



# Design and Development of Smart Liquid-Cooled Battery Thermal Management System for EV Application

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**Abstract** - The rapid growth of Electric Vehicles (EVs) has increased the demand for efficient Battery Thermal Management Systems (BTMS) to ensure battery safety, reliability, and performance. Lithium-ion batteries generate significant heat during charging and discharging operations, which can lead to thermal runaway, capacity degradation, reduced cycle life, and safety hazards if not properly managed. This paper presents the design and development of a Smart Liquid-Cooled Battery Thermal Management System for electric vehicle applications. The proposed system employs a 3S4P lithium-ion battery pack integrated with copper cooling channels, ethylene glycol coolant, a submersible pump, temperature sensors, and an Arduino Nano-based control unit. The developed system continuously monitors battery temperature and automatically activates cooling devices when the battery temperature exceeds predefined limits. Experimental analysis demonstrates improved thermal stability, enhanced temperature uniformity, and effective heat dissipation. The proposed solution provides a low-cost and practical approach for thermal management in electric vehicle battery systems.

**Keywords**— Battery Thermal Management System, Electric Vehicle, Liquid Cooling, Lithium-Ion Battery, Arduino Nano, Thermal Runaway, Battery Safety.

## I. INTRODUCTION

Electric Vehicles (EVs) are becoming increasingly important in modern transportation due to their high efficiency and low environmental impact. Lithium-ion batteries are widely used in EVs because of their high energy density, long cycle life, and fast charging capability [1], [4].

However, battery performance is highly dependent on operating temperature. During charging and discharging processes, heat is generated due to internal resistance and electrochemical reactions. Excessive heat accumulation can cause capacity degradation, reduced battery life, increased internal resistance, thermal runaway, and safety hazards [2], [3].

Research indicates that lithium-ion batteries perform optimally within a temperature range of 20°C–45°C [2], [8]. Therefore, maintaining battery temperature within this range is essential for safe and efficient operation.

Battery Thermal Management Systems (BTMS) are developed to regulate battery temperature and improve thermal stability. Among available cooling technologies, liquid cooling provides

superior heat transfer capability compared with conventional air-cooling systems [6], [7].

The present work proposes a Smart Liquid-Cooled BTMS incorporating temperature sensing, automated cooling control, and emergency protection mechanisms for EV battery applications.

## II. LITERATURE REVIEW

Several researchers have investigated thermal management techniques for lithium-ion batteries. Air-cooling systems are simple and economical but suffer from low thermal conductivity and poor temperature uniformity [5].

Liquid cooling systems have attracted significant attention because of their higher heat transfer rates and improved thermal performance. Wang et al. [7] demonstrated that liquid cooling can effectively maintain battery temperature within safe operating limits. Karimi and Li [10] reported that liquid cooling significantly improves thermal uniformity and reduces hotspot formation.

Recent research has focused on advanced cooling approaches such as microchannel cooling, cold plates, phase change materials (PCM), and hybrid thermal management systems [6], [11]. Smart BTMS solutions integrating sensors, microcontrollers, and intelligent algorithms have also been investigated to improve thermal control and battery safety [8], [11].

Battery Management Systems (BMS) play a crucial role in monitoring voltage, current, state of charge, and temperature. Modern BMS architectures are increasingly integrated with BTMS to improve battery reliability and lifespan [8], [15].

## III. RESEARCH GAP

Despite significant advancements in BTMS technologies, several challenges remain. Existing liquid cooling systems often increase system complexity and auxiliary power consumption [6], [10]. Many commercial systems lack low-cost smart monitoring solutions suitable for educational and prototype-scale EV applications [11].

Furthermore, temperature non-uniformity among cells remains a major concern because it accelerates battery aging and reduces overall pack performance [2], [10]. Most available studies focus on industrial-scale systems, while limited work

has been reported on compact Arduino-based BTMS architectures integrated with automated safety mechanisms [6], [11].

#### IV. NOVELTY OF THE PROPOSED WORK

The novelty of the proposed system includes:

- Integration of liquid cooling and smart control in a low-cost prototype.
- Real-time battery temperature monitoring using LM35 sensors.
- Automatic pump and fan activation using Arduino Nano.
- Emergency overheating warning through buzzer indication.
- Compact and scalable architecture suitable for EV applications.
- Cost-effective implementation using commercially available components.

#### V. METHODOLOGY

The proposed Smart BTMS utilizes real-time temperature monitoring and liquid cooling to regulate battery temperature. Battery heat generation is primarily caused by internal resistance and electrochemical reactions and can be represented by:

$$Q = I^2R$$

which is widely used in battery thermal analysis studies [2], [13].

The battery temperature is continuously monitored using LM35 sensors, while an Arduino Nano controller processes the measured values. When the temperature exceeds the predefined threshold, the controller activates the cooling pump and fan automatically.

The cooling system employs ethylene glycol coolant flowing through copper cooling channels. Similar liquid cooling approaches have demonstrated excellent thermal performance in previous studies [7], [10], [14].

#### VI. THERMAL ANALYSIS

Thermal behavior of the battery pack is analyzed using convective heat transfer principles. The heat transfer between the battery surface and coolant is expressed as:

$$Q = hA(T_s - T_f)$$

where  $h$  is the convective heat transfer coefficient,  $A$  is the heat transfer area,  $T_s$  is battery surface temperature, and  $T_f$  is coolant temperature [7], [10].

Previous studies have shown that increasing coolant flow rate enhances heat removal capability and improves temperature

uniformity throughout the battery pack [7], [14]. Experimental and numerical investigations have further confirmed the effectiveness of liquid cooling systems in maintaining battery temperatures below critical limits [13], [14].

#### VII. OBSERVATIONS

- Battery temperature remained below 35°C.
- Cooling response was automatic and reliable.
- Temperature distribution improved significantly.
- Thermal runaway risk was reduced.
- Battery operating stability increased.

#### VIII. ADVANTAGES

The proposed system offers:

- Improved battery safety
- Better thermal uniformity
- Higher cooling efficiency
- Longer battery life
- Reduced thermal runaway risk

#### IX. EXPERIMENTAL RESULTS

| Experimental Performance Analysis |                 |                           |
|-----------------------------------|-----------------|---------------------------|
| Parameter                         | Without Cooling | With Smart Liquid Cooling |
| Maximum Battery Temperature       | 52°C            | 34°C                      |
| Temperature Uniformity            | Poor            | Good                      |
| Thermal Stability                 | Moderate        | Excellent                 |
| Cooling Response Time             | High            | Low                       |
| Safety Level                      | Medium          | High                      |

#### X. RESULTS & DISCUSSION

Experimental testing demonstrated that the proposed Smart Liquid-Cooled BTMS effectively reduces battery temperature and improves thermal stability. Similar observations have been reported by Wang et al. [7] and Shah et al. [14], who found that liquid cooling systems significantly outperform conventional air-cooling methods.

The integration of temperature sensing, automatic pump control, and safety alarms improved overall battery protection. The developed system maintained battery temperature within the recommended operating range reported in the literature [2], [8].

The results indicate that the proposed low-cost BTMS can serve as an effective thermal management solution for EV battery applications while minimizing the risk of thermal runaway [3], [11].

## CONCLUSION

A Smart Liquid-Cooled Battery Thermal Management System for EV applications has been successfully designed and developed. The proposed system integrates liquid cooling, temperature sensing, automated control, and safety protection features. Experimental evaluation demonstrates improved thermal stability, enhanced temperature uniformity, and effective heat dissipation.

The developed BTMS maintains battery temperature within the recommended operating range suggested in previous studies [2], [8], thereby improving battery safety, lifespan, and operational reliability. The proposed architecture offers a practical and economical solution for electric vehicle battery thermal management and can be further extended through IoT-based monitoring and intelligent predictive control techniques [11], [12].

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