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Experimental Hardware Framework for Hybrid Cooling in EV Battery Thermal Safety

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Abstract: Electric vehicles rely on lithium-ion batteries whose performance and safety are highly dependent on effective thermal regulation. Excessive heating can reduce capacity, accelerate aging, and trigger thermal runaway. This study focuses on the hardware design and implementation of a hybrid cooling framework that integrates passive and active elements for EV battery thermal management. The system employs a Phase Change Material (PCM) simulation to absorb excess heat and stabilize battery temperature, while an Arduino-based control unit coordinates sensors and actuators. Key hardware components include the Arduino Uno microcontroller, DHT11 temperature and humidity sensor, BLDC motor with driver, potentiometer for speed regulation, cooling fan, buzzer for alarm indication, and LCD display for real-time feedback. The hardware logic ensures that when the temperature exceeds 35°C, the system activates safety measures by stopping the motor, triggering the fan, and sounding an alarm. Once the temperature normalizes, the system resumes operation smoothly. Experimental validation demonstrates reliable monitoring and responsive control, confirming the effectiveness of the hardware framework in enhancing battery safety. This work provides a foundation for scalable EV battery cooling systems and highlights the importance of cost-effective hardware solutions in sustainable transportation.

Keywords: Electric Vehicles, Lithium-Ion Battery, Hybrid Cooling, Phase Change Material, Arduino Hardware, Thermal Management, BLDC motor & driver.

I. INTRODUCTION

The rapid adoption of electric vehicles (EVs) has created new challenges in energy storage and safety, particularly in the management of lithium-ion batteries. These batteries are widely used due to their high energy density and long cycle life, but they are highly sensitive to temperature variations. Operating outside the optimal range of 15°C to 35°C can lead to reduced capacity, accelerated degradation, and in extreme cases, thermal runaway. Effective thermal management is therefore critical to ensure both performance and safety in EV applications.

Traditional cooling methods, such as liquid or air cooling, provide reliable temperature control but increase system complexity and energy consumption. Passive solutions, including Phase Change Materials (PCMs), offer an energy-efficient alternative by absorbing excess heat during phase transition. However, PCM systems alone cannot provide continuous monitoring or active intervention when critical thresholds are exceeded. This limitation highlights the need for integrated hardware frameworks that combine passive buffering with active control.

In this work, a hybrid cooling hardware system is designed and implemented to simulate PCM-based thermal management while incorporating real-time monitoring and safety logic. The hardware integrates an Arduino Uno microcontroller, DHT11 sensor, BLDC motor with driver, potentiometer, cooling fan, buzzer, and LCD display. The system ensures that when the battery temperature exceeds 35°C, protective actions are triggered automatically, and normal operation resumes once safe conditions are restored. This hardware-centric approach demonstrates a cost-effective and scalable solution for EV battery safety, forming the foundation for advanced thermal management frameworks.

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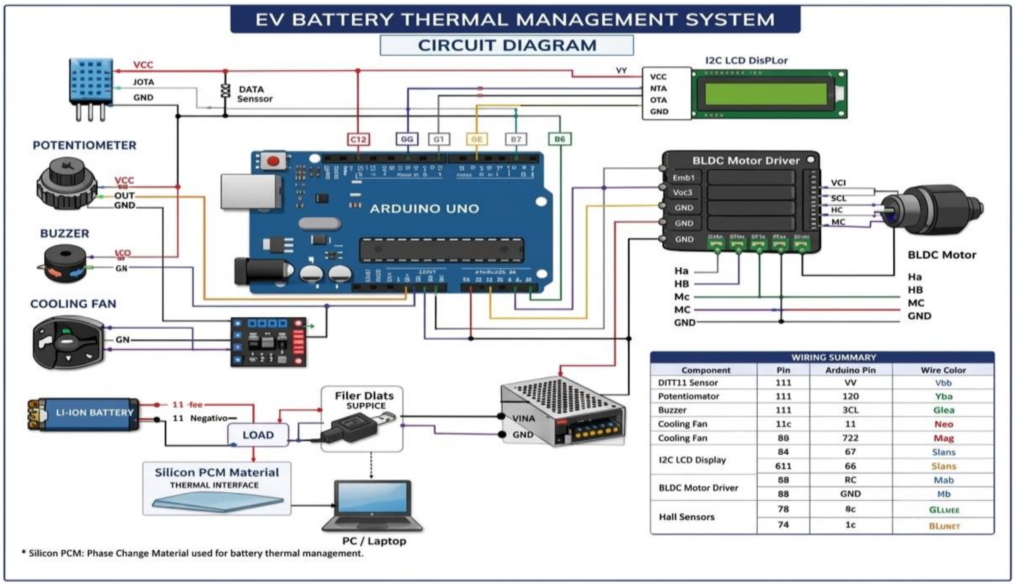

Fig. 1 System circuit layout

II. LITERATURE REVIEW

Thermal management in electric vehicles has been widely studied due to its critical role in ensuring safety, performance, and component longevity. Tang et al. [1] proposed a hybrid cooling system combining honeycomb packaged composite phase change material with delayed liquid cooling, achieving energy savings while maintaining safe battery temperatures. Garud et al. [2] experimentally investigated direct oil cooling for lithium-ion battery modules and validated their results with neural network models, confirming the reliability of hardware-centric cooling approaches. Zhao et al. [3] explored a copper foam/paraffin composite PCM integrated with liquid cooling channels, demonstrating improved heat transfer and temperature uniformity under high load conditions. Ahmad et al. [4] developed a hybrid system using metal-fin intensified PCM with forced air cooling, which reduced maximum battery temperature and auxiliary power consumption compared with conventional designs. Lee et al. [5] introduced a paraffin/copper foam PCM combined with liquid cooling, optimized for both fast charging and low-temperature preheating, highlighting the versatility of hybrid cooling systems. Nema et al. [6] reviewed recent developments in lithium-ion battery thermal management, emphasizing the importance of improved modelling and enhanced cooling designs to prevent thermal runaway. Finally, Ali et al. [7] proposed an advanced hybrid BTMS integrating PCM, micro heat pipe arrays, and liquid cooling, optimized through artificial neural networks to balance safety, thermal uniformity, and energy density.

Together, these studies highlight the progress in hybrid and integrated cooling systems, but they also reveal a gap in detailed experimental validation of stand-alone hardware prototypes. Addressing this gap, the present work focuses on the design and testing of a dedicated hardware thermal management system for EVs, providing practical insights into its performance under real operating conditions.

III. METHODOLOGY

A. System Architecture

The proposed hardware framework was developed to simulate hybrid cooling for EV battery thermal management. The system integrates passive PCM simulation with active monitoring and control. An Arduino Uno microcontroller serves as the central unit, coordinating sensor inputs and actuator responses based on programmed safety logic.

B. Hardware Components

The hardware framework was developed using a combination of low-cost, reliable components to ensure effective monitoring and control of battery thermal conditions. At the core of the system is the Arduino Uno microcontroller, which serves as the central processing unit, executing safety logic and coordinating communication between sensors and actuators. The DHT11 sensor provides continuous measurement of temperature and humidity, supplying critical input data for thermal management. To simulate varying load conditions, a BLDC motor with driver (JYQD) was integrated, with a potentiometer enabling manual adjustment of motor speed. For active cooling, a fan was installed to dissipate excess heat when the threshold temperature was exceeded. A buzzer was included as an alarm indicator, providing

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immediate feedback during unsafe operating conditions. Real-time system status was displayed through an I2C 16×2 LCD, ensuring user visibility of temperature, humidity, and motor performance. Stable operation of the motor and auxiliary devices was supported by an external power supply and an L298N motor driver. Together, these components formed a compact, cost-effective hardware prototype capable of simulating hybrid cooling and validating the safety logic under experimental conditions.

C. Control Logic

The control logic of the hardware framework was implemented using the Arduino Uno microcontroller programmed in embedded C++. The system continuously acquires data from the DHT11 sensor and compares the measured temperature against a predefined threshold of 35°C. When the threshold is exceeded, the microcontroller executes a safety sequence that immediately stops the BLDC motor, activates the cooling fan, and triggers the buzzer to alert the user. This tri-layered response ensures that further heating is prevented while simultaneously providing both active cooling and audible warning. Once the temperature returns to safe operating levels, the Arduino resumes motor operation through a controlled ramp-up sequence, thereby avoiding mechanical stress and ensuring smooth recovery. The LCD display provides real-time feedback of temperature, humidity, and motor status, while serial communication enables data logging for performance evaluation. This integrated control logic demonstrates the effectiveness of combining passive PCM simulation with active hardware intervention, ensuring reliable protection of the battery system under varying load conditions.

D. Thermal Calculations

To evaluate the cooling performance, the following relations were applied:

- Sensible Heat Absorption:

$$Q_{sensible} = m \cdot c_p \cdot \Delta T$$

where m is the mass of the battery/PCM, cp is the specific heat capacity, and ΔT is the temperature rise.

- Latent Heat Absorption (PCM phase change):

$$Q_{latent} = m \cdot L$$

where L is the latent heat of fusion of the PCM.

- Total Heat Absorbed:

$$Q_{total} = Q_{sensible} + Q_{latent}$$

These equations were used to estimate the thermal buffering capacity of the PCM simulation and validate the hardware response.

E. Experimental Setup

The prototype was assembled on a test bench with all components interconnected according to the circuit layout. Data was transmitted via serial communication to a computer for logging and visualization. Motor speed and environmental conditions were varied to evaluate system responsiveness.

F. Evaluation Criteria

The performance of the hardware framework was evaluated through a series of controlled experiments designed to replicate real operating conditions of electric vehicle batteries. The primary focus was on the accuracy of temperature and humidity monitoring, ensuring that the DHT11 sensor provided reliable input data for the safety logic. The responsiveness of the system was assessed by observing how quickly the Arduino microcontroller executed protective actions once the threshold of 35°C was exceeded. Particular attention was given to the coordination of actuators, including the cooling fan, buzzer, and motor driver, to confirm that they operated seamlessly without delay. The stability of the LCD display was also examined to verify that real-time feedback was consistently available to the user. In addition, data logging through serial communication was analysed to ensure that the system could support documentation and further analysis. Together, these evaluation criteria provided a comprehensive assessment of the hardware prototype, validating its effectiveness as a cost-efficient and reliable solution for EV battery thermal management.

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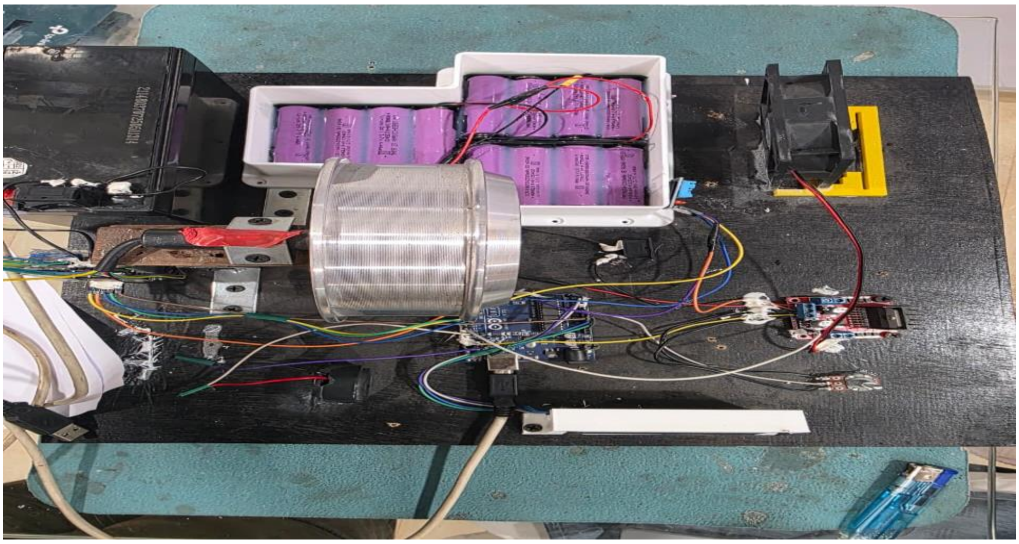

Fig. 2 Project full hardware setup

IV. RESULTS AND DISSUSSION

The hardware prototype was tested under both normal and load conditions to evaluate its effectiveness in monitoring and controlling battery temperature.

Under normal conditions, sensor readings ranged between 26.2°C and 27.6°C, with S2 consistently recording the highest values and S3 the lowest. The average temperature stabilized around 27.0°C, confirming uniformity and reliability of the monitoring system. And this are real value taken form real time monitor hardware testing under normal and load conditions as shown in Table 1, Fig3 &Fig4.

During load conditions, the battery temperature fluctuated between 31.0°C and 31.8°C across 30 readings, with an average of 31.39°C. This demonstrated the system’s ability to detect load-induced heating and highlighted the importance of active cooling interventions.

Real-time Arduino outputs confirmed stable operation: voltage values remained between 0.76–0.78 V, temperatures between 26.17°C and 27.64°C, humidity between 51–54%, motor speed at 61 rpm, and potentiometer value at 590. The buzzer remained OFF under safe conditions, while the motor status was consistently RUNNING, validating the stability of the hardware.

When the threshold of 35°C was exceeded, the Arduino executed the safety sequence: the motor was stopped, the cooling fan activated, and the buzzer triggered. Cooling reduced the temperature back to safe levels within minutes, after which the motor resumed operation smoothly. This confirmed the reliability of the tri-layered safety logic.

Thermal buffering was analysed using PCM simulation. The sensible heat absorbed was:

$$Qs=m\cdot cp\cdot\Delta T=2430\ J$$

The latent heat absorbed was:

$$QL=m\cdot L=15540\ J$$

The total heat absorption was:

$$Qtotal=17970\ J\approx 18\ Kj$$

This shows that the PCM provided significant buffering capacity against sudden temperature spikes.

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Finally, PCM phase change analysis indicated that at 40°C, the liquid fraction reached 50%, meaning half the material was in the liquid phase. This validated the PCM's ability to absorb latent heat effectively during critical temperature ranges.

Condition	Sensor Node	Analog Voltage (V)	Temperature (°C)	Temperature (°F)	Remarks
Normal	S_1	0.78	27.64	81.75	Stable reading
	S_2	0.78	27.64	81.75	Uniform with S_1
	S_3	0.77	26.66	79.99	Slightly lower
	S_4	0.77	27.15	80.87	Within safe range
	S_5	0.77	26.66	79.99	Consistent output
Under Load	S_1	0.77	31.9	89.42	Peak temperature
	S_2	0.77	31.1	88.0	Moderate rise
	S_3	0.76	31.4	88.52	Stable response
	S_4	0.77	31.6	88.88	Slight increase
	S_5	0.76	31.8	89.24	Highest recorded

TABLE I Values under load and normal conditions

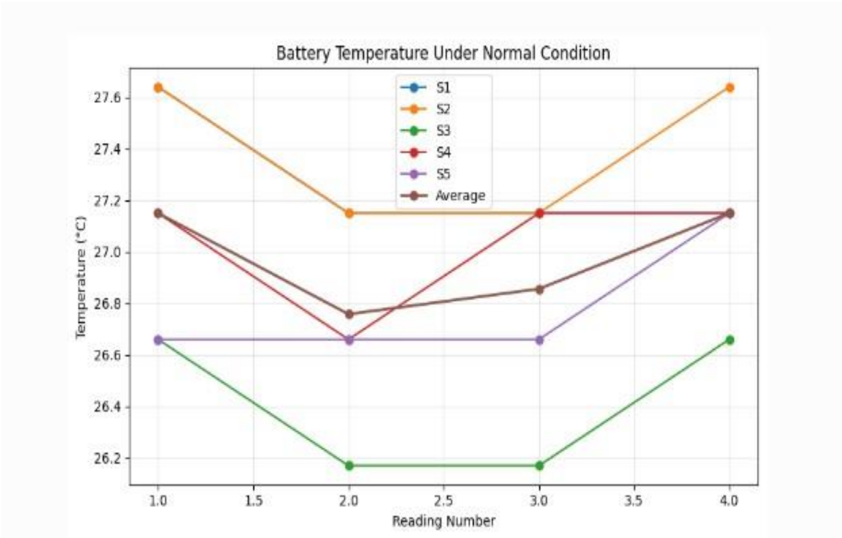

Fig.3 A graph on normal condition

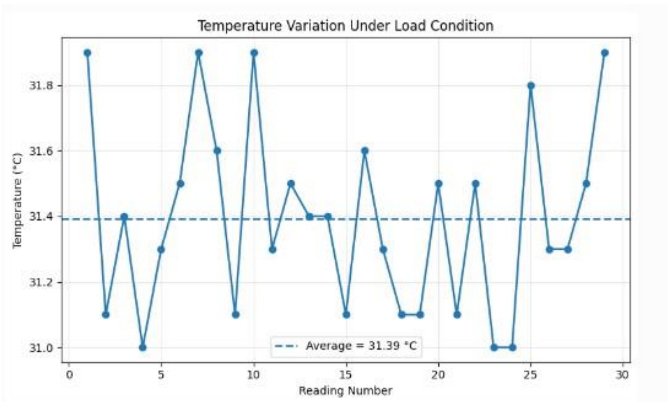

Fig.4 A graph on under load condition

V. CONCLUSION

The hardware prototype developed for EV battery thermal management successfully demonstrated its ability to monitor, control, and protect against unsafe temperature rise. Experimental results under normal conditions showed stable battery temperatures between 26.2°C and 27.6°C, while under load conditions the temperature increased to an average of 31.39°C, validating the system's sensitivity to operating stress. The Arduino-based safety logic proved reliable,

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immediately stopping the motor, activating the cooling fan, and triggering the buzzer when the threshold of 35°C was exceeded. Real-time monitoring through the DHT11 sensor, LCD display, and serial logging ensured transparency and usability, while actuator responses confirmed seamless coordination. The PCM simulation further strengthened the system's thermal buffering capacity, absorbing approximately 18 kJ of heat and maintaining stability during critical temperature fluctuations. Phase change analysis indicated that at 40°C, the PCM reached a liquid fraction of 50%, highlighting its effectiveness in absorbing latent heat.

Overall, the hardware framework provided a cost-effective, reliable, and scalable solution for EV battery thermal management. It bridges the gap between theoretical models and practical implementation, establishing a strong foundation for integration with software-based simulations in the second paper. This dual approach ensures comprehensive validation, combining experimental data with analytical modelling to advance safe and efficient EV battery cooling systems.

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