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Experimental Study on Single-Phase Immersion Cooling for Thermal Management of Lithium-Ion Battery

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ABSTRACT

Battery thermal management is a critical component for maintaining safe and efficient operation, particularly in the context of electric vehicle applications. The immersion cooling technique, which employs S3 X immersion coolant, has been recognized as an effective method to address overheating during battery operation. This study examines the effectiveness of S3 X coolant in managing temperature in LiFePO4 18650-type lithium-ion cylindrical battery packs. Experimental results showed that at a discharge rate of 2.5C, the maximum temperature recorded was 43.2°C with natural cooling and 36°C with immersion cooling. The immersion technique successfully reduced the average surface temperature of the battery by 15.03% and minimized the maximum temperature difference from 4.4°C to 1.9°C at a discharge level of 2.5C. Based on these results, immersion cooling proved to be an efficient solution for the battery thermal management system, supporting more stable and reliable operation.

Keywords: Immersion cooling, dielectric fluids, thermal management, lithium-ion battery,S3 X

1. Introduction

Lithium-ion (Li-ion) batteries play a crucial role in electric vehicles because they offer various advantages such as high energy density, light weight, long duration of use, and minimal self-discharge rate [1]. The heat created during battery use comes from the potential energy at the electrodes, Joule dissipation due to internal resistance, and chemical reactions. To maintain efficiency and extend battery life, the ideal operating temperature ranges from 20°C to 40°C, with surface temperature variations kept to no more than 5°C to avoid damage [2].

Developing an effective thermal management system for batteries (BTMS) is essential, as a reliable BTMS can evenly regulate the temperature inside the battery pack, counteracting efficiency degradation caused by temperature differences between cells. A well-designed BTMS can not only relieve excess heat during periods of high temperature but can also ensure fast and efficient heating during low temperatures. This allows the lithium-ion battery (LIB) to always operate within an optimal temperature range, which in turn can significantly improve the performance and extend the lifetime of the LIB [3,4].

Various thermal management strategies have been developed to dissipate the heat generated by batteries, including air and liquid cooling systems, as well as the use of phase change materials, either individually or in combination [5-6]. Air cooling systems offer the advantages of low operating costs, easy maintenance, light weight, and simple design without the risk of leakage. However, disadvantages include lower thermal efficiency, greater fan energy consumption, and potential operational noise [7]. Meanwhile, liquid cooling systems are superior in providing uniform temperature distribution, have a high specific heat capacity, and offer superior thermal performance. These systems can be configured to cool batteries directly or indirectly; the direct approach, which involves direct contact between the dielectric fluid and the battery, facilitates more efficient heat transfer due to the fluid's dielectric properties of high thermal conductivity and low viscosity. Alternatively, direct immersion cooling, where the battery is immersed in a non-flammable dielectric fluid such as mineral oil or hydrofluoroether, optimizes heat transfer and reduces temperature variations, as well as reducing the risk of overheat. This technique has been applied in a variety of applications, ranging from data servers to electronics, and is emerging as a potential solution for battery thermal management in electric vehicles [8-9].

Immersion cooling methods have long existed and have recently been adopted in the cooling of data servers and electronic devices [10-11]. In the context of lithium-ion batteries, it is a relatively new area of research with limited studies in existence. Experiments comparing the effectiveness of immersion cooling with conventional cooling approaches show different results in temperature management. These studies utilized dielectric fluids under consistent operating conditions, resulting in data that highlighted the importance of the immersion cooling approach for lithium-ion batteries.

Recent research has explored the effectiveness of immersion cooling for cylindrical-shaped batteries. In this study, Dubey et al. [12] found that the immersion method with Novec 7500 improved heat elimination by 32% at an energy discharge rate of 3C. Luo et al. [13] showed that the coolant flow rate has a significant effect on battery temperature management, keeping the temperature below 50°C with a low mass flow rate. In addition, Trimbake et al. [14] compared the cooling effects of the free-jet and submerged methods using mineral oil, recording temperature increases of up to 4.4°C and 5.4°C, while Li et al. [15] found a more significant difference in temperature rise between the use of SF33 liquid and forced air.

The increasing use of electric vehicles requires an effective thermal management system, as battery temperature affects vehicle durability and range. Recent research has shown the advantages of direct cooling methods over indirect methods, particularly in terms of heat transfer efficiency. The immersion method, which immerses the battery directly in a thermal fluid, is considered a potential approach to improve battery thermal management. The limited existing studies regarding immersion cooling of cylindrical lithium-ion batteries, specifically those using oil or hydrofluoroether as the fluid, open up opportunities for further exploration. This experiment investigates the effect of immersion cooling on the temperature distribution of LiFePO4 batteries, starting from tests with natural cooling to the use of S3 X immersion fluid at various discharge rates. While previous studies have looked towards cooling with dielectric fluids, there is still room for deeper exploration regarding LiFePO4 batteries cooled with S3 X, thus this study aims to enrich the existing literature.

2. Material and Methods

2.1. Battery Pack Configuration and Coolant Specification

In this experiment, a LiFePO4-type lithium-ion battery model FERPHOS 18650 with a capacity of 1.8 Ah will be used. The detailed specifications of this battery are provided in Table 1. The battery pack configuration involves 24 cells connected in series (24S) and will be cooled using S3 X immersion fluid, with the properties of the fluid described in Table 2. The battery pack is housed in an acrylic box with dimensions 185 mm × 105 mm × 90 mm[16], arranged symmetrically to ensure uniform temperature distribution, which is a critical aspect in battery thermal management system (BTMS) design. For cooling efficiency, the fluid inlet is arranged near the negative pole and the outlet near the positive pole, with a serpentine channel design consisting of six channels measuring 105 mm × 28 mm. According to research by Kong et al. [17] and Li et al. [18] the temperature variation between cells of a cylindrical battery during discharge can be considered minimal, with the temperature at the center of the battery accurately reflecting the condition of the entire cell. The mounting details and location of the thermocouples are illustrated in Figure 1, which also shows the arrangement of the battery pack with the coolant.

Table 1: Specifications of battery.

Parameter	Value
Nominal energy (mAh)	1800
Nominal voltage (V)	3.2
Internal resistance (mΩ)	30
Max charge voltage (V)	3.65
Discharge cutt off voltage (V)	2.5
Diameter (mm)	18
Height (mm)	65
Weight (g)	46

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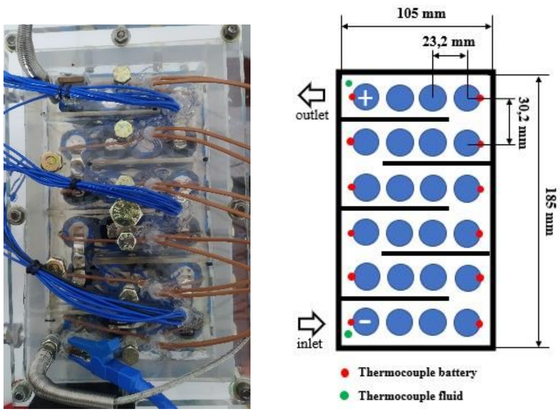
Table 2: Properties of coolant.

Parameter	Value
Density of liquid (kg/m^3)	808
Specific Heat (J/kg·K)	2.028
Thermal conductivity (W/m·K)	0.142
Kinematic viscosity (m^2/s)	$9{,}9 \times 10^{-6}$
Dielectric strength (kV)	30
Boiling point (°C)	85.15



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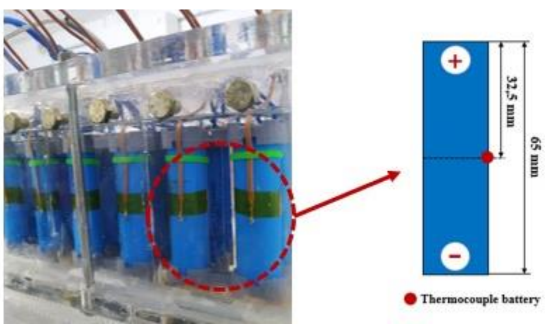

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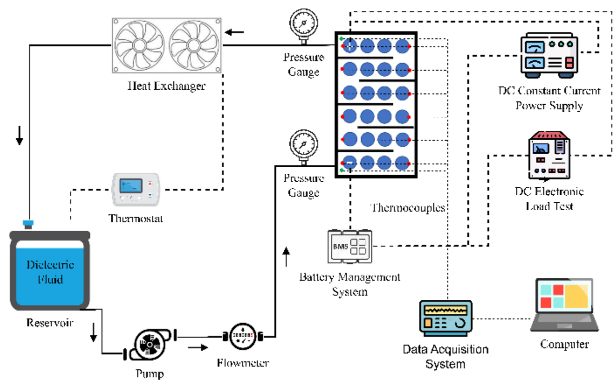
Figure 1: (a) Battery pack configuration (b) location of the thermocouple on the battery.

2.2. Experimental Setup and Procedure

Figure 2 presents the schematic layout of the experimental setup for the direct liquid cooling system on the battery pack under test. In this system, the heat exchanger serves to transfer heat from the air to the liquid coolant. To test the battery pack load, an ET5410 DC electronic load capable of handling voltages between 1 to 150 V and currents from 0 to 40 A, with a maximum capacity of 400 W was used. In addition, an R-SPS1203D DC power supply with a voltage capacity from 0 to 120 V and a current from 0 to 3 A was used for the charging process. Coolant circulation is regulated by a magnetic micro gear pump that operates within a range of 0.1 LPM to 3.5 LPM. K-type thermocouples capable of measuring temperatures between -200°C and 1300°C were placed on the surface of the battery cells to monitor cell temperatures, as well as two additional K-type thermocouples to measure liquid temperatures at the inlet and outlet. Temperature data was recorded using an Omron ZR-RX45 data logger. All experiments were conducted in a room where the temperature was kept constant at 25°C with integrated temperature control.



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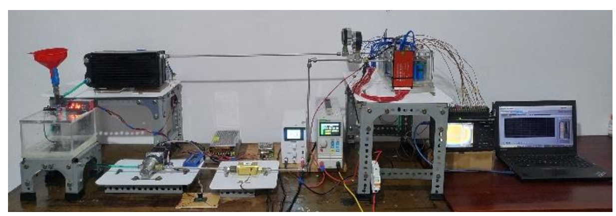

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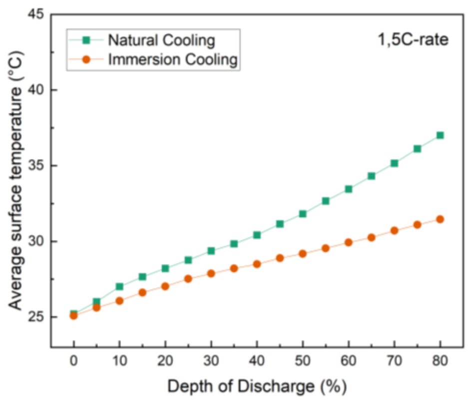
Figure 2: (a) Schematic diagram of the experimental setup (b) photo of the experimental setup.

3. Results and Discussions

This study evaluates the heat transfer characteristics including average temperature, maximum temperature, and temperature variation in the context of discharge rate for a battery pack applying immersion cooling with dielectric fluid.

Figure 3 visualizes the effect of immersion cooling on the average surface temperature of the battery pack at various discharge rates, measured under conditions where the cooling water temperature is stable at 25°C and no flow (0 L/min). Temperature measurements were performed using the arithmetic mean value of the readings of 12 thermocouples. The results reveal an increase in the average temperature during discharge, which is caused by exothermic chemical reactions in the battery. From the data obtained, it was seen that the average surface temperature of the battery was successfully maintained within an optimal range (20°C to 40°C) with the application of S3 X immersion cooling. The maximum temperature recorded was 35.25°C under immersion cooling conditions and 41.48°C under natural cooling conditions at the end of a 2.5C discharge cycle. The use of immersion cooling significantly reduced the average surface temperature of the battery due to higher heat transfer efficiency, with a temperature decrease of 15%, 11.88%, and 15.03% at 1.5C, 2C, and 2.5C discharge levels, respectively, compared to no immersion cooling. Furthermore, the battery temperature increased drastically as the discharge rate increased.



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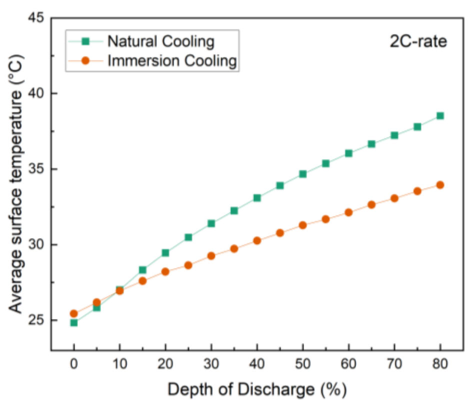

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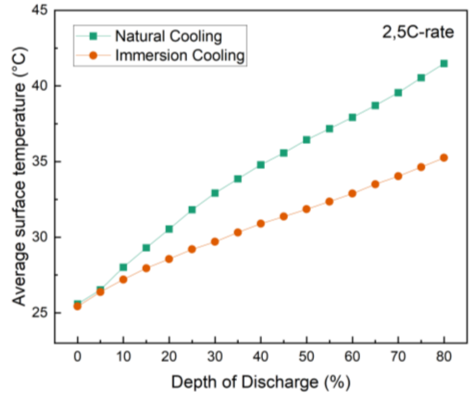
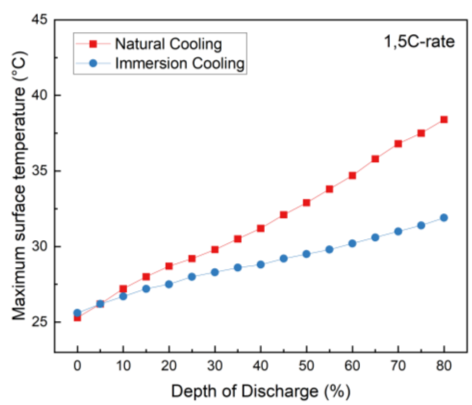


(c)

Figure 3: Effect of immersion cooling on average battery surface temperature for various discharge rates (a) 1.5C, (b) 2C, and (c) 2.5C

Figure 4 shows how the maximum temperature of the battery surface fluctuates with the immersion cooling method at various discharge rates. It can be seen that the temperature distribution on the battery surface is uneven during the discharge process, and there is a tendency for the temperature to increase as the discharge rate increases. Based on the data shown in Figure 4, the maximum temperature recorded was 36°C for immersion cooling and 43.2°C for natural cooling at a discharge rate of 2.5C. These results indicate that immersion cooling is more effective in keeping the battery temperature within the optimal range for various discharge levels, while natural cooling tends to be effective only at lower discharge levels (1.5C). The temperature curves in the figure also show that the maximum battery temperature is greatly affected by the immersion process, where the entire battery system is submerged in S3 X immersion coolant.



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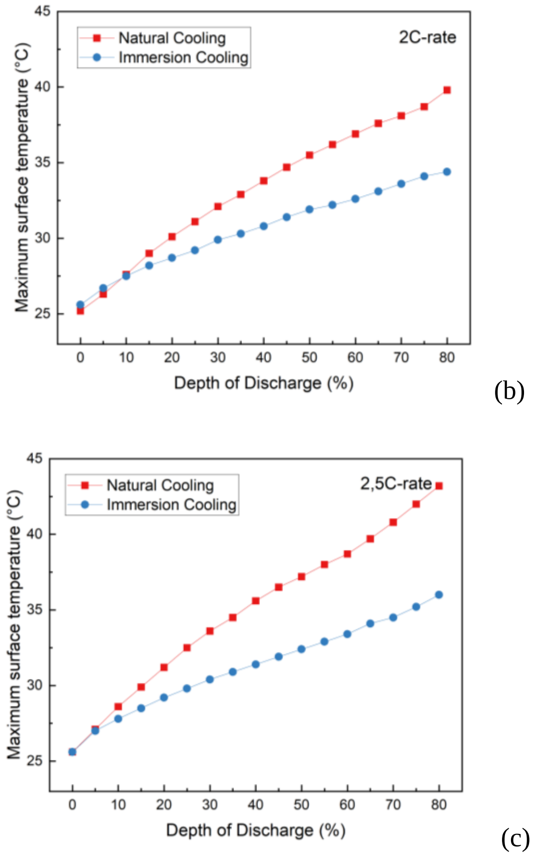

Figure 4: Effect of immersion cooling on maximum battery surface temperature for various discharge rates (a) 1.5C, (b) 2C, and (c) 2.5C

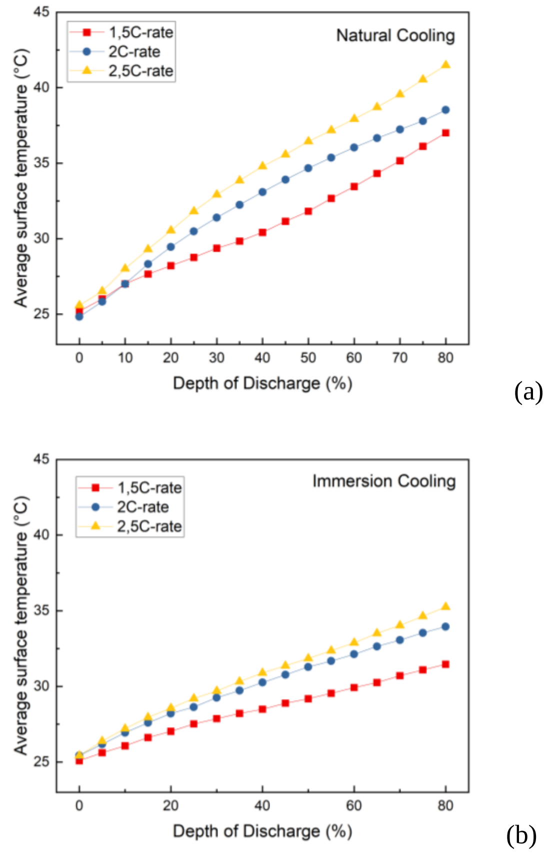

Figure 5: Effect of discharge rate on average battery surface temperature for (a) natural cooling, and (b) immersion cooling.

Figure 5 visualizes the effect of discharge rate on the average surface temperature of the battery under immersion cooling and natural cooling conditions. As expected, there was a consistent increase in the average temperature as the discharge rate and discharge time duration increased for both cooling methods. The findings showed that the highest temperature was recorded during natural cooling, while the lowest temperature was observed when using the immersion cooling method. The average battery surface temperature was recorded to increase by 12.09% and 12.05% when the discharge rate was increased from 1.5C to 2.5C for immersion cooling and natural cooling, respectively, at the final stage of discharge. This increase in temperature at higher discharge rates can be attributed to the intensification of exothermic chemical reactions occurring within the battery.

Figure 6 displays a comparison of the maximum temperature difference between the immersion cooling and natural cooling methods at various discharge rates. The data shows that the maximum temperature difference in the battery applying immersion cooling is successfully kept below 5 °C for discharge levels of 1.5C and 2.5C, which is in line with the expected performance standard for the battery. However, at a discharge level of 2.5C, there was a large temperature difference. This finding indicates that immersion cooling tends to result in a lower maximum temperature gradient, which can reduce the cell degradation rate and improve battery performance, especially at higher discharge rates.

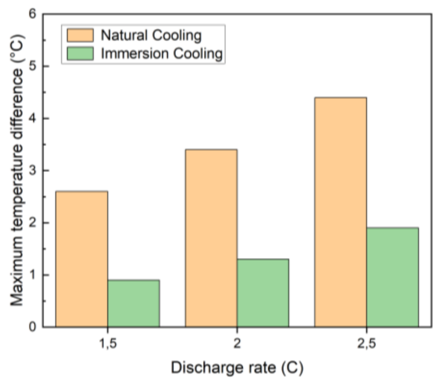

Figure 6: Maximum temperature difference at the end of different discharge rates

4. Conclusion

This study investigates the effects of immersion cooling on the operational performance of LiFePO4-type lithium-ion batteries through an experimental approach using S3 X immersion coolant. Observations were made on the variation of the battery surface temperature at various discharge rates and compared with natural cooling conditions to assess the effectiveness of the immersion cooling method.

The battery surface temperature increased as the discharge rate increased under both natural and immersion cooling conditions due to exothermic chemical reactions in the battery. Under natural cooling conditions, the average battery surface temperature reached the highest value at all discharge rates, with the highest temperature increase of 6.23°C at a discharge rate of 2.5C compared to immersion cooling. Immersion cooling effectively reduced the maximum temperature of the battery surface by approximately 16.67% compared to testing under natural conditions. The use of immersion cooling significantly reduced the maximum temperature difference between the batteries. These results confirm that immersion cooling could be a very effective solution for battery thermal management, with the possibility of further improvement through adjustment of the liquid flow rate or selection of dielectric fluids with better heat capacity and thermal conductivity.

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