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Research Article

Thermal regulation of an EV battery pack using mineral oil: Jordan case study

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ABSTRACT

Thermal management is vital for optimizing the performance, lifespan, and safety of electric vehicle (EV) battery packs. This paper experimentally explores the use of mineral oil as a thermal regulation medium for EV batteries under Jordanian climate conditions. The study includes analyses of the electrical and thermal behavior of battery cells at different temperatures, the compatibility and impact of mineral oil on battery materials, and the practical feasibility of integrating such a system within an EV module. Battery testing was conducted under three cooling conditions: no cooling, air cooling, and mineral oil cooling. The electrical behavior of the battery was studied across these three cooling cases under 0.5C and 1C discharge rates, as well as under a 0.5C charge rate. The results indicate that mineral oil significantly moderates the battery temperature, keeping it within optimal operational ranges compared to other cooling methods. Specifically, the temperature delta is reduced by 50% at a discharge rate of 0.5C, while temperature uniformity is maintained within 2°C. This study designs and utilizes a mineral oil cooling system to investigate the thermal behavior of an existing battery module from the HTU student Racing Formula Team under Jordanian climatic conditions. The ambient temperatures during the testing period ranged between 28°C and 34°C. The findings suggest that mineral oil cooling is a feasible solution for improving the thermal management of EV batteries under variable conditions.

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INTRODUCTION

Electrical Vehicles (EV) are widely regarded as the future of the automotive industry [1, 2]. The battery, component of EVs, is responsible for storing energy and discharging it to the powertrain, making it a critical factor in the industry's advancement [3]. Proper thermal management of EV batteries is essential, as extreme heat can damage their chemistry [4], while harsh cold weather can degrade their performance and limit their capacity [5]. Most EV manufacturers recommend storing vehicles in environments protected from cold weather to safeguard battery performance [6, 7]. Consequently, a thermal management system for

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batteries is essential for maintaining battery temperature within an optimal range, minimizing thermal safety risks, and extending battery lifespan [8]. Rapid and efficient heat dissipation methods play a crucial role in ensuring longer battery life and safe operation [9]. To achieve optimal performance, lithium-ion batteries should within a temperature range of 15–35°C. Furthermore, the ideal operating temperature may vary depending on the geographical location of the country [9]. Nagasubramanian [10] investigated the impact of extremely cold temperatures on Li-ion battery cells, examining their electrical performance characteristics. Different tests were conducted to measure performance parameters across a temperature range of -40°C to 35°C. The study analyzed several parameters, including internal resistance (both ohmic and interfacial resistance between cathode and anode), specific energy, delivered power, energy density, and voltage drops across these temperature conditions. Similarly, a study conducted in the UK by Koncar et al. [5] assessed and quantified the impact of extreme cold temperatures on EV batteries. This study focused on vehicles utilizing Li-ion battery cells in their battery packs, where probabilistic analysis of power consumption was performed under different winter temperatures. The findings revealed that during the coldest ambient temperatures, an additional 630 MW of peak power was observed on the grid compared to optimal temperature conditions.

Different cooling methods are currently employed, including air cooling, liquid cooling, and phase change material (PCM) cooling. Among these methods, air cooling is the most commonly used because it is simple in design, lightweight, environmentally friendly, and cost-efficient. It is particularly suitable for mild temperature control compared to other cooling methods [9, 11]. In air cooling system, heat generated by the battery dissipates into the surrounding air, resulting in cooling based on the natural principles of heat transfer [12]. This method is generally preferred for small battery packs due to their lower power demands [12]. However, air cooling method has many limitations, including a low heat transfer coefficient, which restricts its ability to meet the cooling requirements in extreme temperatures. Additionally, temperature non-uniformity can lead to safety risks, including fire hazards [13]. Phase change material (PCM) cooling offers higher efficiency due to its high latent heat capacity. However, it is not suitable for EV batteries due to their low thermal conductivity and significant volume expansion during the melting process [11]. Also, materials used in PCM cooling typically exhibit high flammability [13], and when used directly, they pose risks such as toxicity and leakage [14]. These limitations are particularly challenging in the EV industry, especially in regions with extreme ambient temperatures. For example, in Jordan, summer temperatures can reach up to 45°C [15], directly affecting battery performance [8,9]. Furthermore, when battery temperatures rise to 60-70°C, the battery management system (BMS) may disconnect, negatively impacting battery health and overall performance [16]. Therefore, it is essential to explore various cooling methods capable of maintaining consistent thermal performance under extreme ambient conditions. Liquid cooling is considered a highly effective approach for EV battery thermal management due to its high thermal conductivity and heat capacity. It delivers up to 3,500 times the efficiency of air cooling, enabling energy savings of up to 40% [17]. Immersion cooling is an emerging technology for battery thermal management [13], classified into single phase cooling (utilizing sensible heat) and two-phase cooling (utilizing latent heat), both enhance cooling performance by dissipating heat from battery cells. Immersion cooling also holds significant potential for preventing thermal runaway and its subsequent propagation [13]. Several studies have investigated the use of liquid cooling methods, particularly mineral oil for lithium-ion batteries cooling. Trimbake et al. [11] were the first to experimentally examine mineral oil-based cooling for lithium-ion batteries, analyzing charging and discharging characteristics in terms of temperature uniformity both among cells and within individual cells. Their findings indicated that mineral oil maintained uniform temperatures (within 1°C) and suggested that modular jet oil cooling is a viable cooling option for lithium-ion battery packs. Liu et al., [18] compared mineral oil and natural ester oil for lithium-ion battery immersion cooling. Their study found that both oils effectively reduced battery temperature and restricted temperature variation among cells to within 2°C. The researchers suggested that natural ester oil could be a promising candidate for immersion cooling of lithium-ion batteries. Satyanarayana et al. [19] conducted experimental immersion cooling studies using mineral oil and therminol oil on a 20-cell, 10A lithium-ion battery stack at different discharge rates. Their findings revealed that, at a 3C discharge rate, the maximum battery module temperature was reduced by 43.83% with forced air cooling, 49.17% with therminol oil cooling, and 51.54% with mineral oil cooling compared to natural air-cooling method [19]. However, this study utilized partial immersion cooling. The results demonstrated that immersion cooling provides superior temperature control across different discharge rates. Among the tested methods, mineral oil cooling proved to be more effective than therminol oil cooling due to its lower viscosity, leading to better heat dissipation. Overall, mineral oil cooling systems enhance battery safety by minimizing the risk of thermal runway [11, 12], preventing direct oxygen contact with battery cells in the case of punctures, and demonstrating superior heat dissipation efficiency compared to air cooling [11].

Lecuna et al. [20] compared mineral oil to other synthetic and natural liquids used in power transformers cooling. Their study highlighted that mineral oil not only performs effectively in narrow channels but also exhibits a superior convection heat transfer coefficient, making it a viable cooling solution for compact battery systems. Mineral oil is widely recognized for its high thermal conductivity, high heat capacity, good electrical insulation, low cost, low toxicity, non-combustibility, low corrosion properties, and it is available in large quantities [18]. However, oil-immersed cooling systems also present certain limitations [18]. Studies have shown that beyond a certain flow rate, further increases in coolant circulation might reduce temperatures but at the cost of higher pumping power requirements [18]. To the best of our knowledge, no previous study has investigated the thermal management of lithium-ion batteries using mineral oil cooling systems under Jordanian climate conditions, where heat dissipation rates are significantly affected by ambient conditions such as temperature and pressure [21-23]. This study investigates the thermal and electrical behavior of lithium-ion batteries and evaluates long-term material compatibility under Jordanian climatic conditions. The findings provide novel insights into the practical feasibility and effectiveness of mineral oil-based cooling for EV batteries. Thus, it provides a novel insight into its practical feasibility and effectiveness.

MATERIALS AND METHODS

Project Description

The proposed method of using mineral oil for cooling EV batteries offers a dual advantage: it not only effectively cools the batteries but also insulates them from external extreme temperatures that could impact their performance, safety, and service life. Mineral oil is intended to thermally regulate the battery cells, ensuring they remain within an optimal temperature range, as specified in datasheets and studies on battery chemistry and performance [11-19]. Additionally, its insulative properties can help mitigate performance limitations caused by extreme temperatures [10]. Regarding safety requirements for lithium-ion batteries, one of the primary concerns is excessive temperature rise, which may lead to an increased risk of cell explosions [24]. Another major risk is punctures in any of the battery cells. If the inner battery material comes into contact with oxygen molecules, a chemical reaction could trigger ignition and cause a chain reaction within the cells [25, 26]. Therefore, by using mineral oil for battery cooling, the risk of oxygen to battery cells is significantly reduced. Additionally, integrated control systems can be explored to detect punctures in the cells, providing early alerts and allowing sufficient time for professional intervention, ultimately preventing fire or explosion hazards. Mineral oil is known for its excellent thermal properties and insulation capabilities, as presented in Table 1 below. It is cost effective, widely available, biodegradable and environmentally friendly, non-toxic, and non-combustible material [11]. In addition, mineral oil has the potential to stabilize battery temperature under both high heat and severe cold conditions, ensuring optimal battery performance and longevity.

As presented in Table 1, mineral oil is suitable for most applications due to its high flash and ignition temperatures, allowing it to withstand extreme thermal conditions [27]. In general, maintaining a stable battery temperature is crucial for optimal performance, with the peak efficiency range typically between 15°C and 35°C [9]. However, keeping batteries within this range can be challenging, especially when external environmental factors significantly impact temperature. This research aims to mitigate the effects of external temperature fluctuations, whether high heat during the summer or extreme cold in winter, where many EVs lose approximately 30% of their expected driving range [3]. During cooling, the batteries are fully submerged in mineral oil, which is continuously circulated using a pump connected to a small reservoir. A heat exchanger is incorporated into the system to cool the oil before it is recirculated back to the battery pack, effectively maintaining optimal operating temperatures. For heating in cold winters conditions, heating coils will be integrated into the oil transfer tubes, allowing the oil to be warmed before circulating through the battery system. This regulated heating process is crucial for maintaining battery efficiency and longevity, preventing performance loss due to low temperatures.

In this study, an accumulator prototype, designed by the HTU Racing Formula Team was used as presented in Figure. 1. This prototype is set to compete in the 2024 Formula Student competition, where the intense racing

Table 1. Mineral oil thermal and electrical properties

Properties	Specifications
Boiling temperatures	Greater than 280°C and an auto ignition temperature > 320°C [27].
Freezing temperature	-40°C [27]
Density (ρ)	924 kg/m^3 [12]
Viscosity (μ)	0.05 Pa.s [12]
Thermal conductivity (k)	0.1296 W/m·K [29,30]
Heat capacity (C_p)	1.9 KJ/kg K [28]
Electrical conductivity (σ)	10^{-12} to 10^{-15} (S/m) [31]

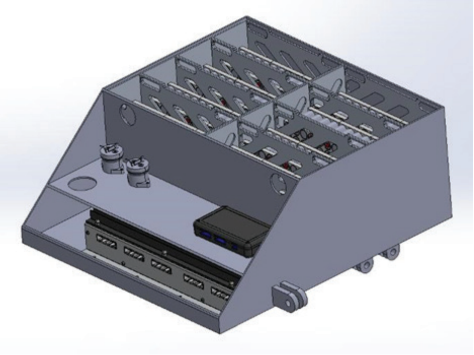


Figure 1. Battery accumulator prototype (Obtained from the HTU Racing Formula Team).

conditions are expected to exhaust and overheat the batteries. Testing the proposed thermal management system under these conditions will provide valuable insights into its effectiveness and performance.

Experimental Setup

The experiment was conducted between April and June 2024 under hot Jordanian conditions, with ambient temperatures ranging from 28°C to 34°C. The experimental setup is summarized in the flow chart presented (Fig. 2).

The set up for testing the electrical and thermal characteristics of the batteries utilized a 12S/8P Panasonic (Tesla) 18650 Li-ion Battery Pack. This battery pack was designed, manufactured, and provided by the HTU Racing Formula Team. It consists of 96 Li-ion cells, capable of delivering a maximum voltage of 50.4V at full charge, as illustrated in Figure 2. The battery data presented in Table 2 was obtained through extensive and repeated testing of a single cell by the HTU Racing Formula Team. (Fig. 3) A total of 28 thermistors (10k NTC type) were used in the experiment. Their placement included 24 thermistors placed on the negative tabs of the cells (2 per tab), one thermistor at the container inlet, one thermistor at the container outlet, one thermistor for ambient temperature, and one thermistor to monitor the load temperature for safety purposes. A microcontroller-based circuit was implemented, comprising 4 microcontroller units (MCUs) connected via serial communication with a PC. The system recorded data at a sampling rate of 30 seconds, ensuring precise monitoring of thermal and electrical parameters.

The second component used in the research is battery Management System (BMS), provided by the HTU Racing Formula Team (Supower *Battery, China). It is* a 12S pack, and the expected voltage gap between the cells is 2.5-4.2 Volt. The selected BMS is rated as operating on a 44.4 V pack, which is just above the nominal voltage of the used module allowing safe operation of the cells. The cut-off limit of the BMS was hard-wired to stop discharge at 38.5 V.

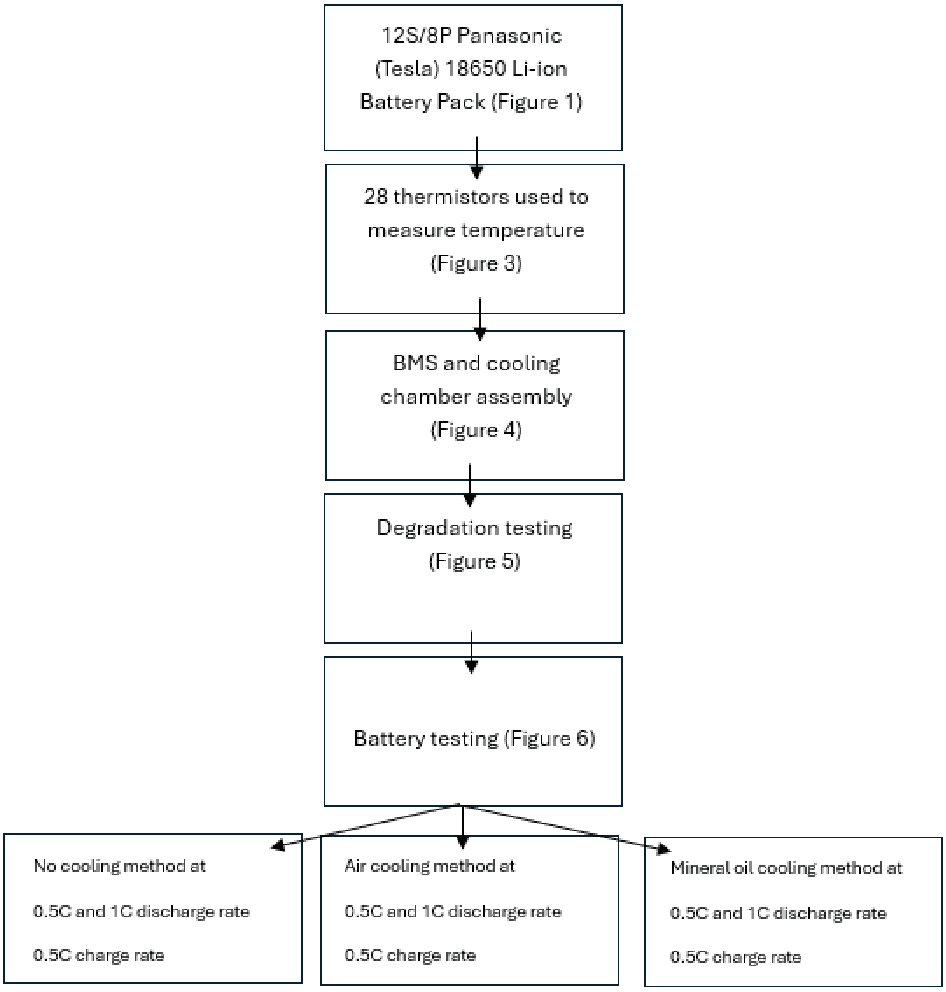


Figure 2. Experimental set up flow chart.

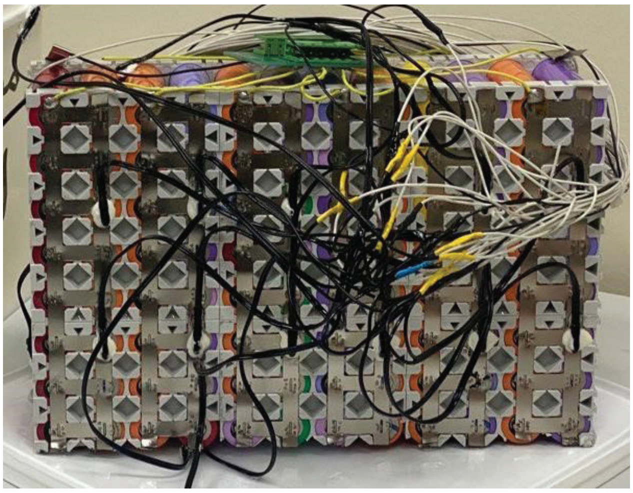


Figure 3. Battery module used for testing (Obtained from the HTU Racing Formula Team).

Table 2. Battery module testing characteristics (obtained from the battery data sheet)

Properties	Specifications
Battery capacity	24 Ah
Nominal voltage	43.2 V
Cutoff voltage	30 V
Charging voltage	50.4 V
Weight	4.6 kg
Size	7cm×24cm×17cm

Table 3. Pierburg Pump Specifications (Pierburg CWA 150 Tecomotive, Germany obtained from [32])

Properties	Specifications
Operating Voltage	9 - 16 V
Current Consumption	15 A maximum
Nominal diff. Pressure	Greater than 1.4 bar
Max Speed	6700 rpm
Weight	1 kg

This poses a limit on the discharge and charge cycles, utilizing only 60% of the pack capacity. The third component used in the experimental setup is Coolant Pump (Pierburg CWA 150 Tecomotive, Germany). The pump specifications are summarized in Table 3 below. This pump was also provided by the HTU Racing Formula Team. It is considered a standard automotive pump, which is suitable for different types of fluids.

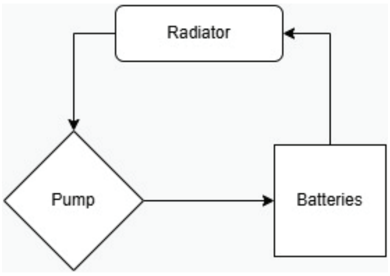


Figure 4. Schematic diagram for the cooling system used in the testing.

The fourth component used in the experimental setup is a cooling chamber. A metal container with one inlet and one outlet was designed and manufactured to place the battery module with proper spacing for oil to flow around (as presented in Fig. 4) to allow for effective heat transfer in the chamber while achieving the desired immersion cooling with mineral oil. Furthermore, a household fan was used to imitate the dispersed and turbulent flow observed in vehicles with active air cooling. Air cooling was achieved after directing the natural flow of air caused by a vehicle moving towards the battery pack. The fan will direct a high-speed turbulent flow of air towards the battery cells.

Material Degradation Testing

Material degradation testing is important due to lengthy battery exposure to mineral oil; therefore, it was conducted to evaluate the long-term effects of mineral oil on different components of an EV battery module (Fig. 5). This type of testing is very important, as the integrity of materials with direct contact with the cooling medium has an impact on safety, efficiency, and durability of the battery system.

The experiment involved submerging a complete battery module, including all its associated wiring and printed circuit boards (PCBs) for one month in mineral oil (100% Paraffin). This setup is designed to simulate the actual

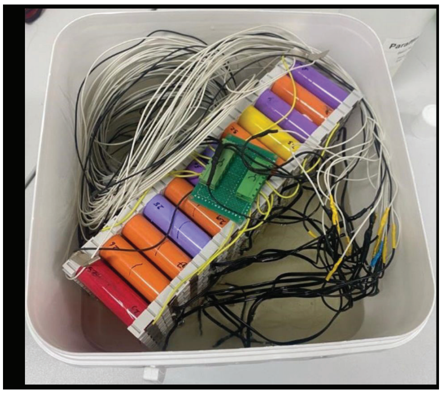


Figure 5. Degradation testing for the battery pack immersed in mineral oil.

conditions under which the battery would operate under a mineral oil environment. Two lithium-ion cells were tested; one covered with a heat shrink and another uncovered cell, to assess the impact of mineral oil on the cell casings. Over one month period, observations and measurements were recorded to detect any signs of material degradation, chemical reactions, or physical alterations to battery cells. It is observed that there are no significant changes in the structure or functionality of the battery module, wiring, PCBs, or the lithium-ion cells, which confirm the compatibility of mineral oil as a cooling medium with the materials being used in the EV battery systems. However, it was observed that the thermal paste used to mount the thermistors to the batteries had loosened when immersed in mineral oil, in which it was suggested that the thermal paste is not suitable to be used with mineral oil, which is likely due to the oil's properties affecting the adhesive quality of the thermal paste. Additionally, mineral oil affects certain types of plastics, specifically polycarbonate (PC) and acrylonitrile butadiene styrene (ABS), which are known for their brittle nature and are not used in battery packs [33]. Furthermore, mineral oil also demonstrated properties that act as a protective insulator for metals while reducing the risk of corrosion. This characteristic adds another layer of benefit for using mineral oil in battery systems, as it could potentially enhance the longevity and reliability of metallic components [34]. In future experimental trials, different placement strategies for the thermistors will be adopted along with the use of an alternative type of thermal glue specifically compatible with mineral oil and its superior adhesive properties under test conditions, which will consequently improve the reliability of temperature measurements.

Battery Testing

The testing methodology was designed to evaluate the efficiency of different cooling methods for an EV battery, using an existing battery module from the HTU Racing Formula Team. This study focused on three cooling cases: no cooling, air cooling, and mineral oil cooling. First, the battery module was placed in a custom-designed container, linked to a BMS (Fig. 6) and interfaced with four Arduino microcontrollers. These controllers were connected to thermistors positioned around the battery module to record temperature data every 30 seconds. Arduino boards were used to facilitate real-time temperature monitoring, which enabled continuous measurement of thermal metrics to assess the performance of the cooling system.

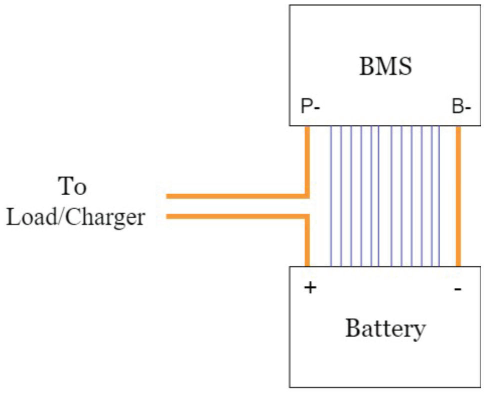


Figure 6. Testing power connection.

Table 4. Charge and Discharge Cycles

Cooling cases	Discharge rate	Charge rate
No cooling	0.5C 1C	0.5C
Air cooling	0.5C 1C	0.5C
Mineral oil cooling	0.5C 1C	0.5C

Data logging was programmed in Python, which not only collected the data from the thermistors but also processed it into a structured format. Then, it was exported to an Excel spreadsheet for further analysis. The testing was structured among three parameters: a discharge rate of 1C (equivalent to 24 Amps), a discharge rate of 0.5C (equivalent to 12 Amps) alongside a charging protocol set at 0.5C (equivalent to 12 Amps). The selected discharge and charge rates were limited to the existing battery load and a more spacious area compared to the lab, where the experiments were conducted, to utilize higher rates of charge. In addition, battery module testing under different thermal loads was conducted. Battery testing cases are presented in table 4 below while focusing on the overall capacity to maintain optimal battery temperatures, enhance battery efficiency, and potentially extend the battery's operational lifespan. In this research the 1C charge rate was not investigated as it is utilized in more intensive EV battery studies, however, it will be considered for future work studies.

Review of Literature Related to Mineral Oil Cooling Used for Lithium-Ion Batteries

A comparison with similar studies involving the use of mineral oil cooling for lithium-ion batteries is presented in this section. Table 5 provides a direct comparison among different studies while considering the temperature delta, type of cells number of cells, and nature of the work. In this study the temperature delta was within 2°C where 18650 Panasonic cell types were used with 96 cells in total. The findings of this study align closely with those of Trimbake et al. [11], Lui et al, [18], and Satyanarayana et al. [19], in which mineral oil demonstrated significant temperature reduction (~18°C in this study, ~15–20°C in their studies).

The temperature uniformity observed in this study was within 2°C that matches findings from the literature. This study tested mineral oil cooling with an operational

Table 5. Summary of research work related to mineral oil cooling for e-vehicle battery pack

Literature	Temperature Delta (ΔT, °C)	Type of cells	Number of Cells
Trimbake et al. [11]	< 1	18650	4 cells
Ya-Chi Ho [35]	>3	18650	1 cell
Satyanarayana et al. [19]	< 2	18650	20 cells
Celen [36]	>5	LiFePO4 Pouch	60 cells
Ya-Chi Ho [37]	>2	18650	1 cell
Lui et al. [18]	>2	18650	4 cells

EV battery module under Jordan climate (28°C–34°C) with full immersion cooling for the battery pack, filling a gap in practical implementation studies. The results also indicate that mineral oil cooling systems not only ensure effective thermal regulation but also maintain material integrity and safety, aligning with the goals of previous literature while expanding its scope. Its consistent performance across both mean temperature and low maximum temperature delta offers promising implications for its utilization in improving battery efficiency, lifespan and safety. Nevertheless, the limited availability of published data and long-term documentation regarding the performance of mineral oil immersion cooling for lithium-ion batteries leads that most battery producers hesitating to adopt these methods in their industry. Furthermore, the scarcity of available data highlights a significant knowledge gap within the industry concerning the environmental requirements for operating an oil immersion cooling method for different applications [38]. Therefore, it is important to investigate further the mineral oil cooling under different environmental conditions and verify that it is a suitable method for thermal management of lithium-ion batteries.

Uncertainty Analysis

There are many variables that have a significant impact on the accuracy of the measurements, such variables include environmental conditions and inadequate calibration [39]. To enhance the accuracy and reliability of the collected data, an uncertainty analysis is conducted using the specifications provided in the manufacturers' datasheets. The stated accuracies for the experimental devices were as follows: ±1°C for the thermistor, and ±3% for the pump. The uncertainty analysis accounted for the experimental equipment used, as well as potential sources of error such as probe positioning, calibration quality, and inherent measurement variability. The uncertainties associated with the main experimental parameters were calculated using Equation (1) [39].

$$U_R = \left[\left(\frac{\partial R}{\partial X_1} U_1 \right)^2 + \left(\frac{\partial R}{\partial X_2} U_2 \right)^2 + \left(\frac{\partial R}{\partial X_3} U_3 \right)^2 + \ldots\ldots + \left(\frac{\partial R}{\partial X_n} U_n \right)^2 \right]^{\frac{1}{2}} \quad (1)$$

R denotes to the dependent experimental parameter, and U_R represent its associated uncertainty. The independent experimental parameters are denoted as X_1, X_2, X_3,…, X_n, with their respective uncertainties given by U_1, U_2, U_3,…, U_n. Therefore, it is very important to ensure that all devices and sensors are well calibrated prior to experimental work in order to minimize systematic errors.

RESULTS AND DISCUSSION

Electrical Study Results: Discharge Behavior

Depth of discharge (DOD) was investigated as part of an electrical study at two discharge rates (e.g., 0.5C and 1C) among three cooling cases as presented in Figure 7 below, which will help to study the effect of different cooling methods towards battery discharge capacity. DOD is defined as a percentage of the discharge capacity relative to the maximum available capacity of the battery cell [40], in which a higher DoD means a larger amount of capacity being discharged. For EV vehicles a higher capacity is desirable, as it means a larger range for the vehicle driven.

It is observed that the BMS cutoff voltage (ca. 39V) allows the battery to discharge at a capacity of around 65 % (Fig.7), though this capacity varies depending on thermal and electrical control. The initial voltage was found to drop significantly at higher discharge rates. The air-cooling method reduces the voltage drop for the two discharge rates (i.e., 0.5C and 1C). At a 0.5C discharge rate, mineral oil cooling maintains a consistent slope throughout the discharge process, achieving a higher depth of discharge (DoD) compared to the no-cooling case. At a 1C discharge rate, the cells cut off with a slightly higher DoD, indicating that the internal resistance of the cells (likely due to increased heat generation) is deviating more. This is expected, as all cells experience an increase in internal resistance under high-power discharge conditions. Table 6 below summarizes the depth of discharge (DoD) for the two discharge rates, in which the DoD varies slightly with C-rate and thermal mitigation. This comparison helps to study the effect of different cooling methods along with discharge rates on the capacity consumption of the cells. These results are best interpreted with the temperature

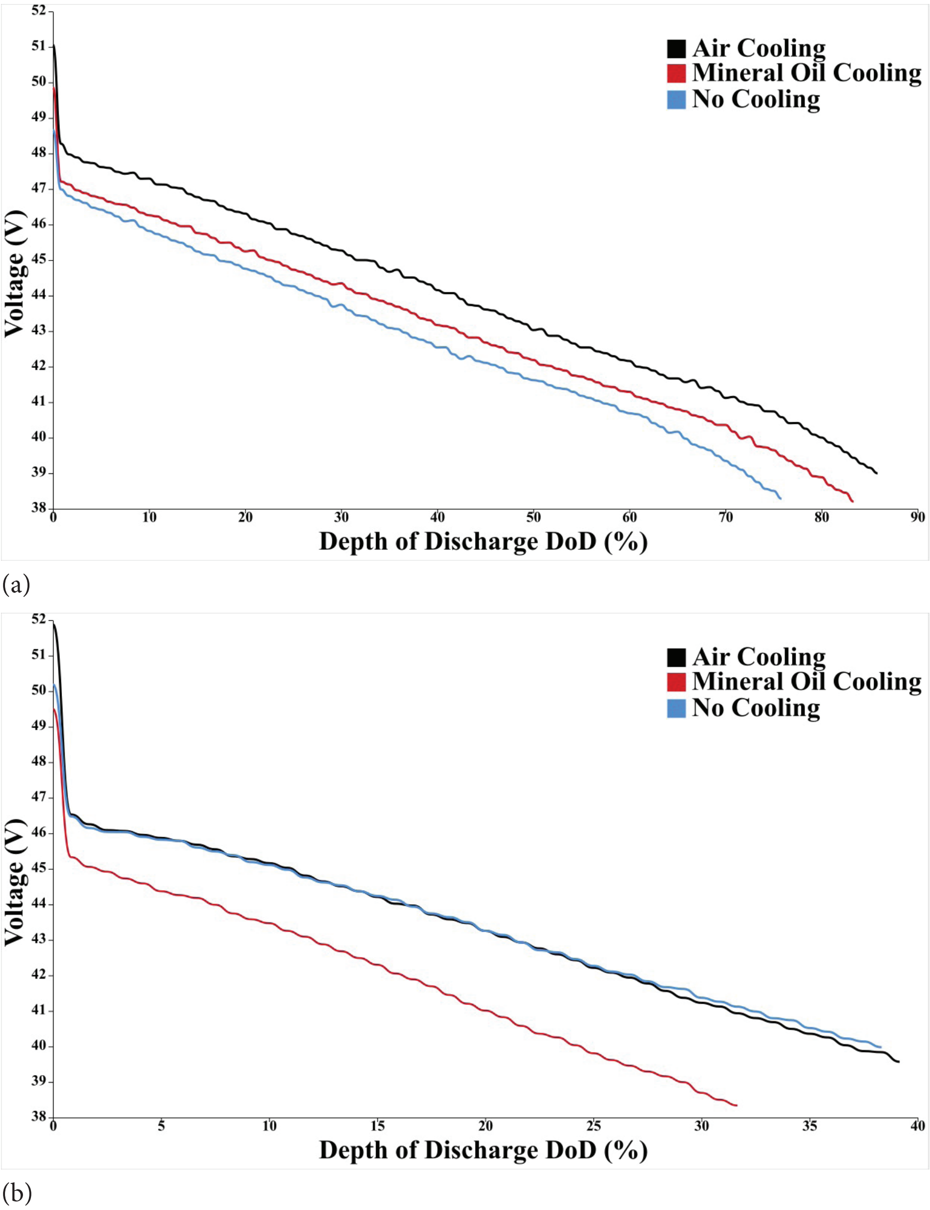


Figure 7. Depth of Discharge (DoD) of the battery pack among different cooling methods, with discharge rates of (a) 0.5C, and (b)1C.

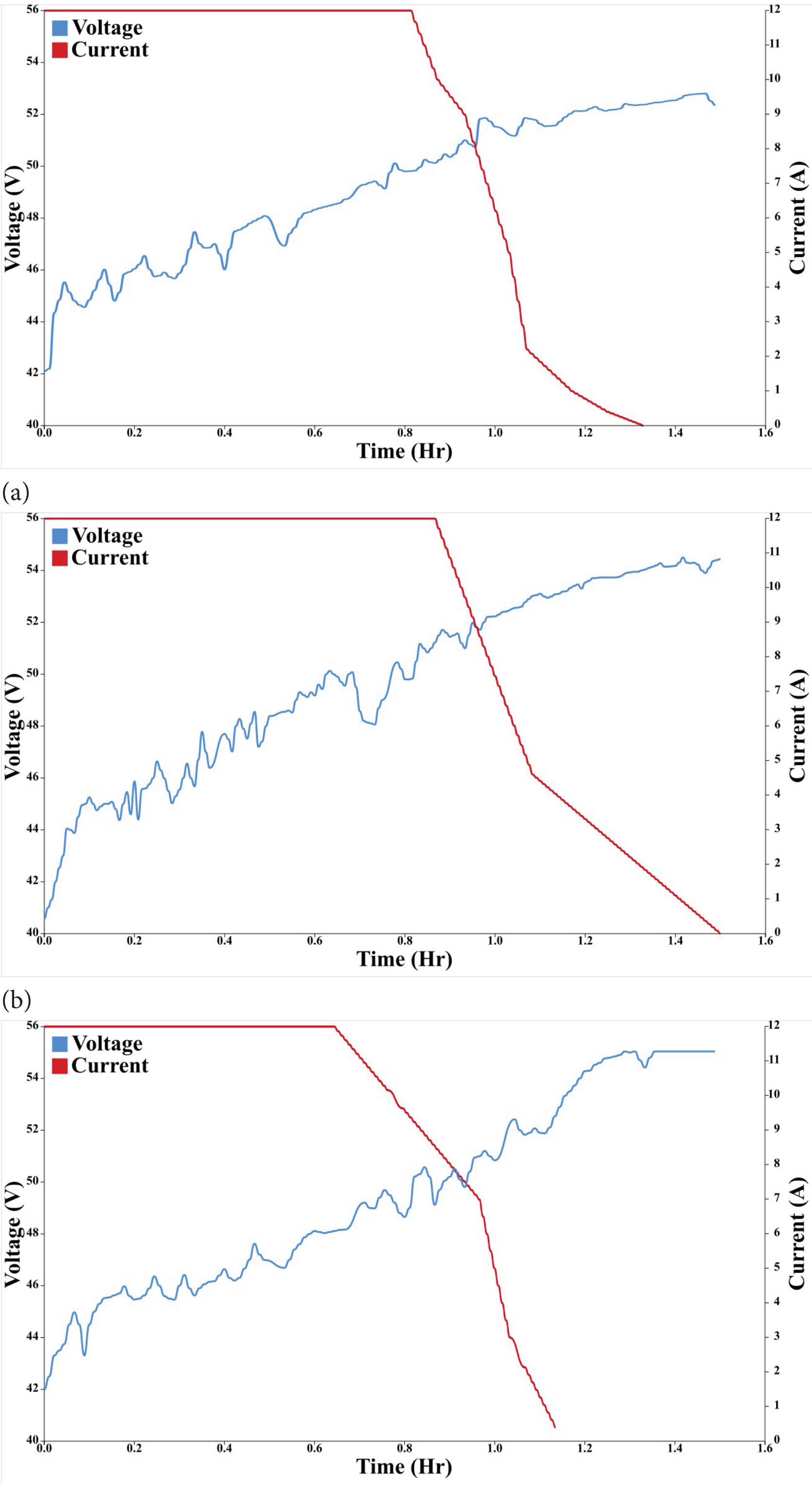
Table 6. Depth of discharge (DOD) for discharge cycles

Depth of discharge by cooling method (100%)			
Discharge current	**No cooling**	**Air cooling**	**Mineral oil cooling**
0.5C	63.6%	73.3%	69.8%
1C	65.3%	67.6%	53.6*%

delta graphs (please check Figures. 9,10, and 11) in the thermal study section below, as they show the effect of heating which changes the battery electrical behavior. As an example, of mineral oil cooling, battery cells achieve a high DoD at 0.5C discharge rate compared to 1C. Therefore, in order to effectively interpret the noted value of 53.6 %, further investigations with a programmable cut-off BMS are required. The BMS used for this study had a relatively high cut-off voltage. Future work will include a suitable cut-off value in the 32-34 V range.

Electrical Study Results: Charge Behavior

The charging method selected in this study is the constant current-constant voltage (CC-CV) method because it allows maximum capacity utilization and ends charging with a stable terminal voltage for the battery pack. This method is divided into two stages as follows:



(a)

(b)

(c)

Figure 8. The electrical behavior of the battery pack during charge at 0.5C, showing CV and CC phases among different cooling cases (a) No cooling (b) Air cooling (c) Oil cooling.

Stage 1: Bulk Charging (Constant Current CC). The current is kept constant at a level usually equal or lower than 1C, while the voltage level rises to the float voltage.

Stage 2: Float Charging (Constant Voltage CV). Once the voltage reaches the pack's maximum voltage, the charger stabilizes at a slightly higher voltage called the float voltage. In this phase, the current organically decreases as the state of charge (SoC) of the cells reaches 100%.

Figure 8 presents different charge cycles among the three cooling cases, with cycle duration varying for each case. This variation is likely due to thermal regulation, which enhances the cells' ability to discharge and charge. Charging for both the no cooling and oil cooling cases was completed in less than 1 hour, with the oil-cooling case reaching a higher float voltage. This indicates that more capacity was charged within the same timeframe. The air-cooling case took 1.2 hours to complete, demonstrating superior performance compared to the no cooling case in terms of charge and discharge capacity. It was observed that stage 1 ended at around 70% SoC, while Stage 2 continued until the end of the charging process. The pulsing in voltage levels is attributed to the charger's properties, which cause oscillations until the desired float voltage is reached, after which the voltage stabilizes.

Thermal Study Results: 0.5C Discharge

The data obtained from the thermal investigation of electric vehicle (EV) battery cooling methods during a 0.5C discharge cycle illustrates distinct temperature management capabilities of no cooling, air cooling, and mineral oil cooling systems. While analyzing the mean temperature and the maximum temperature delta graphs, a notable difference in performance was observed among different cooling methods under constrained testing conditions. As an example, in Figure 9, the mean temperature reveals distinct trajectories for the three cooling cases. With no cooling, the temperature steadily rises, highlighting a lack of heat mitigation. For air cooling it does not stabilize effectively compared to mineral oil cooling. Despite starting at a higher initial temperature due to elevated ambient conditions, overall mineral oil cooling consistently maintains the lowest and had the most stable mean temperature throughout the testing, which suggests its superior capability in heat absorption and dissipation. The main reason why the experimental runs have different initial temperatures is due to the test area being affected by the ambient temperature because experiments were conducted on different times of the day, which will be eliminated in future experimental runs.

For the maximum temperature delta presented in Figure 10, different variations in the peak temperatures relative to initial values were observed. For no cooling case, a sharp rise was observed that causes a potential risk for thermal runaway. On the other hand, air cooling showed an improved behavior but allows for a considerable temperature increase. Mineral oil cooling demonstrated the smallest increase in the maximum temperature delta while starting from a higher baseline due to the surrounding ambient conditions. This confirms its effectiveness in managing heat under less-than-ideal initial conditions, further proving its robustness as a thermal regulation mechanism.

Thermal Study Results: 1C Discharge

For the 1C discharge rate, it is observed that the temperature rises sharply for the no cooling scenario as presented in Figure 11, emphasizing the inadequacy of passive thermal management under intense discharge conditions. The rapid temperature increase from the initial state could potentially lead to thermal runaway. In contrast, the air-cooling

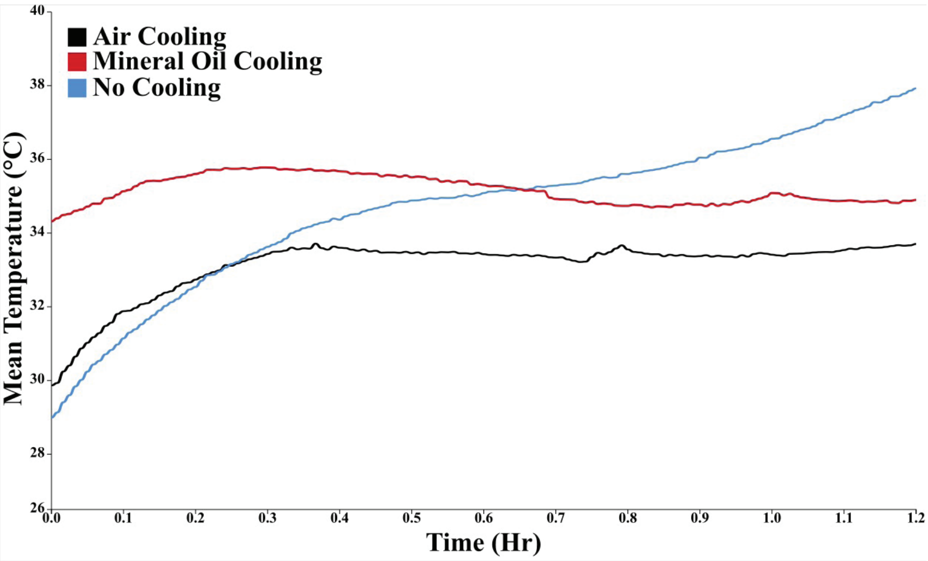


Figure 9. The mean temperature across the cells at 0.5C discharge rate for three cooling cases.

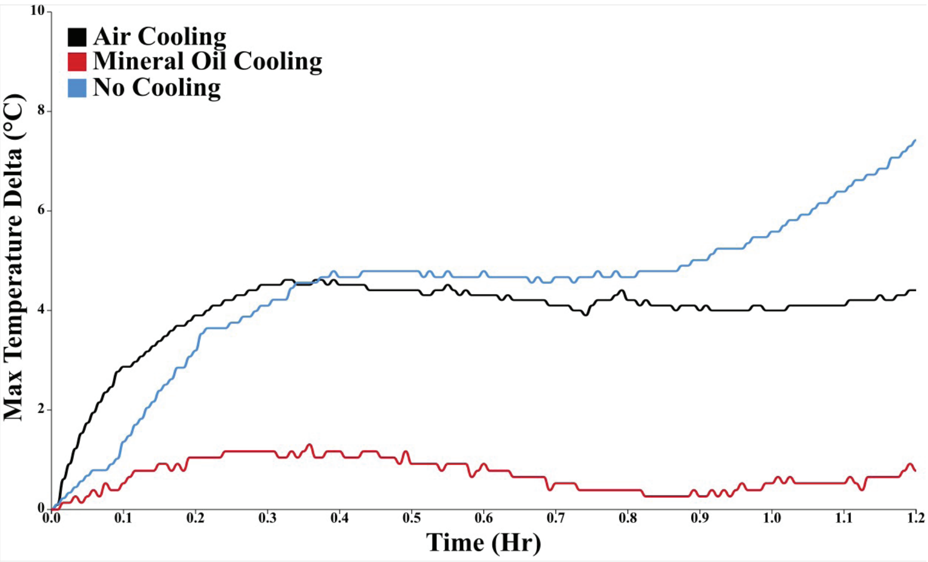


Figure 10. The maximum temperature delta at 0.5C discharge rate among three cooling cases.

case moderates the temperature rise but fails to stabilize after the initial period, indicating that while it can dissipate heat, it is insufficient to manage the sustained thermal output under 1C discharge rate. For mineral oil cooling, the temperature remains stable and low throughout the cycle compared to no cooling case. Maintaining thermal stability is crucial for the battery, as it helps to prevent excessive thermal stress that could degrade battery components and reduce performance.

These experiments were conducted using a suboptimal heat exchanger in a confined space, which may have hindered heat dissipation and led to higher ambient temperatures. Furthermore, the proximity of resistor loads to the pump contributed to localized heat generation, potentially worsening ambient conditions within the cooling system operation. Despite these limitations, the performance of mineral oil cooling compared to other methods highlights its potential effectiveness in real-world applications.

Thermal Study Results: 0.5C Charge

The thermal performance of different cooling methods at 0.5C charge rate for EV battery packs is presented in Figure 12 for the maximum temperature delta, such data is important to select the proper cooling method that can impact battery efficiency and lifespan during the charging cycle.

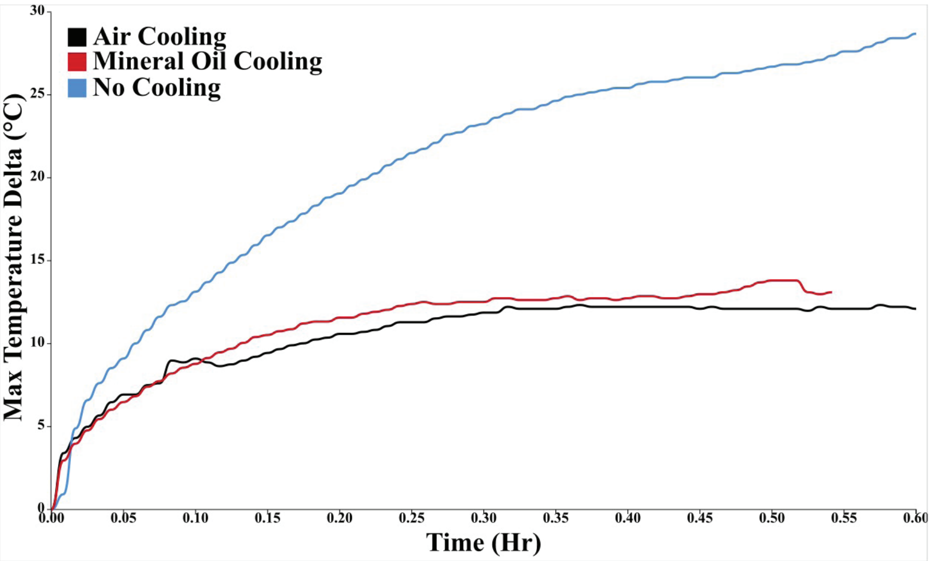


Figure 11. The maximum temperature delta at 1C discharge rate among three cooling cases.

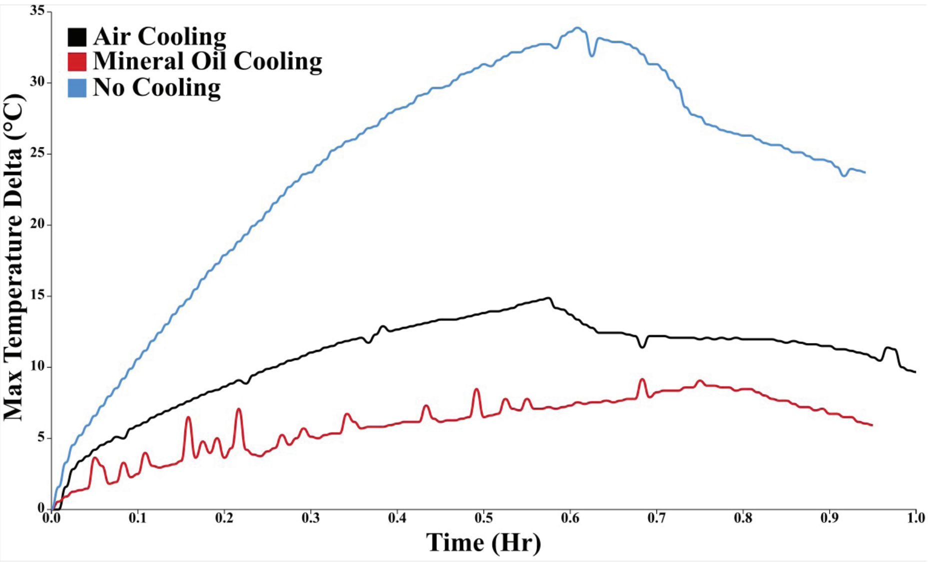


Figure 12. The max temperature delta at 0.5C charge rate among three cooling cases.

From Figure 12, the no cooling case shows a drastic increase in the maximum temperature delta, highlighting the high thermal risk associated with unmanaged charging. On the other hand, air cooling cases show a lower temperature rise, yet it plateaus at a moderate level, which indicates some heat accumulation. For mineral oil cooling, it maintains the lowest and most consistent maximum temperature delta, affirming its effectiveness in minimizing temperature fluctuations that can accelerate battery degradation.

CONCLUSION

This study integrated mineral oil cooling system into an operational EV battery module under real-world climatic conditions, demonstrating its feasibility in addressing thermal challenges. Unlike prior studies that focused on partial immersion cooling experiments or controlled laboratory environments, this research provides practical insights on the performance and material compatibility of full immersion cooling systems. The use of mineral oil for lithium-ion batteries has attracted significant interest among many researchers globally; however, most investigations remain exploratory, involving experimental approaches. Mineral oil has high thermal capacity and effective heat transfer characteristics, which make it an exceptionally viable solution for thermal management in EV batteries. Its ability to maintain battery efficiency and safety across varying environmental conditions, particularly under high discharge rates, offers a notable advantage. In this study the temperature delta for mineral oil cooling method was within 2°C, which is consistent with previous observations found in the literature. Notably, at a 1C discharge rate, the mineral oil cooling method achieved a lower depth of discharge (DoD) (53.6%) compared to air cooling (67.6%). This suggests that mineral oil cooling helps to conserve battery capacity and mitigates the buildup of internal resistance.

For future work, it is recommended to conduct lithium-ion battery testing under Jordanian winter conditions and under telemetry monitoring to further investigate the impact of ambient temperature on mineral oil characteristics and to optimize cooling solutions for diverse environmental conditions. A comprehensive thermal analysis comparing air and mineral oil cooling will be performed, incorporating heat dissipation and energy consumption calculations to theoretically validate the experimental results. Additionally, expanding the study to include a wider range of C-rates, which would require the use of industrial resistors capable of handling the specified high discharge rates.

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AUTHORSHIP CONTRIBUTIONS

Conceptualization, Methodology, Supervision, Writing – Original and review draft Preparation: [Alzaben.H], Formal Analysis and Investigation, Writing – Review and Editing, Experimentation, Resources: [Faddah, T, AlSawair, A].

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that supports the finding of this study are available from the corresponding author, upon request.

CONFLICT OF INTEREST

Authors declare no conflicts of interest in this article.

ETHICS

There are no ethical issues with the publication of this article.

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STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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