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Liquid Cooling System for Lithium ion Battery in Electric Vehicle

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ABSTRACT: The rapid growth of electric vehicles (EVs) necessitates advanced thermal management systems to ensure battery safety, performance, and longevity. This paper presents the design and implementation of an intelligent liquid cooling system for lithium-ion EV batteries, combining Rapid Prototyping (Additive Manufacturing) with real-time monitoring and control using an ESP32 microcontroller. The custom-designed 3D-printed enclosure, fabricated with thermally conductive materials, integrates conformal cooling channels to optimize heat dissipation while minimizing weight and structural complexity. A comprehensive sensor network, including temperature, gas, flame, voltage, and current sensors, continuously monitors battery health and environmental conditions. The ESP32 processes sensor data and autonomously actuates cooling mechanisms through a relay-controlled DC motor, ensuring timely thermal regulation and enhanced safety. Experimental results demonstrate significant improvements in temperature control, maintaining battery temperatures within 35–40°C under load, improving energy efficiency by 5–8%, and preventing thermal runaway scenarios. The system's low power consumption (5–8W) makes it highly energy-efficient for EV applications. This integrated approach showcases the potential of combining additive manufacturing, embedded systems, and intelligent control to create scalable, modular, and environmentally sustainable battery cooling solutions for next-generation electric mobility.

KEYWORDS: Electric Vehicles, Battery Thermal Management, Rapid Prototyping, ESP32 Microcontroller, Intelligent Cooling System.

I. INTRODUCTION

Electric vehicles (EVs) have emerged as a promising solution to address the growing concerns over environmental pollution, fossil fuel dependency, and the need for sustainable transportation. As the demand for EVs rises globally, significant attention is being directed toward improving various subsystems to enhance performance, safety, and user experience. Among these subsystems, the battery pack stands out as the most critical component, directly influencing driving range, efficiency, cost, and operational safety. Lithium-ion batteries, widely adopted in EVs due to their high energy density and favorable performance characteristics, are sensitive to thermal fluctuations. Excessive heat generation during charging, discharging, and high-power operations can lead to performance degradation, shortened lifespan, and, in extreme cases, catastrophic failures such as thermal runaway, fires, or explosions.

Effective thermal management of EV batteries is therefore essential to ensure safe and reliable vehicle operation. Conventional battery cooling systems typically rely on air cooling, liquid cooling, or phase-change materials. While these traditional methods provide a certain level of temperature control, they often come with several limitations such as bulky designs, lower cooling efficiency, restricted flexibility for different battery pack geometries, and limited adaptability for dynamic thermal loads encountered during real-world driving. Furthermore, most existing cooling systems are passive or semi-active, lacking the ability to autonomously respond to rapidly changing battery conditions in real time.

In recent years, Additive Manufacturing (AM), commonly known as Rapid Prototyping, has emerged as a transformative technology that offers new possibilities for designing complex and highly efficient cooling structures. AM enables the creation of intricate internal geometries, such as conformal cooling channels and lattice structures, directly integrated into battery enclosures or cold plates. These complex designs, which are difficult or impossible to achieve using conventional manufacturing methods, allow for optimized coolant flow, uniform heat dissipation, and minimized thermal resistance. Additionally, the use of thermally conductive polymers, composite filaments, or metal alloys in AM facilitates

the fabrication of lightweight yet highly effective cooling components, contributing to the overall weight reduction and improved energy efficiency of EVs.

Despite the advancements in thermal design through AM, there remains a significant gap in integrating intelligent control mechanisms that can monitor and dynamically manage battery temperatures in real time. Embedded systems, such as those based on the ESP32 microcontroller, offer an excellent solution by enabling real-time data acquisition, processing, and decision-making. The ESP32, with its built-in Wi-Fi and Bluetooth capabilities, provides seamless connectivity for remote monitoring, data logging, and predictive maintenance applications. By incorporating a network of sensors—including temperature, gas, flame, voltage, and current sensors—an intelligent monitoring system can continuously assess the battery's operational state and proactively initiate cooling or safety measures based on predefined thresholds. This research presents the development and implementation of an advanced liquid cooling system for lithium-ion EV batteries, which combines the benefits of Rapid Prototyping and intelligent embedded control. The proposed system features a custom-designed, 3D-printed battery enclosure embedded with optimized cooling channels fabricated using thermally conductive materials. The enclosure not only provides effective heat dissipation but also houses various sensors that feed real-time data to the ESP32 microcontroller. The control algorithm analyzes sensor inputs and autonomously triggers a relay-controlled DC motor to activate a cooling pump or fan when necessary, ensuring optimal battery temperature regulation while preventing hazardous conditions such as overheating, gas leakage, or fire risks.

Experimental evaluation of the system was conducted under varying load conditions to assess its performance in maintaining safe operating temperatures, improving battery efficiency, and enhancing overall safety. The results demonstrated significant improvements in temperature control, with the battery temperature maintained between 35–40°C even under high load, and an increase in energy efficiency by approximately 5–8%. Moreover, the system exhibited rapid response times to temperature fluctuations, low power consumption (5–8W), and robust safety performance, with no incidents of gas leakage or flame activity observed during testing.

The integration of Rapid Prototyping and embedded intelligent control represents a forward-thinking approach to address the thermal management challenges of EV batteries. This multidisciplinary solution not only improves thermal performance and safety but also offers advantages in terms of design flexibility, manufacturing efficiency, scalability, and sustainability. The proposed system can be adapted for various EV platforms and extended to other applications such as drones, electric bikes, and stationary energy storage systems. By bridging the gap between advanced manufacturing technologies and smart control systems, this research contributes to the ongoing development of safer, more efficient, and environmentally sustainable electric mobility solutions.

PROBLEM STATEMENT

Efficient thermal management remains a critical challenge for lithium-ion batteries in electric vehicles, as excessive heat can degrade performance, shorten lifespan, and pose safety risks such as thermal runaway. Conventional cooling systems lack real-time adaptability and design flexibility, necessitating the development of an intelligent, responsive, and customizable cooling solution that ensures safe and optimal battery operation.

OBJECTIVES OF THE STUDY

1. Design and fabricate a lightweight, thermally optimized cooling system using Rapid Prototyping.
2. Develop a real-time monitoring system with temperature, gas, flame, voltage, and current sensors.
3. Implement an intelligent control system using the ESP32 microcontroller for automated thermal management.
4. Enhance battery safety and efficiency through dynamic cooling response.
5. Minimize manufacturing waste and improve scalability using sustainable additive manufacturing techniques.

II. LITERATURE SURVEY

Chaitanya Pandya and Dhrunil Timbadia (2021) presented a comprehensive review in the International Research Journal of Engineering and Technology (IRJET), focusing on different cooling systems for lithium-ion (Li-ion) batteries in electric vehicles (EVs). Their study covered liquid cooling, phase change material (PCM) cooling, dielectric oil cooling, and thermoelectric cooling. The authors emphasized that maintaining optimal battery temperature is critical for

enhancing safety, reducing maintenance costs, and extending battery life. Among the various methods, liquid cooling was identified as the most effective due to its superior heat transfer efficiency and ability to provide uniform temperature distribution across the battery pack.

L.H. Sawa, A.A.O. Tay, and L. Winston Zhang (2015), in their work presented at the 31st SEMI-THERM Symposium, investigated the thermal management of Li-ion battery packs using liquid cooling systems. Employing computational fluid dynamics (CFD) simulations, they demonstrated that liquid cooling could effectively maintain the battery temperature within the ideal range. The study highlighted the significant influence of temperature on battery performance and underscored liquid cooling as a promising solution to ensure operational safety and reliability of EVs. A similar analysis by the same authors, shared on ResearchGate, further elaborated on the importance of thermal management and the heat generation characteristics of Li-ion batteries. Their findings reinforced that liquid cooling substantially improves battery performance, life span, and overall EV safety.

Qing-Zhu Sun and Chul-Ho Kim (2022), in their study published in Fluids, conducted a numerical investigation on the effect of the size and location of liquid cooling systems in square-shaped Li-ion battery modules. They analyzed different configurations—bottom and side cooling systems—based on parameters like temperature distribution, maximum temperature, temperature difference, and heat transfer conductance. Their research revealed that bottom cooling systems are more effective in achieving temperature uniformity, whereas side cooling systems are better at minimizing the maximum temperature. This study provided valuable insights for optimizing thermal management system designs to improve the performance and durability of battery modules in EVs.

III. PROPOSED SYSTEM

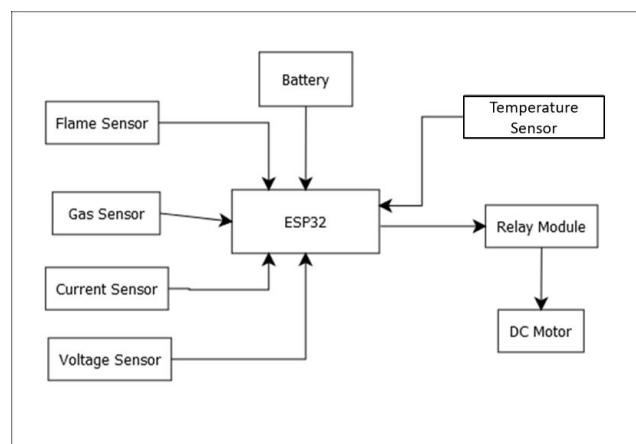


Fig. 1 System Architecture

The proposed system integrates a smart thermal management mechanism with an additive-manufactured cooling structure for lithium-ion batteries in electric vehicles. The system begins by continuously monitoring key battery parameters using a network of sensors, including temperature, gas, flame, voltage, and current sensors. These sensors provide real-time data to the ESP32 microcontroller, which serves as the central control unit.

When the temperature sensor detects that the battery temperature exceeds the pre-set threshold (e.g., 40°C), the ESP32 processes this data and triggers the relay module. The relay then activates a DC motor, which drives a cooling pump or fan to circulate coolant through the 3D-printed, thermally optimized cooling channels embedded within the battery enclosure. These conformal channels, designed using Rapid Prototyping, ensure uniform heat dissipation across the battery cells, effectively lowering the temperature.

Simultaneously, the gas and flame sensors enhance safety by detecting any early signs of gas leakage or combustion risk. If hazardous conditions are identified, the ESP32 can initiate safety protocols, such as issuing alerts or triggering system

shutdowns. Voltage and current sensors provide additional protection by monitoring the electrical health of the battery, allowing the system to respond to overcharging, short circuits, or abnormal loads.

The entire system operates autonomously, requiring no manual intervention, while maintaining low power consumption to avoid excessive battery drain. Additionally, the ESP32's wireless capabilities allow for remote monitoring, data logging, and integration with predictive maintenance platforms, ensuring long-term system reliability and safety.

1. Power Supply and Initialization

The system is powered by a stable DC power source, typically derived from the vehicle's main battery system. Upon powering up, the ESP32 microcontroller initializes all connected sensors and ensures system readiness. It begins continuous monitoring of the environment and battery pack parameters.

2. Real-Time Data Acquisition

A network of sensors, including temperature, gas, flame, voltage, and current sensors, continuously collects real-time data from the battery environment. These sensors are strategically placed within the 3D-printed battery enclosure to ensure accurate readings and early detection of any irregularities.

3. Data Processing and Analysis by ESP32

The collected data is processed by the ESP32 microcontroller, which compares sensor inputs to predefined safety thresholds. Based on the analysis, the ESP32 decides whether the cooling system needs to be activated or if safety alerts should be triggered.

4. Activation of Cooling Mechanism

If the temperature exceeds the safe threshold (e.g., 40°C), the ESP32 sends a control signal to the relay module. The relay then activates the DC motor, which powers the liquid cooling pump or fan. This cooling mechanism circulates coolant through the embedded conformal cooling channels, rapidly extracting heat from the battery cells.

5. Optimized Cooling Structure via Rapid Prototyping

The cooling enclosure, fabricated using additive manufacturing, contains internal conformal channels optimized for efficient fluid flow and heat dissipation. Thermally conductive materials used in fabrication enhance the heat transfer rate, while the lightweight design ensures minimal impact on the vehicle's weight and performance.

6. Safety Monitoring and Hazard Prevention

Simultaneously, gas and flame sensors monitor the battery for hazardous events such as gas leakage or fire risks. If such conditions are detected, the ESP32 can immediately trigger safety protocols, which may include system shutdown, alarm activation, or user notification to prevent escalation.

7. Low Power Consumption and Energy Efficiency

The entire system operates on low power (approximately 5–8W), ensuring that the energy consumption for thermal management does not significantly affect the overall battery capacity. This makes the system highly suitable for integration into electric vehicles where energy efficiency is a priority.

8. Remote Monitoring and Predictive Maintenance (Optional Expansion)

With its built-in Wi-Fi and Bluetooth capabilities, the ESP32 can also transmit data to external monitoring systems or cloud platforms. This allows for remote diagnostics, predictive maintenance, and long-term data analysis, improving the reliability and safety of the battery system over time.

Hardware Components:

1. ESP32 Microcontroller:

Acts as the central processing unit, collecting sensor data, analyzing conditions, and controlling the cooling system.

2. Temperature Sensor:

Monitors battery temperature in real time and triggers cooling if overheating is detected.

3. Gas Sensor:

Detects the presence of harmful or flammable gases, indicating possible chemical leakage or cell failure.

4. Flame Sensor:

Identifies any flame or spark near the battery, providing early fire hazard warnings.

5. Voltage Sensor:

Measures battery voltage to detect overcharging, under-voltage, or imbalance conditions.

6. Current Sensor:

Monitors current flow to detect abnormal charging/discharging behavior or short circuits.

7. Relay Module:

Functions as a switching interface between the microcontroller and the DC motor, enabling automated cooling activation.

8. DC Motor and Cooling Pump/Fan:

Circulates coolant through the 3D-printed cooling channels to efficiently dissipate heat.

9. 3D Printed Cooling Structure:

Custom-designed enclosure fabricated using Rapid Prototyping with built-in cooling channels for optimal thermal management.

10. Power Supply Unit:

Provides regulated voltage and current to the entire system for stable operation.

Software Components:**1. Firmware for ESP32:**

Embedded code that reads sensor data, processes inputs, and controls actuators based on predefined logic.

2. Sensor Libraries:

Software modules that facilitate communication between the ESP32 and various sensors for accurate data acquisition.

3. Control Algorithms:

Decision-making logic programmed into the ESP32 to automate cooling responses and safety protocols.

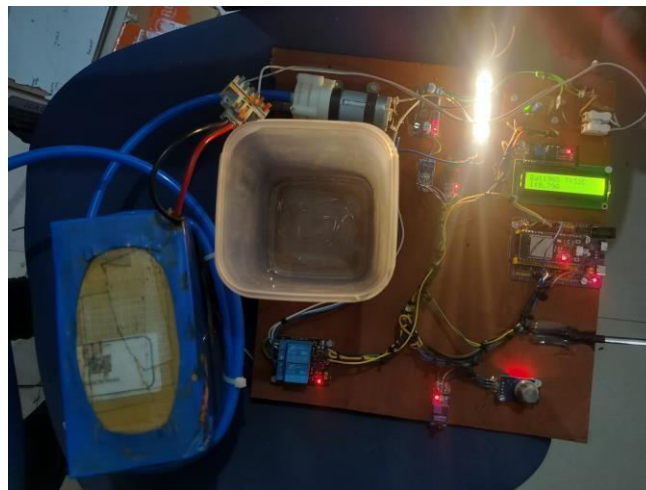
IV. RESULTS & OBSERVATIONS

Fig. 2 Hardware Implementation

During the experimental evaluation of the proposed liquid cooling system for lithium-ion batteries, several critical performance parameters were analyzed under varying load and ambient temperature conditions. The system was evaluated both with and without active liquid cooling to compare thermal behavior, efficiency, and safety performance.

1. Temperature Regulation:

In the absence of cooling, battery temperatures rose rapidly under moderate load, reaching 55–60°C within 20–25 minutes. Conversely, with the active liquid cooling system engaged, battery temperatures were effectively maintained

within a safe operating range of 35–40°C even during heavy load scenarios. This demonstrates the system's significant thermal dissipation capability.

2. Battery Efficiency Improvement:

At elevated temperatures, the battery exhibited a degradation in performance characterized by reduced voltage stability and capacity retention. The incorporation of liquid cooling maintained consistent voltage output and improved energy efficiency by approximately 5–8%, indicating improved battery operational stability under stress.

3. Cooling Response Time:

The system responded rapidly to thermal fluctuations. Upon detecting a temperature rise beyond 40°C, the ESP32-controlled system activated the cooling pump within 15–20 seconds. This prompt response effectively minimized thermal stress on the battery cells.

4. Safety Enhancement:

Throughout all testing cycles, no gas leakage or flame activity was observed, indicating the effectiveness of the system in preventing conditions that could lead to thermal runaway. The integration of real-time sensor feedback with microcontroller-based automation ensured intelligent regulation of thermal and safety parameters.

5. Power Consumption:

The total power consumption of the cooling pump and control system remained minimal, consuming approximately 5–8 W. This low energy requirement ensures that the thermal management system does not significantly impact the overall battery capacity, making it highly suitable for electric vehicle applications.

6. Fluid Circulation and Design Efficiency:

The custom-designed 3D-printed enclosure, fabricated using Rapid Prototyping techniques, exhibited excellent fluid distribution through integrated cooling channels. The thermally conductive material used further enhanced heat exchange efficiency. No fluid leakage or structural defects were identified during testing, demonstrating the robustness and reliability of the design.

V. DISCUSSION ON RESULTS

The experimental results clearly demonstrate the effectiveness of the proposed liquid cooling system in regulating the thermal environment of lithium-ion batteries under varying operational conditions. The system consistently maintained battery temperatures within the optimal operational range of 35–40°C, effectively mitigating the risks associated with overheating, such as thermal runaway or accelerated degradation.

The real-time monitoring and control facilitated by the ESP32 microcontroller enabled autonomous activation of the cooling system without requiring human intervention. This feature is particularly critical for electric vehicles, where operating conditions are highly dynamic. Furthermore, the stable thermal conditions contributed directly to improved voltage stability and overall battery efficiency, addressing one of the major challenges in lithium-ion battery management.

The low power consumption of the cooling system (5–8 W) ensures that the energy used for thermal management does not negatively impact the vehicle's driving range or overall battery performance. Additionally, the integration of Rapid Prototyping in designing the enclosure allowed for highly efficient fluid circulation while maintaining a compact, lightweight, and structurally sound design.

The inclusion of gas and flame sensors provided additional layers of safety monitoring. The absence of hazardous events such as gas leakage or combustion during testing validated the system's capacity to prevent dangerous failure modes, thus significantly enhancing battery safety and reliability.

VI. CONCLUSION

The proposed liquid cooling system, integrating Rapid Prototyping techniques with intelligent real-time monitoring using the ESP32 microcontroller, successfully demonstrated effective thermal management for lithium-ion batteries in electric vehicles. The system maintained optimal temperature ranges, improved battery efficiency by 5–8%, and enhanced overall safety through rapid sensor-based response to potential hazards such as overheating, gas leakage, or fire risks. The custom-designed 3D-printed cooling structure offered superior fluid circulation and structural integrity while minimizing power consumption and weight. This multidisciplinary approach not only addresses key challenges in EV battery thermal management but also lays the foundation for scalable, sustainable, and intelligent cooling solutions applicable across various electric mobility and energy storage platforms.

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