matte or glossy finishes, PVC stickers can be custom-cut and printed in full color. In this project, they may cover the front panel, decorate sides, or seal openings to create a polished, commercial-grade finish.

CHAPTER 5

SOFTWARE ANALYSIS

5.1 Software

- Arduino IDE

5.2 Arduino IDE

The Arduino IDE (Integrated Development Environment) is a key software platform used to program and control Arduino microcontroller boards. In this thermoelectric refrigeration project, the Arduino IDE served as the primary interface for writing, compiling, and uploading the logic required to automate temperature control. Developed by the Arduino community, this open-source software simplifies embedded system development by providing a clean and user-friendly environment, especially for real-time control systems like refrigeration units.

The Arduino IDE enables users to write code in a simplified version of the C/C++ programming language and upload it to Arduino boards such as the Arduino Uno, which is used in this project. The software includes a basic text editor, a compiler, an error debugger, a serial communication monitor, and a library manager. These built-in tools help developers implement their ideas quickly while maintaining stability and compatibility with various hardware components.

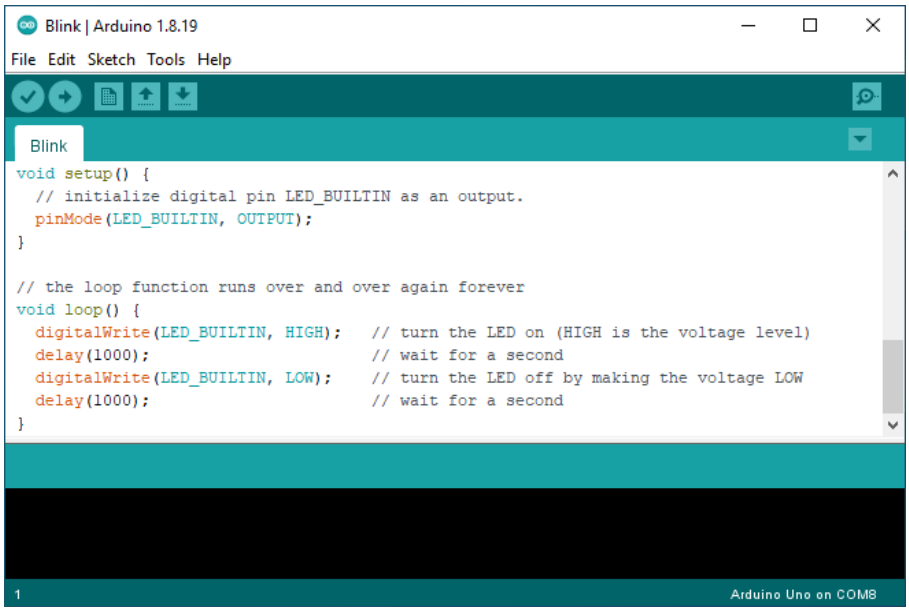


Fig 5.1: User Interface of Arduino IDE Software [19].

In the context of this project, the Arduino IDE was essential in developing a microcontroller-based control system for maintaining the internal temperature of the refrigeration chamber. The software was used to create the logic that reads real-time data from the temperature sensor, evaluates it, and then sends a signal to the relay module to turn the Peltier module and DC fan on or off based on the sensed temperature. Additionally, the IDE made it possible to control the digital temperature display, allowing users to observe temperature changes during system operation.

One of the most significant features of the Arduino IDE is the Serial Monitor, which played a critical role in testing and debugging this system. The Serial Monitor allows real-time data communication between the Arduino and a connected computer. During development, this tool was used to verify that the temperature sensor was functioning correctly and to confirm that the system was responding appropriately when crossing preset temperature thresholds. Observing temperature values in real-time helped in tuning system performance and verifying the reliability of sensor readings and relay operation.

Another important feature used in the Arduino IDE was the Library Manager, which allows users to add pre-written libraries that simplify communication with sensors, displays, and other modules. In this project, libraries related to the DS18B20 or LM35 temperature sensor, as well as the LCD display, were installed using this tool. These libraries reduced the complexity of code writing by providing built-in functions to access temperature data or update the display with just a few commands. Without such libraries, manually writing drivers for each component would have required significantly more time and technical effort.

The Arduino IDE is also valuable because of its cross-platform support. It can be installed on Windows, Linux, and macOS, making it accessible in almost any academic or industrial setting. Its compatibility with a wide range of Arduino and third-party boards also provides flexibility in upgrading or scaling the system for future improvements.

One of the main reasons for choosing the Arduino IDE in this project is its ease of use and strong community support. Since this refrigeration project involved both hardware interfacing and software automation, it was important to have a platform that offered quick setup, minimal configuration, and access to a large knowledge base. The extensive online documentation, example codes, and troubleshooting resources allowed efficient problem-solving during the development phase.

Furthermore, the IDE allowed quick modifications and re-uploading of code, making the testing process more dynamic. If any hardware wiring was changed or a new sensor was introduced, only minor code updates were needed. The Arduino IDE supports this iterative development model, which is crucial in real-world prototyping and academic research.

While the Arduino IDE is not as advanced as professional embedded development platforms, it meets the requirements of medium-complexity systems like this thermoelectric refrigerator. Although it lacks advanced debugging features like breakpoints or simulation tools, these limitations were mitigated using the Serial Monitor and consistent testing. The straightforward structure of the IDE made it easier to isolate problems and modify system logic without rewriting large portions of the codebase.

In summary, the Arduino IDE was instrumental in building the intelligent control system of this thermoelectric refrigeration project. It enabled real-time sensor data acquisition, control signal generation, user interface display, and system monitoring—all through a single development platform. By offering a reliable, intuitive, and well-supported environment for embedded programming, the Arduino IDE helped translate the conceptual design of the system into a fully functional and automated refrigeration unit.

CHAPTER 6

RESULT & DISCUSSION

6.1 Result

The thermoelectric refrigerator demonstrated the development of a compact, energy-efficient, and eco-friendly cooling system. It used a TEC-12706 Peltier module controlled by an Arduino Uno, with a DS18B20 temperature sensor providing real-time input. The relay module switched the Peltier device ON/OFF as needed, while a DC fan and heat sink efficiently dissipated heat. A digital display allowed easy monitoring of internal temperature.

During testing, the system reduced the chamber temperature by 15–20°C below ambient and operated efficiently on a 12V SMPS, consuming less power than conventional systems. Lightweight, durable materials like GI sheet, PU foam, and aluminum foil ensured portability, insulation, and structural stability.

The design offered silent operation, minimal user intervention, and avoided harmful refrigerants, making it suitable for quiet or sensitive environments. Overall, the project confirmed that thermoelectric technology with automation and proper insulation can provide a practical, portable, and eco-friendly solution for small-scale refrigeration, including medical storage, portable coolers, and personal use.

6.2 Data Collection

To evaluate the performance of the thermoelectric refrigerator, experimental data were collected under two conditions: without load and with load. Initially, the refrigerator was operated without any internal load to determine baseline cooling characteristics. The system was powered using a 12V DC SMPS, and temperature readings were displayed in real-time on a digital display and noted at specific time points (3, 6, 9, 12, 15, 18, 21, 24, 27, and 30 minutes). Under no-load conditions, the temperature dropped rapidly to 14.6°C after 6 minutes and gradually stabilized, after 30 minutes of observation, the temperature reached 13.7°C.

Next, a load of 0.5 L of water was placed inside the chamber, and the experiment was repeated under the same conditions. Under load, the temperature decreased to 14°C after 12 minutes and stabilized around this value, after 30 minutes of observation, the temperature reached 13.8°C.

This approach allowed assessment of the system's cooling performance under both ideal (without load) and practical (with load) conditions, providing insight into temperature reduction, cooling rate, and stabilization behavior.

Table 2. Data Collection of Cold Temperature Measurement of the Refrigerator

SL No	Time (minutes)	Temperature (℃)	
		Without load	With load
1	0	30	30
2	3	16.8	19.4
3	6	14.6	16.6
4	9	14	15.2
5	12	14	14
6	15	14	14
7	18	13.9	14
8	21	13.9	14
9	24	13.9	13.9
10	27	13.8	13.9
11	30	13.7	13.8

The graph shows that the thermoelectric refrigerator cools rapidly in the first 10 minutes, then stabilizes around 13–14°C. Cooling is slightly faster without load, but both reach a similar steady-state temperature after 30 minutes.

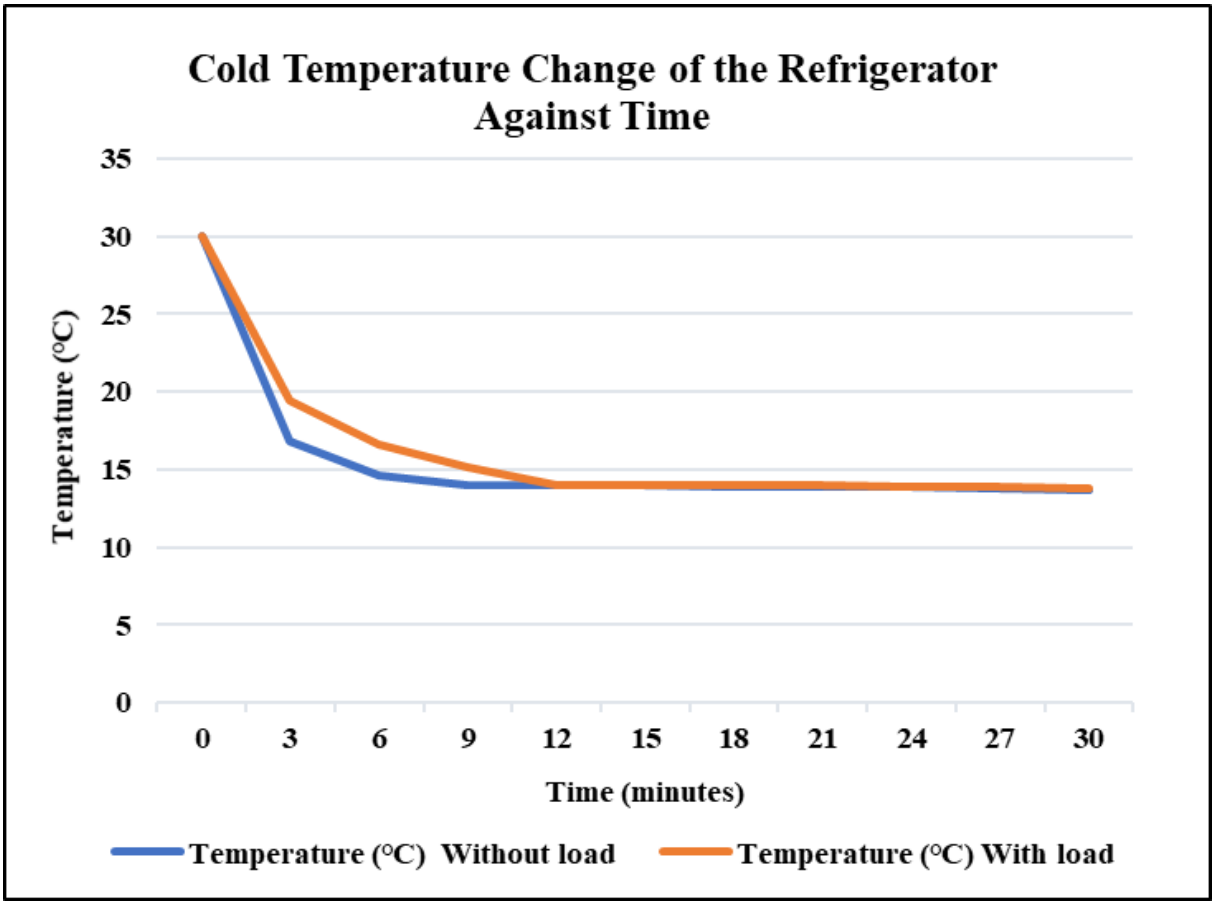


Fig 6.1: Cold Temperature Change of the Refrigerator against Time

6.3 COP of Thermoelectric Refrigerator

- **Outer dimension:**

Length = 35.56 cm

Width = 43.18 cm

Height = 43.18 cm

Volume = (35.6 43.18 × 43.18) cm^3

= 66302 cm^3

= 0.063302 m^3

- **Inner dimension:**

Length = 26.5 cm

Width = 27 cm

Height = 30 cm

Volume = (26.5 × 27 × 43.18) cm^3

= 21465 cm^3

= 0.021465 m^3

All the Electronics component consume current about 14.8A to 15.2A.
So, we take the average current consume around 15A and Voltage 12V

- **Input power = voltage × current**

= 12 × 15

= 180 watts

Under load condition, the temperature decreased to 14°C after 12 minutes and stabilized around this value. So, we take 12 minutes (720 second) observation of the system

- **Input work, (W):**

W = Input power × Time

= 180 × 720

= 129600 J

- **Calculate mass of water inside the refrigerator (m_w):**

0.5 L of water taken as experiment purpose, so the volume of the water will be,

$v = 0.5 \times 10^{-3}\ m^3$ [1 liter = 10^{-3} Cubic meter]

We know,

Mass of water, $m_w = \rho\ v$

$= (1000 \times 0.5 \times 10^{-3})$

= 0.5 kg

Here,

Initial temp. = 30℃ = 303.15°K

Final temp. = 14℃ = 287.15°K

Changing temp. = 16°K

- **Total refrigeration effect, (Q)**

$$Q = m_w \times C_p \times \text{Changing temp.}$$

$$= 0.5 \times 4.2 \times 16$$

$$= 33.6 \text{ KJ}$$

$$= 33600 \text{ J}$$

- **COP (Coefficient of performance)**

$$= \frac{\text{Refrigeration efffect (Q)}}{\text{Input work (W)}}$$

$$= \frac{33600}{129600}$$

$$= 0.26$$

The calculated COP of the thermoelectric refrigerator was found to be 0.26, which is acceptable for small-scale Peltier cooling. The prototype achieved a temperature reduction of 16°C within 12 minutes under load and maintained stable performance throughout the test period. These results demonstrate that, despite limited efficiency, the system is effective for small-scale applications where portability, silent operation, and eco-friendliness are prioritized, such as medical storage, personal cooling, and off-grid use.

6.4 Power Consumption Comparison (Thermoelectric vs. Conventional Refrigerator)

For a Thermoelectric Refrigerator (180 W, 60% duty cycle):

$$P_{avg} = 180 \times 0.6 = 108 \text{ W}$$

So, 1 hour:

$$E = 108 \text{ Wh} = 0.108 \text{ kWh}$$

For a 144 L Conventional Refrigerator (avg. 60 W):

$$E = 60 \text{ Wh} = 0.06 \text{ kWh per hour}$$

The power consumption of the thermoelectric and 144 L conventional refrigerators was calculated using their rated power and duty cycles. The thermoelectric unit (180 W, 60% duty cycle) averaged 108 W, while the conventional unit (120 W, 50% duty cycle) averaged 60 W. Energy use was recorded at 3-hour intervals up to 12 hours for comparison.

Table 3. Cumulative Energy Consumption (3-Hour Steps, up to 12 Hours)

SL No.	Time (hour)	Thermoelectric Refrigerator (kWh)	Conventional Refrigerator (kWh)
1	3	0.32	0.18
2	6	0.65	0.36
3	9	0.97	0.54
4	12	1.28	0.72

The experimental results confirm that the thermoelectric refrigerator can achieve effective cooling, reducing the temperature from ambient 30°C to around 14°C within a short period. Although its power consumption is higher and COP is lower compared to a conventional refrigerator, the system successfully demonstrates stable cooling performance, especially for small-scale and portable applications. These findings validate the feasibility of thermoelectric refrigeration as an eco-friendly and compact alternative, with potential for further efficiency improvements through material and design optimization.

6.5 Discussion

The thermoelectric refrigerator offers a wide range of applications due to its compact size, noiseless operation, and environmentally friendly design. One of its most important uses is in the medical field, especially for storing vaccines, blood samples, and other temperature-sensitive medicines in rural or remote areas where electricity supply is unreliable. Since the system operates on low voltage, it can be powered by batteries or solar panels, providing an effective off-grid solution and ensuring the safe storage of critical medical supplies.

In addition to medical use, thermoelectric refrigerators are well-suited for personal and portable cooling. Their lightweight and compact structure makes them convenient for keeping drinks, snacks, or medicines cool in offices, study rooms, vehicles, or during travel. Laboratory environments also benefit from such systems, as they provide stable and precise cooling for small biological or chemical samples without the need for bulky conventional refrigeration units.

Another significant application is in the electronics industry, where thermoelectric cooling protects heat-sensitive devices such as CPUs, sensors, and laser systems, enhancing both reliability and lifespan. Campers, travelers, and outdoor users also benefit from its battery or car-powered operation, which eliminates the need for fuel-driven compressors and enables eco-friendly portable cooling solutions.

Thermoelectric refrigerators are also valuable in education and research, where they demonstrate principles of energy conversion, thermal management, and microcontroller-based automation. Their quiet and clean operation aligns with modern trends toward sustainable and energy-efficient technologies.

In terms of performance, the developed system achieved a coefficient of performance (COP) of 0.26. Typical thermoelectric refrigerators record COP values between 0.2 and 0.25, with optimized systems rarely exceeding 0.3. Achieving 0.26 highlights the role of proper component selection, effective heat dissipation, and Arduino-based control in improving efficiency.

Overall, the study confirms that thermoelectric refrigeration is a versatile, sustainable, and efficient technology, suitable for medical, laboratory, electronic, and portable cooling applications while maintaining low power use and quiet operation.

CHAPTER 7

CONCLUSION

7.1 Conclusion

The thermoelectric refrigerator project successfully illustrates the practical implementation of a compact, efficient, and environmentally friendly cooling system using thermoelectric technology and modern microcontroller-based control. By integrating a Peltier module (TEC-12706) with an Arduino Uno and temperature sensors such as the DS18B20, the system achieves stable and precise temperature regulation within a well-insulated chamber. The use of a relay module to control the Peltier device and auxiliary components like a heat sink and DC fan for effective heat dissipation further enhance the system's overall performance.

This project highlights the key advantages of thermoelectric refrigeration, such as its silent operation, absence of harmful refrigerants, and low power consumption, which make it suitable for a variety of small-scale cooling applications. Although the cooling capacity and efficiency of this system are lower compared to conventional compressor-based refrigerators, it excels in areas where portability, compactness, and eco-friendliness are priorities. The design's compatibility with battery or solar power makes it particularly valuable for use in remote or off-grid regions, such as for vaccine storage or portable food cooling.

Moreover, the project demonstrates a valuable blend of hardware and software integration, combining sensors, microcontrollers, and display units to create an automated, user-friendly refrigeration system. It provides a strong foundation for students, researchers, and developers interested in advancing sustainable cooling technologies. With further improvements in insulation, power management, and cooling efficiency, this technology holds promise for broader applications in both commercial and domestic sectors.

In conclusion, the thermoelectric refrigerator project not only fulfills its intended purpose but also opens pathways for future innovations that align with global environmental goals and the growing need for energy-efficient refrigeration solutions. It serves as a practical example of how emerging technologies can be leveraged to develop cleaner, quieter, and more adaptable cooling systems suitable for diverse real-world needs.

7.2 Advantages

There are certainly many advantages of our project and some of the major ones have been given below -

- Eco-friendly – no harmful refrigerants
- Low power consumption (12V DC)
- Compact and space-saving design
- Lightweight and portable
- Requires very low maintenance
- Silent and vibration-free operation
- Accurate temperature control with Arduino
- Real-time digital temperature display
- Fast cooling in small chambers
- Cost-effective components
- Easy and user-friendly operation
- Safe to use – no high voltage or toxic materials

7.3 Limitation

It is a demo project so we found some limitation. In future we will work for reduce this kind of limitation. These limitations are -

- Limited cooling capacity
- Low energy efficiency (low COP)
- Requires effective heat dissipation
- Temperature instability in high ambient conditions
- Sensitive components (e.g., Peltier module can be damaged easily)

7.4 Application

Some of the application areas of the project has been pointed out below-

- Vaccine and medicine storage in remote areas
- Portable mini cooler for personal use
- Cooling system for electronic devices
- Laboratory sample storage
- Small-scale food and beverage storage

- Camping and outdoor refrigeration
- Battery-operated or solar-powered refrigeration
- Temperature-controlled storage for cosmetics
- Scientific and academic demonstration projects
- Cooling compartments in electric vehicles or robotics

7.5 Future Scope

The thermoelectric refrigerator project has great potential for improvement and wider application. Future work can focus on enhancing efficiency, integrating renewable energy, adding smart features, and scaling the system for various uses.

- Improve cooling efficiency with better Peltier modules
- Use advanced insulation to reduce heat loss
- Integrate solar power for off-grid operation
- Add IoT for remote monitoring and control
- Optimize battery usage for longer run time
- Scale up design for larger cooling capacity
- Develop hybrid systems combining thermoelectric and conventional cooling
- Use eco-friendly and recyclable materials

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APPENDIX

Arduino Uno Programming Code:

```
#include <OneWire.h>
#include <DallasTemperature.h>
#define ONE_WIRE_BUS 2
#define RELAY_PIN 7
OneWire oneWire(ONE_WIRE_BUS);
DallasTemperature sensors(&oneWire);
bool relayState = false;
void setup() {
  Serial.begin(9600);
  sensors.begin();
  pinMode(RELAY_PIN, OUTPUT);
  digitalWrite(RELAY_PIN, LOW); // শুরুতে রিলে OFF থাকবে
}
void loop() {
  sensors.requestTemperatures();
  float tempC = sensors.getTempCByIndex(0);
  Serial.print("Current Temperature: ");
  Serial.print(tempC);
  Serial.println(" °C");
  if (tempC >= 21 && !relayState) {
    digitalWrite(RELAY_PIN, HIGH); // রিলে ON — ঠান্ডা করার জন্য
    relayState = true;
    Serial.println("Relay ON (Cooling Started)");
  }
  else if (tempC <= 18.50 && relayState) {
    digitalWrite(RELAY_PIN, LOW); // রিলে OFF — যথেষ্ট ঠান্ডা
    relayState = false;
    Serial.println("Relay OFF (Cool enough)");
  }
  delay(2000);
}
```