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# Li-ion Battery Pack Thermal Control using Air and Liquid Cooling Techniques

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**Abstract**: *Thermal management plays a critical role in ensuring the safety, performance, and longevity of lithium-ion (Li-ion) batteries, especially in high-capacity applications such as electric vehicles and energy storage systems. This study presents the design and comparative evaluation of a Battery Thermal Management System (BTMS) for a 48V, 24Ah Li-ion battery using both air cooling and liquid cooling techniques. The primary objective is to maintain the battery cell temperatures within an optimal operating range (20°C–40°C), preventing thermal runaway while enhancing overall efficiency and lifecycle performance. An integrated thermoelectric module (Peltier device) is incorporated to enable both heating and cooling functions, controlled via temperature sensors and a microcontroller-based system. Liquid cooling demonstrated a higher heat transfer coefficient and more uniform temperature distribution, making it suitable for high-load conditions. In contrast, air cooling was found effective under moderate loads due to its low cost and ease of implementation. Experimental results indicate that while liquid cooling offers superior heat dissipation and temperature uniformity, air cooling remains a simpler, more cost-effective alternative for moderate thermal loads. The research provides valuable insights into hybrid BTMS configurations and their impact on battery thermal stability, making it relevant for EV and stationary battery applications.*

**Keywords:** Li-ion Battery, Battery Thermal Management System (BTMS), Air Cooling, Liquid Cooling, Thermoelectric Cooling, Peltier Module, Heat Dissipation, Temperature Regulation

## I. INTRODUCTION

Lithium-ion batteries have emerged as the preferred energy storage solution for electric vehicles (EVs), hybrid electric vehicles (HEVs), and various portable electronic systems due to their high energy density, low self-discharge rate, and long cycle life. However, these batteries are highly sensitive to temperature fluctuations, which can significantly affect their performance, safety, and lifespan. Efficient thermal management is therefore critical to maintaining the battery temperature within an optimal range—typically between 20°C and 40°C—during charging, discharging, and idle conditions. Deviations from this range can lead to reduced efficiency, accelerated aging, thermal runaway, or even catastrophic failure. As battery capacities and power demands increase, the importance of a well-designed Battery Thermal Management System (BTMS) becomes more pronounced, especially in high-capacity battery packs such as 48V 24Ah systems. Managing heat in large-capacity battery packs introduces several engineering challenges. These include maintaining uniform temperature distribution across all cells, avoiding hot spots, and ensuring quick thermal response under varying operational loads. Without proper cooling mechanisms, high-power batteries can generate excessive internal heat due to resistive losses and electrochemical activity, especially during fast charging or discharging. To address these challenges, several BTMS configurations have been developed, including air cooling, liquid cooling, phase change materials (PCM), and thermoelectric modules (TECs). Among these, air and liquid cooling remain the most commonly implemented methods due to their practical efficiency and adaptability. This study focuses on a comparative evaluation of air and liquid cooling methods specifically for a 48V 24Ah lithium-ion battery pack, aiming to determine the optimal solution in terms of thermal regulation, energy consumption, and system complexity.

A critical review highlights key thermal issues in lithium-ion batteries, including capacity fade, thermal runaway, and imbalance at extreme temperatures. It emphasizes the need for accurate heat generation measurement and improved thermal modelling. High charge/discharge rates intensify these challenges. No current thermal management strategy fully meets all EV performance requirements. [1]

A comprehensive review on a passive (phase change materials) and an active (thermoelectric cooler) battery thermal management system and their limitations were discussed in this paper. to identify the future research possibilities in the area of BTMS for EVs.[2]

In this paper, prospects and challenges of EVs are discussed and the importance of thermal management in EVs is highlighted. Among the thermal management systems available, the liquid cooling.[3]

Battery temperature management is the core technology of new energy vehicles concerning its stability and safety. Starting with the temperature management, this paper establishes mathematical and physical models from two dimensions, battery module and temperature management system. Finally, here it was absorbed that, the battery module can obtain the best cooling performance with low battery distribution density if the battery module keeps a cone angle of 60°.[4]

Recently, the phase change material (PCM) battery thermal management system (BTMS) attracted attention and here its utilization advantages and limitations were carried out. However, enhancement and optimization for the BTMS are required due to volumetric system design and low thermal conductivity. This study provides a novel design optimization to improve the environmental aspect of the cooling system and reduce its weight.[5]

A liquid cooling system is an effective type of battery cooling system on which many studies are presented nowadays.[6]

The battery thermal management system (BTMS) plays a vital role in the control of the battery thermal behavior. The BTMS technologies are: air cooling system, liquid cooling system, direct refrigerant cooling system, phase change material (PCM) cooling system, and thermo-electric cooling system as well as heating. These systems are analyzed through a trade-off between performance, weight, size, cost, reliability, safety and energy consumption. According to the analysis two prime battery thermal management systems are recommended: combined liquid system (CLS) and a variant system with PCM.[7]

Due to its compact structure, high reliability, and safety characteristics, the air-cooling BTMS has been widely used in EVs and HEVs industry with cost-reduction demand or under severe and unpredictable working environments. This paper first reviews battery heat generation mechanisms and their impact (e.g. thermal aging, thermal runaway and fire accident) on the powertrain system in EVs and HEVs. Then the basic air-cooling BTMS design is reviewed, and a variety of novel design improvements is evaluated to explore the benefits and challenges of the use of the air-cooling BTMS.[8]

The cycle life, environmental adaptability, driving range, and charging time of the battery currently used in EV are far beyond comparison with internal combustion engines. Therefore, studies have focused on batteries, and battery thermal management systems (BTMSs) have been developed. Battery performance is highly dependent on temperature and the purpose of an effective BTMS is to ensure that the battery pack operates within an appropriate temperature range.[9]

BTMSs have been implemented in EVs by adopting different technologies that include natural air-cooling systems, forced air cooling systems, liquid cooling systems, and using heat pipes and fins. In the last two decades, thermoelectric coolers (TECs) have also been applied to BTMSs to make an active or semi-passive system with another cooling system. In this paper, a state of the science comprehensive literature review is presented on PCM (a passive system) and TEC (an active system) based BTMSs.[10]

A detailed review of the latest advancements in Battery Thermal Management Systems (BTMS) for electric vehicles. It evaluates various cooling technologies such as air cooling, liquid cooling, phase change materials (PCM), and hybrid methods. The authors analyse each system in terms of thermal efficiency, energy consumption, system complexity, and suitability for different EV architectures. The review also highlights current limitations and identifies future research directions for optimizing BTMS design in terms of cost-effectiveness, safety, and battery longevity. [11]

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## II. METHODOLOGY

**Origins of battery heat generation**

Heat is produced in batteries from three fundamental sources: activation (interfacial kinetics), concentration (species transport), and ohmic (Joule heating from the movement of charged particles) losses. For small cells, the heat loss from the movement of electrons in the current collectors is usually negligible. However, as the battery increases in size, the length from the current source to the tab and the concentration of current near the tabs may cause significant heat generation

Electrochemical process heat generation. — Bernardi et al.45 derived an expression for battery heat using a thermodynamic energy balance on a complete cell. Discrete phases inside the battery interact with each other by means of electrochemical reaction, phase changes, and mixing. By applying the first law of thermodynamics around the cell control volume (not including current collectors) and making numerous simplifications, they determined the following expression for heat generation inside the battery.

$$Q = I(U-V) - I\left(T\frac{dU}{dT}\right) \qquad (1.1)$$

The first term is the over potential due to ohmic losses in the cell, charge transfer over-potentials at the interface, and mass transfer limitations. The electrode potential is determined at the average composition. The second term is the entropic heat, and the potential derivative with respect to temperature is often referred to as the entropic heat coefficient.

Heat generation in a cell can be defined quite simple for the case where the cell is operating within its normal limits. The first expression gives the heat flow [W].

$$Q = I\left(V - Voc - Tref\frac{dVoc}{dT}\right) \qquad (1.2)$$

$$I(V - Voc) = Joule\ heating\ (Irreversible\ Term)$$

$$I \times Tref \times \frac{dVoc}{dT} = Entropy\ change$$

The first part of this equation 1.1 is the irreversible Joule heating term, the $I^2R$ term. The second part of equation 1.2 is the reversible entropy term or Reaction heat terms. The charge and discharge reaction can be exothermic or endothermic under certain conditions.

**Cooling In li-ion battery**

A fundamental Battery Thermal Management System (BTMS) typically utilizes a single cooling method to regulate battery temperature. Enhancing the effectiveness of any individual BTMS type is therefore a critical research focus. When forced air or liquid is employed as the heat transfer fluid (HTF), the design of the flow channels becomes a key factor affecting performance. This includes considerations such as channel geometry, inlet and outlet placement, flow parameters, and flow direction. The objective is to optimize these parameters to suit specific operating environments and battery requirements. In the case of thermoelectric cooling (TEC), the system cannot rely on TEC alone to sufficiently dissipate heat from the battery surface. Instead, TEC serves as an auxiliary technology within hybrid BTMS configurations, enhancing local heat removal at targeted hot spots on the battery module surface.

### 2.1 Active Battery Thermal Management Systems

Active BTMS approaches mainly consist of forced-air cooling, liquid cooling, and thermoelectric cooling. Such systems involve additional energy consumption to actively manage heat dissipation, necessitating a trade-off between cooling effectiveness and energy efficiency. At moderate temperatures and heat generation levels, forced-air cooling can meet thermal management requirements without complex apparatus or excessive power consumption compared to liquid cooling. However, when batteries experience high charge rates or generate substantial heat, liquid cooling becomes essential due to its superior heat removal capabilities and potential for energy savings. The goal of an active BTMS is to achieve adequate temperature control while minimizing auxiliary energy use.

**2.2 Forced-Air Cooling**

Forced-air cooling systems can be divided into two categories: natural convection-based and forced convection-based systems. Natural convection alone is generally insufficient for battery cooling due to air's inherently low thermal conductivity and heat capacity. Forced-air systems overcome these limitations by increasing airflow rates, but to match the cooling efficiency of liquid systems, relatively high airflow is required. One significant challenge of forced-air cooling is uneven temperature distribution across the battery cells. This nonuniformity arises from two main factors: the temperature of the cooling air changes as it progresses along the flow path, and the varying distances between individual cells and the air inlet/outlet cause differences in airflow distribution across battery gaps. Despite these drawbacks compared to liquid cooling, forced-air BTMS offers advantages in simplicity and cost-effectiveness. Research in this area often focuses on optimizing channel geometry, cell arrangement, and airflow configurations to improve thermal uniformity and overall system performance.

**2.3 Liquid Cooling**

Liquid cooling systems use a fluid, such as water, glycol mixtures, or dielectric liquids, to absorb and transfer heat away from battery cells more efficiently than air-based methods. Due to the higher thermal conductivity and heat capacity of liquids compared to air, liquid cooling offers superior heat dissipation, making it particularly suitable for high-power and high-energy battery applications where significant heat is generated. These systems typically involve coolant circulation through channels or plates in direct contact with the battery cells or modules, allowing effective removal of heat from critical areas.

Although liquid cooling systems provide excellent temperature control and help maintain uniform thermal distribution within the battery pack, they come with increased complexity and cost. The system requires pumps, heat exchangers, piping, and sensors, which add weight and require maintenance. Additionally, careful design is needed to prevent leaks and ensure the coolant flow is balanced across all battery cells to avoid hotspots. Despite these challenges, liquid cooling is widely adopted in electric vehicles and large-scale energy storage due to its capability to maintain batteries within optimal temperature ranges under high load conditions, improving battery performance, safety, and lifespan.

**System Architecture and Functional Description**

The thermal management system for lithium-ion batteries is composed of several integrated components that work together to ensure safe and efficient operation. Fig. 1 illustrates the block diagram of the proposed system, including the power source, Li-ion battery pack, battery management system (BMS), temperature sensing mechanism, cooling methods, and heat dissipation components. Each block plays a crucial role in maintaining the battery pack within its optimal operating temperature range.

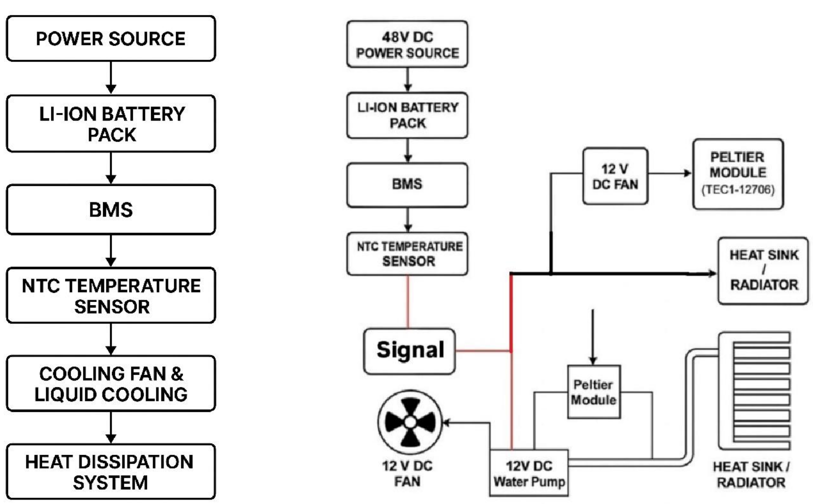


*Figure No.1 Block diagram of Thermal Management of Li-ion Battery*

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It consists of -

**A. Power Source**

The power source supplies electrical energy required to operate the system, including charging the battery pack and powering the auxiliary thermal management components. It may consist of grid-connected chargers, renewable sources like solar panels, or onboard power electronics. The quality, stability, and voltage range of the power source directly affect the efficiency of charging cycles and the activation of cooling mechanisms. Ensuring a stable input is essential to maintain controlled battery charging and to avoid thermal stress caused by overcurrent or voltage spikes.

**B. Li-ion Battery Pack**

The lithium-ion battery pack is the core energy storage unit and consists of multiple cells arranged in a series-parallel configuration to achieve the required voltage and capacity. These batteries are preferred in electric vehicles and portable systems due to their high energy density and long cycle life. However, their performance and safety are highly dependent on maintaining appropriate temperature levels. The battery pack is embedded within the thermal management system to continuously monitor and regulate heat generation during operation.

**C. Battery Management System (BMS)**

The Battery Management System (BMS) is an intelligent control unit that oversees the operation of the battery pack. Its key responsibilities include voltage balancing, state-of-charge (SOC) estimation, protection against overcharging/discharging, and thermal monitoring. In the context of thermal management, the BMS processes input from temperature sensors and triggers active cooling mechanisms when required. It ensures that thermal thresholds are not exceeded and provides data logging and fault detection capabilities to enhance system safety and reliability.

**D. NTC Temperature Sensor**

A Negative Temperature Coefficient (NTC) thermistor is employed as the primary temperature sensing element in the system. NTC sensors exhibit a decrease in resistance with an increase in temperature, providing a reliable and fast response for detecting thermal changes within the battery modules. These sensors are strategically placed at various points across the battery pack to capture real-time thermal data. The sensor output is continuously relayed to the BMS, enabling precise temperature-based decision-making for cooling control.

An **NTC (Negative Temperature Coefficient) temperature sensor** plays a crucial role in automated thermal management systems. It enables **real-time temperature monitoring** and allows a microcontroller (like an Arduino) to **switch cooling systems ON or OFF** based on predefined temperature thresholds. This ensures that lithium-ion batteries operate within a **safe and efficient thermal range** (typically 20°C to 40°C). You define **two thresholds** in the code:

**Upper Limit (e.g., 40°C)** → Turn ON cooling

**Lower Limit (e.g., 30°C)** → Turn OFF cooling

E. Cooling Fan and Liquid Cooling System

This block represents the active cooling mechanisms used to extract heat from the battery pack. The system integrates both forced air cooling (via fans) and liquid cooling (via circulating coolant through embedded channels or cold plates). Cooling fans facilitate convective heat transfer by directing airflow across the battery surfaces, which is effective for moderate thermal loads. Liquid cooling, on the other hand, uses a coolant (commonly water or ethylene glycol) that flows through channels in thermal contact with battery cells, offering higher thermal conductivity and more uniform cooling. The BMS activates these systems based on thermal thresholds and dynamic load conditions.

F. Heat Dissipation System

After absorbing the heat from the battery modules, the thermal energy must be transferred away from the system to prevent accumulation. The heat dissipation system consists of radiators, heat exchangers, or thermoelectric elements designed to release heat to the environment. The effectiveness of this stage is crucial to ensure that heat removed from the battery is not recycled into the system. A well-designed dissipation unit improves overall thermal efficiency and helps maintain battery temperature within the safe operating range during prolonged usage or high-load event.

**Design of li-ion battery: -**

Cells in Series (Voltage)

Typical Li-ion cell nominal voltage: 3.7 V

Number of cells in series = 48 V / 3.7 V ≈ 13 cells

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Parallel Strings for Capacity
Desired capacity: 24 Ah
Each cell: 2.8 Ah
Strings in parallel = 24 ÷ 2.8 ≈ 8.57, so round up to 9P
Total cells = 13 × 9 = 117 cells.

**Software Design:**

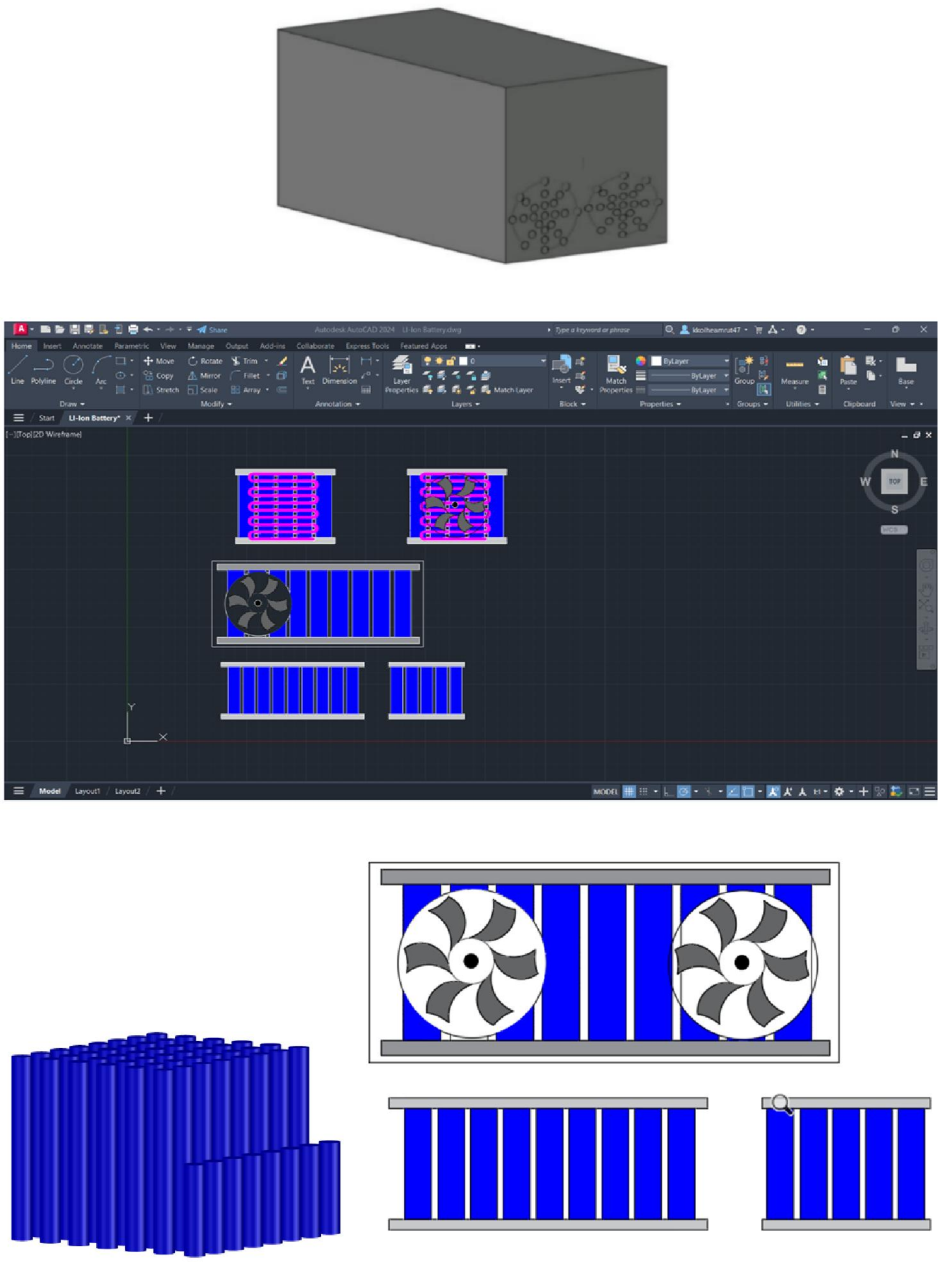

*Figure No 2 - CAD Module*

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**Hardware Model:**

The thermal management system of a Li-ion battery ensures safe and efficient operation by maintaining the battery temperature within optimal limits. The system begins with a power source that supplies energy to the Li-ion battery pack.

The Battery Management System (BMS) monitors key parameters such as voltage, current, and temperature to ensure safe operation. Integrated within the system is an NTC (Negative Temperature Coefficient) temperature sensor, which continuously measures the battery temperature.

When the sensor detects that the temperature has reached a preset threshold—such as 45°C—it activates the cooling system. This triggers the operation of the cooling fan and liquid cooling mechanisms, which work to bring the temperature down.

The absorbed heat is then transferred to the heat dissipation system, such as a heat sink or radiator, where it is released into the surrounding environment. This process helps protect the battery from overheating, enhances performance, and extends battery life.

## III. RESULT & DISCUSSION

As shown in *Figure No.3 Actual Model Part A & Part B* This study focuses on maintaining the lithium-ion battery within an optimal temperature window to improve its performance, safety, and longevity. In electric vehicles, keeping battery temperature stable is vital because both excessive heat and cold can degrade battery efficiency, accelerate aging, and create risks such as thermal runaway. To tackle these challenges, this research proposes a hybrid battery thermal management system (BTMS) combining thermoelectric modules for heating and cooling with air-based cooling to regulate battery temperature effectively.

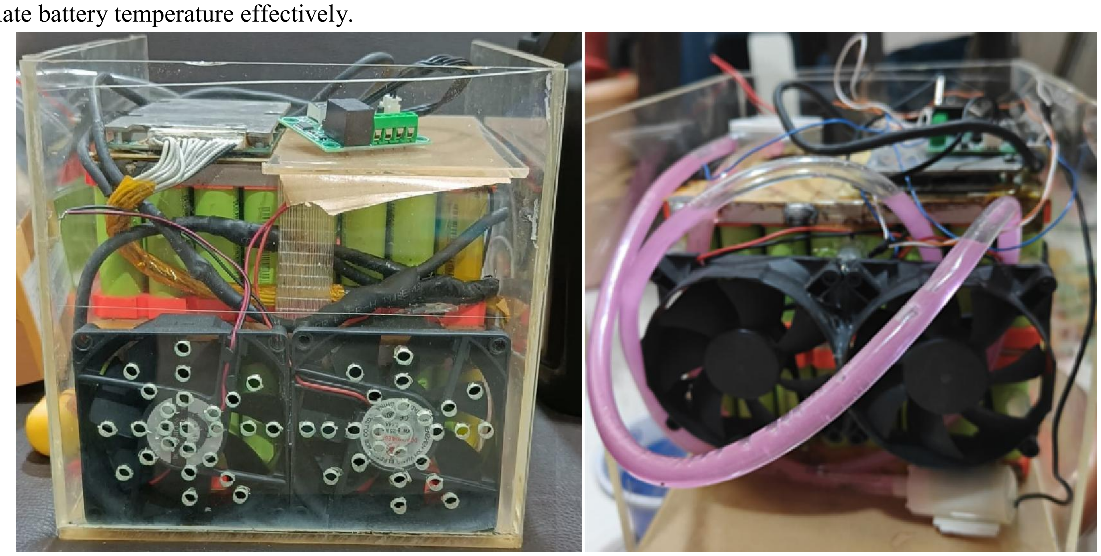

*Figure No.3 Actual Model Part A*

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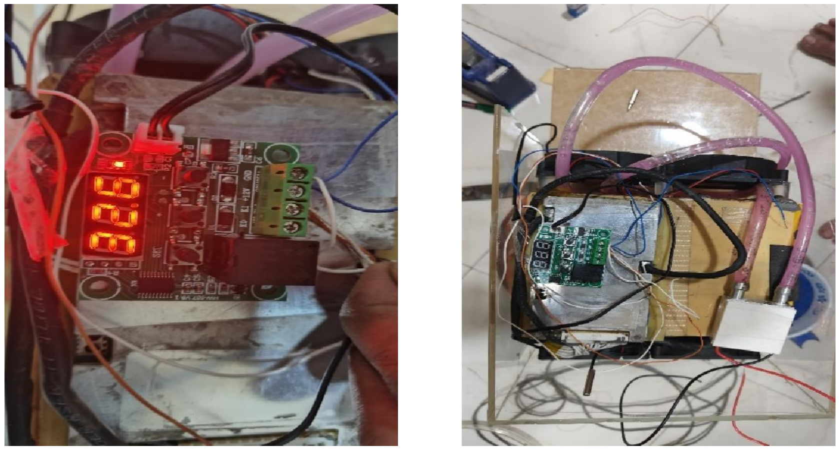

*Figure No.3 Actual Model Part B*

**Natural Air-Cooling Performance** The initial tests investigated the battery pack's thermal response under passive, natural air-cooling conditions. Experiments were conducted at different applied voltages to analyses heat generation variations with increasing electrical load. Results showed that as voltage and current increased, internal heat generation rose markedly due to intensified electrochemical activity and resistance losses converting electrical energy into heat. This led to a proportional temperature rise, indicating that natural convection cooling alone cannot adequately maintain safe battery temperatures at higher loads.

**Thermal Behavior during Charge-Discharge Cycles** The thermal dynamics during multiple charging and discharging cycles were also evaluated. Rapid charging with high current caused a pronounced temperature increase, which could adversely impact battery lifespan and efficiency if unmanaged. Similarly, high-rate discharges combined with warm ambient temperatures resulted in significant heat buildup. In these scenarios, passive cooling frequently failed to keep the temperature within recommended limits, highlighting the need for an active thermal control approach.

**Thermoelectric Cooling and Heating System** To address these issues, a thermoelectric BTMS was implemented using Peltier devices capable of both cooling and heating by reversing current flow. In cooling mode, these modules extract heat from the battery and dissipate it through heat sinks and fans. In colder environments, they switch to heating mode to raise battery temperature to an optimal operating range, generally between 20°C and 40°C. Testing demonstrated that the thermoelectric system effectively stabilized battery temperature between 25°C and 35°C during high load, outperforming natural cooling, which allowed temperatures to exceed 45°C. The system's energy use was also within acceptable limits, minimally impacting the battery's available energy for vehicle propulsion.

**Temperature Uniformity** Ensuring uniform temperature distribution among battery cells is crucial to prevent cell imbalance and degradation. The hybrid setup achieved improved thermal uniformity, reducing temperature variations across modules to within ±2°C. Supplementary forced-air cooling via heat sinks enhanced heat removal and overall system efficiency as Shown in Figure 4.

**Energy Efficiency and Practicality** Although thermoelectric coolers are generally less efficient than vapor compression systems, their compact size, simplicity, and ability to provide both heating and cooling make them attractive for electric vehicle battery packs. Their lightweight and modular design support integration in space-constrained and cost-sensitive applications.

**Impact on Battery Life and Vehicle Range** Maintaining optimal battery temperature reduces capacity degradation rates, extending battery service life and decreasing replacement frequency. Moreover, efficient thermal control reduces energy losses, preserving usable battery capacity and potentially increasing driving range—a critical factor for consumer acceptance of electric vehicles.

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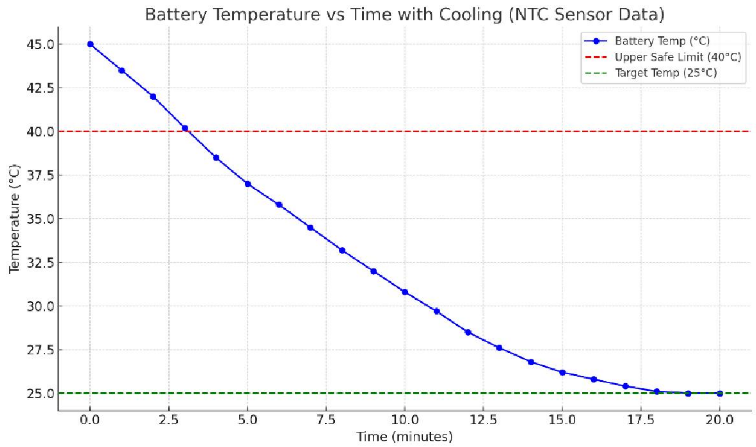


*Figure No.4 Temperature Vs Time of cooling Graph*

## IV. CONCLUSION

Effective thermal management is essential to maintain lithium-ion batteries within their optimal temperature range, ensuring safety, performance, and longevity. The hybrid system combining thermoelectric modules with air cooling demonstrates significant improvement in temperature control and uniformity compared to passive cooling alone. This approach not only extends battery life by reducing thermal stress but also enhances energy efficiency, contributing to better overall electric vehicle performance and range.

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