Experimental Study of Hybrid Thermal Management System of Li-ion Battery Pack with Eutectic PCM-Embedded Heat Transfer Fluid

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Session 2021-23

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THESIS ACCEPTANCE CERTIFICATE

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Dedication

Dedicated to my parents who have been my pillars of strength and support throughout my academic journey. I am thankful to my teachers, who have imparted me with valuable knowledge and skills and have inspired me to excel in my field of study. I am indebted to my siblings, who have been my best friends and companions and have cheered me up in times of difficulty. I am appreciative of my friends, who have shared my joys and sorrows and have enriched my life with their friendship. Without their guidance, assistance, and encouragement, this work would not have been possible.

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Aamir Khan

Abstract

Lithium-ion batteries (LIBs) are widely used in the automobile, electronics, and aerospace industries due to their low self-discharge rate, extended lifespan, high efficiency, high power density, and superior operational performance. However, under extreme operating conditions, LIBs generate significant heat, which degrades their performance and can lead to thermal runaway. An appropriate cooling system is essential to improve battery life, safety, capacity, and performance. This study investigates the effects of various cooling methods on a 5000mAh Li-ion battery pack during charging and discharging at 1C, 1.5C, and 2C rates. The cooling techniques evaluated are natural cooling, heat transfer fluid cooling, eutectic PCM cooling, and hybrid cooling. The eutectic PCM comprises lauric acid and stearic acid, with a melting temperature of 33.29°C, a latent heat of 151.76 J/g, and a thermal conductivity of 0.356W/mK. Experimental results indicate that with natural air cooling, the battery pack reaches maximum temperatures of 66.9°C, 57.9°C, and 45.6°C when charging and discharging at 2C, 1.5C, and 1C rates, respectively. Compared to natural air cooling at the 2C rate, heat transfer fluid cooling reduced the maximum temperature by 22.42%, eutectic PCM cooling by 40.90%, and hybrid cooling by 46.18%. These findings demonstrate that hybrid cooling significantly reduces both the maximum surface temperature and the temperature gradient, suggesting it as an effective method for cooling battery packs.
Keywords: LIBs pack, Battery thermal management system, eutectic phase change materials, Hybrid cooling system, Electric vehicles

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Journal: Journal of Energy Storage
Status: Published

Title: Hybrid Thermal Management of Li-ion Battery Pack: An Experimental Study with Eutectic PCM-Embedded Heat Transfer Fluid
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List of Abbreviations/Nomenclature

PCM	Phase Change Material
BTMS	Battery Thermal Management Systems
EV’s	Electric Vehicles
DSC	Differential Scanning Calorimetry
TGA	Thermo Gravimetric Analysis
SA	Stearic Acid
LA	Lauric Acid
HP	Heat pipes
C-rates	Charge Rates
NMC	Lithium-Nickel-Manganese-Cobalt-Oxide
CC-CV	Constant Current-Constant Voltage
LIBs	Lithium-ion batteries

Chap#1: Introduction

1.1 Introduction

The increased energy demand leads to a great challenge in finding potential energy sources and emerging solutions in the era of the energy crisis [1]. Current energy conventional resources, including coal, oil, and natural gas, are expensive, harmful to the environment, and cause risk to the future balance of energy generation and demand. However, fossil fuel supplies are limited and rapidly depleted, requiring focused attention and sustainable solutions to prevent future energy crises. Furthermore, fossil fuels cause global warming by emitting harmful pollutants like greenhouse gases [2]. In recent decades, climate change has become significant, and there has been an increased awareness of environmental protection. Though, attention has been paid to renewable energy resources [3]. However, the main issue with renewable resources is their non-uniform energy output which decreases their usability during peak hours. Therefore, for uniform energy output, energy storage using batteries could be a better solution [4], where different batteries such as nickel cadmium, lead acid, and lithium-ion could be used to store energy [5]. Merely Lithium- Ion Batteries (LIBs) are ideal for EV's due to their high energy (705Wh/L), power density (10,000 W/L), longer life cycle, high voltage, low self-discharge rate (< 2% /month). In terms of energy efficiency, LIBs presents the highest (≅ 95%) with up to 100% discharge permissible [6,7].

Ideal conditions for operating LIBs are between 15°C to 35°C, with less than five °C temperature difference between them (Figure 1.1) [8–11]. If the temperature of the LIBs is inappropriate or the temperature difference is large for a longer period of time, it would cause a series of problems [12]. In a cold climate, the power capacity and lifespan of a battery are degraded [13]. Nagasubramanian [14] examined the power density of LIBs at various temperatures and found that when the temperature dropped from 25°C to -40°C, the battery power density reduced significantly from 800 W/L to 10 W/L. Whereas Petzl et al. [15] found that in low-temperature environments (-22°C), LIBs lifespan can be reduced up to 90-140 cycles. However, in hot climates, heat is accumulated inside the LIBs, causing the battery to overheat, and negatively affecting its durability, safety, and performance. If the temperature reaches 80°C, LIBs can readily overheat and lead to thermal runaway, risking the safety of electric vehicles (EV's) and passengers [16,17]. Feng et al. [18] studied thermal runaway in LIBs and found that 12% of the heat produced in thermal runaway had the potential to initiate thermal runaway in the next LIBs. Therefore, to address the thermal runway limitation of LIBs and to ensure their efficiency in an ideal environment, Battery Thermal Management System (BTMS) must be developed [18].

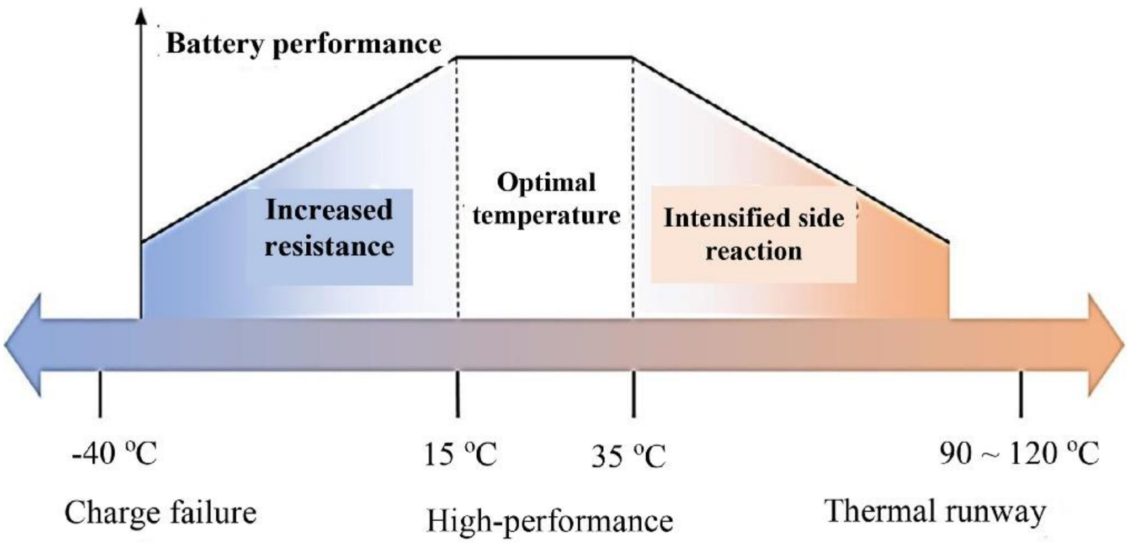

Figure 1.1. LIBs optimum temperature [8]

1.2 Thermal Runway

Thermal runaway is a phenomenon that occurs in LIBs when a series of exothermic reactions cause a rapid rise in the internal temperature of the battery. This leads to the deterioration and destabilization of the battery's internal structures, which can result in the complete failure of the battery. Thermal abuse, mechanical abuse, and electrical abuse are some of the factors that can trigger thermal runaway. These factors can damage the separator that separates the anode and the cathode, causing an internal short-circuit. This produces a large amount of heat, which accelerates the electrochemical reactions and generates more heat. This positive feedback loop increases the temperature of the battery sharply and releases flammable gases. The gases increase the internal pressure of the battery, causing the outer casing to expand and potentially explode or catch fire (Figure 0.2) [19–21].

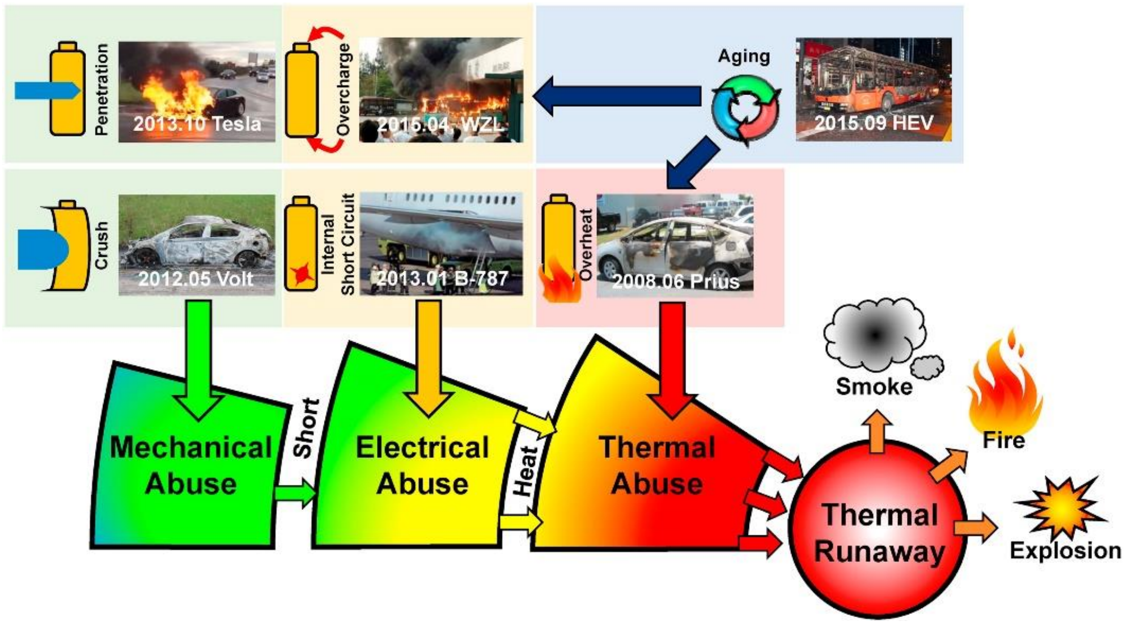

Figure 1.2. Thermal runway propagation in LIBs [22]

1.3 Battery Thermal Management System

Battery Thermal Management System (BTMS) is reliable in maintaining the optimum temperature of LIBs either by cooling or heating. A BTMS can use different methods to transfer heat to or from the battery, such as air, liquid, or phase change materials. The preheating BTMS are classified as either external or internal while the cooling are classified based on the power source, which mainly consists of three types: i) Active cooling, ii) Passive cooling, and iii) hybrid cooling (Figure 1.3) [23–25].

Ambient temperature affects the performance of LIBs. At low temperatures (such as 15°C), LIBs performance can be problematic. Both the charging and discharging performance will be affected because the electrochemical process cannot take place normally [26]. Under subzero temperatures, decreased power capacity and degradation can occur. To ensure battery performance in abnormal temperature conditions, efficient heating methods are to be developed. BTMS manages the heat that is produced during the electrochemical process for the secure and efficient operation of the battery [27].

High temperature has several negative impacts on battery performance, such as capacity/power fade and self-discharge. These impacts can cause a significant loss of available energy. it was reported the capacity and power fade of various positive electrode materials under high temperature cycling and storage. They showed that the capacity degraded when the temperature increased above approximately 50 °C. For example, the Sony 18650 cells lost 36% of their capacity after 800 cycles at 45 °C and more than 70% after 490 cycles at 55 °C [28]. In order to enhance the cooling efficiency of Li-ion battery packs, several cooling techniques have been developed by researchers. These cooling techniques have their own set of pros and cons, and the choice of technique used will be determined by the specific requirements of the battery pack and its application [29]. A particularly planned and executed BTMS is a fundamental element of any battery system that aims for reliable performance and prolonged durability. Through the regulation of the battery pack's temperature and the control of temperature variations, a BTMS can ensure the safe and efficient operation of the battery system throughout its entire lifespan [30].

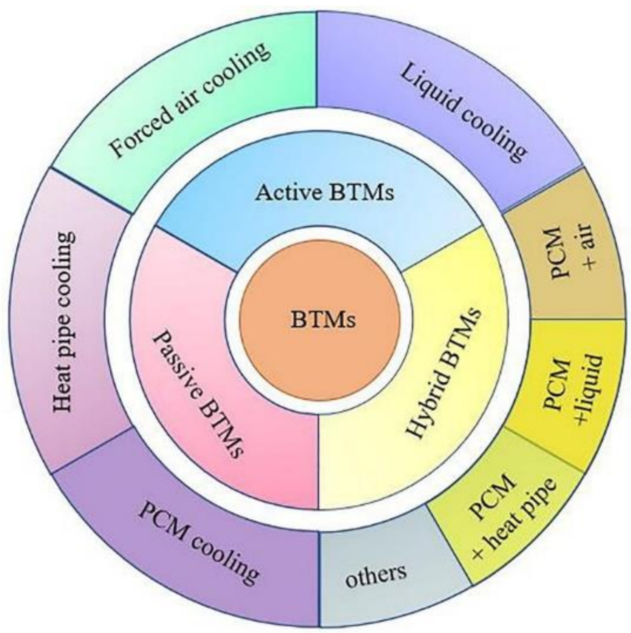

Figure 1.3. BTMS classification according to the power source [25]

1.4 Problem Statement

LIBs are essential components of EV’s, but they have safety risks due to their high energy density and potential for thermal runaway. Thermal runaway is a phenomenon where heat generation in the batteries triggers a series of electrochemical and exothermic reactions that further increase the temperature and lead to disastrous failure. Thermal runaway can be caused by extreme operational circumstances, such as overcharging, short-circuiting, mechanical damage, or external fire. To prevent thermal runaway and ensure personal and vehicle safety, BTMS are required. BTMS are designed to regulate the temperature of the batteries within a safe range and to dissipate the excess heat generated during normal or abnormal operation. BTMS can also improve the performance, efficiency, and lifespan of the batteries by avoiding excessive heating or cooling. Therefore, BTMS are crucial for the development and deployment of EV's.

1.5 Objectives of Study

1) To design and implement an active thermal battery management system for LIBs pack using heat transfer fluid cooling methods.
2) To evaluate and characterize the thermal performance and properties of eutectic phase change material for passive cooling of battery pack.
3) To analyze and model the behavior of battery pack during charging and discharging cycles under different operating conditions of hybrid cooling using heat transfer fluid and eutectic PCM.

Summary

The primary objective of this study is to compare natural cooling, heat transfer fluid cooling, eutectic PCM cooling, and hybrid cooling methods for battery thermal management systems. The study will fabricate the battery pack and conduct experiments to evaluate the thermal performance of each method, as well as identify the most suitable cooling for battery thermal management system at high charging discharging conditions.

Chap#2: Literature Review

2.1 Thermal Management of LIBs

To ensure better thermal stability, researchers always focus on the cooling of the LIBs because heat is generated in LIBs, which is necessary to be dissipated. According to different heat dissipation methods, the cooling system may be classified into three main types, namely, active, passive, and hybrid systems (Figure 2.1) [31–33].

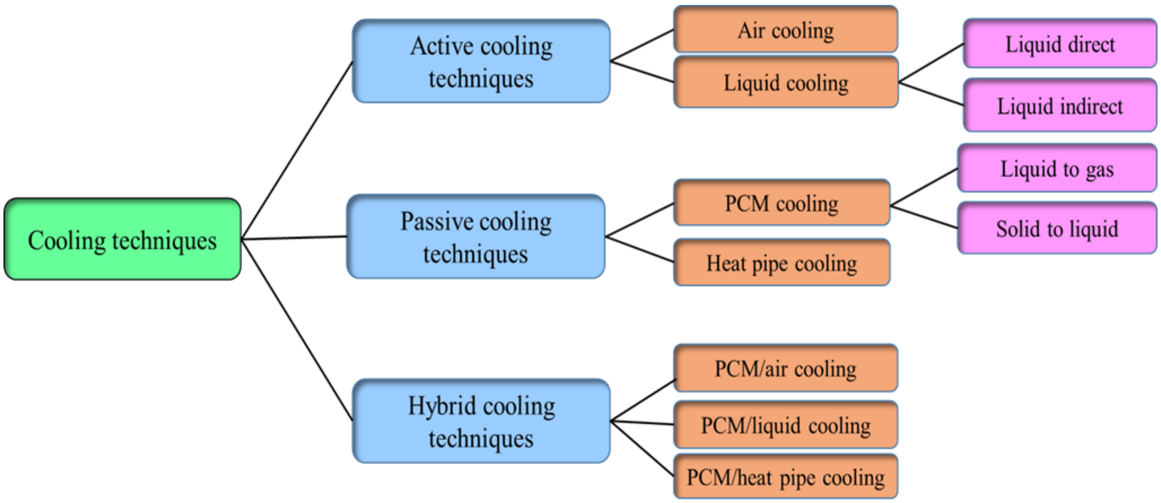

Figure 2.1. Classification of cooling system

2.2 Active Cooling of LIBs

In active cooling external energy source is required to facilitate heat transfer. Consequently, an active cooling technique that employs forced air or liquid flow with a fan, blower, or pump is a costly technique. However, it improves the system's thermal performance by extracting heat from the battery. It is crucial to optimize the power consumption to enhance the efficiency of the battery pack. Active cooling has been extensively studied to evaluate maximum temperature and ensure uniform temperature distribution within the battery pack. Active cooling includes air cooling (Figure 2.2) and liquid cooling [34,35].

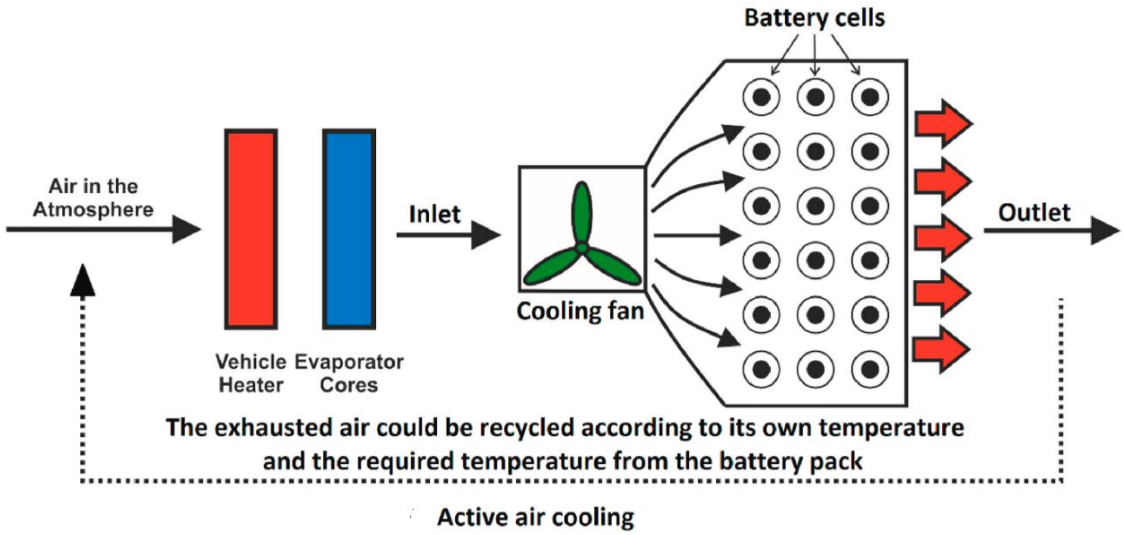

Figure 2.2. Schematic diagram of the active-cooling system [35].

2.2.1 Air cooling

The air cooling has been considered the most convenient method frequently and extensively used in commercial Applications. Air cooling systems are used in EV's due to their low cost, easy maintenance, lightweight, long life and no leakage issues compared with other cooling BTMS [36,37]. Despite the numerous advantages of air-cooled BTMS strategies over other methods, they also have drawbacks, such as the low heat capacity and challenges in achieving a uniform distribution of air to achieve the same thermal performance as other battery thermal management systems[38,39]. In recent years, the improvement of forced air cooling has been mainly focused on battery pack design, inlet and outlet design, and airflow channel design [40]. Wang et al. [41] studied different air cooling strategies on battery modules and found that an axisymmetric LIBs pack layout had the most effective cooling effect compared to other cell arrangements, such as 24×1 line, 8×3 rectangular, and 5×5 square layouts. Ultimately, the 5×5 layout was selected due to its excellent thermal performance and cost savings. Fan et al. [42] experimentally studied and compared aligned, staggered and cross battery pack arrangements. The aligned arrangement shows optimal thermal performance and minimal energy consumption. (23% less than that of the cross battery packs). The cooling capacity was enhanced with higher air inlet velocity but reached a limit due to the exponential rise in power consumption. Chen et al. [43] studied that positioning the inlet and outlet in the middle of the battery pack was optimal for air-cooling BTMS. Compared to the original BTMS with Z-type flow, the peak battery temperature is reduced by 4.3°C. Yang et al. [44] examined the cooling performance of axial air flow, focusing on the optimal radial distance between LIBs. They found that enhancing radial distances between LIBs caused a slight rise in average temperature but enhanced temperature uniformity within the battery pack and reduced the cooling system's energy cost. Furthermore, a higher air flux enhanced temperature uniformity within the battery pack.

2.2.2 Liquid cooling

Liquid coolants have a better thermal conductivity than air cooling, making them a more desirable choice as a cooling medium. A liquid-type thermal management system could use less energy and produce more effective cooling for high heat load conditions [45]. Liquid cooling for LIBs is divided into direct and indirect methods based on the contact between the coolant and the battery [28].

Direct liquid cooling exhibits superior cooling performance, improved temperature consistency, and greater compactness. However, a major challenge for the direct liquid cooling type is to ensure the sealing of the battery packs. The direct-contact type requires liquid media that can either flow over the cell surface or remain stationary [46]. The battery module is submerged in a liquid coolant, which should possess certain properties such as electrical insulation, non-toxicity and chemical stability to prevent the occurrence of short circuits at the interface between the coolant and the LIBs. Recently, mineral oil and silicon oil have been primarily used as coolants [47]. The entire surface of the battery pack is cooled when it is submerged in a coolant liquid, which helps to increase temperature uniformity and reduce maximum temperature [47]. Patil et al. [48] investigated four different cooling techniques, i.e. natural convection, battery immersion in stationary mineral oil without tab cooling, battery immersion in stationary mineral oil with tab cooling, and battery immersion in flowing mineral oil with tab cooling. The experiment findings showed that the battery cell submerged in flowing mineral oil with tab cooling enabled a 46.8% drop in the maximum temperature when compared to natural convection. They also found that by adopting the proposed mineral oil immersion cooling instead of the conventional water-ethylene glycol (indirect cooling method), the battery pack temperature was decreased by 9.3%. Tan et al. [49] proposed a novel hydrofluoroether (HFE-6120) based direct cooling method for fast-charging battery packs. The direct cooling parameters were quantitatively examined using CFD. They found that at 0.05 m/s inlet velocity, 20.3% increase in mass energy density and 95.3% reduction in energy consumption. Additionally, a multilayer channel is combined with a crossflow configuration and utilizing 30 mm channel height, the maximum temperature difference between the battery cells can be reduced by 18.1%.

Despite direct-contact mode, the indirect cooling system typically employs cold plates, fins and microchannels to exchange heat between the battery pack and the coolant to prevent liquid leakage and short circuiting. Chen et. al [50] developed an ideal thermal control strategy to manage the LIBs temperature within an ideal operating range of 15°C to 35°C. ANSYS/Fluent was used to vary the mass flow or heat transfer coefficient and determine the cooling effect of four different cooling structures: air cooling, direct liquid cooling, indirect liquid cooling, and fin cooling. They found that air cooling requires 2 to 3 times more energy than alternative methods to keep the same average temperature. Indirect liquid cooling provides the largest temperature difference due to the longer coolant channel, but because water/glycol coolant has a higher heat capacity, the temperature difference declines more quickly than with other methods. Direct liquid cooling using mineral oil improves cooling performance as compared to indirect liquid cooling, although there are problems with liquid leakage. Fin cooling adds an additional 40% weight to the battery when compared to other cooling methods with the same volume.

2.3 Passive Cooling of LIBs

On the other hand, passive cooling techniques do not require additional cooling sources. Passive cooling can be divided into two main categories, namely, Heat Pipes (HPs) and PCM [51,52]. Passive cooling techniques are distinguished for their energy efficiency, economical cost, and prolonged reliability and durability. However, they have some drawbacks, including low thermal conductivity the possibility of leakage, and limited capacity for thermal energy storage applications [53].

2.3.1 PCMs Cooling

A LIBs pack temperature is often managed by liquid or air cooling. Yet, these systems are more expensive and have higher operating costs because they rely on electricity and power. Therefore, using PCMs could be an interesting choice [54]. The BTMS, which is based on PCMs, has the property of absorbing and releasing latent heat during the phase change. They reduce the maximum temperature rise during the charge and discharge process. PCMs have a strong ability to maintain battery temperature in transient situations, even when temperatures vary significantly [55]. The PCMs can be classed as solid-liquid PCM and liquid-gas PCM based on the phase change type.

When a liquid turns into a gas, a significant amount of heat is absorbed, and this process operates without consuming any energy. Therefore, the passive BTMS in the LIBs was frequently used as a liquid-gas PCM [56]. The conventional liquid-gas system includes evaporation and boiling systems. To increase the effectiveness of heat transmission in liquid-gas phase change systems, HP was frequently used [57,58]. To reduce the risk of a short circuit, the boiling system utilized a dielectric fluid as the PCM. The non-conductive boiling liquid has a greater cooling capacity than air cooling, and because the temperature is equally distributed during boiling, the battery's ageing effect may be lessened.

Solid-liquid PCMs are more frequently used than liquid-gas PCMs because the ratio of volume change is low. They are simpler to operate, more efficient, and don't need any additional mechanical components like blowers or pumps. There are four stages to the phase transition process of solid-liquid PCMs. In the first stage, the temperature of the LIBs quickly increases. In the second stage, PCMs slow down the rate of temperature rise as heat conduction takes place. In the third stage, the thermal balance between PCMs heat absorption and LIBs heat generation is achieved. In the last stage, when the PCM completely melted, the heat was naturally released through convection.

2.3.2 Heat Pipes cooling

Heat pipes (HPs) are effective heat transfer devices with high thermal performance, high efficiency, lightweight and maintenance-free BTMS. Their thermal conductivity and phase transition provides a novel way to regulate the temperature of the LIBs in EV's [59]. The HPs working principle can be divided into the evaporator, isothermal, and condenser sections. In this arrangement, the evaporator section of the HP is positioned in direct contact with the LIBs pack. The working fluid absorbs heat from the LIBs in the evaporator section, and it changes to vapor. The high vapor pressure and low molecular weight create a pressure gradient that travels the vapor towards the condenser section. When the vapour reaches the condenser section, it condenses, releasing heat into the atmosphere and returning to a liquid condition. To maintain continuous operation, the HP must transmit heat from the evaporator portion to the working fluid and then absorb that heat at the condenser section [60,61]. Ling et al. [62] examined the effects of ambient temperature, coolant temperature and coolant flow rate on the battery temperature in the HP thermal management system. They found significant improvement in system performance when operating under low ambient and coolant temperature conditions. The cooling performance of the HP exhibited a slight enhancement as the flow rate increased to a certain value (2 L/min). Additionally, they observed that the cooling capacity slightly increased when the ambient temperature dropped below 25°C. Furthermore, they recommended adopting an intermittent cooling strategy for the HP will give equivalent results with less power usage.

2.4 Hybrid Cooling of LIBs

According to a literature study, conventional cooling systems such as active and passive cooling are inefficient for extreme working environments for LIBs. As a result, to maintain the effective cooling performance of EV's batteries, a more effective cooling method is necessary. Hybrid cooling combines two or more active or passive cooling methods to overcome the drawbacks of conventional methods and achieve excellent thermal performance. Currently, hybrid cooling of LIBs frequently uses PCMs with forced air [63,64], liquid [65,66], and HPs [67,68]. PCMs rely heavily on the specific heat's capacity to absorb the heat generated by the LIBs. However, if the melting point is reached, the PCM's performance is dramatically reduced, and it can serve as an insulator. In order to control the PCM temperature and ensure the proper functioning of LIBs, it is crucial to consider integrating cooling techniques with PCM.

2.4.1 Air-PCM Cooling

BTMS uses air in electric vehicles because of their simple design, low cost, and ease of implementation. However, due to a low convective heat transfer coefficient in particular circumstances and when the ambient temperature is near the LIBs maximum temperature, this cooling strategy alone may not be able to regulate the maximum temperature rise in EV's. So, to enhance the rate of heat dissipation to the ambient environment, the addition of air cooling in combination with PCM has been employed. Yang et al. [69] conducted an investigation and comparative analysis of the cooling performances of a LIBs pack during charging-discharging cycles utilizing different cooling methods: natural convection, natural convection with PCM, and forced convection with PCM. The findings show that at 1C, the battery maximum temperature with natural convection only exceeds the ideal operating temperature. However, the implementation of combined forced convection with PCM successfully maintained the temperature of the LIBs within the desired range, ensuring that both the maximum temperature and temperature difference were within the ideal range at 2C.

2.4.2 Liquid-PCM Cooling

Liquid cooling is frequently employed in battery management systems and provides better heat transfer rates than air cooling because the thermal conductivity of the liquid is significantly higher than that of air. Even in some situations of large battery packs, liquid cooling alone cannot provide sufficient cooling performance. To get higher performance, liquid cooling systems with PCMs have been developed. Among the various methods employed for battery BTMS, cooling plates, particularly the integrated liquid-PCM system, are widely adopted [70–72]. Wang et al. [73] proposed hybrid BTMS that combines PCM with a water cooling plate. The battery cooling system is numerically simulated using a three-dimensional thermal model and validated using existent data from literature. Results show that at a 5C rate, the maximum LIBs temperature can be lowered from 64°C to 46.3°C using two-sided cold plates. Mousavi et al. [74] developed hybrid BTMSs to regulate the temperature of battery cells in five-cell modules, sandwiched between cold plates. They investigated two types of cold plates: the mini-channel cold plate and the newly designed hybrid mini-channel cold plate (adding n-eicosane PCM inside the cold plate). The BTMS performance was significantly influenced by the battery orientation. Consequently, the optimal orientation resulted in a 30°C reduction in the maximum temperature in the battery packs. Under constant heat generation, the hybrid cooling system lowered the peak battery temperature by 10.35°C compared to active cooling. Akbarzadeh et al. [75] introduced a liquid (water) cooling plate with composite paraffin/graphite PCM to improve the thermal management of EV's batteries. The results show that employing a hybrid liquid cooling plate can reduce the pump energy consumption for coolant circulation by up to 30% compared to an aluminum liquid cooling plate. Additionally, the hybrid cooling plate facilitated a greater degree of temperature uniformity in the battery pack.

2.4.3 HP-PCM Cooling

In recent years, a passive hybrid BTMS based on HPs and PCM has been widely used to regulate the battery packs' temperature. PCMs depend greatly on the latent heat's ability to absorb the heat generated by the LIBs. However, if the melting point is reached, the PCMs abilities are severely decreased, and it can serve as an insulator. Therefore, it is recommended to investigate integrating HP with PCMs to control the LIBs temperature and ensure proper functioning. In this BTMS, the thermal energy released by the LIBs is initially stored by the PCMs and then by the HPs evaporator. The remaining heat is released into the atmosphere through the condenser section. Peng et al. [76] examined the thermal behaviour of a novel, compact HP with a PCM cooling system for cylindrical Li-ion modules. In the experimental module, the PCM is paraffin wax, and the heat transfer fluid for the HP is acetone. The findings show that during the discharge process, the paraffin wax liquid fraction distribution is non-uniform. The outer layer and top portion of PCM melt first. Due to varying melting rates, the temperature difference between batteries slightly increases. Additionally, paraffin wax with extended graphene exhibits improved heat dissipation compared to pure PCM. The composite thermal conductivity increases with higher graphene content, but heat capacity and latent heat decrease.

Summary

This chapter explores various cooling techniques employed in BTMS to address the critical issue of thermal management in LIBs. The techniques include Active cooling (air-cooling and liquid cooling), Passive cooling (PCMs cooling and heat pipes cooling), and hybrid cooling (Air-PCM, Liquid-PCM, and heat pipe-PCMs). A comparative analysis of these cooling methods is also conducted.

Chap#3: Experimental procedure

3.1 Specifications of cell

This study utilized a LIBs of cylindrical shape, which had a capacity of 5000mAh and was composed of Lithium Nickel Manganese Cobalt Oxide (NMC) as the cathode material. The anode of the NMC battery consisted of graphite, whereas the cathode of the battery was composed of a mixture of cobalt, nickel, and manganese. The nominal voltage of the battery was 3.7 V, and it had a maximum charging voltage of 4.2 V and a maximum discharging voltage of 3 V. The key specifications of NMC are presented in Table 3.1.

Table. 3.1: The Li-ion cell used in experimentation has the following specifications.

Name	**Specification**
26,650 Li-ion Cell	
Nominal capacity (mAh)	5000
Nominal voltage (V)	3.7
Operating temperature (℃)	-20 to +65
Charging Voltage (V)	4.2
Discharge cut-off voltage (V)	3
Mass (g)	86
Storage (days)	~180

3.2 Battery pack configuration

The battery pack was constructed to examine the impact of different charge-discharge rates on the thermal performance of the LIBs. To ensure optimal structural arrangement of cells within the battery pack, cell spacers were employed, specifically designed for the NMC-26650 cells. The LIBs were arranged in a rectangular configuration, with a uniform spacing of 2 mm between each cell. Six LIBs were used in this experiment, and three-dimensional view of their arrangement is presented (Figure 3.1).

Figure 3.1. Three-dimensional view of the *LIBs* pack

3.3 Thermocouple

In this experimental setup, a k-type thermocouple is used to measure the temperature of the battery cells as shown in figure 3.2. The k-type thermocouple principal based on the Seebeck effect, which produces a voltage that is proportional to the temperature difference between its two junctions. By attaching one junction of the thermocouple to the surface of the LIBs and the other junction to a reference point, we can accurately monitor the temperature fluctuations within the battery. These thermocouples can measure a wide temperature range, typically ranging from -200 to 1260 ℃.

Figure 3.2. K-Type thermocouple for temperature measurements

3.4 Battery analyzer

To charge and discharge a LIBs pack, the BTS-5V30A-8 Channel battery analyzer has been employed, as shown in figure 3.3. The analyzer can accommodate a current range of 0.1A to 30A and voltage range of 0.5V to 5V. Each channel of the analyzer is controllable by a computer and comes equipped with independent constant voltage and constant current sources. Furthermore, these channels can be programmed as per specific requirements.

Figure 3.3. Eight Channel battery analyzer

3.5 Temperature data logger

A data logger is a device that measures and records temperature variations over time. It can have a single channel or multiple channels, depending on the number of parameters to be monitored. The data logger (Figure 3.4) was used in this setup, accurately measured and recorded the temperature of the LIBs. A k type thermocouple, which is a sensor that detects temperature changes, was connected to the data logger. The device recorded the temperature fluctuations of the cell at intervals of 30 seconds.

Figure 3.4. Temperature data logger

3.6 Phase Changing Materials

PCMs are widely utilized in various fields for regulating temperature and storing energy due to their high latent heat value, superior thermal storage capacity, and cold storage capability. PCMs can be classified based on their chemical composition i.e., organic, inorganic, and eutectic PCMs. This study employs stearic acid (SA) and lauric acid (LA) as effective PCMs for battery thermal management (Figure 3.5).

Figure 3.5. Stearic acid and Lauric Acid PCM

3.7 Experimental setup

In this study the experimental setup consists of battery charging/discharging equipment (BTS-5V30A-8CH) and the six high-capacity 26650 LIBs, which cell spacers support to ensure their optimal placement. A 2 mm thick acrylic sheet, which acts as a durable casing, securely encloses the battery pack. Additionally, the experimental setup features eutectic PCM, a liquid storage vessel, a pump, and a copper channel, which have been specifically designed to facilitate efficient heat transfer. To ensure precise data collection and comprehensive monitoring, the experimental setup is outfitted with data loggers that are equipped with K-type thermocouples and a monitoring computer. A series of experiments was designed to study the thermal behaviour of the battery pack using four different cooling strategies: 1) natural air cooling, 2) heat transfer fluid cooling, 3) eutectic PCM cooling, and 4) hybrid cooling. The experimental setup of hybrid cooling of LIBs pack (Figure 3.6).

Figure 3.6. Experimental system of hybrid cooling of Li-ion battery pack

Summary

This chapter provides an overview of the LIBs specification and battery pack configuration. It also explains the instruments that were used to examine the thermal performance of the battery pack under various thermal management systems. The chapter's aim is to present the experimental setups that were employed to evaluate the performance and safety of the battery pack.

Chap#4: Experimental methodology

4.1. Materials

The materials used to prepare eutectic PCM were Stearic Acid (SA, 95% purity) supplied by Sigma-Aldrich, and Lauric Acid (LA, 99% purity) supplied by Chemical Reagents. Both materials were used without further purification to prepare the SA/LA mixture. The thermochemical properties of the pure PCMs measured through differential scanning calorimetry (DSC) are given in Table 4.1.

Table. 4.1: Thermochemical properties of pure PCMs.

Chemical Name	Scientific Name	Molecular Formula	CAS Number	Melting Point [°C]	Latent Heat Capacity [J/g]	Density [kg/m^3]
Stearic Acid	Octadecanoic acid	$C_{18}H_{36}O_2$	57-11-4	56.81	192.20	941
Lauric Acid	Dodecanoic acid	$C_{12}H_{24}O_2$	143-07-7	44.53	180.51	880

4.1.1 Theoretical prediction of the eutectic point for SA/LA eutectic PCM

Eutectic point is the common melting point, at which two or more base materials tend to undergo a phase transition and their melting temperature is always lower than individual materials. In this study, Schrader equations is used to design and calculate the eutectic composition and eutectic melting point of the organic SA/LA PCM. Schrader equation provides the relationship between thermophysical properties of the designed eutectic component at different composition. The melting temperature and the composition for a binary eutectic SA/LA are theoretically predicted by equation (1) [36,37] Based on the melting temperature, phase diagram is plotted with the melting temperature of SA/LA on the y-axis and composition on the x-axis. The intersection of these two curves represents the optimal proportion for a specific eutectic mixture, commonly referred to as the eutectic mass ratio. This ratio has a characteristic melting point commonly known as the eutectic point. The SA/LA PCM has a melting temperature of 35°C at a theoretical eutectic point with a molar ratio of 38/62 (Figure 4.1).

$$Tm = \left[\frac{1}{Ti} - R\frac{\ln Xi}{\Delta Hi}\right]^{-1} \quad (1)$$

Where i denotes the PCM components A and B, Tm represents the predicted melting temperature in Kelvin of the eutectic mixture, Ti represents the onset melting temperature of the individual components A and B in Kelvin, Xi represents the mole fractions of components A and B, and ΔHi represents the molar latent heat for components A and B in j/mol. R is the general gas constant (8.314 J/(K·mol)) used in equation (1).

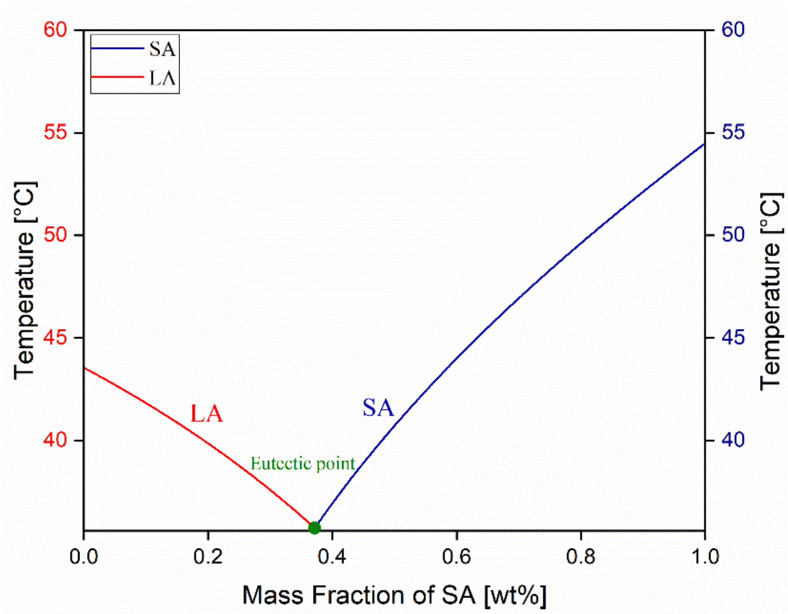

Figure 4.1. The SA/LA binary eutectic mixture phase diagram

4.1.2 Preparation of SA/LA eutectic mixture

The preparation of the binary mixture involved heating, followed by successive ultrasonication and solidification. The pure PCMs were measured with an analytical balance (AS 220.R2) and taken in the desired mass ratios (SA:38%, LA:62%) in a beaker. The homogenous SA/LA eutectic mixture was heated at a constant water bath of 75°C and stirred at 400 rpm for 60 minutes. The resulting liquid mixture was ultrasonicated with the FSF-080ST model sonicator provided by Huanghua Faithful Instrument Co., LTD. The sonicator operates at a frequency of 40 kHz at 75°C for about 20 minutes. After that, the eutectic mixture was placed in a thermostat at 10°C for 120 minutes, allowing it to cool and solidify (Figure 4.2).

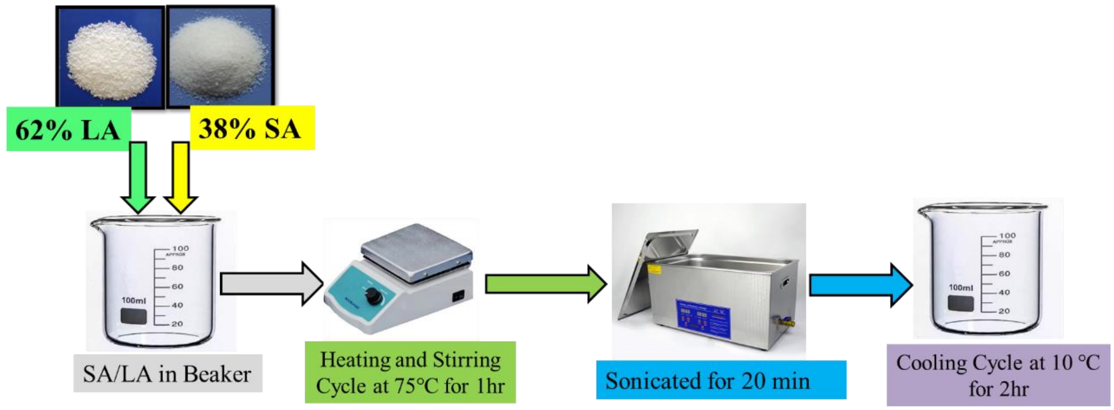

Figure 4.2. Material preparation steps

4.2 Methodology

The methodology of the experiment involved designing and assembling a LIBs pack using specified cells (26,650 NMC Cell) and applying different cooling techniques to regulate its temperature during operation. The cooling techniques included natural cooling, heat transfer fluid cooling, eutectic PCMs cooling, and hybrid cooling. The thermal behavior of the battery pack and the cooling system was monitored and recorded using temperature sensors and data loggers. The battery pack was subjected to various discharge rates (C-rates) using a BTS-5V30A-8 Channel battery analyzer. This research work employed the following methods to achieve its goal (Figure 4.3).

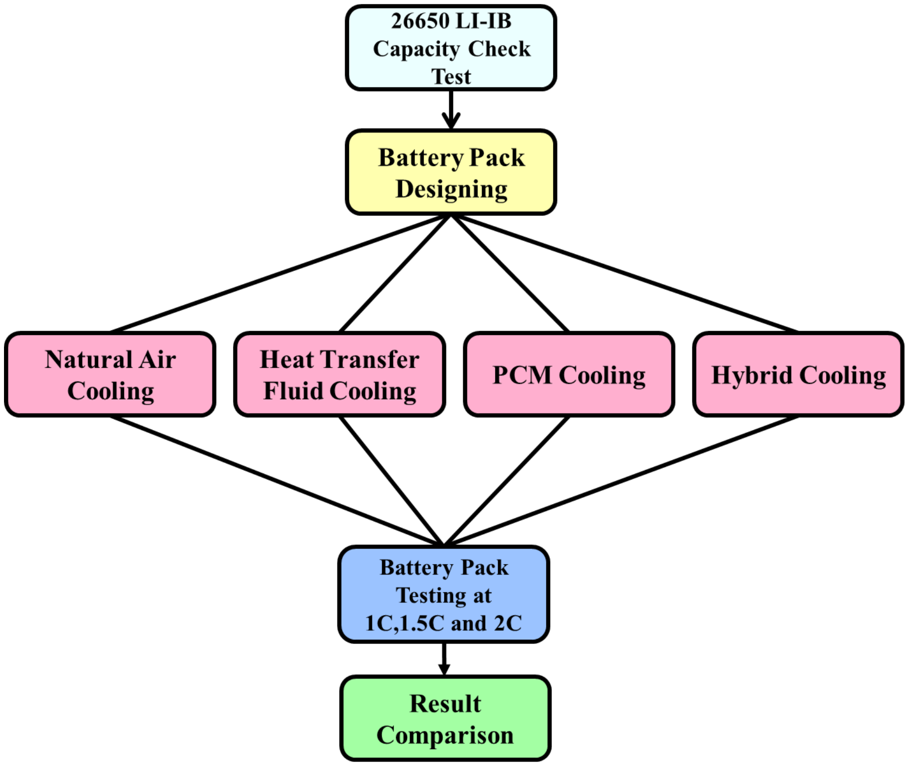

Figure 4.3. Flow chart of methodology

4.3 Natural air cooling

The natural air cooling setup mainly consists of a battery pack, a battery analyzer, and data loggers with thermocouples (Figure 4.4). The battery pack had a rectangular configuration with six 26650 Li-ion cells. Before the experiment, a comprehensive analysis of the battery pack was conducted to validate its capacity and voltage. Additionally, the temperature of each cell was precisely verified to ensure uniformity and consistency. A computer-controlled battery analyzer that changed the operational parameters of the cells was connected to the positive and negative terminals of the battery pack. The Li-ion cells were charged and discharged at various C rates, including 1C (5000mAh), 1.5C (7500mAh), and 2C (10,000mAh), to evaluate their thermal performance. The cell temperature was monitored using K-type thermocouples positioned at the midpoint height of the cell surface with a data logger. The use of natural air cooling for Li-ion batteries serves as the standard reference for evaluating the effectiveness of other cooling methods.

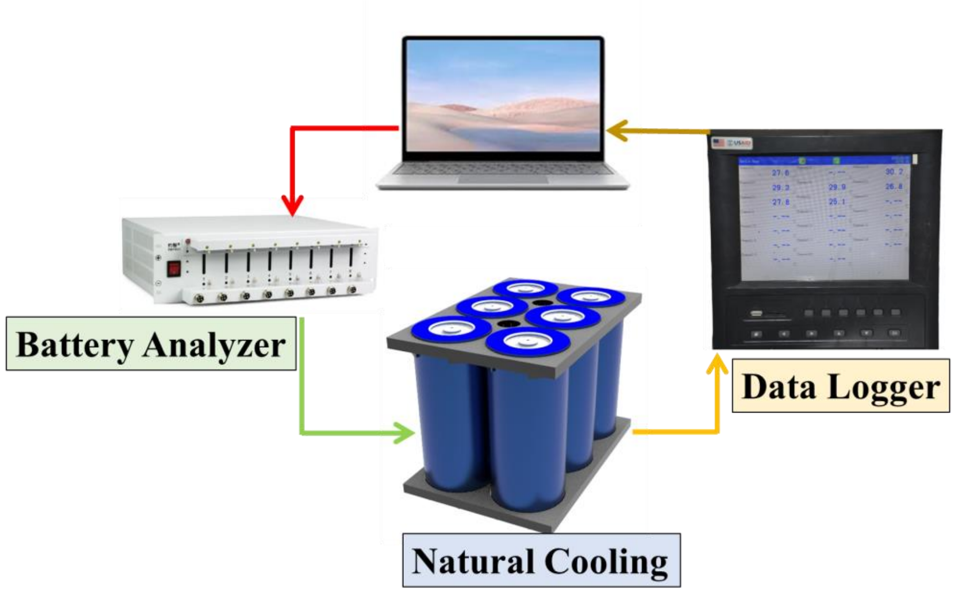

Figure 4.4. The schematic diagram of the natural Cooling experimental system

4.4 Heat transfer fluid cooling

The heat transfer fluid cooling system is composed of a pump, the liquid storage vessel, copper channels, cell box, computer-controlled battery analyzer, and data loggers (Figure 4.5). The copper channel design has a single inlet and a single outlet, connected by four flow headers and six flow channels. The heat transfer fluid enters the inlet and flows through two headers that distribute it evenly among the channels. Then, the heat transfer fluid is collected by the other two headers and exits through the exit tube (Figure 4.6). The dimensions of cooper channels are provided in Table 4.2. Water is used as the heat transfer fluid and the pump (multifunction submersible) maintains the water flow. The copper channels, which are in direct contact with the battery pack, extract heat from the pack and transfer it to the liquid storage vessel in a closed loop. Before starting the experiment, the temperature uniformity of the cells was ensured, and the same layout and structural arrangement were used.

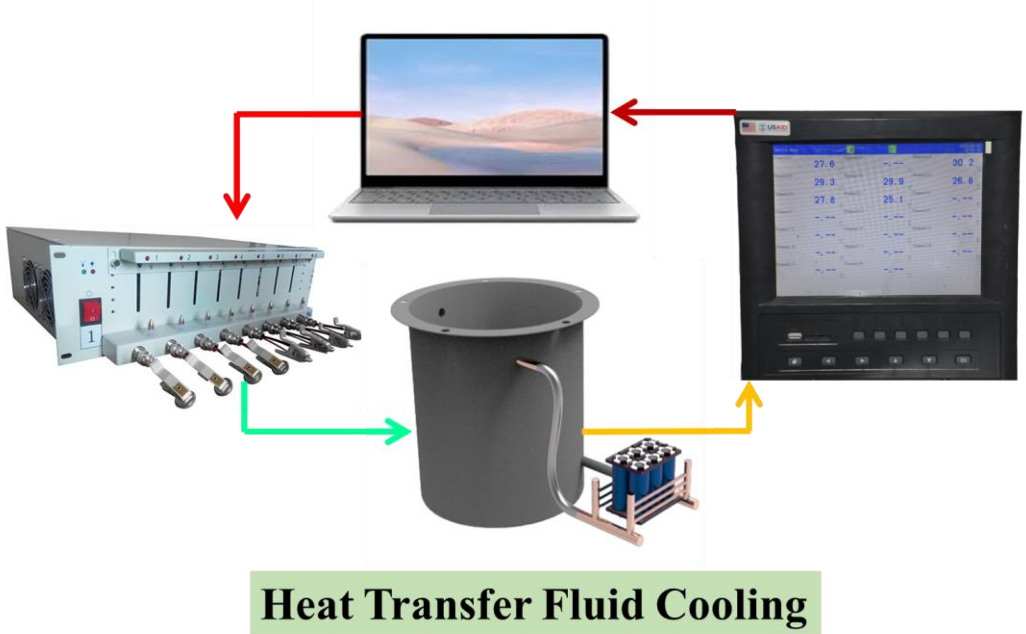

Figure 4.5. The schematic diagram of the heat transfer fluid cooling experimental system

Table. 4.2: The copper channel dimensions.

Dimensions	Nominal size inches	Length (mm)	Outer diameter (mm)	Inner diameter (mm)	Thickness (mm)
Inlet	3/8	100	12.70	10.21	1.24
Outlet	3/8	100	12.70	10.21	1.24
Flow header	1/4	50	9.53	7.75	0.89
Flow channel	3/16	110	4.76	3.48	0.64

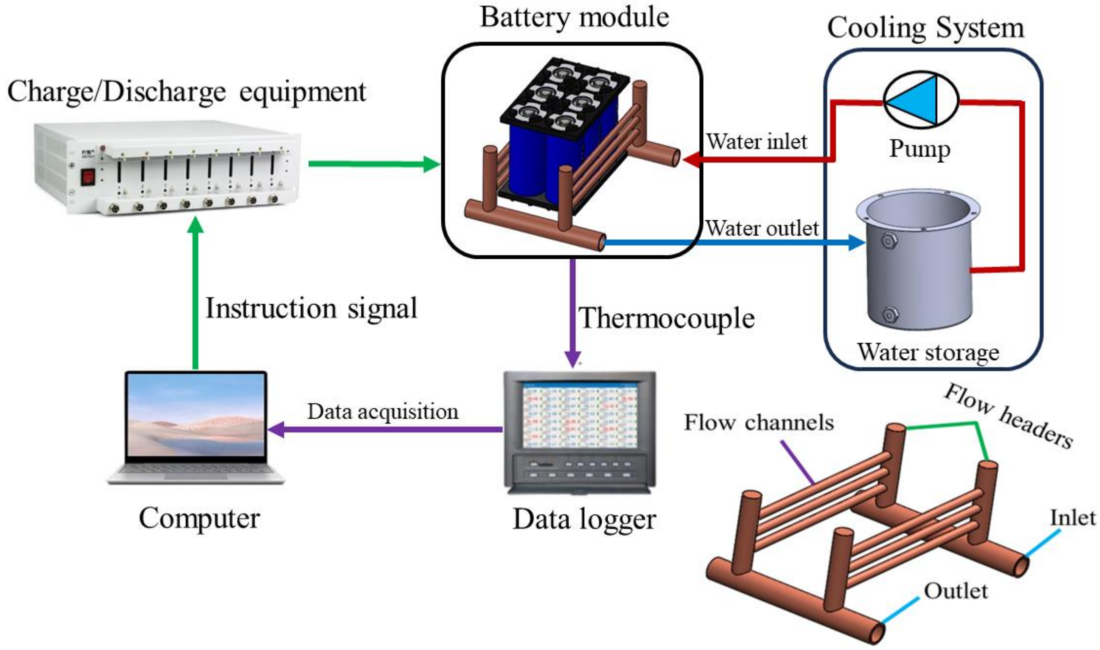

Figure 4.6. Heat transfer fluid cooling system

4.5 PCM Cooling

The PCM cooling setup mainly consists of a lauric acid/stearic acid eutectic PCM, cell box, a battery analyzer, and data loggers with thermocouples (Figure 4.7). The details of theoretical prediction and preparation of eutectic PCM are discussed in section 4.1. The PCM absorbs the heat from the LIBs pack in sensible form from room temperature up to 33.29 °C. After that, it absorbs the heat from the battery pack in latent form and changes its phase. The PCM cooling keeps the battery pack at a constant temperature with uniformity among them.

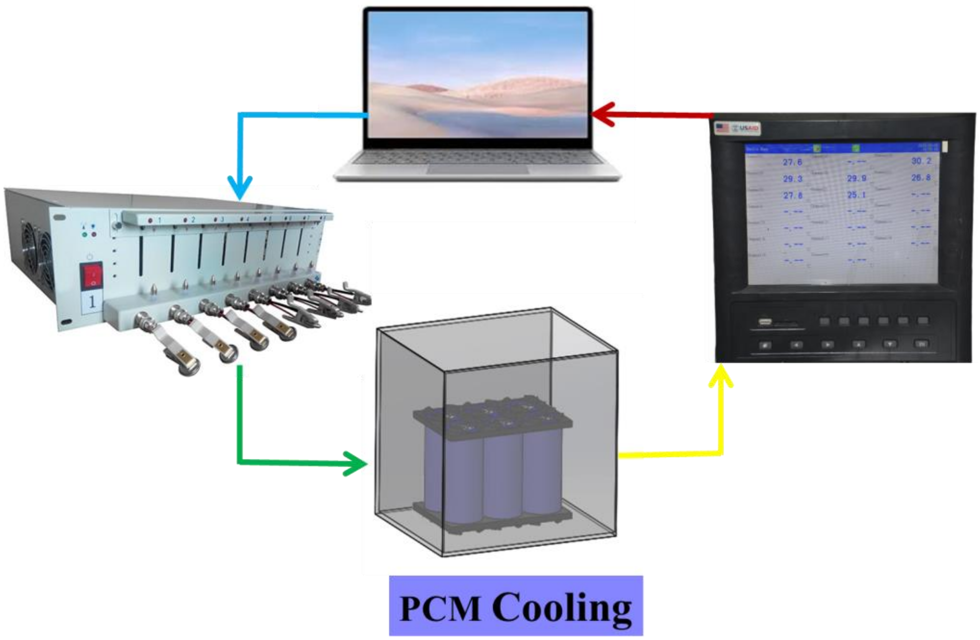

Figure 4.7. The schematic diagram of the heat transfer fluid cooling experimental system

4.6 Hybrid Cooling

Hybrid cooling combines the use of a heat transfer fluid and a PCM to cool down Li-ion cells. The PCM absorbs heat from the LIBs pack and keeps them at a constant temperature during the phase change process. The heat transfer fluid then removes the heat from the PCM and releases it to the environment. This method can lower the thermal resistance and enhance the heat dissipation performance of the battery pack. Hybrid cooling can also increase the safety and lifespan of the Li-ion cells by preventing thermal runaway and degradation. Figure 4.8 shows an example of this cooling system, where water is used as the heat transfer fluid, and SA/LA is used as PCM. SA/LA PCM can store a sensible and latent heat when it changes from solid to liquid. However, SA/LA PCM has a limited heat storage capacity. When the heat generated by the Li-ion cells exceeds the latent heat of PCM, the heat transfer fluid becomes necessary to extract the excess heat from the PCM.

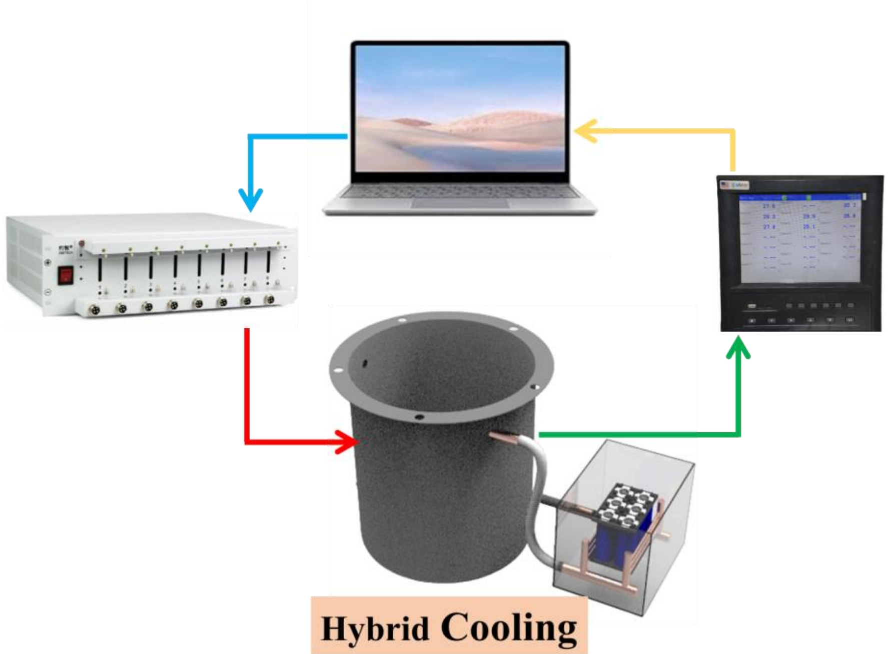

Figure 4.8. The schematic diagram of the Hybrid Cooling experimental system.

Summary

This chapter presents the research methodology, which follows a systematic and sequential approach to conduct the experiment. The main objective is to investigate the thermal performance of various cooling techniques for Li-ion batteries under different discharge rates (1C, 1.5C and 2C-rates). The cooling techniques include natural cooling, heat transfer fluid cooling, eutectic PCMs cooling and hybrid cooling. The chapter also describes the methods for predicting and preparing the eutectic composition of the PCMs and designing the copper channel for the heat transfer fluid cooling in detail.

Chap#5: Characterization of Phase Change Materials

5.1 Differential scanning calorimetry (DSC)

DSC thermal analysis was used in the determination of material's thermal properties, including its melting point, latent heat, crystallization, phase transitions, and reaction kinetics. Samples at and near to the theoretical eutectic composition of mixture were taken for thermal property analysis. DSC instrument (TA DSC250) that works on the principle of heat flux was used to characterize the mixture (Figure 5.1). The samples, each weighing 10 mg, were placed in an aluminium pan, and sealed with a lid. The samples were subjected to heating and cooling at a rate of 10°C/min, within the temperature range of 0°C and 100°C. The heat flow and temperature signals were recorded by the instrument. The latent heats and phase transition temperatures of the samples were obtained from the DSC curves.

Figure 5.1. DSC instrument (TA DSC250)

5.2 Thermo gravimetric analysis (TGA)

The thermal stability of PCM was investigated by using TGA 5500 instrument (TA Instruments, USA) as shown in Figure 5.2. The instrument was equipped with a nitrogen gas to prevent any unwanted reactions before the sample reached its decomposition temperature. A 10 mg sample of PCM was placed on a pan inside a furnace. The sample was heated at a rate of 10 °C/min, within the temperature range of 25°C to 300°C. The instrument recorded the weight loss of the sample as a function of temperature. The TGA curve shows the thermal stability of the eutectic PCM. The region on the TGA curve where the sample weight decreases significantly indicates the decomposition temperature of the PCM.

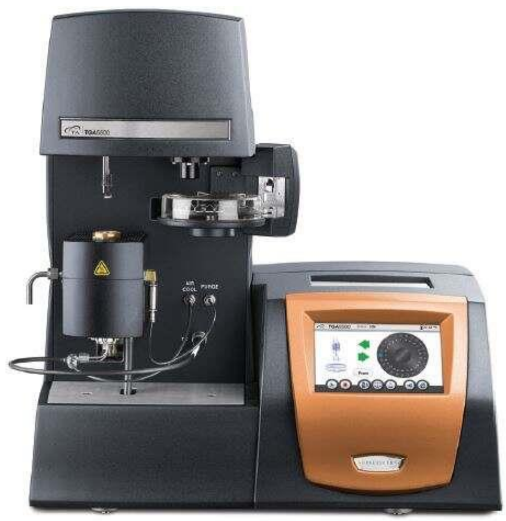

Figure 5.2. TGA instrument (TA TGA5500)

5.3 Thermal conductivity

The thermal conductivity of the PCM was measured by using a DTC 300 instrument (TA Instruments, USA), which operates under a guarded heat flow test method, ASTM-E1530 (Figure 5.3). This method is based on creating a steady state heat flow through a sample material and measuring the temperature difference across the material. The thermal conductivity is calculated by using Fourier's law of heat conduction. The sample of PCM was prepared as a solid round disk with a diameter of 50 mm and a thickness of about 18.86 mm. The sample was placed between two plates with known thermal conductivities and temperatures. The thermal conductivity measurements were performed at set point of 16.63°C.

Figure 5.3. DTC instrument (TA DTC 300)

Summary

The chapter provides a detailed characterization of eutectic PCM that have improved thermal performance compared to pure PCMs. DSC and TGA as the main analytical methods to evaluate the latent heat, melting temperature, and maximum operating temperature of the eutectic PCMs, which are important parameters for thermal energy storage applications in LIBs pack. The thermal conductivity of the eutectic PCMs was also investigates, which is a key factor for enhancing the heat transfer rate and reducing the charging and discharging time.

Chap#06: Results and discussion

6.1 DSC of eutectic PCM SA/LA

Figure 6.1 illustrates the results of the DSC analysis of the eutectic mixture (SA/LA). The endotherm curve corresponds to the heat flow that the SA/LA sample absorbs from the surroundings when it changes from solid to liquid state, which is known as melting. The exotherm curve corresponds to the heat flow that the SA/LA sample releases to the surroundings when it changes from liquid to solid state, which is known as freezing. The onset temperature of the endotherm peak is 30.40°C, which indicates the temperature at which the melting of the eutectic PCM begins. The peak temperature of the endotherm curve is 33.29°C, which indicates the temperature at which the melting of the eutectic PCM is completed. Similarly, the onset temperature of the exotherm peak is 29.25°C, which indicates the temperature at which the freezing of the eutectic PCM begins. The peak temperature of the exotherm curve is 28.18°C, which indicates the temperature at which the freezing of the eutectic PCM is completed. The results show that SA/LA absorbs a latent heat of 151.76 J/g during melting and releases a latent heat of 147.09 J/g during freezing. The high latent heat and low melting point of SA/LA make it a suitable material for BTMS applications.

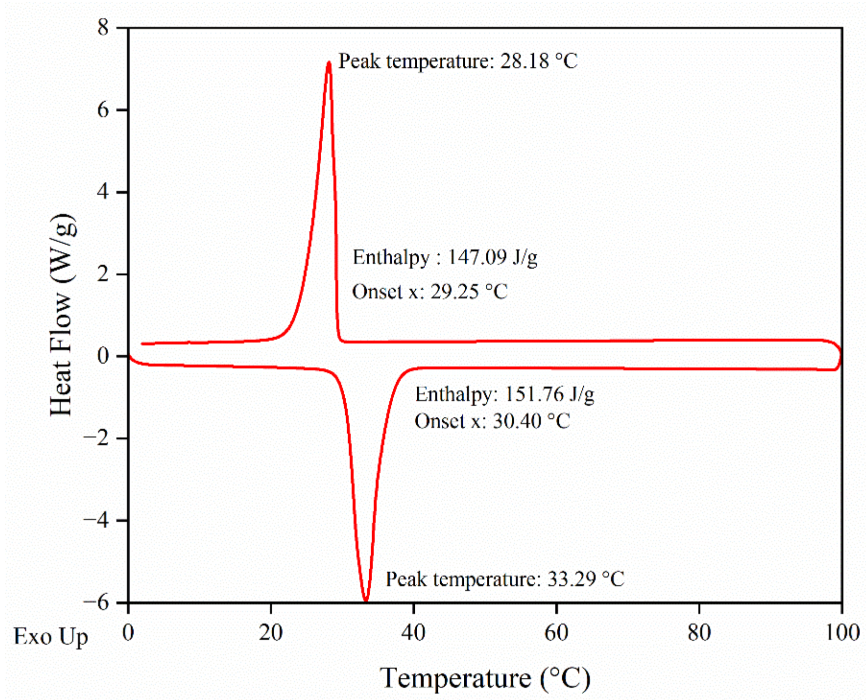

Figure 6.1. DSC of eutectic PCM SA/LA

6.2 TGA of eutectic PCM SA/LA

The result of TGA analysis showing reduction in sample weight with respect to increasing temperature is plotted in Figure 6.2. The estimated decomposition temperature of the SA/LA eutectic PCM was found from the plot is 160 °C. However, this temperature is much higher than the typical operating temperature range of PCMs in BTMS applications, which is usually below 100 °C. Therefore, the SA/LA eutectic PCM exhibits excellent thermal stability and can withstand repeated heating and cooling cycles without significant degradation. This makes the PCM a promising candidate for thermal energy storage applications in BTMS.

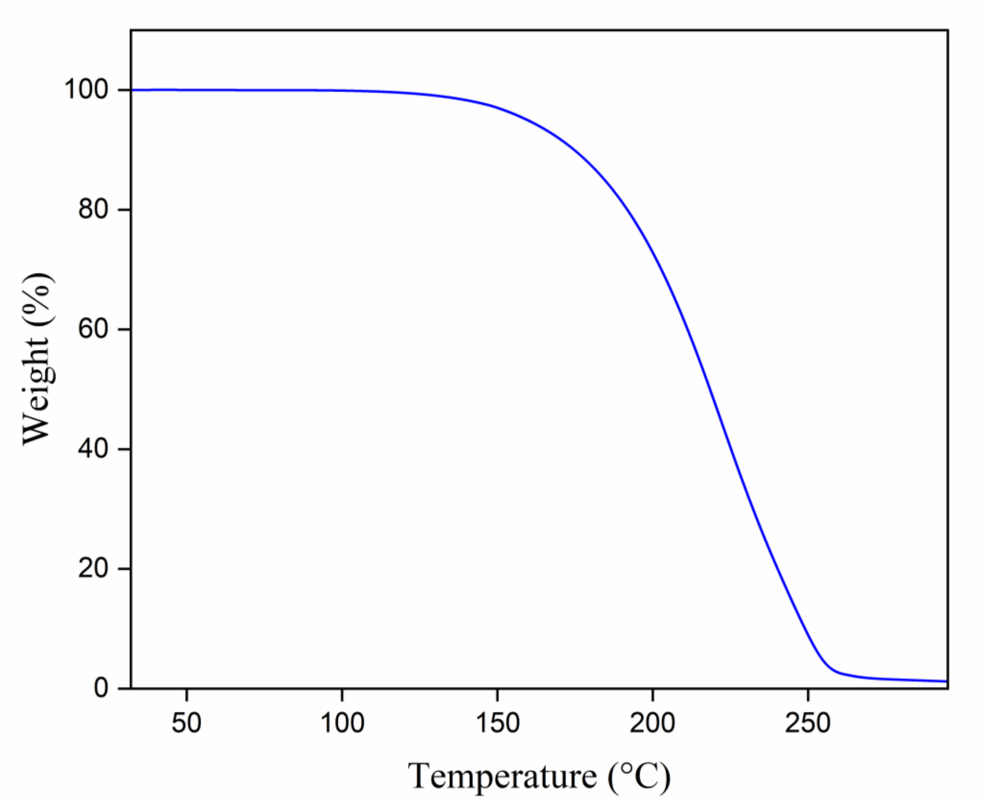

Figure 6.2. TGA of eutectic PCM SA/LA

6.3 Thermal conductivity

The eutectic SA/LA PCM thermal conductivity was measured to be 0.356 W/mK at a setpoint of 16.63°C, which should be an excellent choice for BTMS application. This is because the eutectic SA/LA PCM has a low melting point of about 33.29°C and a high latent heat of fusion of about 151.76 J/g, which means it can store and release a large amount of heat during the phase change process. Moreover, the SA/LA PCM has a good thermal stability and compatibility with other materials, such as expanded graphite and carbon nanotubes, which can enhance its thermal conductivity and mechanical properties. Therefore, the eutectic SA/LA PCM can effectively regulate the temperature of the battery pack and improve its performance and lifespan.

6.4 Battery pack thermal performance under natural air cooling

The battery pack was subjected to the following charge and discharge test experiments: 1C, 1.5C, and 2C rates when room temperature is around 25°C. The battery module was charging with a constant current-constant voltage (CC-CV) approach and discharging with a constant current (CC) approach. The CC-CV approach consists of two stages: CC and CV. In the CC stages, the battery pack temperature rises continuously until it reaches the stop voltage (3V). Then, the system switches to the CV mode automatically. The charging current in this mode reduces gradually until it reaches the stop current (0.5A) to charge the battery module to 100%. The temperature data were recorded for each cycle (Figure 6.3). In this study, the temperature of the whole battery pack undergoes a gradual increase during the charging and discharging processes and a gradual decrease during the rest process. The experiment involved three charging-discharging cycles to evaluate the actual performance of the cooling methods in EV's. To stabilize the voltage of the battery pack, 20 minutes of rest time is provided after each charging and discharging cycle. In natural air cooling, the battery pack reaches a maximum temperature of 66.9°C, 57.9°C, and 45.6°C when subjected to 2C, 1.5C, and 1C charging-discharging rates. The battery temperature in this study is much higher than the ideal working temperature range for Li-ion batteries (between 15 °C and 40 °C), which can negatively affect the lifetime, performance, capacity, and safety of the battery cells. Additionally, the temperature distribution of the pack is non-uniform, where the mid-cell temperature is higher than the lateral cells. The generated heat dissipated more easily from the outer cells to the environment rather than the inner cell with natural air cooling. The maximum temperature difference between the cells was 7.6°C at a 2C rate, suggesting an effective BTMS is needed for the power battery module. Table 6.1 presents the peak temperature rise and the surface temperature difference of the Li-ion cells under natural air cooling.

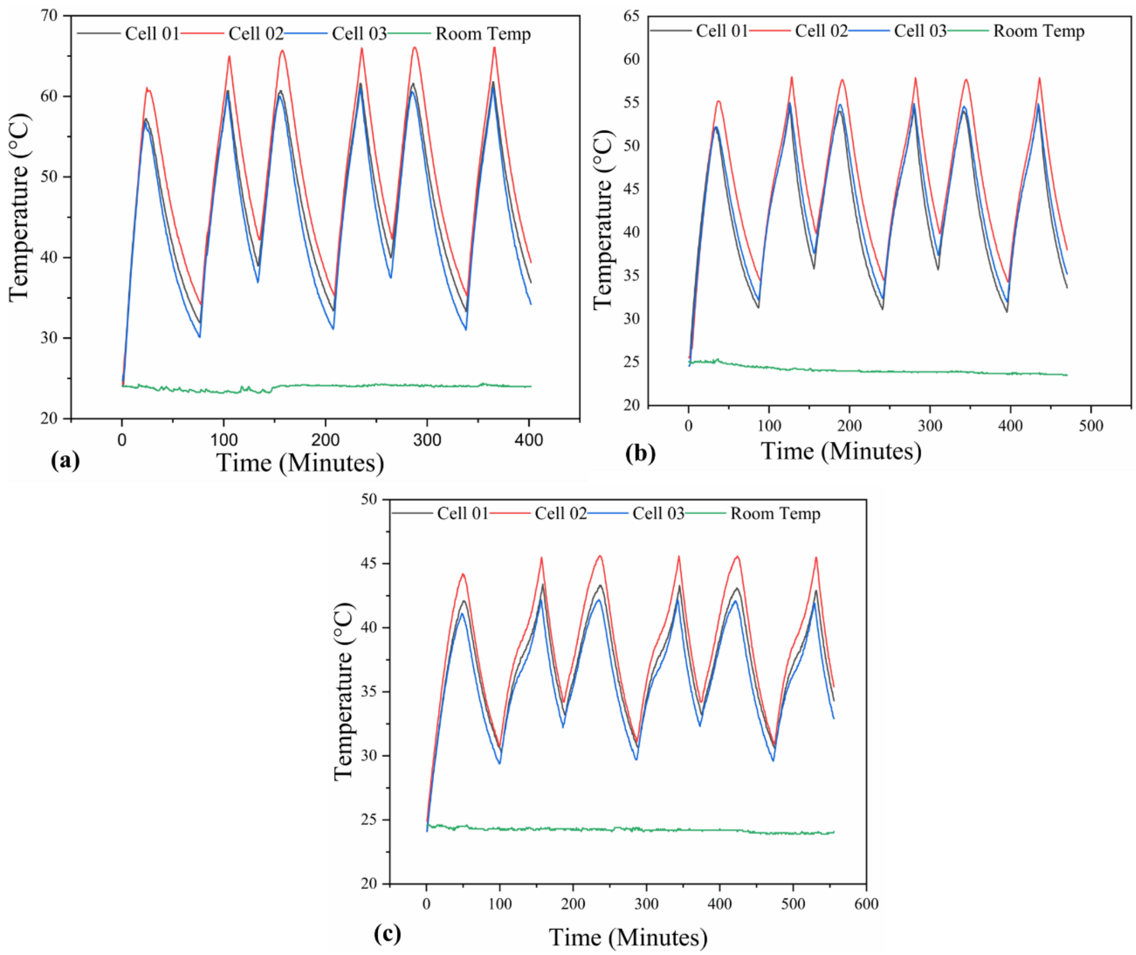

Figure 6.3. Temperature variations of battery cells using natural cooling (a) 2-C rate (b) 1.5-C rate (c) 1-C rate

6.5 Battery pack thermal performance using heat transfer fluid cooling

The Li-ion battery pack was placed in an experiment box to perform charge and discharge experiments at room temperature of 25°C, and the heat transfer fluid cooling cycle was started simultaneously. The temperature distribution over the battery pack surface (Figure 6.4). The water pump maintains a flow rate of 8 L/min with a constant inlet temperature of 25 °C. The liquid storage vessel contains 5 liters of water. The copper channel, which is in direct contact with the Li-ion battery pack, conducts the heat from the battery pack and transfers it to the water circulating through the cycle. Three testing cycles were performed on the battery pack, and temperature data were recorded using thermocouples. The heat transfer fluid cooling system leads to a lower battery pack maximum temperature than air cooling due to the larger water cooling capacity. However, the temperature of the mid cell with the heat transfer fluid cooling system is significantly hotter than the side cell due to heat accumulation. The peak temperature of the Li-ion cells was effectively regulated using a water-based cooling system, with the peak temperature observed in all three cycles being approximately the same. Compared to natural air cooling, it was found that by utilizing the heat transfer fluid cooling the battery pack maximum temperature is reduced from 66.9°C to 51.9°C during 2C charge-discharge experiment, with temperature difference between the cells maintained below 3.5°C. Additionally, at 1.5C and 1C charge-discharge experiment, the maximum temperature drops to 43.7°C and 36.9°C, respectively, from 57.9°C and 45.6°C, which were found during natural air cooling.

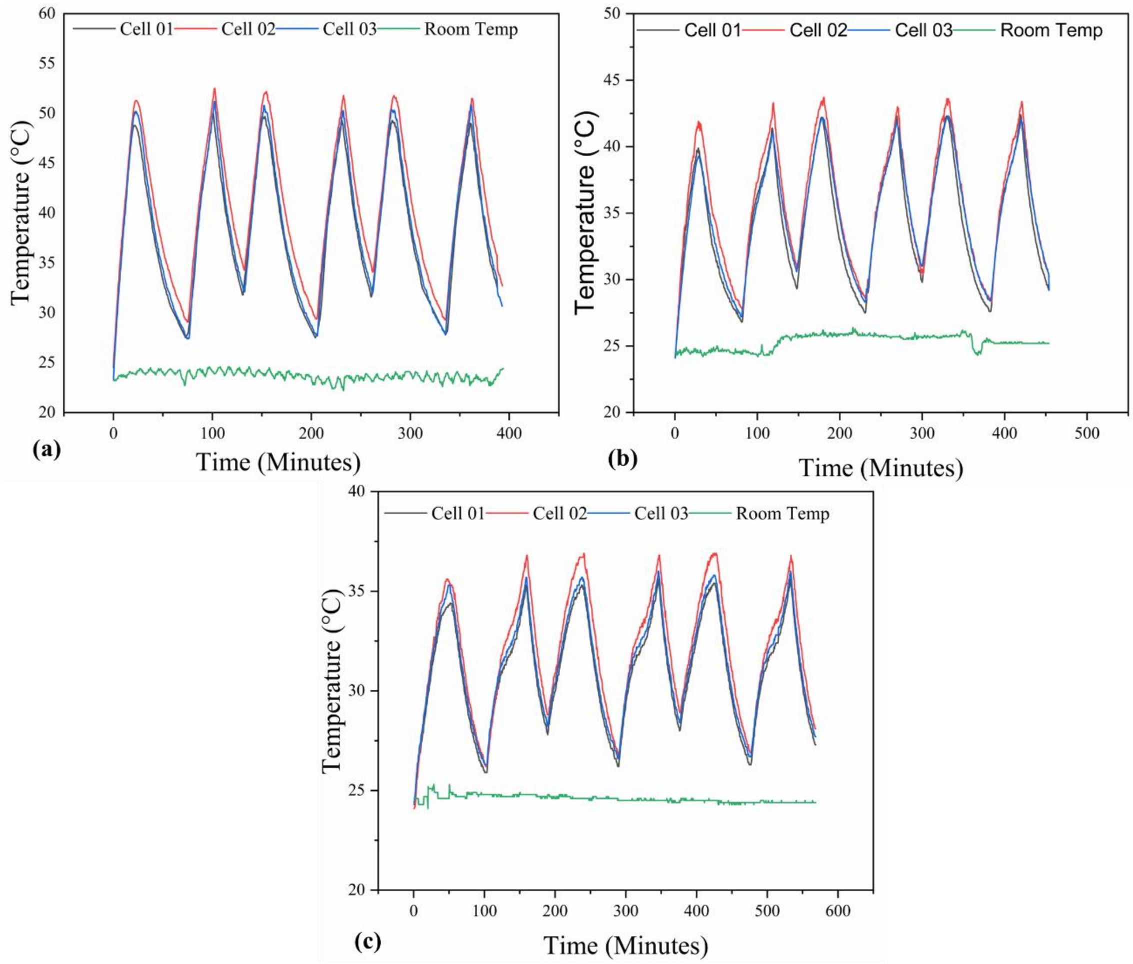

Figure 6.4. Temperature variations of battery cells using heat transfer fluid cooling (a)2-C rate (b)1.5-C rate (c) 1-C rate

6.6 Battery pack thermal performance using PCM cooling

The results of the temperature distribution of PCM cooling are shown in Figure 6.5. The battery pack was enclosed within an acrylic sheet box, with a 600g eutectic PCM comprised of LA and SA. The melting temperature of SA/LA PCM is 33.29°C, with a latent heat of 151.76 J/g. In this study, we found that by employing PCM, the temperature pattern shows a gradual increase in the temperature profile of the battery module, implying that the PCM effectively dissipated the heat produced by the Li-ion battery. Additionally, PCM significantly influences temperature fluctuations during the charging discharging cycle. It was noted that the PCM absorbed the heat from the Li-ion battery from 25°C to 33°C without changing phase, and the heat stored was as sensible. However, when the Li-ion battery pack temperature reaches the melting point of 33.29°C, PCM shifts from solid to liquid, stored the heat as latent. During the rest time of 20 minutes, the PCM initiated to freeze at 33.29°C and almost completely solidified at 28.18°C. The maximum temperature of the battery pack was 39.5 °C, 36.7°C, and 34.5°C, at charging discharge rates of 2C, 1.5C, and 1C, respectively, with the maximum temperature difference between the cells is 2.4°C. Compared to the natural air cooling method, the PCM-based method achieved a significant temperature drop of 27.4°C, indicating better thermal performance. Furthermore, the PCM-based method also improved the temperature uniformity, which is vital for preventing thermal runaway and prolonging battery life.

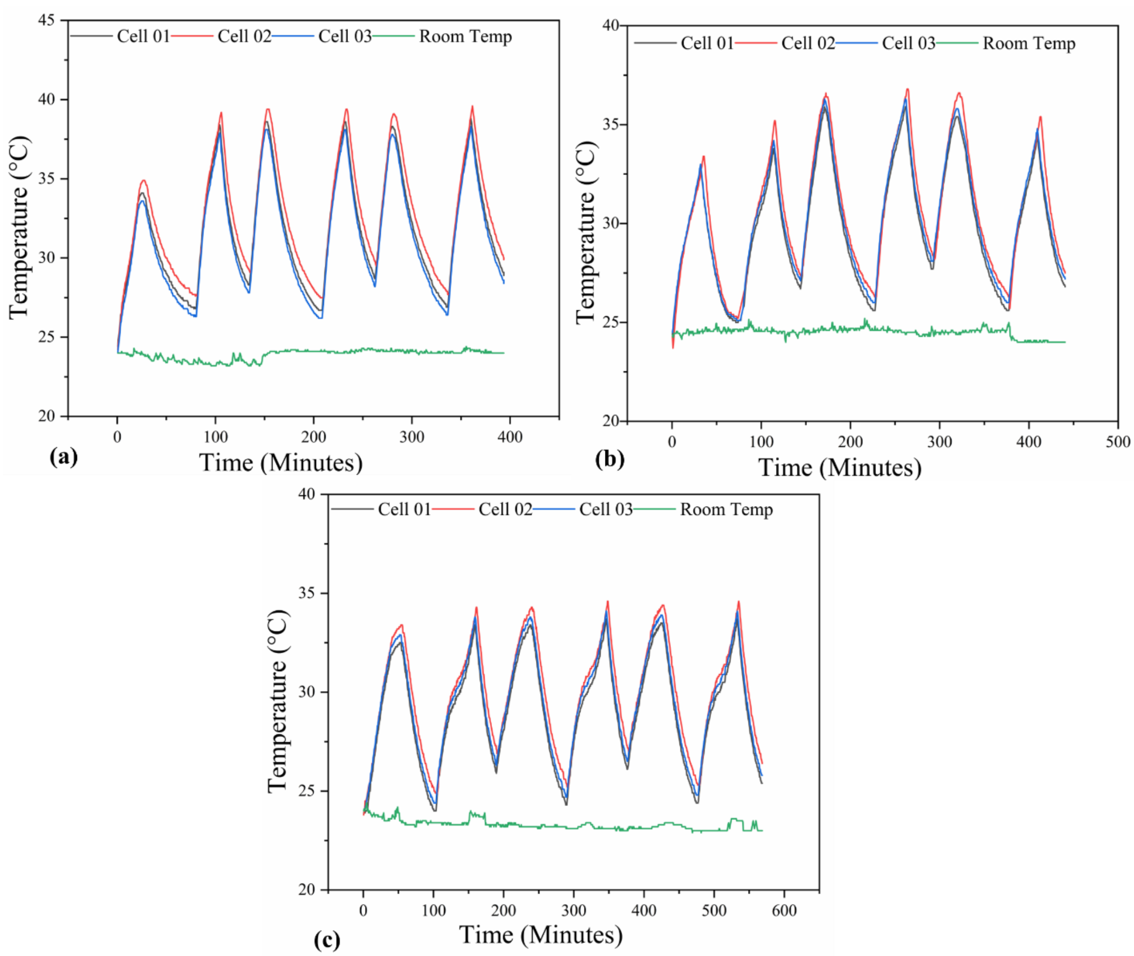

Figure 6.5. Temperature variations of battery cells using PCM cooling (a)2-C rate (b)1.5-C rate (c) 1-C rate

6.7 Battery pack thermal performance using hybrid cooling

Despite the significant thermal performance of PCM cooling, a common issue with PCM is its ineffective secondary heat dissipation, specifically in hot conditions. In this study, a hybrid PCM based battery pack is introduced that uses water flow inside the copper channel to improve secondary heat dissipation. The SA/LA PCM, which absorbs the heat from the Li-ion cells, transfers it to the channel. The water flows inside the copper channel with an inlet temperature of 25°C, taking the heat from the PCM and battery pack and dissipating it to the environment. By facilitating the rapid solidification of PCM and enhancing the heat dissipation to the environment, hybrid cooling helps the battery pack cool faster in harsh conditions. The temperature distribution over the battery pack surface is shown in Figure 6.6. At charging discharge rates of 2C, 1.5C, and 1C, the peak temperature of the battery pack attains the maximum values of 36°C, 31.8°C and 29.2°C, respectively, with a maximum temperature difference of 1.4°C among them. The hybrid cooling method exhibited superior performance at high C-rates by reducing the temperature up to 30.9°C, which was much lower than the natural air cooling method.

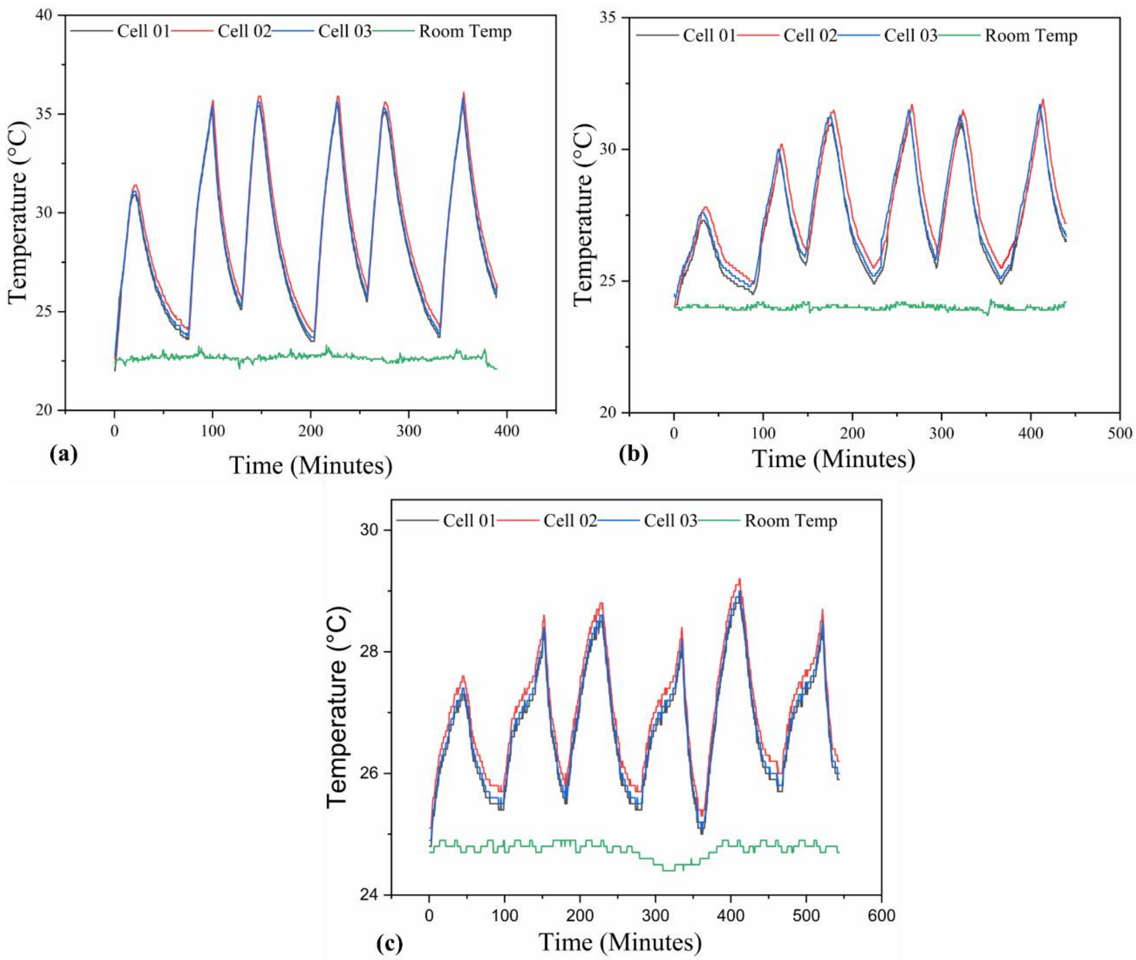

Figure 6.6. Temperature variations of battery cells using hybrid cooling (a)2-C rate (b)1.5-C rate (c) 1-C rate

Table. 6.1: Comparison of temperature during various charge/discharge C-rates under different cooling techniques.

Cooling Techniques	Maximum temperature (°C)			(%) of reduction in temperature (°C)		
	2C	1.5C	1C	2C	1.5C	1C
Natural Cooling						
Cell 1	61.7	54.4	43.3	-	-	-
Cell 2	66.9	57.9	45.6	-	-	-
Cell 3	61.0	54.9	42.2	-	-	-
Heat transfer fluid Cooling						
Cell 1	50.0	42.4	35.6	18.96	22.42	17.78
Cell 2	51.9	43.7	36.9	22.42	24.52	19.07
Cell 3	51.2	42.3	36.0	16.06	22.95	14.69
PCM Cooling						
Cell 1	38.8	35.9	33.7	37.10	34.00	22.17
Cell 2	39.5	36.7	34.5	40.90	36.61	24.34
Cell 3	38.3	36.3	34.0	36.88	33.87	19.43
Hybrid Cooling						
Cell 1	35.6	31.3	28.8	42.30	42.46	33.48
Cell 2	36.0	31.8	29.2	46.18	45.07	35.96
Cell 3	35.8	31.6	28.9	41.31	42.44	31.51

6.8 Comparison of cooling effect

A comparative analysis of four different cooling techniques of single charging and discharging tests at various C-rates, as shown in Figure 6.7, assessed the cooling performance of the battery pack. The ambient temperature was almost identical for all cooling methods. Natural air cooling was used as the benchmark, and all the other cooling methods were compared with it. The maximum natural cooling temperature at 2C-rate was 61.1°C and 65°C in the charging and discharging cycle. Using heat transfer fluid, the maximum temperature of the Li-ion battery was dropped to 51.3°C and 52.5°C in the charging and discharging cycle, which is much higher than the ideal operating range of Li-ion battery. Heat transfer fluid cooling cannot keep the Li-ion battery temperature within the safe operating limit at a high C-rate. The temperature drop was 24% and 25.34% at the charging and discharging cycle. PCM cooling can play an important role in dissipating the heat generated by the battery pack and keeping it within the safe operating range. However, the PCM has a low heat transfer rate to the ambient, which results in a prolonged solidification process at high C- rates. The maximum temperature in PCM cooling was 34.9°C and 39.2°C, with a temperature drop of 42.9% and 39.6% at 2C-charging and discharging cycles. Hybrid cooling plays a vital role in dissipating the heat from the PCM faster and maintaining it within the safe operating range at high charging discharging cycle. The temperature drop was 49.6% and 51.69% in the charging and discharging cycle. This work achieved a lower maximum battery temperature than similar work that operated in a continuous mode. Table 6.2 presents a comparative analysis of the present work and the literature results. It reveals that the present work has achieved superior results in terms of reducing the maximum temperature and enhancing the temperature uniformity of the battery pack.

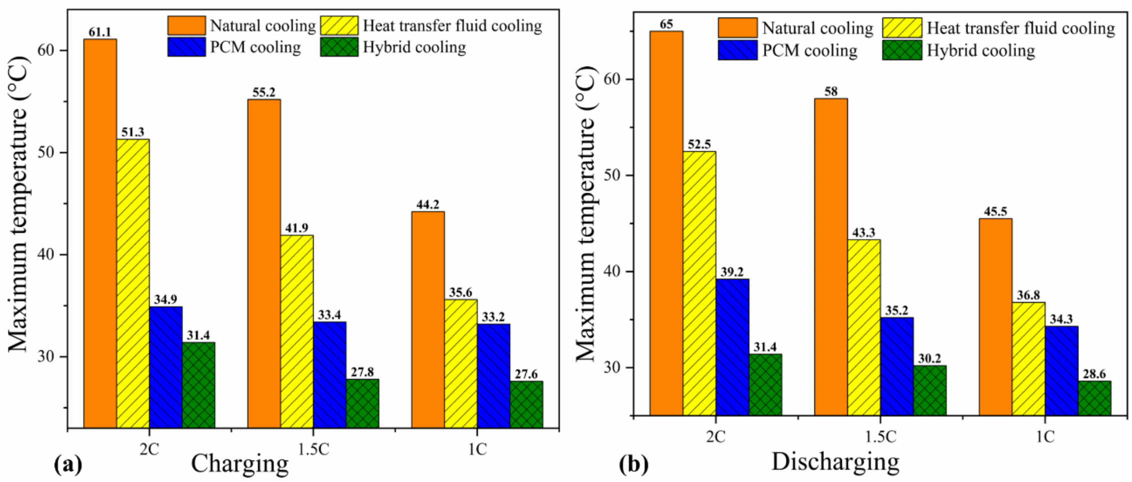

Figure 6.7. Maximum temperature of Li-ion cell using natural cooling, heat transfer fluid cooling, PCM cooling and hybrid cooling at varying c rate of (a) charging (b) discharging

Table. 6.2: Comparison of the present work with literature results.

Source	**Rajan et al.** [79]	**Lv et al.** [80]	**Present Study**
Cooling system	PCM Cooling	Liquid+ graphene oxide-modified silica gel cooling	Heat transfer fluid+ eutectic PCM cooling
Battery module detail	LiFePO4 battery pack	LR1865SK battery pack	NMC battery pack
Approach	Experimental/simulation	Experimental	Experimental
Cell capacity	6000 mAh	2000 mAh	5000 mAh
Discharge rate	2C	2C	2C
Maximum temperature	49.34°C	63.5°C	66.9°C
Temperature drops	13.17%	38.58%	46.18%

Summary

The chapter discusses the results of DSC, TGA, and thermal conductivity measurements of SA/LA PCMs in detail. The eutectic PCM has a melting temperature of 33.29°C, a latent heat of 151.76 J/g, and a thermal conductivity of 0.356 W/mK. The chapter also explains the effects of different cooling methods on the performance of LIBs packs at various discharge rates (1C, 1.5C, and 2C). The cooling methods include natural cooling, heat transfer fluid cooling, PCM cooling, and hybrid cooling. Results indicate that with natural air cooling, the battery pack reaches maximum temperatures of 66.9°C, 57.9°C, and 45.6°C when charging and discharging at 2C, 1.5C, and 1C rates, respectively. Compared to natural air cooling at the 2C rate, heat transfer fluid cooling reduced the maximum temperature by 22.42%, eutectic PCM cooling by 40.90%, and hybrid cooling by 46.18%. Correspondingly, the inter-cell temperature differences diminished by 53.94%, 68.42%, and 81.57% for heat transfer fluid, PCM, and hybrid cooling techniques, respectively.

Chap#7: Conclusions and Recommendations

7.1 Conclusions

In this study, the thermal performance of a Li-ion battery pack was experimentally investigated, employing four different cooling techniques: natural cooling, heat transfer fluid cooling, eutectic SA/LA PCM cooling, and hybrid cooling. Each method was subjected to three charge-discharge cycles at high C-rates, revealing significant variations in thermal efficiency. Based on the experimental results, the major findings are summarized below:

- **Natural Cooling**: The Li-ion battery pack experienced significant temperature rises across all C-rates. Specifically, peak temperatures reached were 66.9°C, 57.9°C, and 45.6°C for 2C, 1.5C, and 1C rates, respectively, with a maximum inter-cell temperature difference of 7.6°C.
- **Heat Transfer Fluid Cooling**: This method kept the maximum temperatures to 51.9°C, 43.7°C, and 36.9°C for 2C, 1.5C, and 1C, respectively. The temperature difference between battery cells was reduced to 3.5°C. Notably, this technique struggled to maintain safe operating temperatures at higher C-rates.
- **Eutectic PCM Cooling**: Demonstrating enhanced uniformity in temperature distribution, the peak temperatures were reduced to 39.5°C, 36.7°C, and 34.5°C for 2C, 1.5C, and 1C rates, respectively. The maximum temperature difference between cells was further reduced to 2.4°C.
- **Hybrid Cooling**: Representing the most efficient method, it reduced peak temperatures to 36°C, 31.8°C, and 29.3°C for 2C, 1.5C, and 1C rates, respectively, with an inter-cell temperature difference of just 1.4°C.

Compared to natural air cooling, heat transfer fluid cooling reduced the battery pack's maximum temperature by 22.42%, PCM cooling by 40.90%, and hybrid cooling by 46.18%. Correspondingly, the inter-cell temperature differences diminished by 53.94%, 68.42%, and 81.57% for heat transfer fluid, PCM, and hybrid cooling techniques, respectively.

In conclusion, while natural cooling proved least effective, hybrid cooling showcased superior thermal management capabilities, emphasizing the potential of integrating heat transfer fluids with eutectic PCMs for Li-ion battery packs, especially in high-temperature environments.

7.2 Recommendations

The thermal management of large-capacity battery packs is a significant challenge, as the battery pack temperature can exceed the current research limits. In regions where the average summer temperature surpasses 40 ℃, the battery performance deteriorates. Based on our research, we suggest the following measures:

- Investigate the effects of various nanomaterials, such as expanded graphite and carbon nanotubes, on the thermal properties and performance of PCM-based battery pack cooling systems, which can enhance the low thermal conductivity of PCM.
- Compare the thermal performance of different heat transfer fluid, such as ethylene glycol, water-ethylene glycol mixture, coolant and refrigerant, for battery pack cooling systems.
- Evaluate the effects of the hybrid cooling system design parameters, such as the PCM mass, the PCM layer thickness, the cooling channel geometry, and the copper plate usage, on the thermal management of the LIB pack.

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APPENDIX-I

A state-of-the-art review on heating and cooling of lithium-ion batteries for electric vehicles

Abstract

Currently, lithium-ion batteries are attracting the attention of various sectors, such as the automobile, electronics, and aerospace industries, due to their remarkable characteristics, including high energy density, power density, and superior operational performance, when compared to other batteries. However, these batteries face challenges such as performance loss and thermal runaway due to temperature variations. Electric vehicles need to operate both in warm and cold climates, which demand lithium-ion to maintain optimal performance at various temperature levels. In past decades, numerous investigations have been conducted to examine the thermal management techniques employed in lithium-ion batteries. This study examines and categorizes the recent research progress of battery thermal management systems, including both external and internal preheating techniques and active, passive and hybrid cooling techniques. It also evaluates different thermal management technologies from multiple aspects, such as; heating and cooling performance, system simplicity, internal temperature difference, adaptability and safety.

Journal Name

Journal of Energy Storage (Published)

APPENDIX- II

Hybrid Thermal Management of Li-ion Battery Pack: An Experimental Study with Eutectic PCM-Embedded Heat Transfer Fluid

Abstract

Lithium-ion (Li-ion) batteries are widely used in the automobile, electronics, and aerospace industries due to their low self-discharge rate, extended lifespan, high efficiency, high power density, and superior operational performance. However, under extreme operating conditions, Li-ion batteries generate significant heat, which degrades their performance and can lead to thermal runaway. An appropriate cooling system is essential to improve battery life, safety, capacity, and performance. This study investigates the effects of various cooling methods on a 5000 mAh Li-ion battery pack during charging and discharging at 1C, 1.5C, and 2C rates. The cooling techniques evaluated are natural cooling, heat transfer fluid cooling, eutectic PCM cooling, and hybrid cooling. The eutectic PCM comprises lauric acid and stearic acid, with a melting temperature of 33.29°C, a latent heat of 151.76 J/g, and a thermal conductivity of 0.356 W/mK. Experimental results indicate that with natural air cooling, the battery pack reaches maximum temperatures of 66.9°C, 57.9°C, and 45.6°C when charging and discharging at 2C, 1.5C, and 1C rates, respectively. Compared to natural air cooling at the 2C rate, heat transfer fluid cooling reduced the maximum temperature by 22.42%, eutectic PCM cooling by 40.90%, and hybrid cooling by 46.18%. These findings demonstrate that hybrid cooling significantly reduces both the maximum surface temperature and the temperature gradient, suggesting it as an effective method for cooling battery packs.

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