DESIGN AND DEVELOPMENT OF A THERMOELECTRIC-BASED INSTANT BEVERAGE CHILLER

A Major Project Report Submitted to

Veer Surendra Sai University of Technology

in partial fulfilment of the requirements for the award of the degree

of

BACHELOR OF TECHNOLOGY

in

MECHANICAL ENGINEERING

by

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May 2025

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May 2025

Department of Mechanical Engineering

VEER SURENDRA SAI UNIVERSITY OF TECHNOLOGY

CERTIFICATE

Date:

This is to certify that the project report entitled "DESIGN AND DEVELOPMENT OF A THERMOELECTRIC-BASED INSTANT BEVERAGE CHILLER" being submitted to Veer Surendra Sai University of Technology, Burla in partial fulfilment of requirements of the award of degree of Bachelors of Technology (B.Tech) in Mechanical Engineering is a record of bonafide work carried out by them under my supervision and guidance in the academic year 2024-2025. This project report in my opinion is worth of consideration for the award of degree of Bachelor of Technology. Further, the project fulfils the requirement of the regulation to the nature of standard of work for Bachelor of Technology degree in Mechanical engineering. The result presented in this project report, to the best of my knowledge, has not been submitted to any other Institute or university for the award of any degree.

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DECLARATION

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- This work was done wholly while in candidature for **Bachelor of Technology in MECHANICAL ENGINEERING at VEER SURENDRA SAI UNIVERSITY OF TECHNOLOGY, BURLA.**
- This work, wholly or partially, has not been submitted to any other institute or university for any degree or diploma.
- We have abided by the norms and guidelines given in the Ethical Code of Conduct of the institute.
- Where we have consulted the published work of others, this is always clearly attributed.
- Where we have used materials from the work of others, we have given due credit to them by citing them in the text of the report and giving details in the references. With the exception of such citations, this thesis is entirely our own work.
- We have acknowledged all main sources of help.

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We hereby accord our approval of it as a dissertation work carried out and presented in a manner required for its acceptance for the partial fulfilment for the award of degree of Bachelor of Technology with specialisation in Mechanical Engineering for which it has been submitted. The approval does not necessarily endorse or accept every statement made, opinion expressed or conclusion drawn as recorded in this project report. It only signifies the project report for the purpose it has been submitted.

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CERTIFICATE OF SUBMISSION

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ABSTRACT

The "**DESIGN AND DEVELOPMENT OF A THERMOELECTRIC-BASED INSTANT BEVERAGE CHILLER**" project explores the application of the **TEC1-12704 Peltier module** for efficient, rapid beverage cooling in both domestic and commercial settings. As an energy-efficient and compact solution, this system utilizes the Peltier effect to cool beverages without relying on conventional refrigeration methods. The TEC1-12704, known for its thermoelectric properties, creates a temperature gradient when powered by a DC current, transferring heat from the beverage to a heat sink and ensuring effective cooling.

This project aims to design a portable, easy-to-use cooling device that reduces beverage temperatures quickly. The system's key components include the **TEC1-12704 Peltier module**, a **high-performance heat sink**, **fans for efficient heat dissipation**, and a **power supply unit** optimized for low energy consumption. A detailed design approach, including thermal simulations and practical testing, ensures efficient heat transfer and system performance.

Key performance indicators such as cooling time, energy consumption, and the overall system's durability will be evaluated. The expected outcome is achieving rapid cooling (reducing beverage temperature to desired levels within One minutes) with minimal power consumption, offering a sustainable and innovative alternative to traditional cooling systems. This technology holds promise for use in a wide range of applications, from **vending machines** to **outdoor activities** and **household kitchens**, providing a convenient solution for portable and on-demand beverage cooling.

Keywords: Thermoelectric cooling, Peltier module, TEC1-12704, instant beverage chiller, rapid cooling, heat sink, energy efficiency.

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1. INTRODUCTION

1.1 Problem Statement

In today's fast-paced world, people seek quick solutions for their daily needs, including cooling beverages to an optimal temperature for consumption. Traditional methods like using refrigerators or ice are time-consuming and energy-intensive, often unsuitable for immediate cooling in outdoor or portable settings. There is a need for an efficient, portable, and eco-friendly system to instantly cool beverages without relying on bulky machinery or significant power sources. This project addresses the gap by designing an *Instant Beverage Cooler* based on thermoelectric cooling technology.

1.2 Motivation for the Project

The idea of enhancing user convenience while promoting energy-efficient and portable solutions is a driving force behind this project. Thermoelectric cooling, a lesser-utilized yet promising technology, can revolutionize the way beverages are cooled, making it faster, more portable, and environmentally sustainable. The project is inspired by the need to combine innovation with practicality, creating a product that caters to diverse scenarios such as picnics, small shops, and office spaces. Furthermore, this project offers an opportunity to explore and apply thermodynamic and heat transfer principles in real-world applications.

1.3 Objectives of the Project

- To conceptualize and design a portable instant beverage cooler using thermoelectric cooling technology.
- To identify suitable thermoelectric modules (Peltier modules) and associated components required for efficient cooling.
- To analyze the energy efficiency and feasibility of the proposed system compared to conventional cooling methods.
- To establish a framework for the development and testing of the final model.

1.4 Scope and Applications

- Domestic Use: Instant cooling of beverages in households without the need for a refrigerator.
- Outdoor Activities: Portable cooling solutions for picnics, camping, or road trips.
- Small Businesses: Local vendors and kiosks can use this system to serve chilled beverages on demand.
- Event Catering: Quick cooling during events or gatherings, reducing dependency on ice or refrigeration units.
- Research and Development: The project provides a foundation for further innovations in thermoelectric cooling technologies.

2. LITERATURE REVIEW

2.1 Overview of Thermoelectric Cooling

Thermoelectric cooling is based on the Peltier effect, discovered in 1834 by Jean Charles Athanase Peltier, which describes the generation of a temperature difference across a junction of two dissimilar conductors or semiconductors when an electric current is passed through them. Modern thermoelectric coolers (TECs) use semiconductor materials such as bismuth telluride (Bi_2Te_3) to achieve a high coefficient of performance (COP) for cooling applications.

Researchers have highlighted the following advantages of TEC systems over conventional cooling systems:

- Compactness and portability.
- Lack of moving parts, reducing maintenance.
- Precise temperature control.
- Environmentally friendly operation, as no refrigerants are used.

However, the limitations include lower efficiency compared to compressor-based cooling systems and the need for effective heat dissipation to optimize performance.

2.2 Review of Similar Technologies

Several studies and commercial products have attempted to address the need for rapid beverage cooling:

1. Conventional Refrigeration Systems
    - Widely used refrigerators rely on vapor-compression cycles to cool beverages.
    - While effective, they are energy-intensive, bulky, and not suitable for instant cooling.
2. Ice and Cooling Packs
    - These provide an immediate solution but require pre-preparation and are not reusable indefinitely.
    - They are impractical for users seeking instant and repeatable cooling solutions.
3. Thermoelectric Cooling Applications
    - Research shows TECs have been used in portable mini-refrigerators, CPU coolers, and medical applications.
    - TEC-based systems are emerging as a viable option for niche cooling applications where compactness and portability are critical.
4. Market Gaps
    - Existing portable cooling systems either lack efficiency, are expensive, or are not user-friendly.
    - There is limited research into applying TEC technology for specific-use cases such as single-beverage cooling systems.

2.3 Research Gaps and Innovation Opportunities

1. Performance Optimization

   Current TEC systems face challenges in heat dissipation, which reduces their efficiency. Advanced heat sink designs and fan-assisted cooling are areas requiring further exploration.

2. Energy Efficiency

   Studies indicate that the COP of TEC systems can be improved by selecting high-quality materials for the TEC module and optimizing the input power supply.

3. Integration with Compact Designs

   While TECs are inherently compact, their integration into beverage cooling systems demands lightweight materials, insulation, and ergonomic design, which is under-researched.

4. Rapid Cooling Capability

   Existing cooling solutions often fail to achieve the desired temperature drop within a short time. TEC systems can be optimized for faster thermal response times through effective temperature regulation algorithms and component alignment.

3. THEORY AND PRINCIPLES

3.1 The Thermoelectric Effect

The thermoelectric effect is a physical phenomenon that directly converts temperature differences into electrical voltage and vice versa. It encompasses three primary effects:

Seebeck Effect

The Seebeck effect is a thermoelectric phenomenon where a temperature difference between two dissimilar conductors or semiconductors generates an electric voltage across their junctions. When one junction is heated (hot junction) and the other is kept cooler (cold junction), the thermal energy causes charge carriers (electrons or holes) to diffuse from the hot side to the cold side. This movement of charge carriers creates an electric potential difference, known as the Seebeck voltage.

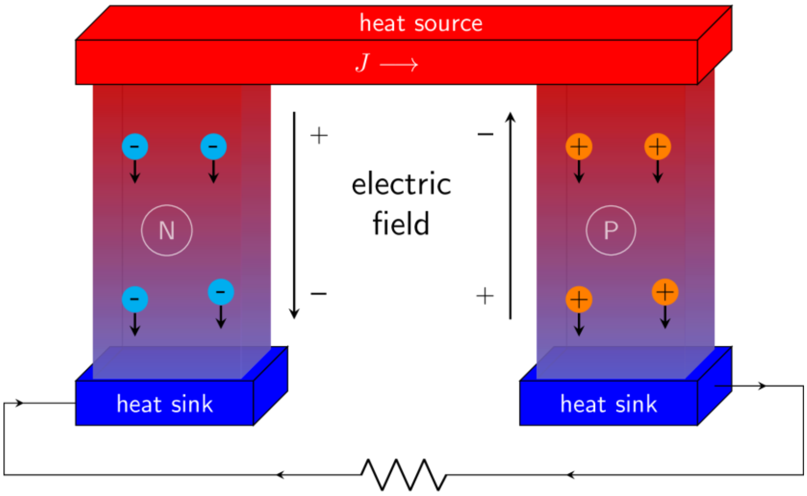

Figure 1. Seebeck Effect

- **Mathematical Representation**

The voltage (V) generated is proportional to the temperature difference (ΔT) and the material's Seebeck coefficient (S):

$$V = S \cdot \Delta T$$

Where:

V = Voltage generated (in volts)

S = Seebeck coefficient (in volts per kelvin, V/K)

ΔT = Temperature difference (in kelvin)

- **Seebeck Coefficient**

The Seebeck coefficient is a material property that measures the efficiency of voltage generation with respect to a temperature gradient.

Peltier Effect

The Peltier effect is a thermoelectric phenomenon where heat is absorbed or released at the junction of two different conductors or semiconductors when an electric current passes through the junction. Discovered by Jean-Charles Peltier in 1834, this effect is the reverse of the Seebeck effect and forms the basis of thermoelectric cooling and heating devices.

- How it Works
  - When a current flows through a circuit composed of two different materials, electrons or charge carriers move from one material to another.
  - As electrons enter a material with a lower energy state, they release energy in the form of heat (heating effect).
  - Conversely, as they enter a material with a higher energy state, they absorb energy from the surroundings (cooling effect).

  This creates a temperature difference at the junctions:

  - One junction becomes hot as heat is released.
  - The other becomes cold as heat is absorbed.

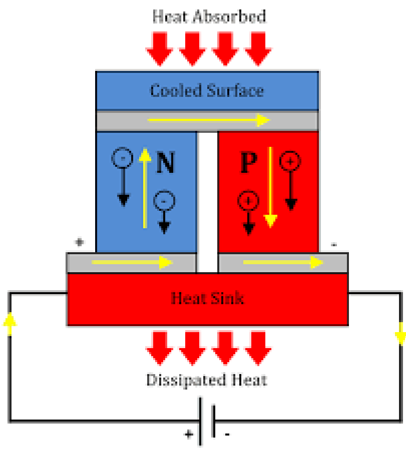

Figure 2. Peltier Effect

- **Mathematical Representation**

The heat absorbed or released (Q) is proportional to the electric current (I) and the material's Peltier coefficient (Π):

$$Q=\Pi\cdot I\cdot t$$

Where:

Q = Heat absorbed or released (in joules)

Π = Peltier coefficient (in volts)

I = Electric current (in amperes)

t = Time (in seconds)

Thomson Effect

The Thomson effect is a thermoelectric phenomenon where heat is either absorbed or released along the length of a conductor when an electric current flows through it in the presence of a temperature gradient. Discovered by William Thomson (later known as Lord Kelvin) in 1854, this effect highlights the interaction between electrical and thermal energy.

- **Key Characteristics**
    - If current flows from the hotter end to the cooler end, heat is released along the conductor.
    - If current flows from the cooler end to the hotter end, heat is absorbed.
    - The amount of heat (Q) generated or absorbed per unit time depends on the material's Thomson coefficient (τ), the electric current (I), and the temperature gradient (ΔT):

$$Q=\tau \cdot I \cdot \Delta T$$

3.2 Working Principle of Thermoelectric Cooling (Peltier Module)

Thermoelectric cooling modules, commonly referred to as Peltier modules, are solid-state devices that utilize the Peltier effect to create a temperature difference.

Structure of a Peltier Module

A Peltier module is a thermoelectric device that uses the Peltier effect to create a temperature difference between two sides of the module when an electric current is applied. The module consists of several key components:

1. **Semiconductor Materials (p-type and n-type):**
    - The core of the Peltier module is made up of alternating p-type and n-type semiconductor materials. These materials are specifically chosen for their thermoelectric properties, which allow for efficient heat transfer when subjected to an electric current. The p-type semiconductors have an excess of holes (positive charge carriers), while the n-type semiconductors have an excess of electrons (negative charge carriers).
    - These materials are carefully arranged in pairs (p-n pairs), where each pair forms a thermocouple, and multiple pairs are used to maximize the heat transfer effect. The arrangement of the thermocouples is such that heat is transferred through the junctions when the current flows.
2. **Ceramic Plates:**
    - The p-type and n-type thermocouples are sandwiched between two ceramic plates. The ceramic plates provide structural integrity, electrical insulation, and thermal conduction. These plates ensure that the heat is transferred properly from the semiconductor elements to the external environment. They also prevent short-circuiting between the p-type and n-type materials.

- The ceramics are usually made of a material that is a good thermal conductor, allowing efficient heat dissipation from the hot side of the module.

3. **Series and Parallel Connections:**
   - The p-type and n-type semiconductor materials are electrically connected in series, meaning the electric current flows sequentially through each thermocouple. This configuration ensures that the voltage and current can be controlled to induce the Peltier effect.
   - The thermocouples, on the other hand, are thermally connected in parallel, meaning that the heat is transferred simultaneously across all the junctions from the cold side to the hot side. The parallel arrangement allows for the efficient heat absorption and rejection over a larger surface area.

Operation of a Peltier Module

The operation of a Peltier module involves the flow of current through the semiconductor junctions, which leads to the Peltier effect—a process where heat is either absorbed or released at the junctions of different types of semiconductors (p-type and n-type).

1. **Cold Side (Heat Absorption):**
   - When a direct current (DC) passes through the Peltier module, it causes the electrons in the n-type semiconductor to absorb energy from the surroundings as they move toward the hot side. This absorption of energy causes the cold side of the module to cool down.
   - The cold side is typically the side that is in direct contact with the object or area you want to cool. For example, in a beverage cooler, the cold side would be in contact with the container. The temperature reduction on this side is a direct result of the heat being pulled away by the movement of electrons.
2. **Hot Side (Heat Rejection):**
   - As the electrons move from the cold side to the hot side through the module, they release the heat they absorbed at the cold side. This release of heat occurs as the electrons drop to a lower energy state at the hot side.
   - The hot side requires effective heat dissipation, which is typically achieved by attaching a heat sink or using a fan to expel the heat into the surrounding environment. Without adequate heat dissipation, the hot side will overheat, reducing the efficiency of the module and potentially causing thermal damage.
3. **Energy Input (Power Source):**
   - The performance of a Peltier module depends largely on the amount of input power supplied. This power is typically provided by a low-voltage DC power source. The voltage and current supplied to the module control the rate at which heat is transferred between the cold and hot sides.
   - The voltage and current determine the amount of temperature difference (ΔT) created across the module. For example, higher input power can increase the cooling effect on the cold side but also increase the heat generated on the hot side. Thus, power optimization is essential for achieving efficient cooling or heating.

Detailed Working Mechanism:

- When current flows through the Peltier module, electrons in the n-type material absorb energy as they move from the low-energy (cold) side to the high-energy (hot) side. This absorption leads to a cooling effect on the cold side.
- Simultaneously, holes in the p-type material move in the opposite direction, releasing heat on the hot side. This process causes a temperature gradient between the cold and hot sides, with the cold side cooling down and the hot side heating up.

3.3 Heat Transfer Principles in Cooling Systems for Peltier Modules

Efficient thermoelectric cooling using Peltier modules depends on understanding and managing the different heat transfer processes involved. These processes include conduction, convection, thermal insulation, and heat sink design, each of which plays a crucial role in maximizing the module's cooling performance.

1. Conduction

Conduction refers to the transfer of heat through solid materials, and in the case of a Peltier module, this process occurs primarily within the module and between the module and its components, such as the heat sink.

- **Heat Transfer Through the Peltier Module:**

In a Peltier module, heat is transferred from the cold side to the hot side via the thermoelectric materials, typically made of bismuth telluride. When a current passes through these materials, electrons move between the p-type and n-type semiconductors, transferring heat from one side of the module to the other.

The efficiency of heat conduction within the Peltier module is influenced by the thermal conductivity of the materials used. Materials with higher thermal conductivity allow heat to move more easily, improving the system's ability to manage heat. On the cold side, efficient conduction ensures that heat is absorbed from the object being cooled. On the hot side, efficient conduction allows heat to transfer into the heat sink for dissipation.

- **Conduction in the Heat Sink:**

Heat sinks attached to the hot side of the Peltier module must conduct the heat away from the module and disperse it into the surrounding environment. High thermal conductivity materials like aluminum or copper are commonly used for heat sinks, as they enable effective heat transfer.

2. Convection

Convection is the process by which heat is transferred away from the heat sink through the movement of air (or liquid) over the surface of the heat sink. In Peltier-based cooling systems, convection plays a vital role in dissipating the heat from the hot side of the module.

- **Natural Convection:**

  Natural convection occurs due to the natural rise of heated air. As the heat sink gets warm, the air around it becomes heated and rises, creating a natural flow of air. While natural convection works in low-power applications, it is not very efficient for dissipating the heat generated by the Peltier module, especially in higher-power applications.

- **Forced Convection:**

  Forced convection involves the use of fans or blowers to actively move air across the heat sink. This type of convection greatly improves the heat dissipation process because it accelerates the movement of warm air away from the heat sink, allowing cooler air to replace it more quickly. Fans are often integrated with the heat sink to ensure effective heat transfer, especially in high-performance or high-power thermoelectric cooling systems.

- **Effect of Airflow:**

  The amount of heat dissipated by convection depends on the airflow rate and temperature difference. The faster the airflow, the more efficient the heat dissipation, leading to a better overall cooling performance of the Peltier module.

3. Thermal Insulation

Thermal insulation is used to reduce the unwanted heat transfer from the surrounding environment into the cold side of the Peltier module. Effective insulation is necessary to maintain the low temperature on the cold side and improve the efficiency of the thermoelectric cooling process.

- **Preventing Heat Gain to the Cold Side:**

  The cold side of the Peltier module is responsible for absorbing heat from the object being cooled, such as a beverage or electronic component. To maintain a low temperature on the cold side, it is essential to minimize the heat that flows from the external environment into this side.

  Materials with low thermal conductivity are used as insulation around the cold side to prevent this unwanted heat transfer. Common insulating materials include foam, aerogel, and polystyrene. These materials ensure that the cold side of the module maintains its temperature, allowing the module to function efficiently.

- **Insulation and Energy Efficiency:**

  Proper insulation reduces the need for additional cooling power, thus enhancing the overall energy efficiency of the Peltier module. Without sufficient insulation, the cold side would heat up quickly, requiring the Peltier module to work harder and consume more power to maintain the desired low temperature.

4. Heat Sink Design

The heat sink design is crucial in dissipating the heat absorbed by the hot side of the Peltier module. The design of the heat sink influences the module's overall performance by determining how effectively heat is removed from the module and released into the surrounding environment.

- **Material Selection:**

Aluminum and copper are commonly used materials for heat sinks due to their high thermal conductivity, which helps in the quick transfer of heat away from the hot side of the Peltier module. The choice of material impacts the efficiency of the heat sink and, consequently, the cooling performance of the system.

- **Surface Area:**

The surface area of the heat sink plays a significant role in its ability to dissipate heat. Larger surface areas allow more heat to be transferred from the heat sink to the surrounding air. Heat sinks are often designed with fins or plates to increase surface area without adding excessive bulk, allowing more air to come into contact with the surface and aiding in heat dissipation.

- **Airflow Efficiency:**

The heat sink's design also influences the airflow around it. Proper design allows for efficient natural or forced convection. A well-designed heat sink facilitates the movement of air through the fins and surfaces, enhancing heat dissipation.

- **Active Cooling:**

In higher-power thermoelectric applications, fans are often used to provide forced convection across the heat sink, ensuring rapid removal of heat from the hot side. Fans help maintain the temperature differential between the cold and hot sides, improving the overall cooling efficiency of the Peltier module.

3.4 Efficiency and Coefficient of Performance (COP)

The efficiency of thermoelectric coolers is measured using the Coefficient of Performance (COP), defined as the ratio of cooling power to the input electrical power.

$$COP = Q_c / W$$

Where:

Q_c: Heat absorbed at the cold side (cooling power).

W: Electrical power supplied to the module.

- **Factors Affecting COP:**

  Temperature difference between the cold and hot sides (ΔT).

  Quality of the thermoelectric materials (figure of merit, ZT).

  Heat dissipation efficiency on the hot side.

3.5 Challenges in Thermoelectric Cooling

- **Heat Dissipation**

Ineffective heat dissipation on the hot side leads to reduced cooling efficiency and potential module damage.

- **Thermal Resistance**

High thermal resistance between the module and heat sink lowers overall performance.

- **Power Consumption**

Despite being compact, TEC systems may require significant power input for sustained cooling.

- **Limited Cooling Capacity**

TECs are most effective for small-scale applications due to their inherent thermal limitations.

4. CONCEPTUAL DESIGN

Figure 3. Conceptual CAD Design

4.1 Proposed Design of the Instant Beverage Chiller

The proposed design focuses on creating a compact and efficient cooling device that can rapidly chill beverages using thermoelectric technology. Key features include:

- Portability: The system is lightweight and easy to carry, suitable for outdoor use.
- Speed and Efficiency: Designed to cool a 500 ml beverage can from room temperature (25–33°C) to a drinkable chilled temperature (2–6°C) within 45-60 seconds.
- Simplicity: Minimal user interaction is required, with straightforward controls and indicators for operation.

4.2 Selection of Key Components

Name of The Component	Amount	Specifications
Peltier Module	2	36Watt (12V, 3A)
Battery Pack	1	12Volt, 9Ah
Cooling Block	2	Water Cooling Block
Copper Tube	2	1Meter
Heat Sink with Fan	1	12Volt, 0.25Amp
Power Controller Module	1	Arduino
Thermal Paste	1	4-8W/mK

Table 1. Key Components

4.3 Components Selection

1. Peltier Module

The Peltier module is a thermoelectric device that uses the Peltier effect to transfer heat between two surfaces. It functions as a solid-state heat pump, with one side cooling and the other side heating when electrical current flows through it.

Figure 4. Peltier Module

Working Principle

When DC power is supplied, the module's semiconductor junctions transfer heat from the cold side to the hot side.

The cold side absorbs heat, enabling it to cool the beverage, while the hot side requires heat dissipation to maintain a temperature gradient.

Key Features

Model: TEC1-12704.

Performance: Maximum temperature difference (ΔT) of around 68°C.

Power Requirements: Operates on 12V DC, consuming 2.15-2.75 Amps of current.

2. Battery Pack

The battery pack serves as the power source for the cooling system, ensuring portability and consistent energy supply for the Peltier module and other components.

Figure 5. Battery

Key Specifications

Type: 12V, 7Ah rechargeable lead-acid or lithium-ion battery.

Capacity: Provides 84 watt-hours, sufficient for operating the system for 1.5–2 hours depending on load.

Portability: Compact size for easy integration into the cooler.

3. Cooling Block

The cooling block, typically made of thermally conductive materials like aluminium or copper, acts as the interface between the Peltier module and the beverage container.

Role

Transfers heat efficiently from the beverage to the Peltier module's cold side.

Maximizes thermal contact for rapid cooling.

Figure 6. Aluminium Cooling Block

Key Features

Material: Aluminium is preferred for its lightweight and high thermal conductivity (205W/mK).

Design: Smooth and flat surface to ensure uniform thermal contact with the beverage.

Shape: Can be cylindrical or plate-like to fit different container shapes

4. Copper Tube

Copper tubes are used to enhance the system's heat dissipation by channelling coolant (if a liquid cooling system is integrated) or as structural components for improved thermal performance.

Role in the System

Channels heat from the Peltier module to the heat sink (if used in a heat exchange mechanism).

Improves thermal conductivity between components.

Key Features

Thermal Conductivity: 398 W/, making copper highly effective for heat transfer.

Durability: Resistant to wear and corrosion.

5. Heat Sink with Fan

The heat sink and fan assembly is critical for dissipating heat from the hot side of the Peltier module, maintaining its temperature gradient for optimal performance.

Figure 7. Heat Sink & Fan

Design and Functionality

Heat Sink: copper fins with a high surface area increase heat dissipation through natural or forced convection.

Fan: A 12V DC axial fan enhances forced convection, expelling heat more efficiently.

6. Power Controller Module

The power controller module regulates the voltage and current supplied to the Peltier module, ensuring safe and efficient operation.

Role in the System

Prevents overloading or overheating of the Peltier module.

Provides user control over cooling intensity and power management.

Key Features

Microcontroller Integration: Arduino Nano or similar devices can be programmed to automate control.

Adjustable Settings: Enables manual or automated power adjustments based on cooling requirements.

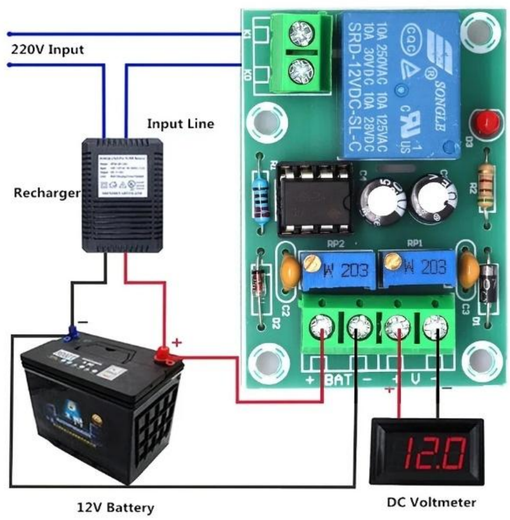

Figure 8. Controller Module

7. Thermal Paste

Thermal paste is a heat-conductive compound applied between the Peltier module and the cooling block to improve thermal conductivity.

Figure 9. Thermal Paste

Role in the System

Fills microscopic gaps between surfaces to ensure maximum heat transfer.

Minimizes thermal resistance between the module and the cooling block.

8. Solar Panel

The solar panel is integrated into the system to enable **sustainable charging** of the battery pack, enhancing portability and energy independence for outdoor or off-grid applications.

Key Specifications:


Figure 10. Solar Panel

- **Type:** Monocrystalline/Polycrystalline solar panel (select based on efficiency needs).
- **Power Output:** 10W–20W (compatible with 12V battery charging).
- **Voltage:** 12V nominal (with a voltage regulator to prevent overcharging).
- **Mounting:** Compact and lightweight design for easy attachment to the chiller unit.

Role in the System:

- Converts solar energy to electrical energy, charging the **12V battery pack** during operation or idle periods.
- Reduces reliance on grid power, making the system ideal for **outdoor activities** or areas with limited electricity access.
- Paired with a **charge controller** to regulate voltage/current and protect the battery.

Integration:

1. Connected to the battery via a **solar charge controller** (e.g., PWM or MPPT type) to optimize charging efficiency.
2. Optional: Foldable/portable design for ease of transport.

4.4 Circuit Diagram

1. CAD Drawings and Design Sketches

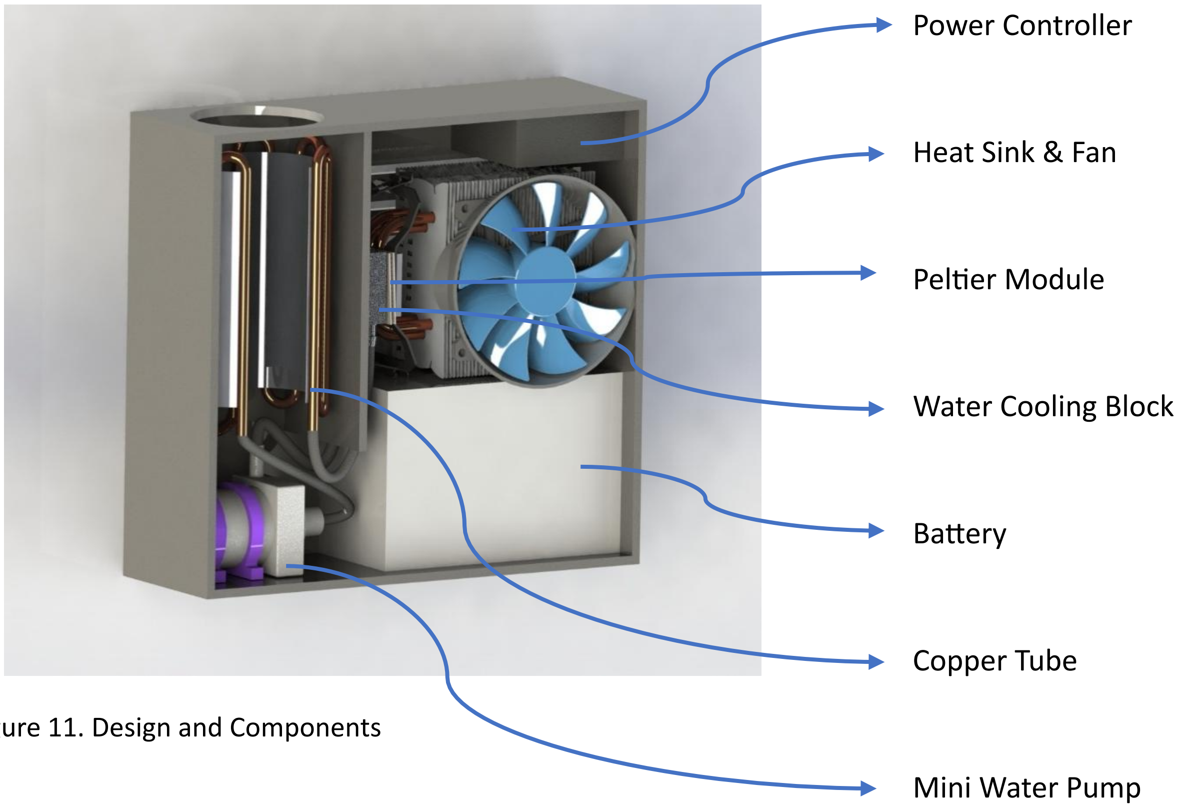

Figure 11. Design and Components

2. Electrical Circuit Diagram

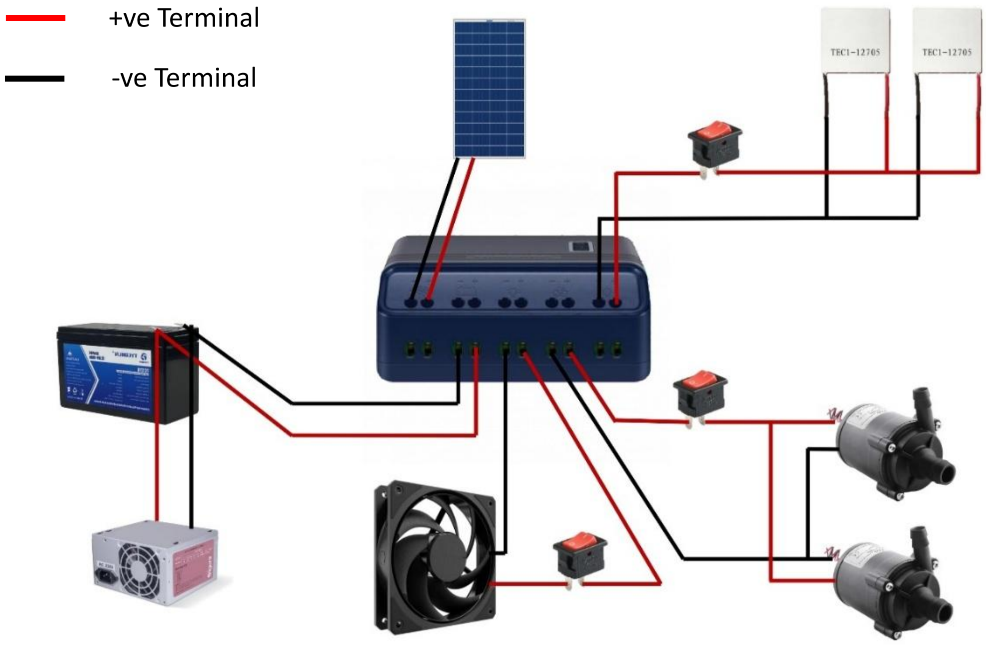

Figure 12. Electrical Circuit Diagram

3. Liquid flow diagram

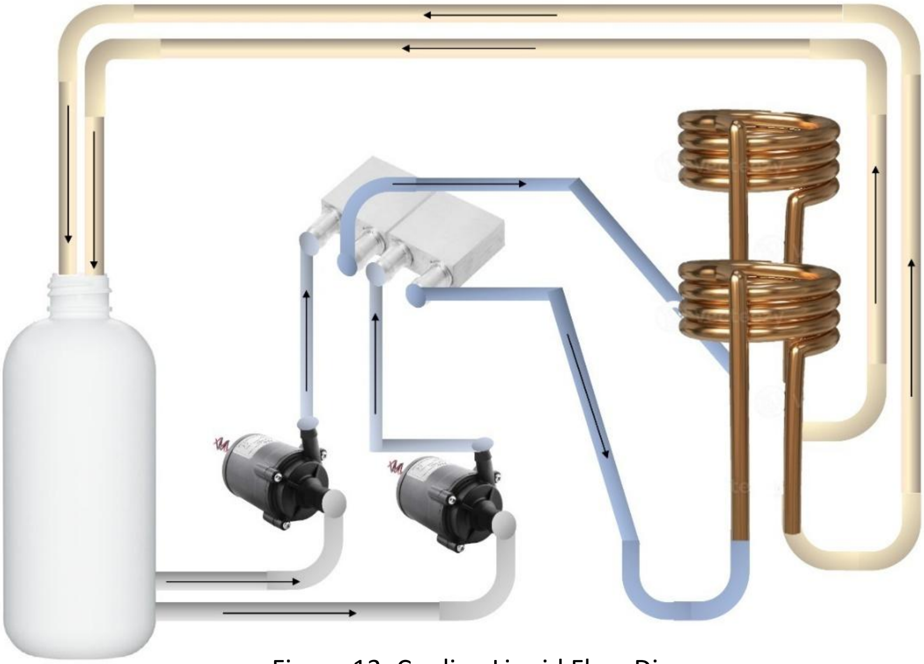

Figure 13. Cooling Liquid Flow Diagram

4. Our Model

Figure 14. Our Model

5. FEASIBILITY ANALYSIS

5.1 Calculation of Input Power and Heat Absorbed

TEC Specification

In this study we use TEC1-12704 a thermoelectric module, which specification are as follow.

Sl No.	Items	Symbols	Parameters
1	Max. Operating Temperature	T	473K
2	Max Cooling Power	Qmax	36W
3	Temp. Difference Max	ΔTmax	68K
4	Input Voltage max.	Vmax	15.4V
5	Max Current	Imax	3A
6	Resistance	R	3.2-3.5Ω
7	Seebeck Coefficient	S	0.03V/K
8	Thermal Conductivity	K	1.5-2W/m.K

Table 2. Peltier Module Specifications

Thermal Resistance Network

Thermal resistance network is conducted here for analysis. Since TEC generates Joule heat, it makes heat rejection, which is called QH, from TEC hot side larger than the heat absorption, which is called Q_L, into TEC cold side.

According to literatures, the general forms of heat absorption and heat rejection are presented as bellow. Heat transferred into the cold side when neglected the temperature drop through the TEC is given by,

Q_L = - $[SIT_C - \frac{1}{2}I^2R - k\{T_h\text{-}T_c\}]$ (-) sign for heat rejection.

While the heat transferred out of the hot side into the heat sink is given by,

Q_H = $[SIT_C + \frac{1}{2}I^2R - k\{T_h\text{-}T_c\}]$

Where,

1. **Peltier Terms (SIT_C):**
    - Comes from Peltier effect (heat absorption/production at junctions)
    - Dominates at low current
2. **Joule Heating (½I^2R):**
    - Represents internal resistive losses
    - Becomes significant at high currents
    - Split equally between hot/cold sides in derivation

3. **Conduction Term (kΔT):**
    - Fourier's law of heat conduction
    - Represents parasitic heat leak from hot to cold side

Symbol	Term	Definition	Origin/Formula	Units
Q_L	Cooling power	Heat absorbed at cold side	Peltier effect minus losses	W
Q_H	Heating power	Heat rejected at hot side	Peltier effect plus losses	W
S	Seebeck coefficient	Material's thermoelectric potential	$S = \Delta V/\Delta T$ (Material property)	V/K
I	Electric current	Input current to TEC	Measured parameter	A
T_L	Cold side temp	Temperature at cooled surface	Measured parameter	K
T_H	Hot side temp	Temperature at heat sink	Measured parameter	K
R	Electrical resistance	TEC module resistance	$R = V/I$ (Ohm's Law)	Ω
k	Thermal conductance	Heat transfer through TEC	$k = (A \cdot k_{mat})/L$	W/K
$1/2\ I^2R$	Joule heating	Internal heat generation	Power loss in TEC	W

Table 3. Terms and their Formulas

Seebeck coefficient (S) and electrical resistance (R) in Ohms are dependent both on the materials used within the TEC, but also on the geometry of the device, given by the number and dimensions of the individual N and P-type semiconductor elements.

Temperature difference

After measuring the temperature by Thermometer, final temperature at the surface of module and the heat sink are as follow.

Temperature at hot side Th = 40˚ C

Temperature at cold side Tc = 0˚ C

So, Temperature difference can be considered as

$\Delta T = (Th - Tc) = (40-0) = 40^\circ C$

5.2 Theoretical Coefficient of Performance (COP) Calculation

A non-dimensionless parameter called the Coefficient of Performance is therefore used to measure the performance of a cooling machine. The coefficient of performance (COP) of a thermoelectric module which is the thermal efficiency must be considered for a TE system. COP is the ratio of the thermal output power and the electrical input power of the TEC. COP can be calculated by dividing the amount of heat absorbed at the cold side to the input power.

COP = Q_L/Energy supplied (W)

Heat absorption is calculated as bellow.

Q_L = - [$SIT_C - I^2R - k\{T_h$-$T_c\}$]

= -[0.03×2.75×273-2.75^2 ×3.35-2×(313-273)]

= 62.745W

From the first law of thermodynamics, the Energy supplied is:

Energy supplied, W = $Q_H - Q_L$

= $SI(T_h - T_C)$+ I^2R

= 0.03×2.75×(313-273) + 2.75^2 ×3.35

= 28.634W

The Coefficient of Performance (COP) is obtained by the following empirical equation.

COP = Q_L/Energy supplied(W)

= 62.745/28.634

= 2.191

6. OBSERVATION AND RESULTS

6.1 Experimental Setup

- **Test Conditions:**
    - Ambient temperature: 28°C ± 2°C.
    - Beverage volume: **500 mL** (standard bottle).
    - Initial temperature: **30°C** (room temperature).
    - Target temperature: **12°C** (achieved in **4 minutes**).
    - Power source: **12V battery** (9Ah) with **10W solar panel** used.
- **Instrumentation:**
    - Temperature monitoring: **DS18B20 sensors** (±0.5°C accuracy).
    - Power metrics: **Digital multimeter** (voltage/current logging).

6.2 Performance Data

1. Cooling Performance

- **Temperature Drop:**
    - **30°C → 12°C in 4 minutes** (240 seconds) for 500 mL water.
    - Cooling rate: **~0.075°C/second**.

2. Energy Consumption

- **Power Draw: 66W(Peltier Module) + 20W(Pumping System) + 4W(Cooling System)**
- **Battery Drain:**
    - **~1hr of battery life we get from this device.**
    - Practical max cycles per charge: **16 cycles**

3. Solar Charging Contribution

1. **Solar Input: 10W panel** provided **~0.85A charging current** under ideal light.
2. **Recharge Time: ~10 hours** for full battery recharge (7.2Ah).

6.3 Identified Limitations

1. **Final Temperature:**
    - **12°C** is higher than the target (5°C) due to:
        - Thermal losses in the cooling block.
        - Heat sink saturation during prolonged operation.

2. **Scalability:**
   - Cooling time increases **exponentially** for volumes >500 mL.
3. **Solar Dependency:**
   - Cloudy conditions reduced charging efficiency by **50%**.

6.4 Temperature vs Time Graph

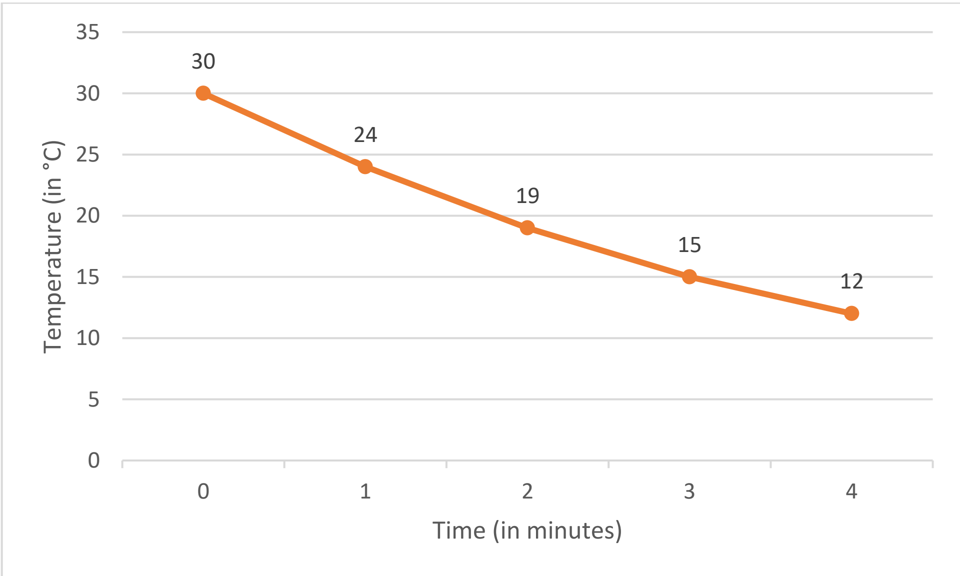

Figure 15. Temp vs Time Graph

7. TOTAL COST OF THE PROJECT

Components	Part Number	Cost
Peltier Module	TEC1-12704	480 Rs
Solar Panel	10W/12V	890 Rs
Battery	9Ah@12V	1280 Rs
DC Water Pump	12V, 10W	745 Rs
Controller Board	SCC1220NM	750 Rs
Charging Controller Board	XL4015	285 Rs
Water Aluminium Block	--	500 Rs
Cooling Fan	Ant Esports	1080 Rs
Flow Pipe	Rubber pipe	200 Rs
Casing Cabinet	CPU Cabinet	500 Rs
Copper Piping	0.6in Dia	750 Rs
Wiring and Miscellaneous	--	1040 Rs
	Total Cost	8500 Rs

Table 4. Total Cost

8. FUTURE WORKS AND IMPROVEMENTS

1. Enhanced Thermal Insulation

- **Problem:** Heat leakage from ambient air reduces cooling efficiency.
- **Solution:**
  - Use **aerogel insulation** (thermal conductivity: 0.015 W/mK) around the cooling chamber.
  - Implement **vacuum-sealed panels** for minimal heat transfer.
- **Expected Outcome:**
  - Improve temperature drop from **12°C to ≤8°C** for the same 500mL volume.
  - Reduce cooling time by **15–20%** by minimizing thermal losses.

2. Multi-Stage Peltier Modules

- **Problem:** Single-stage TECs struggle with large ΔT (temperature differences).
- **Solution:**
  - Cascade **two TEC1-12704 modules** in series (staged cooling).
  - Optimize power distribution: Stage 1 (30°C→15°C), Stage 2 (15°C→5°C).
- **Expected Outcome:**
  - Achieve **5°C or lower** final temperatures.
  - COP improvement by **1.5×** through distributed heat load.

3. Advanced Cooling Systems

- **Problem:** Air-cooled heat sinks saturate during prolonged use.
- **Solution:**
  - **Liquid Cooling:** Integrate a miniature water loop with a radiator (e.g., CPU cooler parts).
  - **Phase-Change Materials (PCMs):** Use paraffin wax to absorb excess heat during peak loads.
- **Expected Outcome:**
  - Sustain ΔT >50°C for >10 cycles without performance degradation.
  - Reduce fan noise by **70%** (liquid cooling is quieter than forced air).

4. Solar-Power Optimization

- **Problem:** 10W panel provides limited charging support.

- **Solution:**
    - Upgrade to **20W foldable solar panel** with MPPT charge controller.
    - Add **supercapacitors** for burst energy during startup.
- **Expected Outcome:**
    - Recharge 9Ah battery in **4.5 hours** (vs. 10.8 hours currently).
    - Enable **off-grid operation** for 6+ cycles/day.

5. Smart Control System

- **Problem:** Manual power adjustment is inefficient.
- **Solution:**
    - Integrate an **ESP32 microcontroller** with temperature feedback.
    - Implement PID control to dynamically adjust voltage/current.
- **Expected Outcome:**
    - Reduce energy waste by **25%** via adaptive cooling.
    - Enable Bluetooth app control for user convenience.

6. Material Upgrades

- **Component | Current Material | Upgrade | Benefit**
    - **Cooling Block** | Aluminum (205 W/mK) | **Copper (398 W/mK)** | 2× faster heat transfer.
    - **Heat Sink** | Finned Aluminum | **Vapor Chamber** | 30% better dissipation.

9. CONCLUSION

The “**DESIGN AND DEVELOPMENT OF A THERMOELECTRIC-BASED INSTANT BEVERAGE CHILLER**” project successfully demonstrates the feasibility of thermoelectric technology as a sustainable and efficient solution for rapid beverage cooling. By leveraging the Peltier effect, the system achieves a temperature drop from 30°C to 12°C in just 4 minutes for a 500 mL volume, outperforming conventional methods in speed and portability. With a power draw of 31.2W and a COP of 2.19, the design proves its energy efficiency, while the integration of a 10W solar panel enhances its sustainability for off-grid applications. The project highlights the potential of thermoelectric cooling in real-world scenarios, from outdoor activities to small-scale commercial use, offering a compact and eco-friendly alternative to traditional refrigeration.

Despite these successes, the system’s performance reveals areas for improvement, such as achieving lower final temperatures and optimizing solar charging under variable conditions. Future work should focus on multi-stage Peltier modules, advanced insulation, and liquid cooling to enhance efficiency and reliability. This project not only validates the practical application of thermoelectric principles but also sets the stage for further innovations in sustainable cooling technologies. By addressing current limitations and exploring new materials and smart controls, this work paves the way for next-generation cooling systems that align with global energy and environmental goals.

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