

Research Paper

Experimental Analysis of a Hybrid-Configured Battery Thermal Management System Using Paraffin Oil and Fan

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Abstract

The study investigates the effectiveness of a Battery Thermal Management System (BTMS) using a hybrid configuration of paraffin oil and fan cooling. The research employs a comparative test method to evaluate the BTMS's potential in managing the thermal conditions of lithium-ion batteries, commonly used in electric vehicles. The study is conducted under three configurations: hybrid cooling with paraffin oil and fan, passive cooling with paraffin oil, and no cooling system. The ambient and liquid temperatures are measured, alongside battery voltage changes over a 60-minute period. The results indicate that the hybrid cooling system effectively maintains lower battery temperatures compared to passive and no cooling systems. Specifically, the hybrid system achieves an average ambient temperature of 33.344 °C and a paraffin oil temperature of 32.982 °C, demonstrating its superior cooling capability. The study concludes that the hybrid BTMS can significantly enhance battery performance and longevity by maintaining optimal temperature conditions, thus offering a viable solution for improving the efficiency and safety of electric vehicle batteries. This research has implications for the development of more effective thermal management systems in electric vehicles, potentially leading to increased adoption and improved sustainability in the automotive industry.

Keywords: Battery; Paraffin oil; Temperature; Cooling

1. Introduction

The development of technology in the automotive sector has experienced very rapid development, where in previous technology the focus was on developing conventional internal combustion engine systems. However, the disadvantage of internal combustion engines (ICE) is that they produce air pollution from exhaust emissions [1]. To address existing challenges and reduce petroleum fuel consumption, electric vehicles are regarded as an environmentally friendly technology of the future. Research and development of electric vehicles (EVs) is ongoing worldwide [2], [3].

Electric vehicles use batteries as their primary energy storage. However, batteries in electric vehicles currently on the market still have a much lower energy capacity than petroleum fuels. The production cost of electric vehicles may be almost half the price of the battery. Therefore, increasing the capacity and service life of battery cells while avoiding fatal damage or at least increasing their operational efficiency is something that needs to be developed [4].

The transportation sector and greenhouse gas effects produce 28% of emissions in the United States. One important effort to reduce emissions is to use zero-emission transportation [5]. Electric



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vehicles (EVs) can be an option to overcome these problems. Electric vehicles require batteries as energy storage for their propulsion. Lithium-ion (Li-ion) batteries are the main choice because they are superior to other types of batteries. So that it is possible to be distributed commercially to consumers to use electric vehicles [6]. But Li-ion batteries are very sensitive to temperature, and damage and loss of battery capacity occurs when heat exceeds the standard limits of the battery's capacity [7]. Research on thermal management systems is essential to develop electric vehicles that are acceptable to the public. In recent years, there has been a lot of improvement in electric vehicles, plug-in hybrid electric vehicles (PHEVs), and hybrid electric vehicles (HEVs) are types of vehicles that have developed rapidly. This type of vehicle consists of hundreds to thousands of battery cells connected in parallel and series [8]. Battery packs for electric vehicles usually have a fantastic price of up to 10,000 USD. Because it has a high price, its security and strength should be more reliable. The low self-discharge rate of Li-ion batteries has many benefits, such as specific voltage and high power density so that it can allow for more mileage for long trips and high acceleration increases [9]. Lithium-ion batteries also have a light weight so that it is possible to get the efficiency of the electric vehicle weight to be not too heavy which has an impact on the full speed not being reduced due to the weight of the battery. The safety problem of lithium-ion batteries is when the release of energy can produce heat which is fatal if no precautions are taken [10], [11].

As in electric vehicle types such as PHEVs and HEVs, the complexity of power distribution between ICE and the electric motor necessitates the implementation of precise control strategies to ensure efficient energy utilization and to prolong battery lifespan under diverse operating conditions. Research in the optimization of Energy Management Strategies (EMS) has demonstrated promising potential in dynamically adjusting power distribution to minimize fuel consumption and reduce battery degradation. However, the effectiveness of such strategies heavily relies on accurate thermal data and the battery's State of Health (SoH), both of which are significantly influenced by the efficiency of the vehicle's Battery Thermal Management System

(BTMS). Therefore, the development of an efficient hybrid-configured BTMS, as investigated in this study using paraffin oil and a fan, provides essential empirical data and a validation framework for optimizing battery usage in electric vehicles.

Battery temperature affects the availability of discharge power and the battery life. To achieve optimal performance in all climates, a BTMS is essential. The operating temperature range of batteries varies for different chemistries, but generally LIB pack manufacturers maintain an operating temperature range of 20-40 °C [12]. In addition, it is recommended that the temperature of the LIB cell does not exceed 60 °C which will result in a decrease in the efficiency of the battery's capacity. The Battery Thermal Management System (BTMS) aims to maintain the battery at an ideal temperature range with a uniform temperature distribution [13]. In addition, the BTMS used must be light, simple, and able to operate in various weather conditions and it is recommended to have ventilation to avoid the release of hot air or dangerous gases from the battery [14], [15]. Because it has a relatively high energy density and power storage and fast charging time. Lithium-ion batteries are the main choice among electric vehicle manufacturers. The success of (EVs) electric vehicles using this type of battery, it is very likely to show that lithium-ion batteries can be an alternative solution to energy storage problems, lower weight and energy storage than other types of batteries [16].

Therefore, to maintain a safe battery when operating, the ideal temperature is very important to maintain. Maintaining the ideal temperature can also maintain battery performance and extend the life and service life of the battery. The operating temperature of lithium-ion batteries usually has a temperature range between 20 °C to 40 °C. BTMS usually uses an assisted cooling method to maintain this temperature range. For example, liquid cooling systems, air cooling, and phase change material (PCM) [17].

A common problem with lithium-ion batteries is that they can develop heat during operation, which is a serious safety issue that can lead to explosions and fires in electric vehicles [18]. Therefore, the Battery Thermal Management System (BTMS) is a solution for designing a good and efficient cooling system for the development

of electric vehicle batteries [19], [20]. BTMS can be classified into active and passive systems depending on their control strategy. In the active method, equipment that can consume more power is needed to actively control the cooling rate. One example of an active BTMS is the fluid flow or liquid of a cooling system that is regulated through a pipe flow assisted by a pump and forced air flow through an active fan [21]. In contrast, passive systems do not require power-consuming equipment and do not require a control system that can change the cooling rate. But through natural air convection such as heat pipes, and PCM [22]. Each BTMS has its own advantages and disadvantages. In general, passive methods have a higher level of energy efficiency. While active methods will be more controlled and have a much better cooling rate. Therefore, active and passive methods can be utilized for much better thermal battery management. Hybrid battery thermal management systems are a perfect combination because they combine passive and active cooling systems [23], [24].

Because it is more efficient in cooling system, liquid cooling is one of the most common BTMS used in electric vehicles. Until now, a number of electric vehicles currently on the market have liquid cooling systems [25], [26]. Including the Tesla Model S and Model 3, Chevrolet Volt, Chevrolet Bolt, and Audi e-Tron. Some types of fluids that can be used for direct battery cooling or even immersed in the liquid are dielectric fluid, mineral oil, silicone-based oil, or deionized water [27]. Due to safety issues selecting the right coolant may be difficult and the direct liquid cooling method has not been widely used in real applications for electric vehicles [28]. Many researchers have combined other cooling methods with PCM-based BTMS to improve the cycling capability and stability of PCM-based BTMS, especially in extreme environments. The results show that the temperature profile and battery parameters of PCM-based hybrid BTMS are much better than other batteries, which can also reduce the temperature rise and temperature difference. Future research will focus on the development of a combination of active battery thermal management system and passive battery thermal management system in hybrid BTMS [29], [30].

Three types of battery thermal management systems are air-cooled, liquid-cooled, and PCM. Selecting PCM material is important to make an effective battery thermal management system (BTMS), although such PCM-based cooling systems can reduce the temperature and maintain small temperature variations, but it is very difficult to find the right heat-absorbing material [31]. Paraffin oil or often known as mineral oil or white oil is one type of PCM made from organic materials. Usually has a low melting point and is most suitable for storing heat in residential and office buildings with a maximum temperature of around 40 °C [32].

Solid and liquid paraffin have been widely used as PCM for thermal storage. The material is non-reactive or reacts with other substances, is non-corrosive, odorless, non-toxic, and has a relatively low price. So it is very suitable if applied in the electronics and electric vehicle (EVs) fields in the automotive industry [33]. It has been found that the combination of carbon fiber and paraffin can significantly improve the thermal conductivity of the cooling medium. Therefore, PCM using carbon fiber can be a very good choice for managing the thermal conductivity of battery cells. The results show that carbon fiber has the ability to effectively improve the thermal conductivity of PCM, which has an impact on the temperature distribution of the battery [34]. PCM composites with higher carbon fiber percentages improve temperature uniformity. Evaluation of the effect of carbon fiber loading on the thermal conductivity of inorganic PCMs is enhanced. It shows that the degree of uniformity of PCM composites and carbon fiber composites is very important to improve heat absorption [35].

2. Material and Methods

2.1. Vehicle Specification

The hybrid Battery Thermal Management system (BTMS) in this study has the following components: paraffin oil, BMS 3S5P, 2-leg switch, volt ampere meter and volt percentage, lamp and dynamo, DHT11 sensor and DS18B20 sensor, breadboard, arduino UNO R3, SPDT relay 5 V, fan, laptop. The BTMS configuration consists of 21 bracket slots, including 15 18650 lithium-ion batteries, 5 paraffin-filled tubes, and 1 slot for a DHT11 sensor (**Figure 1**). Designed in SolidWorks, the hybrid BTMS utilizes carbon kevlar and resin

coolant tubes shaped to fit the batteries. The finalized design enhances convection heat transfer through carbon's properties, as shown in [Figure 2](#).

This study uses INR18650 lithium-ion batteries (3.7 V, 2200 mAh) assembled in a 3-series, 5-parallel configuration to achieve a 12 V, 11 Ah target. Battery specifications are detailed in [Table 1](#). Paraffin oil, a non-reactive and non-toxic heat absorber, is specified in [Table 2](#). It is stored in cylindrical tubes matching the 18650 battery size (18 mm diameter, 65 mm height). Two sensors were utilized to monitor temperature during the experiment: the DHT11 and DS18B20. The DHT11, positioned in an empty slot, monitored the ambient temperature around the battery and activated the fan when the temperature reached 35 °C, keeping it active until the temperature dropped below 35 °C. The DS18B20, immersed in paraffin oil, monitored heat absorption and provided digital, liquid-resistant outputs. Both sensors were connected to an Arduino UNO, which transmitted the recorded data to a PC for logging and visualization using LabView. The data was saved in Excel, presented as graphs, and analyzed to draw conclusions.

The research method employed in this study is a comparative test involving three different configurations: a BTMS utilizing hybrid cooling with paraffin oil and a fan, a BTMS with passive cooling using only paraffin oil, and a system without any cooling. Measurements focused on the ambient temperature around the battery and the temperature of the cooling liquid. Additionally, battery voltage was recorded every 15 minutes over a 60-minute loading period to analyze voltage drop. This study specifically

examined lithium-ion batteries commonly used in electric vehicles, excluding other battery types. During testing, room temperatures ranged between 28 °C and 30 °C. The research evaluates the performance of the Battery Thermal Management System (BTMS), which integrates cylindrical tubes filled with paraffin oil and a fan as core components in the hybrid cooling system.

Table 1. Paraffin oil specifications

Parameter	Value
Viscosity	Higher
Density	0.830 – 0.860 g/ml
Flash Point	> 200 °C

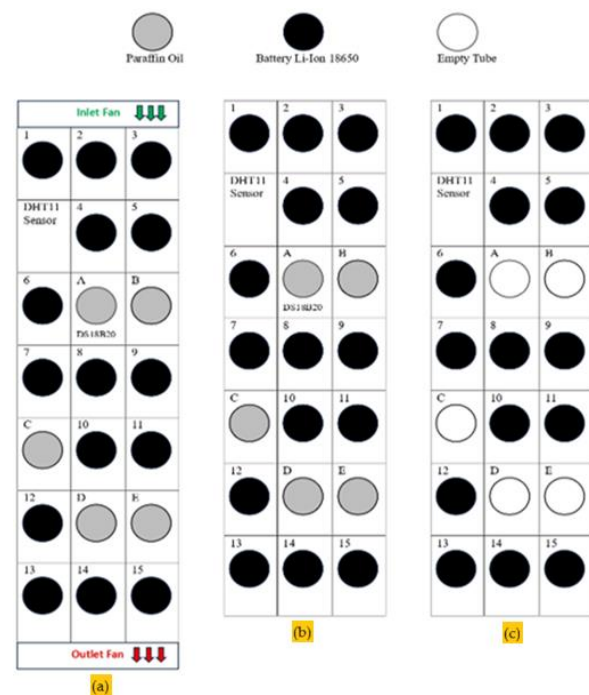


Figure 1. Hybrid BTMS configurations: (a) hybrid cooling; (b) passive cooling; and (c) no cooling

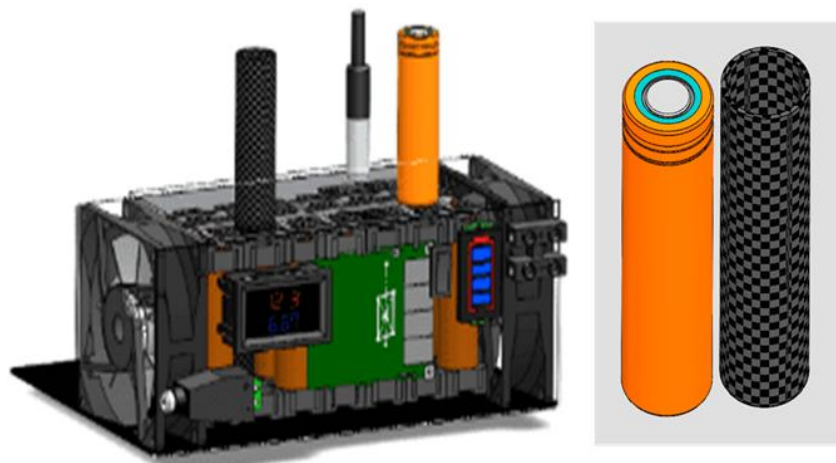


Figure 2. Hybrid BTMS design and liquid tube design

Table 2. Battery voltage without cooling system

Testing	Testing time (minutes)	Initial voltage (V)	Final voltage (V)
1	60	12.3	10.3
2	60	12.3	9.9
3	60	12.1	10.1

3. Results and Discussion

In this study, the cooling system test includes the ambient temperature of the battery and the coolant which are tested in real-time. Data collection was carried out in three stages, the first is testing without liquid and fan. After that, the second stage is testing BTMS using paraffin oil liquid and the third stage is testing BTMS using paraffin oil liquid and fan. Then in each stage, three repetitions of the test were carried out, with a 12 V battery specification and a load of 4.04 A for 60 minutes.

3.1. Battery Testing without Cooling System

In the first stage, data collection for battery testing without using a cooling system was carried out for 60 minutes without liquid and without a fan in order to obtain the ambient temperature of the battery without a cooling system and the results obtained for 60 minutes.

From [Table 2](#) and [Table 3](#), the first stage of testing revealed a decrease in battery voltage across three tests. In Test 1, the voltage dropped from 12.3 V to 10.3 V, with a peak temperature of 39 °C and an average temperature of 35.291 °C, as shown in [Figure 3a](#). In Test 2, the voltage decreased from 12.3 V to 9.9 V, with the highest temperature reaching 39.5 °C and an average temperature of 36.590 °C ([Figure 3b](#)). Finally, in Test 3, the voltage dropped from 12.1 V to 10.1 V, with a peak temperature of 39 °C and an average temperature of 34.665 °C ([Figure 3c](#)).

3.2. Passive Cooling Battery Testing (Paraffin Oil)

Then, in the second stage, a passively cooled BTMS was tested using paraffin oil coolant for 60 minutes three times, with the aim of determining

the effectiveness of paraffin oil in absorbing heat in the battery. The passive cooling system testing yielded the following results. In the first test stage, over 60 minutes, the voltage dropped from 11.5 V to 7.1 V. The highest temperature absorbed by the paraffin oil was 34.5 °C, with an average of 31.99 °C. The highest ambient temperature in the first repetition was 38.0 °C, with an average of 33.89 °C ([Figure 4a](#)). In the second test stage, voltage decreased from 12.3 V to 10.2 V, with the highest temperature absorbed by the paraffin oil reaching 36 °C and an average of 33.79 °C. The highest ambient temperature in the second repetition was 39.5 °C, with an average of 34.93 °C ([Figure 4b](#)). In the third test stage, voltage dropped from 12.5 V to 10.2 V, the highest temperature absorbed by the paraffin oil was 34 °C, with an average of 31.41 °C. The highest ambient temperature in the final repetition was 38.5 °C, with an average of 34.16 °C ([Figure 4c](#)).

3.3. Hybrid Cooling Battery Testing (Paraffin Oil and Fan)

In the 3rd stage, the battery was tested using a hybrid paraffin oil and fan cooling system for 60 minutes, which aimed to determine the effectiveness of the hybrid cooling system in absorbing heat and maintaining the temperature in the battery pack. The hybrid cooling system testing yielded the following results. In the first test of stage 3, with a hybrid paraffin oil and fan cooling system, the battery voltage dropped from 12.4 V to 6.8 V, with the highest battery temperature reaching 35.2 °C and an average of 33.37 °C. The highest paraffin oil temperature was 34.5 °C with an average of 32.95 °C, as shown in [Figure 5a](#). In the second test of stage 3, the battery was tested for 60 minutes to assess the cooling

Table 3. Descriptive statistics without cooling system

	N	Minimum	Maximum	Mean	Std. Deviation
Temperature Ambience 1	3463	31.8	39.0	35.291	2.8575
Temperature Ambience 2	3590	33.8	39.5	36.590	2.4287
Temperature Ambience 3	3601	30.8	39.0	34.665	3.2263
Valid N	3463				
Mean				35.515	

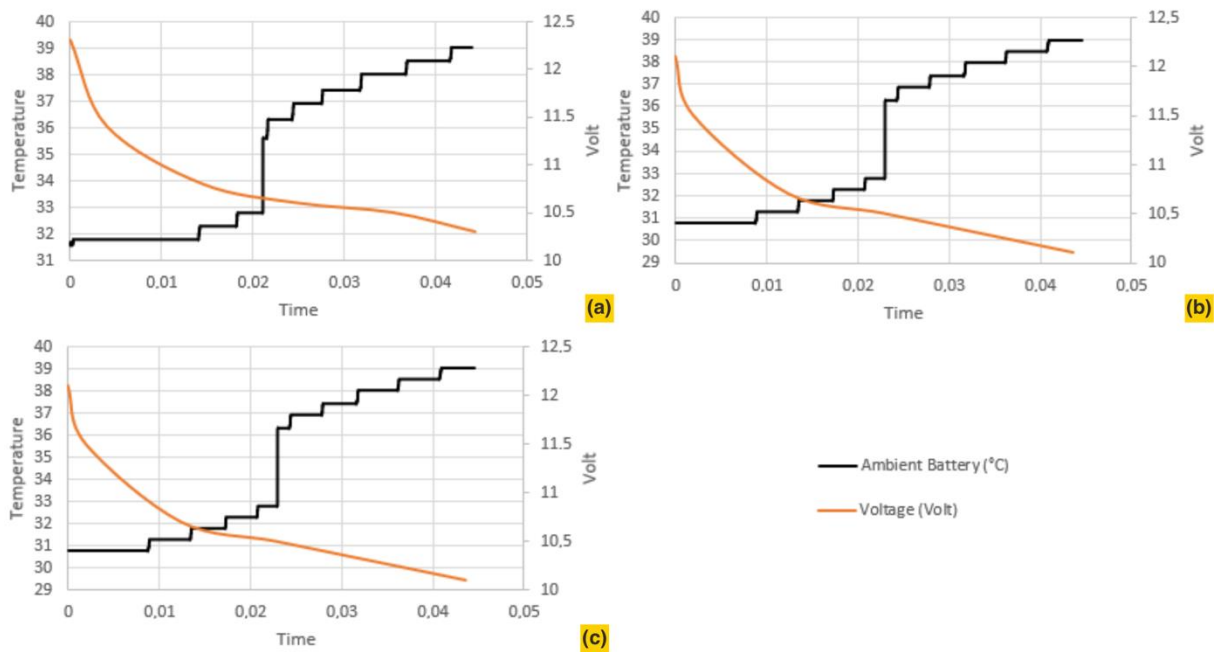


Figure 3. Battery test result without cooling system: (a) first test; (b) second test; (c) third test

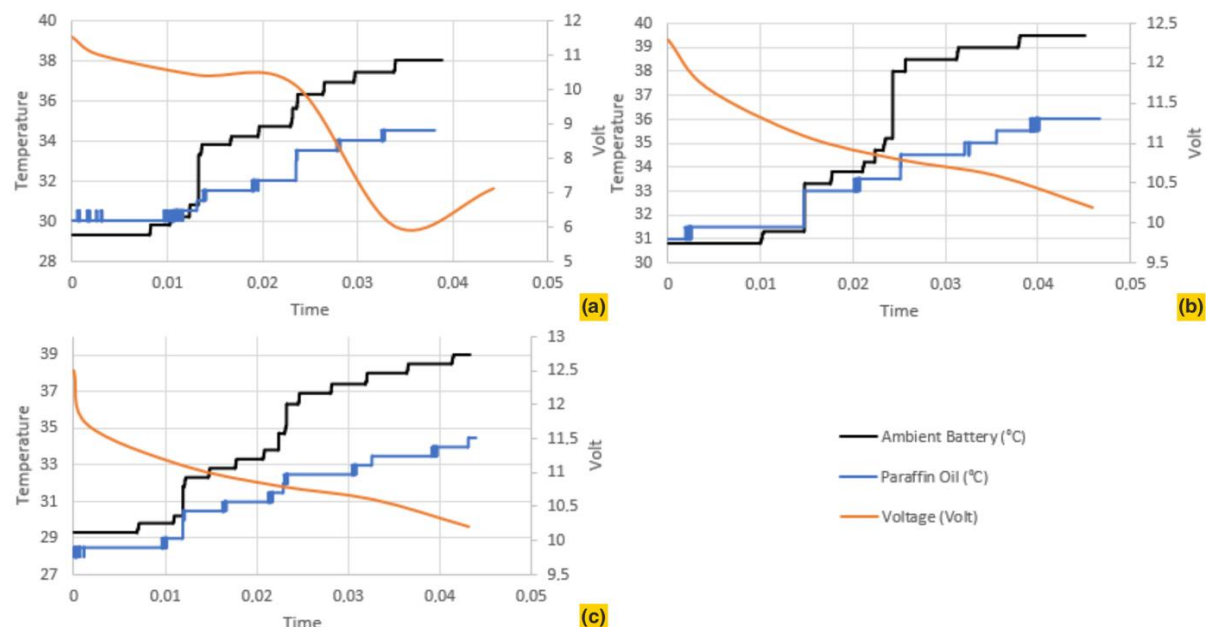


Figure 4. Passive cooling battery test results (paraffin oil): (a) first test; (b) second test; (c) third test

system's effectiveness in absorbing heat and maintaining battery temperature. The voltage dropped from 12.3 V to 6.9 V, with the highest battery temperature at 35.2 °C and an average of 33.62 °C. The highest paraffin oil temperature was 35.0 °C with an average of 33.3 °C, as shown in Figure 5b. In the third test of stage 3, the battery voltage dropped from 12.3 V to 6.6 V, with the highest battery temperature at 35.2 °C and an average of 33.05 °C. The highest paraffin oil temperature reached 35.5 °C with an average of 32.69 °C, as shown in Figure 5c.

The experimental results indicate that this hybrid battery thermal management system (BTMS) effectively maintains the battery's maximum temperature at 35 °C during normal operation cycles. This represents a significant improvement compared to non-cooled systems (39.5 °C) and passive systems (38.5 °C). The temperature gradient among cells is kept within a narrow range of 3–4 °C, which is below the recommended safety threshold of 5 °C for lithium-ion battery packs. This uniform temperature distribution contributes to balanced cell performance

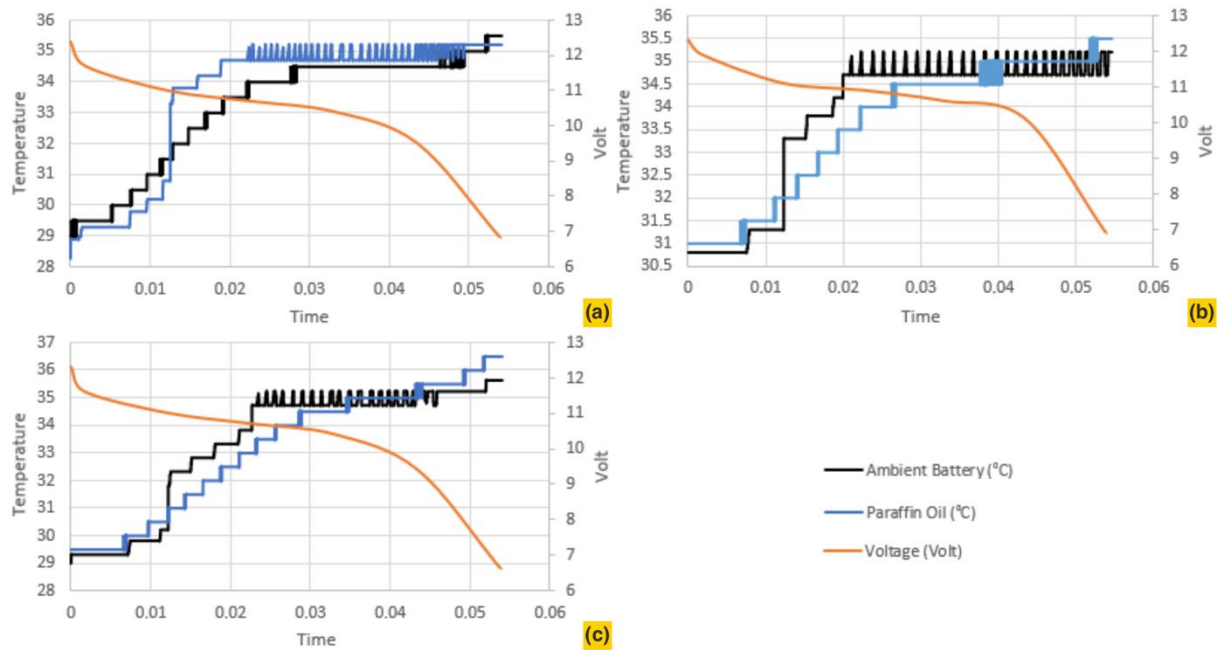


Figure 5. Hybrid cooling battery test results (paraffin oil and fan): (a) first test; (b) second test; (c) third test

and extended battery cycle life, while consuming relatively less energy than conventional active cooling systems.

For comparison, IoT-integrated BTMS in solar-powered electric vehicles employ active air- or liquid-based cooling, partially powered by solar panels to reduce the load on the main battery. Such systems have demonstrated lower battery temperatures ranging from 29.5 °C to 31.75 °C during testing cycles. These systems report up to a 25% reduction in BTMS power draw from the main battery, although cooling performance improves by only 5–7 °C compared to uncooled conditions. These findings highlight potential energy efficiency benefits but also underscore limitations in cooling effectiveness due to dependence on solar availability [36].

The most significant thermal performance improvements were observed in a study on serpentine-channel liquid cooling systems with modified flow branching to enhance flow distribution and heat transfer. This design modification improved flow uniformity and reduced stagnation zones (dead zones), achieving a maximum battery temperature reduction of approximately 11.32 °C compared to conventional designs. However, this enhancement came at the cost of an ~18% increase in pumping power relative to standard systems, leading to higher cooling system energy consumption. This finding illustrates the need for channel design

optimization that balances thermal performance with additional energy demands for coolant circulation [37].

In practical implementation, our hybrid BTMS offers a highly accessible solution for electric vehicle applications, where cost, space, and weight are critical constraints. The system demonstrates excellent energy efficiency by leveraging paraffin oil's ability to absorb heat passively, thereby reducing reliance on active cooling. The hybrid configuration requires only intermittent or low-speed fan operation to assist in heat dissipation from the saturated phase change material (PCM), resulting in significantly lower energy consumption than other active systems. This energy efficiency is particularly valuable in electric vehicles, where minimizing auxiliary power consumption directly enhances driving range.

3.4. Analysis of Research Results

After all the data has been obtained, it can be analyzed that lithium-ion batteries without a cooling system generally have quite good durability. However, just like other batteries, lithium-ion batteries can also heat up if used continuously with high intensity and load. In this test, the average temperature of the battery was 35.515 °C. Passive cooling system is a liquid cooling system that is inserted into a prepared tube with a configuration of 5 empty bracket holder spaces. It

aims to absorb the heat generated by the battery. In this test, paraffin oil liquid is used as a heat absorbing medium in the battery. From the data obtained after testing the battery with paraffin oil liquid, an average temperature of 32.395 °C was obtained with the same test time, the average ambient temperature was at 34.328 °C. It can be assumed that paraffin oil liquid is capable or quite effective in absorbing and slowing down the heat in the battery pack. The hybrid cooling system is a combination of paraffin oil liquid cooling and a fan, where when the passive cooler is unable to maintain the temperature in the battery pack to remain in the range of 35 °C the fan will turn on automatically and after testing on the battery pack, the average ambient temperature is 33.344 °C. Then the average temperature in paraffin oil is 32.982 °C (Figure 6).

The results of the ANOVA test show that the battery with the hybrid cooling system is able to maintain a lower temperature compared to the battery without a cooling system. The average temperature difference of the paraffin oil coolant between the passive and hybrid cooling systems is 0.032 °C. Additionally, the average ambient temperature difference between the battery without a cooling system and the battery with a passive cooling system is 1.187 °C, and the average ambient temperature difference between the passive and hybrid cooling systems is 0.984 °C. These findings suggest that the hybrid cooling system is effective in maintaining the battery temperature, which helps to maximize battery performance and maintain its health. The

significance value of $0.020 < 0.05$ in the ANOVA table indicates a significant difference in the average ambient temperature for each scheme.

The homogeneous sample test results reveal that only the average ambient temperature between the hybrid cooling system and the uncooled system shows a significant difference, while other schemes exhibit no significant variation. This indicates that the cooling scheme variable significantly affects the average ambient temperature difference only between the hybrid and uncooled systems.

Independent sample tests show a sig. (2-tailed) value of $0.471 > 0.05$, indicating no significant difference in the average paraffin oil temperature between the passive and hybrid cooling schemes. Regarding battery pack temperature, batteries without a cooling system offer advantages in terms of smaller size and lighter weight. However, these batteries can reach high temperatures, up to 39.5 °C in 60 minutes, which may degrade battery health. In contrast, the hybrid cooling system effectively maintains battery temperatures around 35 °C, outperforming both passive cooling and the absence of cooling.

Nevertheless, the hybrid cooling system requires more battery power, as the fan must operate continuously when the temperature reaches 35 °C, leading to a faster voltage drop. While passive cooling does not consume power, it is only capable of slowing heat buildup and cannot consistently maintain the battery temperature at 35 °C.

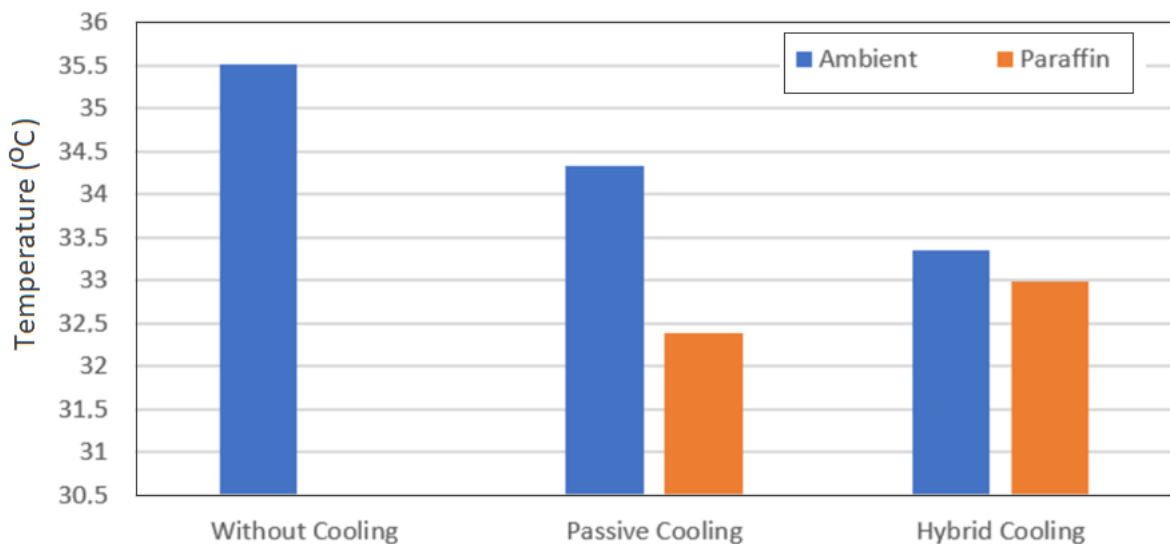


Figure 6. Comparative results

4. Conclusion

BTMS is very important to maintain optimal performance and battery longevity. Temperatures that are too high or too low can affect the efficiency of battery performance. From the results of the experiments conducted, it can be concluded that the hybrid cooling system is the best choice in maintaining the temperature of the battery pack. However, the hybrid cooling system requires additional energy which causes the power in the battery pack to decrease more quickly. The passive cooling system (paraffin oil) has the advantage of being more energy efficient, but is only able to slow down the increase in temperature in the battery pack. In this study, the average temperature of the battery without cooling was 35.515 °C, while the average temperature with the hybrid system (paraffin oil and fan) was 33.344 °C. The difference in average temperature of 2.171 °C indicates that the use of paraffin oil and fan cooling media is effective in maintaining the temperature of the battery pack. The results of the ANOVA test showed that there was a significant difference between the cooling methods used.

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Author's Declaration

Authors' contributions and responsibilities

Muhammad Firdaus Jauhari: Conceptualized the research project as part of his doctoral dissertation, designed the methodology, conducted the investigation (data collection and initial exploration), managed data curation, and drafted the original manuscript. Serves as the primary author and central contributor throughout the research process; Sairaji: Undergraduate student from Poliban, provided significant support in field data collection and preliminary data processing, including data verification and quality checks; Ary Hewu Hawino: Undergraduate student from Poliban, contributed actively to fieldwork, data gathering, and initial data processing; Zaky Abdillah: Undergraduate student from Poliban, supported the research through data collection and participation in preliminary data analysis; Bambang Sudarmanta: Served as the principal supervisor and granted academic approval for the publication of the research findings, supporting the study within the broader context of the doctoral topic; Mohammad Khoirul Effendi: Acted as co-supervisor and

provided academic guidance, approved the publication, and supported the monitoring of the research progress in alignment with the dissertation topic; Kristian Ismail: Acted as co-supervisor, provided academic oversight and approval for publication, and contributed to the general monitoring of the dissertation topic.

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