Thermal Management of Li-ion Batteries by using Active and Passive Cooling Techniques

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Session 2018-20

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THESIS ACCEPTANCE CERTIFICATE

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Dedication

To ***Almighty Allah****, for his blessings throughout my work.*

To my Parents, for their endless support and encouragement.

To my friends who helped me out during the tough phases of my research work. And to my dearest homeland, Pakistan

ABSTRACT

To enhance the safety of Li-ion batteries, it is crucial to understand their behavior when exposed to high temperature. The structural arrangement and identical cell spacing with use of proper thermal management system are key aspects related to safety of Li-ion batteries. In this study a battery pack was constructed by using nine 26650 Li-ion cells, which are discharged on 1C rated and series of experiments conducted on different battery pack thermal management systems including air cooling and PCM based thermal management of battery pack to evaluate the effects of thermal management on the performance of the battery pack. Inorganic phase change material sodium sulphate decahydrate was used to evaluate the thermal management of battery pack. The results show the hike in temperature of battery pack of about 10 ℃ in normal air-cooling operation of battery when discharged at 1C rate, as in comparison with forced air cooling the maximum temperature hike was about 7 ℃ and in PCM based thermal management system was the temperature hike was up to 4.4 ℃. each monitored cell temperature was also analyzed for each thermal management system. With the help of simple modeling, it shows the maximum temperature hike on normal operation for the battery can be reduced up to about 4.2 ℃ and by 6.4 ℃ by using forced air cooling and PCM based thermal management system respectively. It was also analyzed that PCM based thermal management systems does not show any sharp hike in temperature of battery pack cell, which indicated that PCM used properly thermally managing the battery heat. On comparison between these three systems, it clearly shows that PCM based thermal management system having sodium sulphate decahydrate as PCM shows the best result in thermal management of battery pack which can be the potential candidate for future electric vehicles battery pack.

Keywords: Li-ion battery, cylindrical battery, battery thermal management systems, air cooling, phase change materials

Table of Contents

List of Figures

List of Tables

List of Publications

1. "Thermal Management of Li-ion Battery by Using Active and Passive Cooling Method", **Muhammad Waqas Nazar**; Naseem Iqbal; Majid Ali; Hassan Nazir; M. Zain Bin Amjad, Journal of Energy Storage (Under-review).
2. "Performance Assessment of Transformer-less Grid Connected HERIC Inverter Topology with Proportional Resonant Current Control", Abu Bakar Siddique; Hassan Abdullah Khalid; **Muhammad Waqas Nazar**, 3rd International Conference on Sustainable Energy Technologies (ICSET 2021) Peshawar, Pakistan.

List of Abbreviations/Nomenclature

PCM	Phase Change Material
BTMS	Battery Thermal Management Systems
EVs	Electric Vehicles
HEVs	Hybrid Electric Vehicles
MP	Melting Point

CHAPTER 1 INTRODUCTION

1.1 Introduction

Reduction of fossil fuel reserves, energy security, climate change, air pollution and carbon emissions are the world's biggest challenges [1]. It's an ethical and moral obligation to future generations to preserve our planet's sustainability, which cannot be done without replacing conventional energy sources with renewable ones, according to intergenerational theory [2], [3]. To maintain their energy output, it's critical to store them in batteries [4]. Batteries store chemical energy that can be converted into various forms. These challenges are the reason behind the use of electric vehicles (EVs) and hybrid electric vehicles (HEVs) [5]. In transportation sector, battery-powered emission-free automobiles are rapidly replacing conventional internal combustion engine vehicles [6], [7], [8]. Fig. 1.1 shows the increase in demand of electric vehicles from 2013-2025. HEVs and EVs widely powered by Li-ion batteries due to their , compact volume, higher energy density levels, lower self-discharge rate, higher energy density levels, no memory and longer service life [5], [9], [10]. The usage of Li-ion batteries in HEVs and EVs is increasing exponentially in the current decade and is predicted to reach 77% market share by the end of the decade [11]. These batteries are available in a variety of sizes and forms, such as coin cells, cylindrical, and pouch batteries. batteries [12]. Cylindrical batteries are commonly employed as EV energy sources due to their compact volume and higher energy density [13].

Li-ion batteries are much safer as compared to lead-acid batteries and when working, it is easy to control them [14]. These batteries are eco-friendly because they do not contain heavy metal ions as compared to nickel-cadmium. Due to compact volume and greater energy density, these batteries are light in weight. Even though these batteries are one of the most effective energy storage system available but they have numerous disadvantages, including low energy density, degradation and high cost as compared to internal combustion engines. Lithium-ion batteries operate efficiently in temperatures ranging from 20–40 ºC, [15] and research also proves that in this range, batteries perform optimally [16], [17].

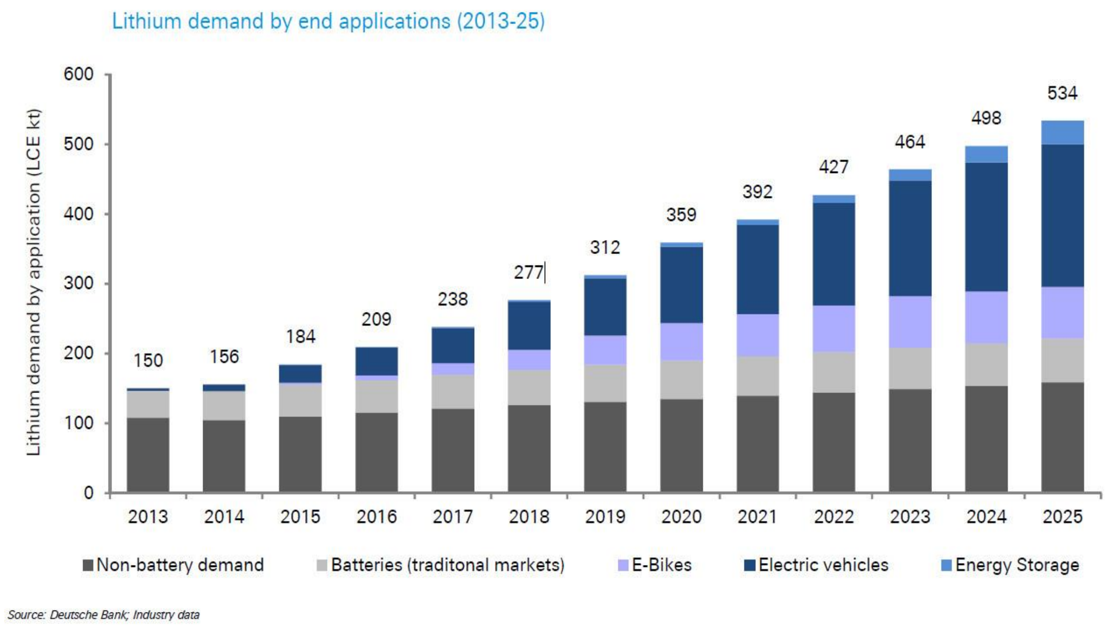


Figure 1.1 Lithium demand from 2013-2025 with respect to applications.

Conventional batteries are employed for charge or current applications. However, a significant current is required during fast charging or when vehicles climb slopes. When a battery pack consisting of Li-ion cells is used in high current applications, a large amount of heat is produced. It is critical to design and build an appropriate BTMS [18]. Furthermore, under high operating temperatures, the maximum temperature of the battery rapidly rises, potentially reducing the battery's lifecycle [19]. Thermal runaway has become more common in Li-ion batteries over the last decade [20], and thermal safety has become a critical concern in preventing its usage [21]. When Li-ion batteries are discharged for an extended period of time or at a high discharge rate, they release a significant quantity of heat [22]. If this heat is not dissipated immediately, in addition to impairing cell performance, it will also cause thermal runaway. As a result, cell explosion and burning will occur [23]. Heat that has a negative effect on cell safety is produced by the chemical reaction of the electrode material and electrolyte [24]. Fig. 1.2 shows the yearly electricity demand for electric vehicles forecasting.

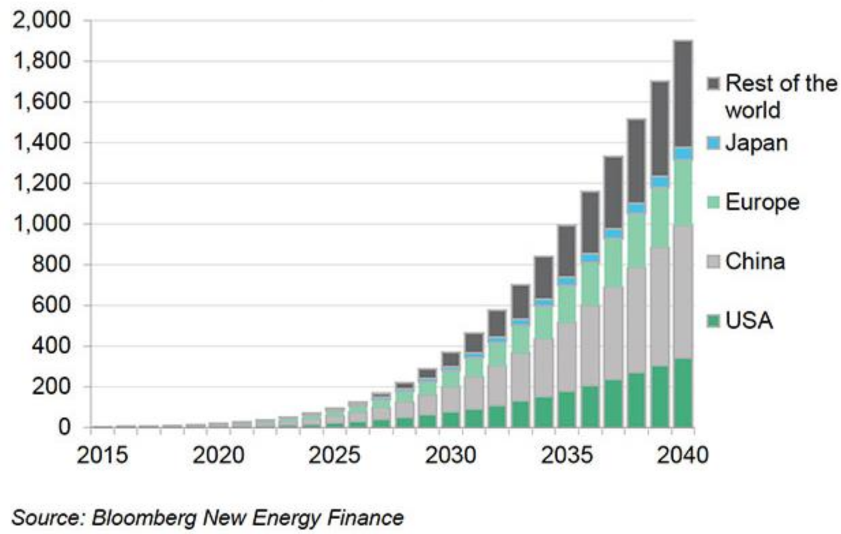


Figure 1.2 Yearly electricity demand for electric vehicles (2015-2040)

1.2 Battery Operations

The maximum battery temperature should be less than 55 ℃ during operation to ensure battery safety. During operation, there should be a uniform temperature distribution among cells of less than 5 ℃ for long cyclic life [17], [25], [26]. Cell performance is badly affected due to higher battery temperature or higher temperature difference among the cells, as a result electrical imbalance of the battery pack occurred [27], Fig 1.3 and fig 1.4 shows the optimum battery temperature range with pros and cons

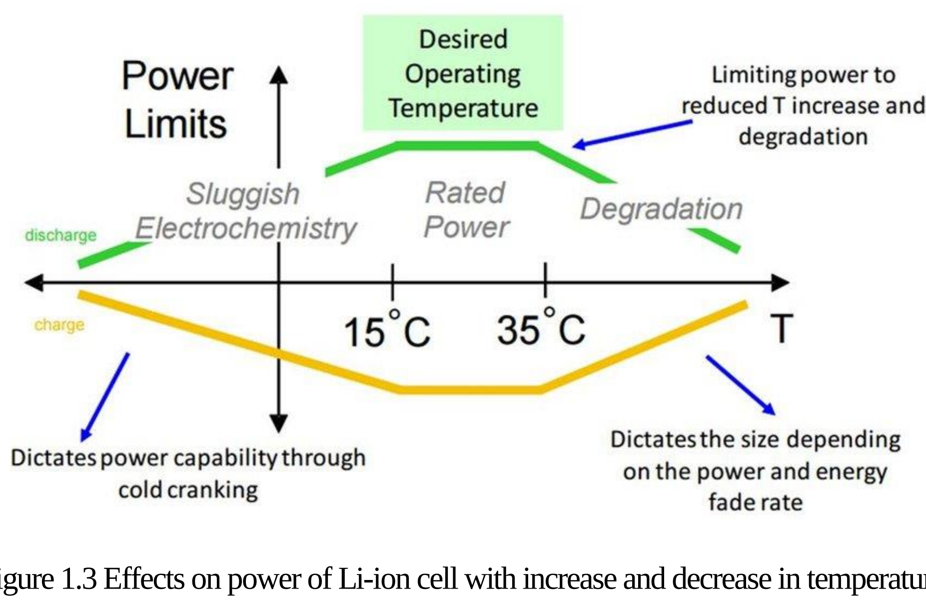


Figure 1.3 Effects on power of Li-ion cell with increase and decrease in temperatures.

on both low and high temperature operations. Furthermore, non-uniform temperature distribution at module level can severely degrade battery performance and accelerate battery degradation [28]. Fig. 1.3 discuss the effects of low and high temperatures on battery chemical conditions and their effects.

Battery cell temperature	Cause	Leads to	Effect
High	Electrolyte decomposition	Irreversible lithium loss	Capacity fade
	Continuous side reactions at low rate	Impedance Rise	Power fade
	Decrease of accessible anode surface for Li-ion intercalation		
	Decomposition of binder	Loss of mechanical stability	Capacity fade
25 °C – 40 °C	Maximum cycle life		
15 °C – 24 °C	Superior energy Storage capacity		
Low	Lithium plating	Irreversible loss of lithium	Capacity/ power fade
	Electrolyte decomposition	Electrolyte loss	

Figure 1.4 Effects on battery chemistry with change in operational temperature.

1.3 Battery Thermal Management Systems

There are two ways to regulate a battery's temperature: either an external battery thermal management system, which enhances heat evacuation from the battery pack, or internal improvements to the battery's materials and composition, which decrease heat generation [29]. For external temperature regulation of these battery packs during operations, it is essential to monitor the peak temperature, average temperature, temperature difference the among cells. [30]. The safety of the cells can be evaluated by monitoring these parameters in the battery thermal management system (BTMS). Cooling methods could enhance the performance of these batteries by reducing the temperature within a safe working range [31]. As a result, a high-performance BTMS is required to boost the performance and cyclic life of these batteries [29].

To improve the cooling capability of Li-ion batteries pack, various researchers have incorporated different cooling techniques [32]. The temperature of the battery back can be maintained within a defined range and the difference in temperature among the cells can also be optimized with the help of BTMS [33], [34]. Liquid cooling, air cooling, and PCM cooling are widely adopted for BTMS [35], [36]. PCM cooling, on the other hand is usually employed because of its low cost and easy control [37]. Depending on the technical requirements and cost, battery pack manufacturers can use one or several cooling methods [38]. Recently, few researchers have also investigated the impact of battery layout (cell structural arrangement) on cell thermal performance. Cell spacing and structural arrangement also reduce the risk of thermal runaway [23]. A previous study found that using identical cell-spacing efficiently reduces the temperature differences among the cells [35]. The common BTMS is now classified into two types, including active and passive cooling systems [39]. Active cooling includes air cooling, heat pipe cooling, fluid cooling and mixed refrigeration processes [35]. During active cooling, the heat from the pack is evacuated by air or liquid [40]. While PCM cooling is passive. PCMs are preferred over air and liquid cooling techniques because no electrical and mechanical components are used [41]. The use of PCM for passive BTMS is becoming highly common. As a key element of the thermal management system, PCMs absorb heat produced during battery operation, enhancing battery performance and extending battery life [42], [43]. Under Various operating conditions, the cooling performance of active cooling and passive cooling was investigated [44].

1.3.1 Air Cooling

The multiple air sources used by different air-cooling battery thermal management systems may be simply categorized. One type of system uses exclusively outside air, while the other employs pre-conditioned compressed air for battery cooling systems. There is another BTMS that uses a secondary evaporator to specifically cool the battery pack in consideration of the varied cooling requirements for the cabin and battery pack [13].

Natural cooling and forced cooling are two kinds of air cooling technologies, whose respective heat transfer mechanisms are naturally convection and forced convection. Natural cooling always depends heavily on radiation heat exchange, which cannot be neglected. In particular application scenarios, air cooling techniques could be employed. Air cooling, as opposed to other ways, can assure that the batteries are operating in a comfortable atmosphere. An air cooling system's structure is also remarkably simple and free of any sealing issues. [45]. Fig. 1.5 shows the cooling system with forced air cooling or fan cooling.

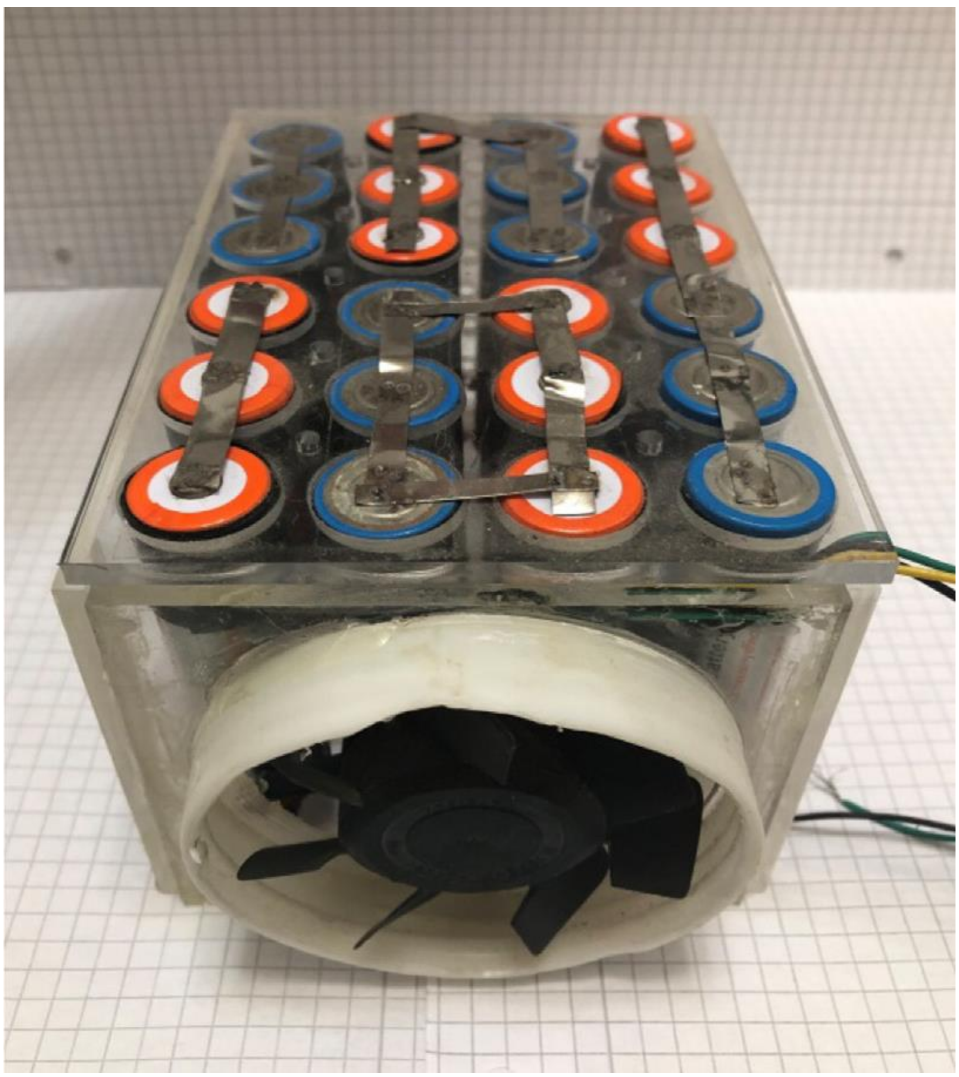


Figure 1.5 Battery pack assembled with forced air cooling with the help of fan.

1.3.2 Phase Change materials

PCM are extensively employed in many domains for temperature control and storage of energy due to their high value of latent heat, better thermal storage capacity, and capability of cold storage. PCMs can be categorized into four groups according to phase change form: liquid-vapor, solid-vapor, solid-liquid, and, solid-solid. PCMs are categorized into three types based on their melting point (MP): high temperature PCMs (> 550 ℃), medium temperature PCMs (90 ℃−550 ℃), and low temperature PCMS (50 ℃− 90 ℃). Low-temperature PCMs are commonly employed for energy storage and building energy usage. PCMs can be divided into organic, inorganic, and composite PCMs based on their chemical composition. Paraffin, fatty acids, esters, polyols, etc. are organic PCMs. Inorganic PCMs include crystalline hydrated salts, molten salts, and their alloys. Composite PCMs includes multi-component or binary composite PCMs. Fig. 1.6 shows a PCM based battery thermally managed battery pack.

PCM is easy to use, inexpensive, has a high energy storage capacity, and provides energy-saving capabilities. In addition to other energy applications, it is crucial for peak power shifting, storage of solar energy, recovery of waste heat, savings of building energy, and cold chain logistics. During the phase change process, PCM simultaneously absorbs and dissipate a significant quantity of heat, achieving the ability to regulate the surrounding environment's temperature. As compared to more typical temperature control methods like active air cooling and circulating liquid cooling, PCM-based thermal management technology has a greater impact on temperature regulation. Additionally, it is more efficient, environmentally friendly, and greener. Numerous studies have revealed that PCM-based cooling methods have become substantially superior in recent years. Its efficiency is better than that provided by other conventional thermal management technologies, and it is used in the BTMS of electric vehicles [13].

Many researchers have combined additional cooling techniques with the PCM-based BTMS to enhance cycle stability and thermal management capability. It is also a very successful optimization technique, according to recent studies. The PCM-based BTMS's recent research priorities are enhancing PCM's thermal conductivity, cycle stability, and thermal management capability. A hybrid thermal management system, which combines the PCM with other active thermal management systems, can optimize the cycle stability of PCM-based BTMS. It is a brand-new and highly efficient battery temperature management system. The PCM packing needs further consideration in real-world applications. Design considerations including leakage, PCM volume variation, and appropriate PCM quality dependent on load should be addressed. The solution to these real-world issues is essential to the development of the PCM-based BTMS in the future [13].

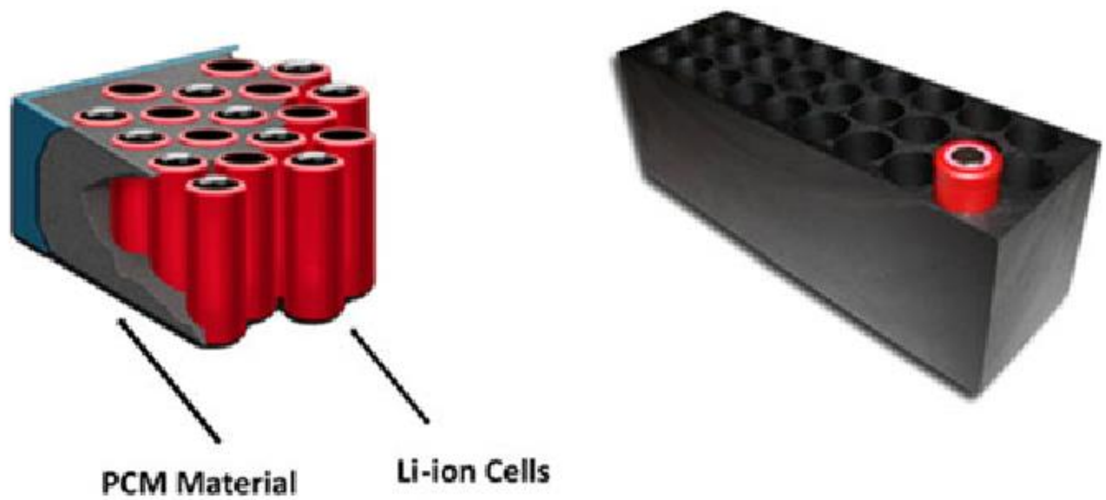


Figure 1.6 Battery pack assembled in PCM materials for thermal management.

1.3.3 Advantages and disadvantages between different thermal management systems

Table 1.1 shows the comparison of different battery thermal management systems with their advantages and disadvantages.

Table 1.1 Advantages and disadvantages of different thermal management systems.

Cooling Technique	**Advantages**	**Disadvantages**
Natural convection	Simple	Less efficient
	Low cost	Uneven temperature distribution
	Passive cooling	Suitable for low temperature

	Low maintenance cost	Dependent on ambient temperature
Forced convection	Simple	Less efficient
	Low maintenance cost	Uneven temperature distribution
		Suitable for low temperature
		Active energy is required
Coolant circuit	Uniform temperature distribution	Complex
	Better efficiency	Expensive
	Enhanced heat transfer	Active energy is required
		Risk of leakage
Heat pipe	Enhanced thermal conductivity	Complex
	Better efficiency	Expensive
	Enhanced heat transfer	Active energy is required
		Risk of leakage
PCM	Simple	Overcooling
	Less expensive	Volume expansion
	No maintenance required	
	Passive cooling	
	Even distribution of temperature	
Hybrid System	Efficient	Expensive
	Suitable for extreme conditions	Complex
	More even distribution of Temperature	Active energy is required
	High heat transfer rate	Risk of leakage

1.4 Problem Statement

The problem statement for the current study is to identify the best suitable thermal management systems with pros and cons. and to use the unique PCM material to verify its viability for use in a BTMS.

1.5 Objective of Study

The objectives of this study are to construct the battery pack and conduct experiments on different battery pack thermal management systems, including forced air cooling and use of unique PCM material as thermal management for the battery pack, and to compare and identify the best system for BTMS.

Summary

In this chapter, the world energy scenario with global battery usage and future energy trends and use of batteries are initially discussed. Furthermore, the battery pack thermal management system is explained and its different kinds of technologies with pros and cons are discussed. At the end of this chapter, the problem statement with the objectives of current research is explained.

References

[1] F. Y. Fu *et al.*, "The dynamic role of energy security, energy equity and environmental sustainability in the dilemma of emission reduction and economic growth," *J. Environ. Manage.*, vol. 280, no. December 2020, p. 111828, 2021.

[2] S. A. R. Khan, Z. Yu, A. Belhadi, and A. Mardani, "Investigating the effects of renewable energy on international trade and environmental quality," *J. Environ. Manage.*, vol. 272, no. April, p. 111089, 2020.

[3] K. Saidi and A. Omri, "The impact of renewable energy on carbon emissions and economic growth in 15 major renewable energy-consuming countries," *Environ. Res.*, vol. 186, no. February, p. 109567, 2020.

[4] A. Afzal *et al.*, "Thermal modelling and characteristic evaluation of electric vehicle battery system," *Case Stud. Therm. Eng.*, vol. 26, no. December 2020, p. 101058, 2021.

[5] A. Sarchami, M. Najafi, A. Imam, and E. Houshfar, "Experimental study of thermal management system for cylindrical Li-ion battery pack based on nanofluid cooling and copper sheath," *Int. J. Therm. Sci.*, vol. 171, no. September 2021, p. 107244, 2022.

[6] F. Chen *et al.*, "Air and PCM cooling for battery thermal management considering battery cycle life," *Appl. Therm. Eng.*, vol. 173, no. February, p. 115154, 2020.

[7] J. He, X. Yang, and G. Zhang, "A phase change material with enhanced thermal conductivity and secondary heat dissipation capability by introducing a binary thermal conductive skeleton for battery thermal management," *Appl. Therm. Eng.*, vol. 148, no. September 2018, pp. 984–991, 2019.

[8] G. Karkera, M. A. Reddy, and M. Fichtner, "Recent developments and future perspectives of anionic batteries," *J. Power Sources*, vol. 481, no. August 2020, p. 228877, 2021.

[9] P. Qin, M. Liao, D. Zhang, Y. Liu, J. Sun, and Q. Wang, "Experimental and numerical study on a novel hybrid battery thermal management system integrated

forced-air convection and phase change material," *Energy Convers. Manag.*, vol. 195, no. June, pp. 1371–1381, 2019.

[10] M. Tousi, A. Sarchami, M. Kiani, M. Najafi, and E. Houshfar, "Numerical study of novel liquid-cooled thermal management system for cylindrical Li-ion battery packs under high discharge rate based on AgO nanofluid and copper sheath," *J. Energy Storage*, vol. 41, no. April, p. 102910, 2021.

[11] M. A. Rajaeifar, P. Ghadimi, M. Raugei, Y. Wu, and O. Heidrich, "Challenges and recent developments in supply and value chains of electric vehicle batteries: A sustainability perspective," *Resour. Conserv. Recycl.*, vol. 180, 2022.

[12] F. Zhu, R. Zhou, D. Sypeck, J. Deng, and C. Bae, "Failure behavior of prismatic Li-ion battery cells under abuse loading condition - A combined experimental and computational study," *J. Energy Storage*, vol. 48, no. December 2021, p. 103969, 2022.

[13] M. Lu, X. Zhang, J. Ji, X. Xu, and Y. Zhang, "Research progress on power battery cooling technology for electric vehicles," *J. Energy Storage*, vol. 27, no. December 2019, p. 101155, 2020.

[14] S. Wiriyasart, C. Hommalee, S. Sirikasemsuk, R. Prurapark, and P. Naphon, "Thermal management system with nanofluids for electric vehicle battery cooling modules," *Case Stud. Therm. Eng.*, vol. 18, no. January, p. 100583, 2020.

[15] L. Giammichele, V. D'Alessandro, M. Falone, and R. Ricci, "Thermal behaviour assessment and electrical characterisation of a cylindrical Lithium-ion battery using infrared thermography," *Appl. Therm. Eng.*, vol. 205, no. December 2021, p. 117974, 2022.

[16] P. Ashkboos, A. Yousefi, and E. Houshfar, "Design improvement of thermal management for Li-ion battery energy storage systems," *Sustain. Energy Technol. Assessments*, vol. 44, no. September 2020, p. 101094, 2021.

[17] Y. Fan, Y. Bao, C. Ling, Y. Chu, X. Tan, and S. Yang, "Experimental study on the thermal management performance of air cooling for high energy density cylindrical

lithium-ion batteries," *Appl. Therm. Eng.*, vol. 155, no. March, pp. 96–109, 2019.

[18] H. Behi *et al.*, "Novel thermal management methods to improve the performance of the Li-ion batteries in high discharge current applications," *Energy*, vol. 224, p. 120165, 2021.

[19] S. G. Leonardi *et al.*, "Investigation on the ageing mechanism for a lithium-ion cell under accelerated tests: The case of primary frequency regulation service," *J. Energy Storage*, vol. 41, no. June 2020, p. 102904, 2021.

[20] J. B. Sangiri, T. Kulshreshtha, S. Ghosh, S. Maiti, and C. Chakraborty, "A novel methodology to estimate the state-of-health and remaining-useful-life of a Li-ion battery using discrete Fourier transformation," *J. Energy Storage*, vol. 46, no. December 2021, p. 103849, 2022.

[21] J. Cao, M. Luo, X. Fang, Z. Ling, and Z. Zhang, "Liquid cooling with phase change materials for cylindrical Li-ion batteries: An experimental and numerical study," *Energy*, vol. 191, p. 116565, 2020.

[22] M. M. Heyhat, S. Mousavi, and M. Siavashi, "Battery thermal management with thermal energy storage composites of PCM, metal foam, fin and nanoparticle," *J. Energy Storage*, vol. 28, no. December 2019, p. 101235, 2020.

[23] Y. Zhang, X. Song, C. Ma, D. Hao, and Y. Chen, "Effects of the structure arrangement and spacing on the thermal characteristics of Li-ion battery pack at various discharge rates," *Appl. Therm. Eng.*, vol. 165, no. June 2019, p. 114610, 2020.

[24] W. Zhang, Z. Liang, G. Ling, and L. Huang, "Influence of phase change material dosage on the heat dissipation performance of the battery thermal management system," *J. Energy Storage*, vol. 41, no. May, p. 102849, 2021.

[25] Y. Wang, Z. Wang, H. Min, H. Li, and Q. Li, "Performance investigation of a passive battery thermal management system applied with phase change material," *J. Energy Storage*, vol. 35, no. January, p. 102279, 2021.

[26] P. R. Tete, M. M. Gupta, and S. S. Joshi, "Numerical investigation on thermal

characteristics of a liquid-cooled lithium-ion battery pack with cylindrical cell casings and a square duct," *J. Energy Storage*, vol. 48, no. December 2021, p. 104041, 2022.

[27] R. D. Jilte, R. Kumar, and M. H. Ahmadi, "Cooling performance of nanofluid submerged vs. nanofluid circulated battery thermal management systems," *J. Clean. Prod.*, 2019.

[28] L. F. Cabeza, A. Frazzica, M. Chàfer, D. Vérez, and V. Palomba, "Research trends and perspectives of thermal management of electric batteries: Bibliometric analysis," *J. Energy Storage*, vol. 32, no. September, 2020.

[29] M. M. El Idi, M. Karkri, and M. Abdou Tankari, "A passive thermal management system of Li-ion batteries using PCM composites: Experimental and numerical investigations," *Int. J. Heat Mass Transf.*, vol. 169, p. 120894, 2021.

[30] Z. Ling, W. Lin, Z. Zhang, and X. Fang, "Computationally efficient thermal network model and its application in optimization of battery thermal management system with phase change materials and long-term performance assessment," *Appl. Energy*, vol. 259, no. July 2019, p. 114120, 2020.

[31] W. Yang, F. Zhou, H. Zhou, Q. Wang, and J. Kong, "Thermal performance of cylindrical lithium-ion battery thermal management system integrated with mini-channel liquid cooling and air cooling," *Appl. Therm. Eng.*, vol. 175, no. April, p. 115331, 2020.

[32] H. Zhou, F. Zhou, L. Xu, J. Kong, and QingxinYang, "Thermal performance of cylindrical Lithium-ion battery thermal management system based on air distribution pipe," *Int. J. Heat Mass Transf.*, vol. 131, pp. 984–998, 2019.

[33] Y. Wang *et al.*, "Experimental study on a novel compact cooling system for cylindrical lithium-ion battery module," *Appl. Therm. Eng.*, vol. 180, no. March, p. 115772, 2020.

[34] X. Xu, G. Tong, and R. Li, "Numerical study and optimizing on cold plate splitter for lithium battery thermal management system," *Appl. Therm. Eng.*, vol. 167, no.

September 2019, p. 114787, 2020.

[35] K. Chen, Y. Chen, Y. She, M. Song, S. Wang, and L. Chen, "Construction of effective symmetrical air-cooled system for battery thermal management," *Appl. Therm. Eng.*, vol. 166, no. April 2019, p. 114679, 2020.

[36] K. Benabdelaziz, B. Lebrouhi, A. Maftah, and M. Maaroufi, "Novel external cooling solution for electric vehicle battery pack," *Energy Reports*, vol. 6, no. September 2019, pp. 262–272, 2020.

[37] J. Weng, D. Ouyang, X. Yang, M. Chen, G. Zhang, and J. Wang, "Optimization of the internal fin in a phase-change-material module for battery thermal management," *Appl. Therm. Eng.*, vol. 167, no. November 2019, p. 114698, 2020.

[38] H. Jouhara *et al.*, "Applications and thermal management of rechargeable batteries for industrial applications," *Energy*, vol. 170, pp. 849–861, 2019.

[39] B. Ruhani, A. Abidi, A. K. Hussein, O. Younis, M. Degani, and M. Sharifpur, "Numerical simulation of the effect of battery distance and inlet and outlet length on the cooling of cylindrical lithium-ion batteries and overall performance of thermal management system," *J. Energy Storage*, vol. 45, no. December 2021, p. 103714, 2022.

[40] K. Chen, W. Wu, F. Yuan, L. Chen, and S. Wang, "Cooling efficiency improvement of air-cooled battery thermal management system through designing the flow pattern," *Energy*, vol. 167, pp. 781–790, 2019.

[41] N. Javani, I. Dincer, G. F. Naterer, and B. S. Yilbas, "Heat transfer and thermal management with PCMs in a Li-ion battery cell for electric vehicles," *Int. J. Heat Mass Transf.*, vol. 72, pp. 690–703, 2014.

[42] J. Cao, Z. Ling, X. Fang, and Z. Zhang, "Delayed liquid cooling strategy with phase change material to achieve high temperature uniformity of Li-ion battery under high-rate discharge," *J. Power Sources*, vol. 450, no. December 2019, p. 227673, 2020.

[43] Y. Galazutdinova, S. Ushak, M. Farid, S. Al-Hallaj, and M. Grágeda,

"Development of the inorganic composite phase change materials for passive thermal management of Li-ion batteries: Application," *J. Power Sources*, vol. 491, no. June 2020, 2021.

CHAPTER 2 LITERATURE REVIEW

2.1 Thermal Management of batteries

When charge is drawn from battery pack, heat is produced in response to Ohm's law; thus, the temperature of the battery pack must be maintained in the optimum operational temperature range to reduce degradation and enhance battery output. There are two key requirements for any battery thermal management system: the ability to control peak temperature of battery pack and prevent temperature gradients while the battery is in operation. In that instance, specific thermal management technologies, such as those outlined below, are employed to control the battery temperature.

2.1.1 Air cooling battery thermal management

In research conducted, the typical air cooling is used for thermal management of li-ion battery cells at different discharge rates, in which there is an inlet and outlet for the air to move between the battery packs as shown in fig 2.1. They also investigated the orifice parameters of the inlet and outlet or air flow. The results show the battery pack can be effectively cooled down when the inlet pressure is increased, which ultimately increases the power rating of the battery [1].

In further research conducted, the performance of BTMS based on air-cooling was investigated under numerous conditions. The results show that the aligned configuration not only shows uniform temperature distribution but also superlative cooling performance, trailed by the staggered and, ultimately, the cross configurations. The lowest temperature is always seen in the second row along the air inlet direction. With an increase in air inlet speed, the consumption of power rises exponentially but, the aligned design has the lowest power consumption, up to 23.0% less than the cross arrangement. Additionally, when air velocity increases, the efficiency of the air-cooling method declines and the cooling capability reaches at maximum limit relative to the current [2].

In a study, air cooling system by using heat pipe was manufactured to maintain the temperature of the Li-ion batteries at a higher current (184 A). The absence of natural convection, natural convection, forced convection, and evaporative cooling are all taken

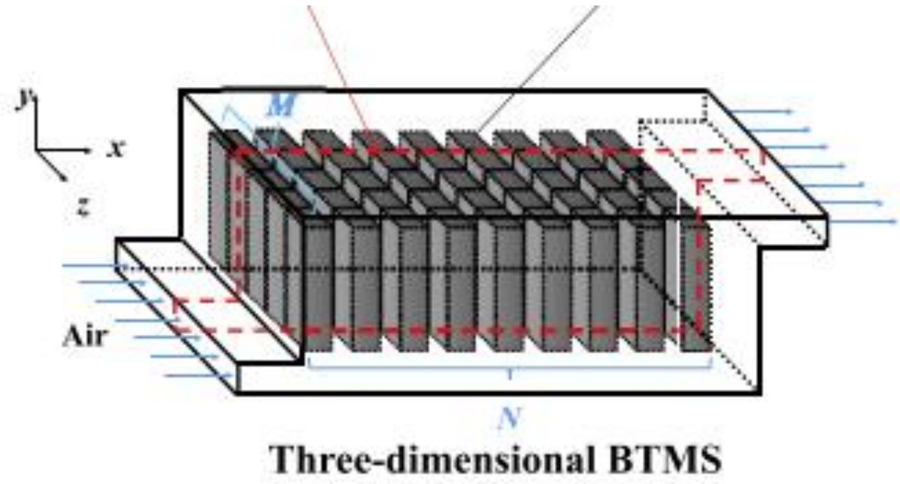


Figure 2.1 Three-dimensional air cooled thermally managed battery pack.

into account when measuring the temperature of the cell or module practically and mathematically. The findings of the experiment show that forced and natural convection both reduce the cell's average temperature by 33.7 and 6.2 percent, respectively. The findings indicate that the evaporative cooling approach has a 35.8% and a 23.8% reduction in the highest temperature of the cell and module, respectively [3].

2.1.2 Liquid based thermal management

In one study, researchers combined air cooling with mini channel fluid cooling, and the resulting thermal efficiency of the combined system was investigated. The findings demonstrate that a substantial increase in power usage causes the peak temperature and temperature differential to decline with an increase in water flow speed. Additionally, it is observed that when the fan is automatically operated in accordance with the heat generation in a battery pack, the highest difference in temperature can be controlled under 5.0 K [4].

In another research work, the innovative design of a battery pack features cylindrical enclosures for the batteries to be inserted into and a liquid cooling medium that flows around it. This works as a transition approach between indirect and direct liquid cooling methods. Using a forced-liquid cooling system, the thermal efficiency of the 25 18,650 Li-ion cells placed in a square-structured battery pack is assessed. To examine the effect of heat production on the battery's cooling performance, a thorough thermal analysis was conducted at various discharge rates including 0.5C, 1.0C, 2.0C, 3.0C, 4.0C, and

5.0C. The results show that the suggested design reduces heat gathering by increasing the exposure of the cell shells to the heat exchange medium. A uniform circulation of coolant to all cells offer even temperature distribution within the battery pack. Additionally, the influence of natural convection has been examined, and the findings show that at a coefficient of convective heat transfer coefficient of 25 W/m2 K, the maximum temperature rise has been significantly decreased [5].

A unique thermal management system with wavy channel liquid cooling and a copper sheath is designed and tested scientifically. As the concentration of alumina nanoparticles in deionized water increased, the maximum temperature and temperature divergence decreased substantially. In comparison to the straight channel, the wavy channel significantly reduced the maximum temperature and temperature non-uniformity of the battery pack during the 5C discharge rate by around 3.59 K and 0.65 K, respectively. The findings demonstrate that these techniques can lower the battery pack's maximum temperature and temperature non-uniformity during 5C discharge and charge cycles to levels below 305.13 K and 2.01 K, respectively [6].

2.1.3 Phase change material based thermal management

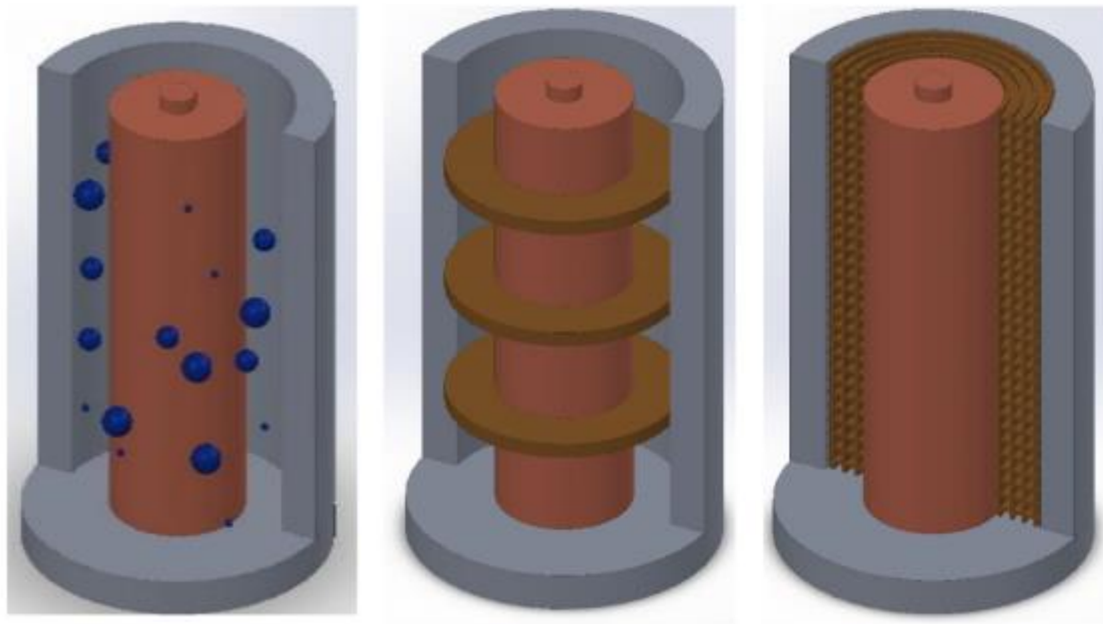
In a study conducted, they investigated the temperature of an EV's battery pack is controlled with the help of PCMs. It demonstrates that, even at varying rates, the battery pack's temperature stays within the optimal range [7].

In another research, the temperature fluctuations of the battery packs were examined at various charge and discharge rates using a synthetic silicone mixed with PCM for thermal regulation of a batteries. The findings revealed that the optimum thermal performance was achieved with 14 mm thick PCM and 3 mm silicone. The temperature of these batteries with silicone combined with PCM can drop by 24 ℃ at a 4.0 C discharge rate in comparison to the cooling system without silicone in PCM. This revealed that the temperature of battery module may be considerably reduced without using extra energy for other cooling during the procedure [8].

In a study conducted, the quantity of PCM employed is studied to identify the appropriate amount to use so that a module may be constructed, followed by the establishment and validation of the numerical model by experimental data. A technique termed "heat ratio" is recommended to correctly assess how PCM quantity affects temperature of the battery pack. A single discharge procedure and conditions for a discharge-charge cycle were used to systematically conduct the comprehensive constant analysis of the PCM quantity and its effect in conjunction with the phase transition temperature, the thermal conductivity of PCM, and the coefficient of heat transfer. According to the findings, a "heat ratio" of 0.75 to 1 is generally sufficient for regulating battery temperature during a single discharge procedure. Therefore, just raising the quantity of PCM is not a solution. It is more beneficial to mix passive and active cooling techniques with a suitable convective heat transfer coefficient to provide a more steady and low-energy-consumption cooling effect [9].

According to the research findings on the BTMS employing PCM-Metal foam mixture for these Li-ion battery packs, the inclusion of aluminum foam leads to efficient thermal management of the pack as shown in fig. 2.2. The optimal control investigation revealed that misjudging the thickness (amount of PCM needed) results in high temperatures. Researchers also reported that adding an additional quantity of PCM has little impact on the surface temperature of cells [10].

Additionally, a study on organic phase change materials (OPCM) was conducted, in which four different types of Li-ion battery packs were designed to demonstrate the performance differences between packs with different OPCMs and packs without OPCMs. Electrical cycling tests were performed on the manufactured batteries, first at room temperature and subsequently at 45 ℃. The study's final phase was conducting a nail penetration test to confirm the nail penetration test was reliable in limiting the spread of thermal runaway. Electrical cycling tests performed at room temperature showed that the No-OPCM pack has the largest temperature profile within the pack, independent of discharge rate, whereas the packs with OPCMs had consistent temperature profiles. Furthermore, when compared to packs containing CPCMs, the No-OPCM pack exhibits substantially higher peak temperatures at all discharge rates; at a 1C discharge rate, the No-OPCM pack reaches 49 ℃, which is roughly 10 ℃ higher than all OPCM packs, which do not get beyond 40 ℃. The maximum temperature of both packs with inorganic



(a) (b) (c)

Figure 2.2 PCM based thermal management system in which Li-ion cell is enclosed in aluminum wrap having PCM material with (a) metal chips (b) fins and (c) metal foam.

PCM is around 1-2 °C higher at this discharge rate than it is for the OPCM wax pack. The No-OPCM pack was paused before starting the first discharge at a 2C discharge rate because it exceeded the 65 °C safety limit. The packs with OPCMs successfully completed the cycling [11].

One more study in which passive and low-cost thermal management with PCM components is considered, in which the performance and roles of BTMS are investigated. The results show that PCM-based systems offer better heat storage ability and also distribute temperature uniformly. The thickness of the PCM unit can be increased to improve its thermal management effectiveness. However, if the limit is exceeded by 6 mm, the cooling enactment of BTMS will be affected. Within the range of 150-1100 W/(m.K), the better the thermal conductivity of the PCM system, the greater the thermal management efficiency of the PCM unit [12].

In a subsequent study, researchers explored the thermal management of Li-ion cells, which shows that employing PCM can moderate temperature excursion and maximum temperature of the batteries. They investigated use PCM within the battery pack with certain thickness between the cells, which shows that PCM 12mm thickness the temperature drop is about 3 ℃, which ultimately cancels reliance on the active refrigeration of the battery pack cells [13].

In further research conducted for PCM based cooling systems with 18,650 lithium-ion batteries, the melting process of PCM in passive BTMS was simulated at 4.6 W and 9.2 W heat generation rates. Researchers further investigated the melting of PCM in passive BTMS using 18,650 Li-ion batteries. This was undertaken by simulating the heat generation rates at 4.6 W and 9.2 W. Additionally, the effects of three significant PCM heat transfer improvement techniques—using metal foam, fins, and nanoparticles were examined and evaluated. The results reveal that employing the spongy-PCM reduced the cells mean temperature by 4-6 ℃ as compared to the pure PCM. Furthermore, with the spongy -PCM formulation, a postponement in the PCM melting start time is reported, which can substantially affect the performance of BTMS [14].

Table 2.1 shows the inorganic and organic phase change materials with their melting point and latent heat [15].

Table 2.1 Phase Change materials with their properties.

Type	**Material**	**MP (℃)**	**LH (J/g)**	**Properties**
Inorganic PCMs	$LiClO_3.3H_2O$	8.10	253.00	Thermal conductivity and undercooling degree is high, large phase change latent heat value, easily separation of phase, reduced reversibility
	$CaCl.6H_2O$	25.80	125.90	
	H_3PO_4	26.00	147.00	
	$LiNO_3.3H_2O$	30.00	189.00	
	$LiNO_3.2H_2O$	30.00	296.80	
	$NaSO_4.10H_2O$	32.50	257.00	
	$Na_2HPO_4.10H_2O$	35.00	265.00/280.00	
	$Na_2S_2O_3.5H_2O$	48.00	188.00/201.00	

	$Na(CH_3COO).3H_2O$	58.00	226.00/264.00	
	$Ba(OH)_2.8H_2O$	78.00	267.00/280.00	
	$Mg(NO_3)_2.6H_2O$	90.00	149.50/162.80	
	$MgCl2.6H_2O$	116.00	165.00/168.60	
	$NaNO_3$	307.00	172.00	
	$MgCl_2$	714.00	452.00	
	MgF_2	1263.00	938.00	
Organic PCMs	Paraffin			Good reversibility , good stability, low thermal conductivity, high latent heat, and no obvious over-cooling
	$C_{18}H_{38}$	28.00	243.00	
	$C_{22}H_{46}$	44.40	249.00	
	$C_{26}H_{54}$	56.10	256.00	
	No Paraffin			
	Glycerol ($C_3H_8O_3$)	26.00	184.00	
	Isoamyl laurate	29.00	205.00	
	Isobutyl octanoate	43.00	177.00	
	Lauric acid	45.00	225.00	
	Myristic acid	55.00	220.00	
	1-octadecyl alcohol	57.00	242.85	
	Palmitic acid	63.00	215.00	
	Stearic acid	70.00	243.00	

Summary

This chapter contains the literature review of conducted research on the initial technologies used for BTMS, such as certain air-cooling technologies, PCM, liquid cooling, etc. At the end of this chapter, a comparison between different PCMs is represented in the form of table.

References

[1] H. Zhou, F. Zhou, L. Xu, J. Kong, and QingxinYang, “Thermal performance of cylindrical Lithium-ion battery thermal management system based on air distribution pipe,” *Int. J. Heat Mass Transf.*, vol. 131, pp. 984–998, 2019, doi: 10.1016/j.ijheatmasstransfer.2018.11.116.

[2] Y. Fan, Y. Bao, C. Ling, Y. Chu, X. Tan, and S. Yang, “Experimental study on the thermal management performance of air cooling for high energy density cylindrical lithium-ion batteries,” *Appl. Therm. Eng.*, vol. 155, no. December 2018, pp. 96–109, 2019, doi: 10.1016/j.applthermaleng.2019.03.157.

[3] H. Behi *et al.*, “Novel thermal management methods to improve the performance of the Li-ion batteries in high discharge current applications,” *Energy*, vol. 224, p. 120165, 2021, doi: 10.1016/j.energy.2021.120165.

[4] W. Yang, F. Zhou, H. Zhou, Q. Wang, and J. Kong, “Thermal performance of cylindrical lithium-ion battery thermal management system integrated with mini-channel liquid cooling and air cooling,” *Appl. Therm. Eng.*, vol. 175, no. January, p. 115331, 2020, doi: 10.1016/j.applthermaleng.2020.115331.

[5] P. R. Tete, M. M. Gupta, and S. S. Joshi, “Numerical investigation on thermal characteristics of a liquid-cooled lithium-ion battery pack with cylindrical cell casings and a square duct,” *J. Energy Storage*, vol. 48, no. October 2021, p. 104041, 2022, doi: 10.1016/j.est.2022.104041.

[6] A. Sarchami, M. Najafi, A. Imam, and E. Houshfar, “Experimental study of thermal management system for cylindrical Li-ion battery pack based on nanofluid cooling and copper sheath,” *Int. J. Therm. Sci.*, vol. 171, no. September 2021, p. 107244, 2022, doi: 10.1016/j.ijthermalsci.2021.107244.

[7] X. Duan and G. F. Naterer, “Heat transfer in phase change materials for thermal management of electric vehicle battery modules,” *Int. J. Heat Mass Transf.*, vol. 53, no. 23–24, pp. 5176–5182, 2010, doi: 10.1016/j.ijheatmasstransfer.2010.07.044.

[8] J. Wang, Q. Huang, X. Li, G. Zhang, and C. Wang, “Experimental and numerical simulation investigation on the battery thermal management performance using silicone coupled with phase change material,” *J. Energy Storage*, vol. 40, no. March, p. 102810, 2021, doi: 10.1016/j.est.2021.102810.

[9] W. Zhang, Z. Liang, G. Ling, and L. Huang, “Influence of phase change material dosage on the heat dissipation performance of the battery thermal management system,” *J. Energy Storage*, vol. 41, no. November 2020, p. 102849, 2021, doi: 10.1016/j.est.2021.102849.

[10] M. M. El Idi, M. Karkri, and M. Abdou Tankari, “A passive thermal management system of Li-ion batteries using PCM composites: Experimental and numerical investigations,” *Int. J. Heat Mass Transf.*, vol. 169, p. 120894, 2021, doi: 10.1016/j.ijheatmasstransfer.2020.120894.

[11] Y. Galazutdinova, S. Ushak, M. Farid, S. Al-Hallaj, and M. Grágeda, “Development of the inorganic composite phase change materials for passive thermal management of Li-ion batteries: Application,” *J. Power Sources*, vol. 491, no. June 2020, 2021, doi: 10.1016/j.jpowsour.2021.229624.

[12] Y. Wang, Z. Wang, H. Min, H. Li, and Q. Li, “Performance investigation of a passive battery thermal management system applied with phase change material,” *J. Energy Storage*, vol. 35, no. October 2020, p. 102279, 2021, doi: 10.1016/j.est.2021.102279.

[13] N. Javani, I. Dincer, G. F. Naterer, and B. S. Yilbas, “Heat transfer and thermal management with PCMs in a Li-ion battery cell for electric vehicles,” *Int. J. Heat Mass Transf.*, vol. 72, pp. 690–703, 2014, doi: 10.1016/j.ijheatmasstransfer.2013.12.076.

[14] M. M. Heyhat, S. Mousavi, and M. Siavashi, “Battery thermal management with thermal energy storage composites of PCM, metal foam, fin and nanoparticle,” *J. Energy Storage*, vol. 28, no. September 2019, p. 101235, 2020, doi: 10.1016/j.est.2020.101235.

[15] M. Lu, X. Zhang, J. Ji, X. Xu, and Y. Zhang, “Research progress on power battery cooling technology for electric vehicles,” *J. Energy Storage*, vol. 27, no. September 2019, p. 101155, 2020, doi: 10.1016/j.est.2019.101155.

CHAPTER 3 EXPERIMENTATION

3.1 Li-Ion Cells

The Li-ion (IFR-26650 3000 mAh, 3.2V) cells were used to assemble the battery pack for thermal testing purposes. Cell spacers (for 26650 Li Cells) were used for the structural arrangement of cells in the battery pack shown in fig. 3.1.

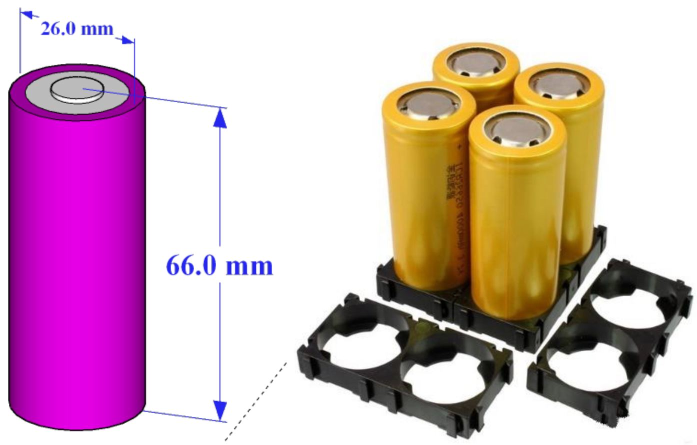


Figure 3.1 26650 Li-Ion cells and cell spacers.

Specification	Nominal Capacity (Ah)	Nominal Voltage (V)	Max Charge Current (A)	Operating Temperature (°C)
Li-ion IFR 26650	3.00	3.2	6	-30-+65

3.2 Temperature Measurement

K-type thermocouples are used for temperature measurements while experimenting, shown in fig. 3.2. K type thermocouple refers to temperature sensor containing Alumel and Chromel conductors. Temperature range K type thermocouples have a general range of -200 to 1260 °C.

Figure 3.2 K-Type thermocouple for temperature measurements.

3.3 Phase Change Material

Sodium sulphate decahydrate (Na_2SO_4 .10 H_2O, CAS No. 7727-73-3) is a promising PCM used for battery thermal management due to its high enthalpy of fusion associated with a proper phase transition temperature. It has melting point of 32.5oC and latent heat of 257 J/g [1]. It is environmentally friendly and it also has advantages because it can be obtained as a byproduct from the disposal process of lead batteries.

3.4 Battery Pack

3.4.1 Casing

Acrylic sheet of 2mm width was used to manufacture the battery pack casing of dimensions 105*105*105 mm to fit 9*26650 Li-ion batteries, as shown in fig. 3.3.

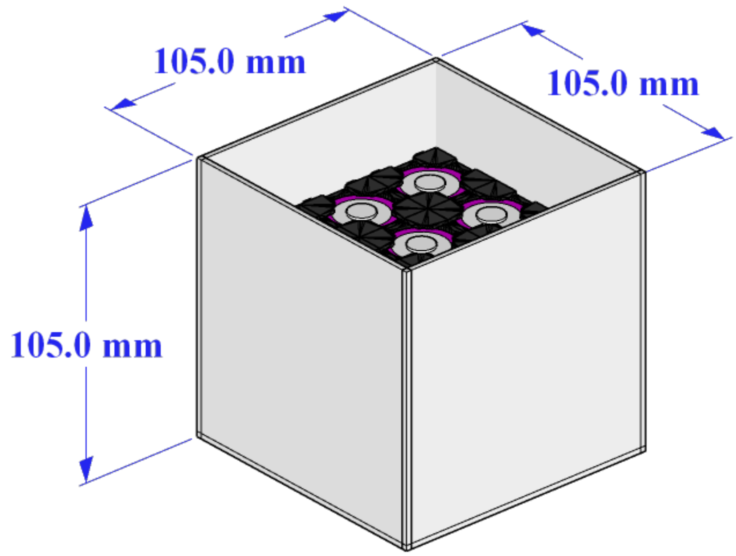


Figure 3.3 Battery pack casing

3.4.2 Battery pack configuration

The square configuration was adopted for nine 26650 Li-ion cells incorporated with cell spacer in the battery pack. Three beaded K-type thermocouples T1, T2, T3 are connected to cells 1, 2, and 5, respectively. Cell 1 is facing the other two cells. Cell 2 is surrounded by three cells and cell 5 is surrounded by four cells as shown in fig 3.4 and fig 3.5. The cells 1,3,7, and 9 are symmetrical with respect to each other. Similarly, cells 2,4,6 and 8 are symmetrical with respect to each other, while cell 5 has a unique position. The Li-ion cells have an identical spacing of 2mm in between. Battery pack casing is design with respect to conduct experiment with fan cooling and PCM cooling.

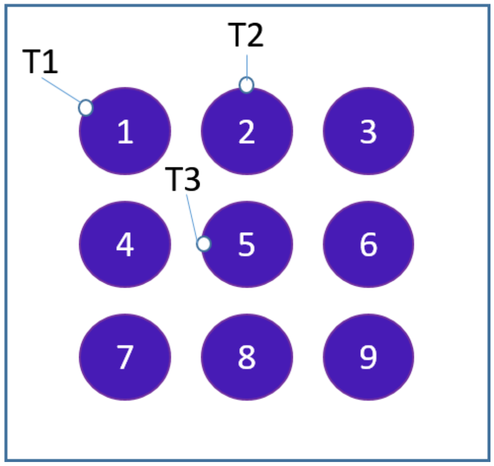


Figure 3.4 Thermocouple positions in battery pack

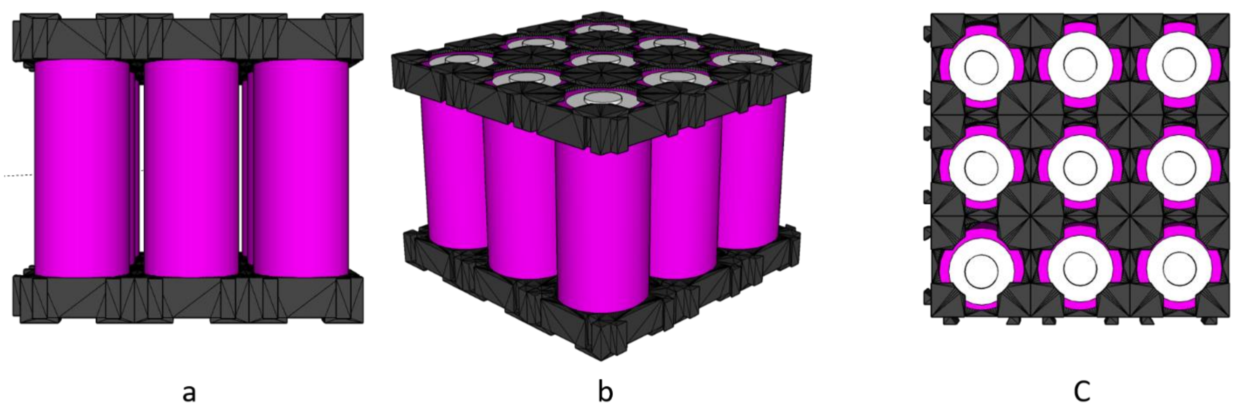


Figure 3.5 Assembled battery pack with nine 26650 Li-ion cells.

3.5 Battery Analyzer

To analyze the battery pack MTI corporation (BST8-3 eight-channel battery analyzer) to analyze from 0.006 A to 3000 A, up to 5V, with gold-plated pins for the best connection, shown in fig. 3.6. Each channel of the analyzer can be controlled by computer and each channel has independent constant voltage and constant current source. These channels can be programmed according to requirements.

Figure 3.6 Battery analyzer

3.6 Data Logger

To record the temperature at instant of time by thermocouples, we used the KT-800 (Pangu Instrumentation) 30-channel data logger for this purpose shown in fig. 3.7. The thermocouples recorded the surface temperature variations of the cells throughout time.

Figure 3.7 Data logger

3.7 Experimental Setup

The experimental setup consists of a battery pack, a battery analyzer, and data logger. The battery pack was developed by using 9*26650 Li-ion cells and cell spacers to arrange in a square configuration as shown in fig. 3.8. Before the experiment, each cell was analyzed to verify its capacity and voltage. The temperature of each cell was maintained in the experiment to ensure them to be at same temperature.

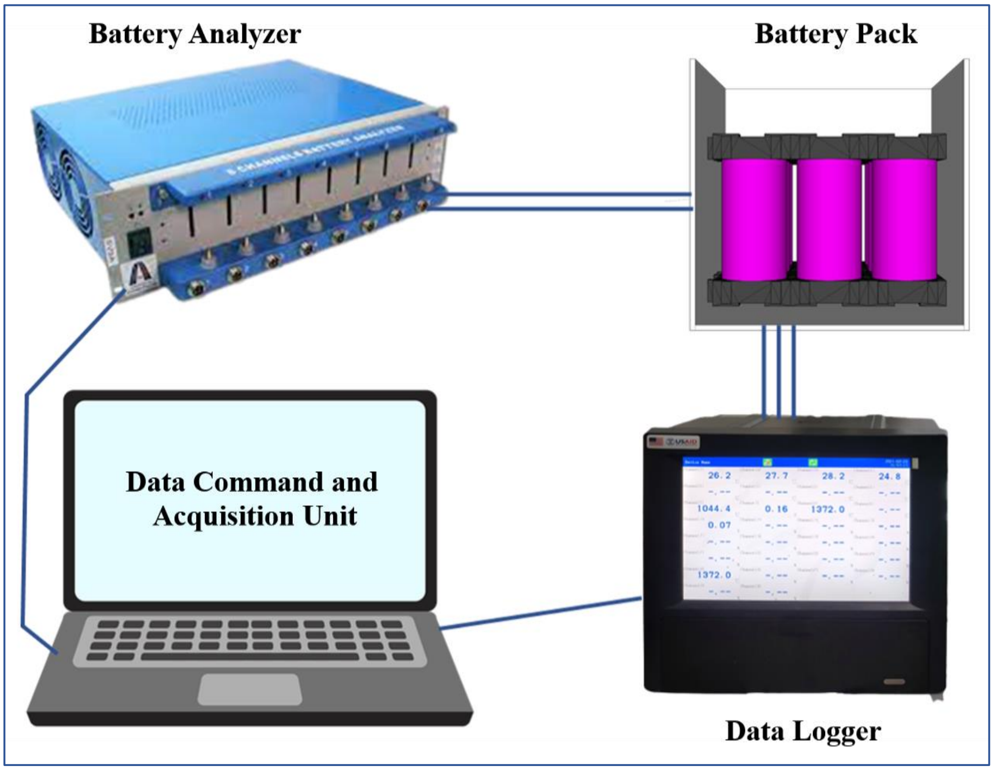


Figure 3.8 Experimental setup

The positive and negative terminals of the cells were connected to a computer-controlled battery analyzer to set the operating parameters of the cells. Cells were discharged by setting the continuous discharge at 1C (3000 mA). The discharge was terminated when the voltage reached the cut-off voltage (2.5V). K-type thermocouples were employed to monitor the cell temperature by using a data logger. These thermocouples were mounted at the midpoint of the cell to determine the surface temperature with the help of data loggers.

3.8 Modeling

The comparison of different thermal management systems is calculated by taking difference between the maximum temperature for each cell of two systems, and by taking difference between the average maximum temperature of two systems.

$$\Delta T = |T_A^1 - T_A^2|$$

Whereas **ΔT** is the temperature difference between two respective battery thermal management systems, while $\mathbf{T_A^1}$ and $\mathbf{T_A^2}$ are the average maximum temperatures of both the battery thermal management system in comparison.

Summary

In this chapter the initially the battery pack cells we are using, and the thing used to make the battery pack are discussed and then the instruments used in analyzing different temperature regimes for each thermal management system for battery pack is discussed. In addition, the experimental setup and mathematical modeling which is used to draw results are also discussed.

References

[1] M. Lu, X. Zhang, J. Ji, X. Xu, and Y. Zhang, “Research progress on power battery cooling technology for electric vehicles,” *J. Energy Storage*, vol. 27, no. September 2019, p. 101155, 2020, doi: 10.1016/j.est.2019.101155.

CHAPTER 4 METHODOLOGY

4.1 Methodology

First of all, we took the Li-ion 26650 cells and tested the individual cell to test its capacity weather it is has full capacity or not, then choose the cell with full capacity to make 3 kind of battery packs including a simple battery pack, a battery pack with forced air cooling system with the aid of 2 fans and a battery pack with cells dipped in the phase change materials. Then we installed the thermocouples on the cell accordingly and tested each battery pack by discharging at 1C-rate and recorded the temperature regimes for each. Then the graphed data is compared with each other to find the thermal management of each system. Fig. 4.1 shows the schematic diagram of methodology:

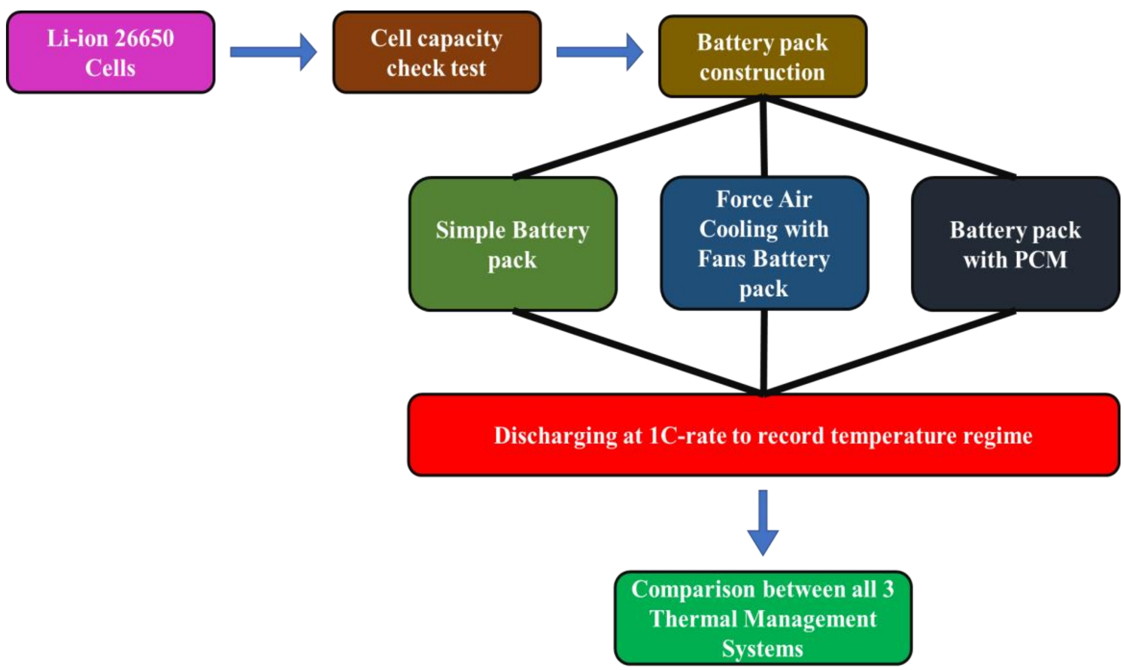


Figure 4.1 Experimental scheme.

4.2 Discharging of cells at Room Temperature

At first, the experiment is conducted by simply discharging the battery pack on 1C rate at room temperature to get the data that how the li-ion cell working temperature regime behaves in square configuration of the battery pack we made.

4.3 Discharging of cells with Air Cooling

To Conduct experiment with integrating the air cooling by two fans on both side of the battery pack, same layout and structural arrangement of battery pack is used as in the previous experiment as shown in fig 4.2. Cells are discharged at 1C rate, and the cell surface temperature was monitored by using K-type thermocouples and recorded with data logger.

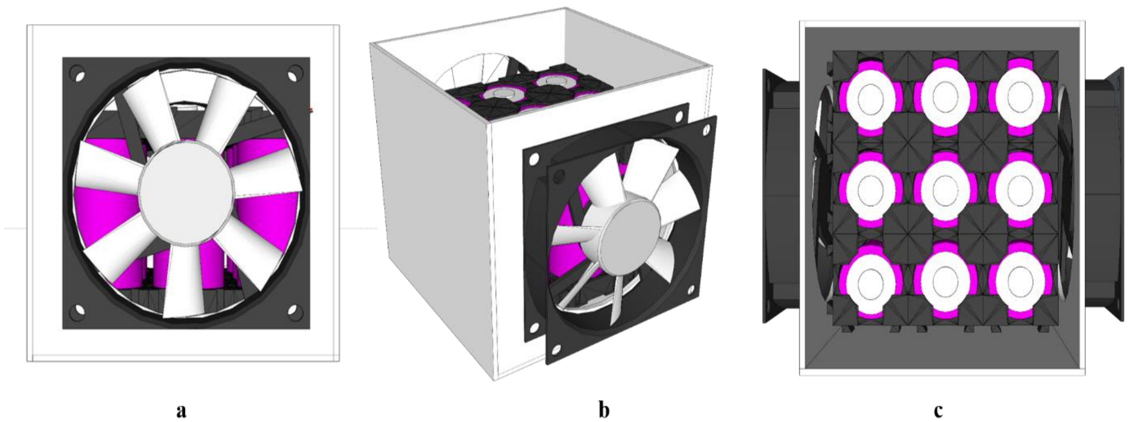


Figure 4.2 Assembled battery pack with forced air-cooling system with the help of fan.

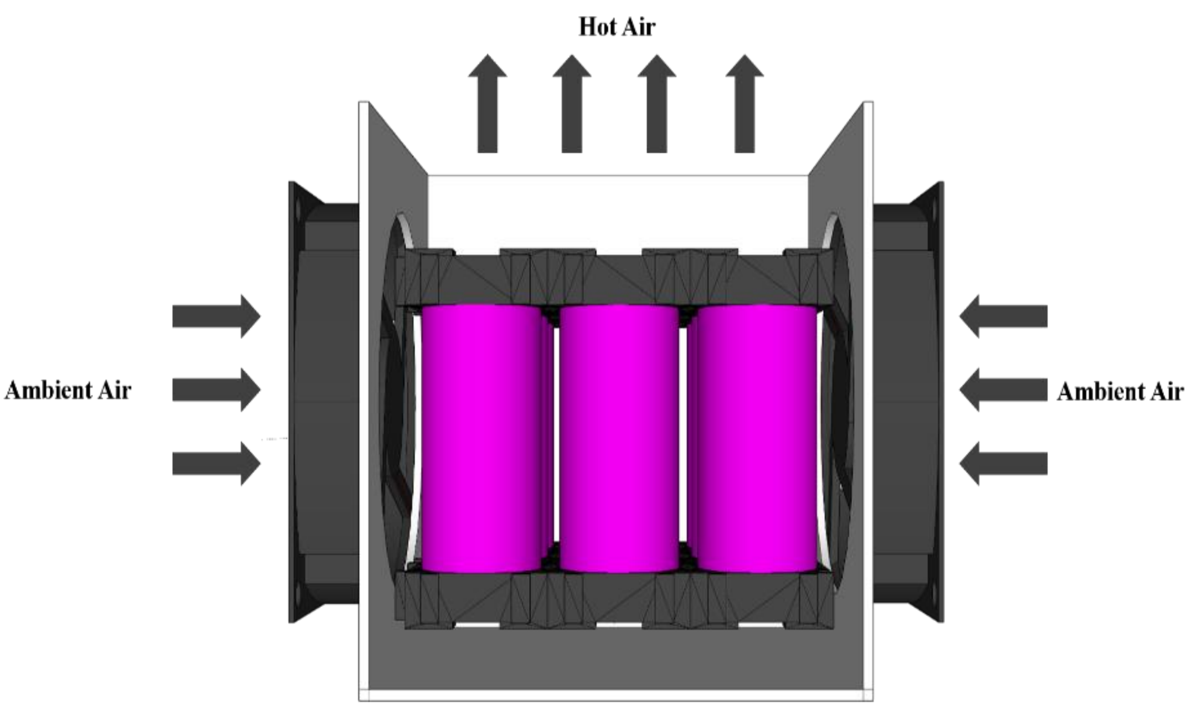


Figure 4.3 Forced air cooling system mechanism.

The air flow field symmetrically corresponds to the central axis when the battery pack is in symmetric shape. Two DC intake fans were deployed for the symmetrical system to carry ambient air inside the box, and hot air from the top of the box was released as shown in fig. 4.3 and fig 4.4 As a result, we got decrease in the maximum operating temperature of the battery pack.

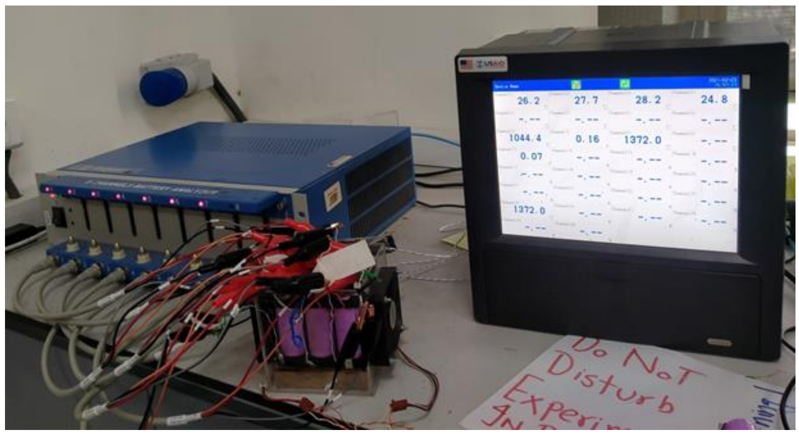


Figure 4.4 Experimental setup of forced air-cooling system.

4.4 Discharging of cells with Phase change material

To Conduct the experiment to employ the phase change material as a cooling agent for the battery pack the same battery pack with battery surrounded by the phase change material. Sodium sulfate decahydrate ($Na_2SO_4.10H_2O$) is used as a phase change material, it has melting point of 32.4 ℃ and latent heat of 257 J g^{-1} [1]. $Na_2SO_4.10H_2O$ was melted properly as shown in fig. 4.5, it was inserted into a leak-proof container containing Li-ion cells. Cells were almost completely dipped into $Na_2SO_4 \cdot 10H_2O$. After that, experiment is conducted at the similar conditions we conducted the pervious experiment, cells are discharged at 1C rate and temperature is recorded.

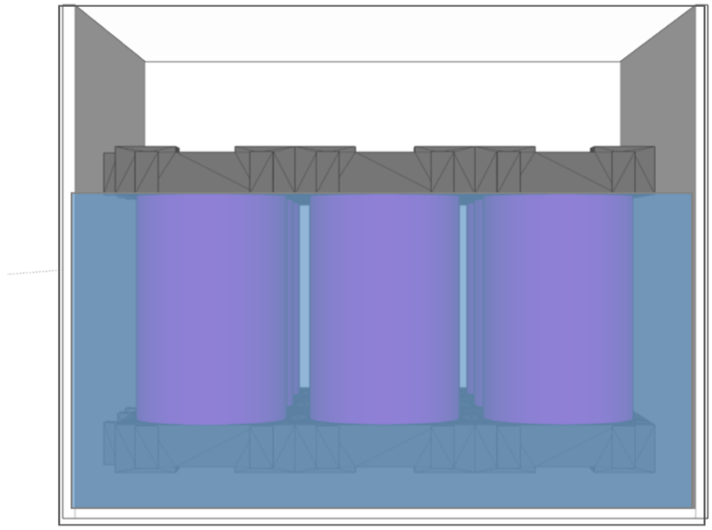


Figure 4.5 battery pack assembled with phase change material.

Summary

In this chapter methodology of the experiment conducted is explained with different type of battery thermal management systems, afterward each thermal management system we are conducting experiment is discussed.

References

[1] M. Lu, X. Zhang, J. Ji, X. Xu, and Y. Zhang, “Research progress on power battery cooling technology for electric vehicles,” *J. Energy Storage*, vol. 27, no. September 2019, p. 101155, 2020, doi: 10.1016/j.est.2019.101155.

CHAPTER 5 RESULTS AND DISCUSSION

5.1 Room temperature operation of battery pack

At Room temperature conditions when the battery pack was discharged at the rate of 1C, the thermocouples mounted on cell 1, cell 2 and cell 5 shows the regime shown in fig. 5.1. and table 5.1. It shows that on room temperature conditions, the square configuration of battery pack including nine 26650 cells when discharged on 1C the maximum temperature can go up to 41 ℃ for cell 5 when the room temperature is around 28 ℃. Table 5.1 Shows the maximum, minimum and average temperature of the battery pack cells.

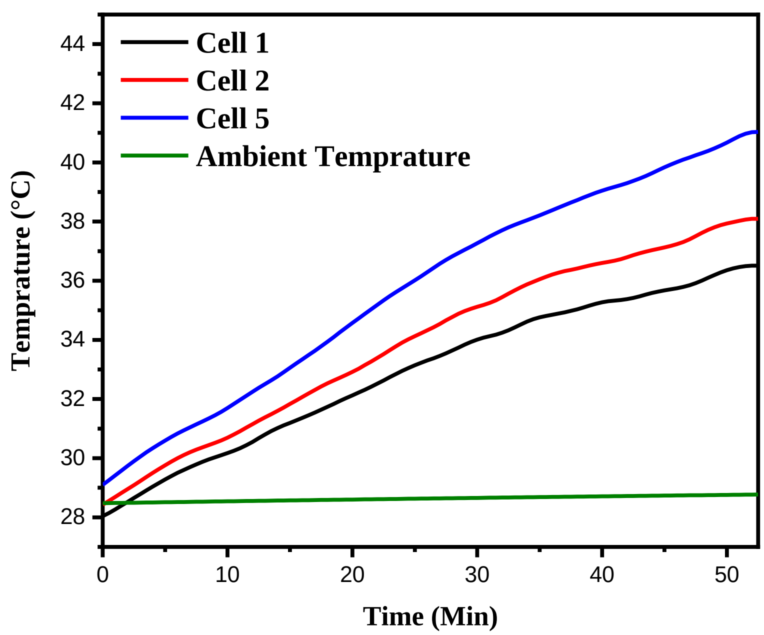


Figure 5.1 Temperature profile of battery pack for room temperature operations.

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Table 5.1 Temperature for room temperature operations of battery pack.

Room Cooling			
	Maximum Temperature	**Minimum Temperature**	**Temperature Difference**
Cell 1	**36.51**	**28.03**	**8.48**
Cell 2	**38.09**	**28.47**	**9.62**
Cell 5	**41.03**	**29.1**	**11.93**

5.2 Forced air cooling with fan

When the same battery pack with same square configuration equipped two fans for forced air cooling of battery pack is discharged at the same rate of 1C, the battery cells show the temperature regime as shown in fig. 5.2. The maximum temperature gone high for the battery pack is by cell 2 which is 35.59 °C when the room temperature is around 28 °C, which is far lower than as compared with normal room conditions working battery pack as previously shown. Table 5.2 shows the maximum, minimum and average temperature for the battery pack equipped with fans for forced cooling.

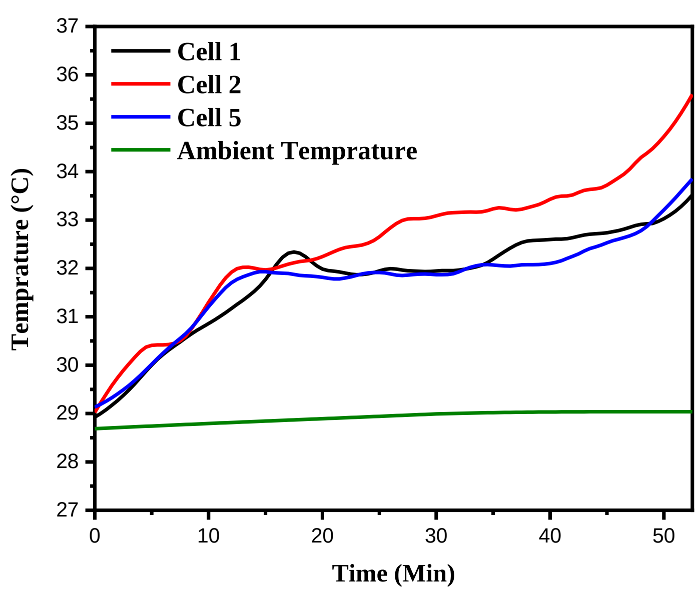

Figure 5.2 Temperature profile of battery pack of forced air-cooling battery pack.

Table 5.2 Temperatures for Forced air cooling battery pack.

Fan Cooling			
	Maximum Temperature	**Minimum Temperature**	**Temperature Difference**
Cell 1	33.5	28.9	4.6
Cell 2	35.59	29.02	6.57
Cell 5	33.8	29.13	4.67

5.3 PCM cooling

To have proper thermal management system for battery thermal management, phase change materials are playing vital role in thermal management system, in this case we are using Sodium Sulfate decahydrate as phase change material for the same battery pack as previously used, which was when discharged at 1C rate shows the temperature regime as shown in fig. 5.3 At room temperature of about 28 ℃, the initial temperature for all the battery pack cell is almost the same and the maximum temperature is achieved by cell 5 which is 32.8 ℃. Table 5.3 Shows the maximum, minimum and average temperature of the battery pack. It can clearly be seen that by use of PCM as coolant for battery pack the temperature regime shows smooth rise in the working temperature of cell and showing that the heat energy produced by the cell is vitally being used by the phase change material to change the phase of material and hence we are getting a smooth rise in temperature regime and a proper thermal management of battery pack as compared with room condition and forced fan thermal management case.

Table 5.3 Temperatures for PCM based thermal management system for battery pack.

PCM Cooling			
	Maximum Temperature	**Minimum Temperature**	**Temperature Difference**
Cell 1	31.6	28.53	3.07
Cell 2	32.06	28.6	3.46
Cell 5	32.8	28.4	4.4

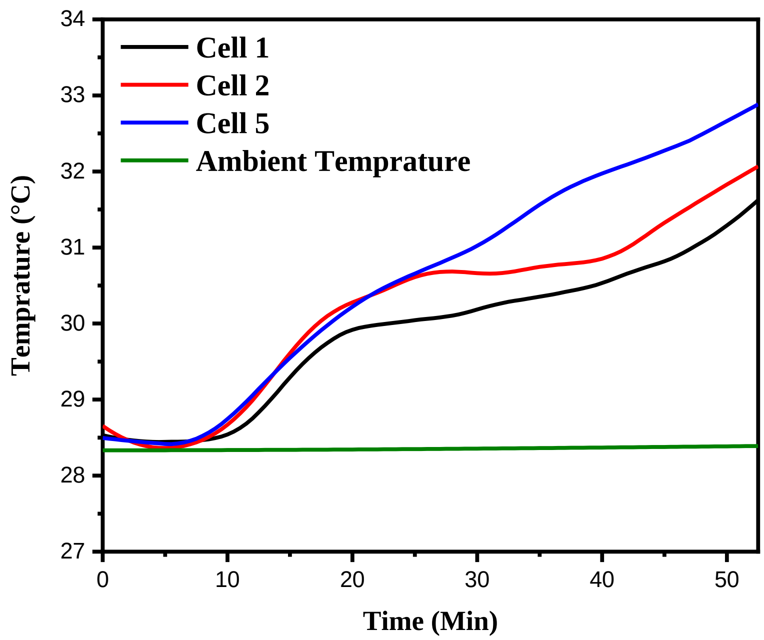

Figure 5.3 Temperature profile for PCM based battery pack.

5.4 Battery Pack Cell Temperature Regimes

While we analyze the battery pack we made by different thermal management systems, we also analyses each thermal management system effects on each cell we are monitoring.

In Case of Cell 1, which is the cell at the extreme corner of the battery pack, by the fig. 5.4 and table 5.4 shown that we can clearly understands that there is high rise in working temperature of battery in case of room conditions operation, while in case of forced Fan cooling there are sharp rise in temperature regime after the battery starts discharging and after some time he forced air cooling by fans tried to overcome that drastic change in temperature, which shows that forced fan cooling not properly maintaining the temperature of cell 1. In case of PCM cooling of battery pack it can clearly be seen that the temperature regime of cell1 rises smoothly and heat energy generated by battery is smoothly dissipated to the material, which is used in changing the phase of material, hence we are getting a proper thermal management by it.

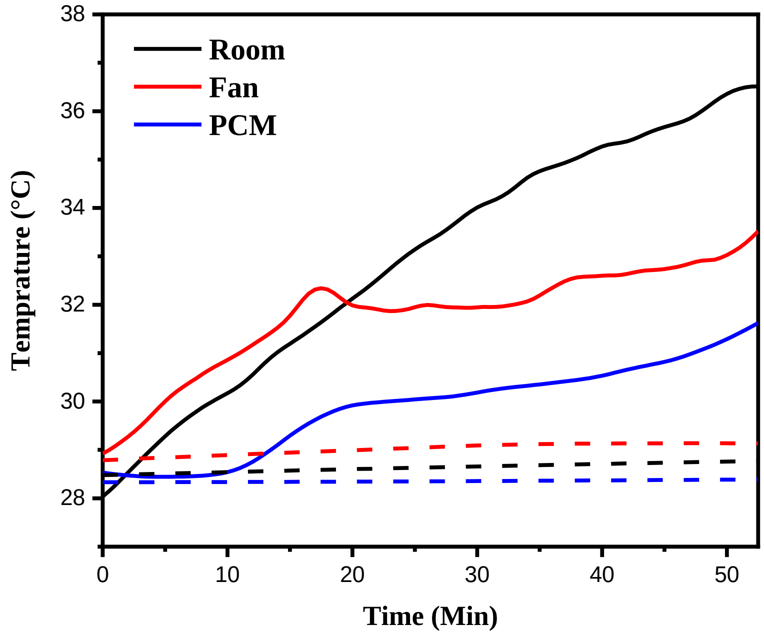

Figure 5.4 Temperature profile of cell 1 for each thermal management system for battery pack.

Table 5.4 Temperatures of cell 1 for each thermal management system for battery pack.

Cell 1			
	Maximum Temperature	**Minimum Temperature**	**Average Temperature**
Room Cooling	36.51	28.03	32.27
Fan Cooling	33.5	28.9	31.2
PCM Cooling	31.6	28.53	30.065

In case of Cell 2, as shown in fig. 5.5 and table 5.5 which is the second cell behind the cell 1 and it face 3 other Li-Ion cells, the temperature profile shows that in case of room temperature operation the temperature of cell 2 rises up to 38 ℃ as compared to the cell 1 in which it rises up to 36.5 ℃, which is due to the fact that cell 2 is facing 3 other cells also which cause the increase in temperature. In case of Force air cooling by fan the temperature of cell 2 rises with sharp rising in between and heat energy is being dissipated by the forced air flowing causing the maximum temperature of cell 2 to be rises to 35.59

°C, as compared to Cell 1 whose temperature rises to 33.5 °C. In Case of PCM Cooling the maximum temperature of cell 2 rises to only 32.06 °C with a smooth temperature profile indicating PCM is effectively working to manage the heat generated by the operation battery.

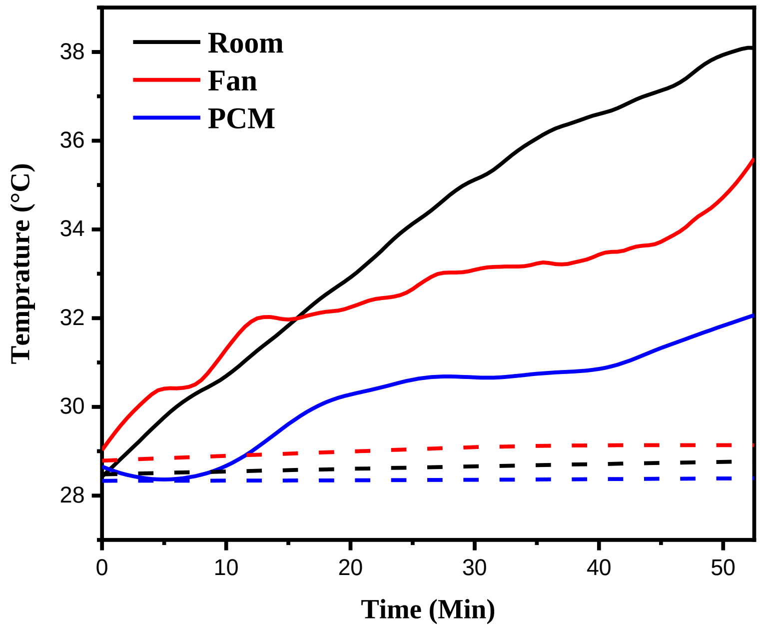

Figure 5.5 Temperature profile for cell 2 for each thermal management system for battery pack.

Table 5.5 Temperatures of cell 2 for each thermal management system for battery pack.

Cell 2			
	Maximum Temperature	**Minimum Temperature**	**Average Temperature**
Room Cooling	38.09	28.47	33.28
Fan Cooling	35.59	29.02	32.305
PCM Cooling	32.06	28.6	30.33

In case of Cell 5 which is the most important cell to be monitored in case of thermal management because of it position which is the center of the battery pack, which means that is surrounded by the 8 other cells, due to which the maximum increase in temperature is recorded for cell 5, which is also the main center of concern for the battery pack to thermally manage the temperature of the cell whose temperature rises the most. As shown in fig. 5.6 and table 5.6, in case of room temperature operation of battery pack shows that the maximum rise can be up to 41 ℃ due to cells presence in between all the cells, while in case of forced air cooling with fans the maximum temperature of cell 5 rises to about 33.8 ℃ which is lower as compared to cell 2 due to the fact that forced air cooling from both the side of the battery pack forces the air to skip from the mid-section which ultimately due to high air flow rate dissipates more heat at the mid-section. In case of PCM Cooling it can be seen the same profile as for the cell 1 and cell 2 that the temperature rises with a smooth profile and manages the heat generated with the help of PCM, the maximum temperature increase for the cell is about 32.8 ℃.

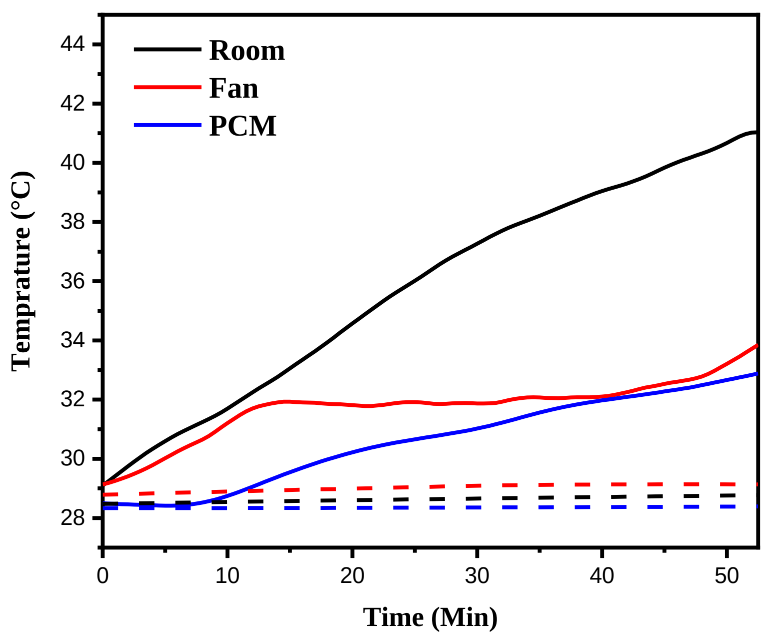

Figure 5.6 Temperature profile for cell 5 for each thermally management system for battery pack.

Table 5.6 Temperatures of cell 5 for each thermal management system for battery pack.

Cell 5			
	Maximum Temperature	**Minimum Temperature**	**Average Temperature**

Room Cooling	41.03	29.10	35.06
Fan Cooling	33.80	29.13	31.46
PCM Cooling	32.80	28.40	30.60

Table 5.7 shows the comparison in between different thermal management and normal room operation of battery pack for each monitored cell obtained by subtracting the respective maximum temperature for each cell, it can be clearly seen from this table that he maximum temperature drop can be obtained by using PCM in which Cell 1, 2 and 5 drops the temperature of the cell by about 5 ℃, 6 ℃ and 8 ℃ respectively, in contrast with forced air cooling the maximum temperature drop for cell 1, 2 and 5 is about 3 ℃, 2,5 ℃ and 7 ℃. In comparison of forced air cooling and PCM Cooling the maximum temperature drop for cell 1, 2 and 5 was 2 ℃, 4 ℃ and 1 ℃, which indicates that both these systems are good for thermally management of batteries.

Table 5.7 Temperature difference between different thermal management systems for each monitored cell.

	Cell 1	**Cell 2**	**Cell 5**
Room cooling and forced air cooling	3.01	2.50	7.23
Room Cooling and PCM Cooling	4.91	6.03	8.23
Forced air cooling and PCM cooling	1.90	3.53	1.00

Table 5.8 shows the average temperature difference for each thermal management system in comparison with room operation working of battery pack, the data shows that forced air cooling can averagely decrease the temperature of battery pack up to 4.2 ℃, while the PCM cooling can decreases the temperature up to 6.5 ℃, while comparing the forced air cooling and PCM cooling the average difference in between them is about 2.4 ℃ of temperature, indicating that PCM is cooling is more suitable for the battery pack thermal management not only because of the fact that PCM is more good in thermal management but also due to the fact that PCM can be enclosed in the battery pack in any configuration and the battery pack can be sealed, while in case of forced air cooling, the battery pack cannot be sealed moreover the fans used for providing air flow requires energy as well maintenance, which can be quiet more complicated in case for the battery packing using in enclosed places such as electric vehicles [1] [2].

Table 5.8 Temperature difference between thermal management systems

Difference between thermal management system	**Average Temperature Difference**
Room Cooling and Fan Cooling	4.25
Room Cooling and PCM Cooling	6.39
Fan Cooling and PCM Cooling	2.14

Summary

In this chapter initially results for all the experiments conducted are shown separately, then all the results are compared by making a comparison in between thermal management systems and each monitored cell.

References

[1] W. Zhang, Z. Liang, G. Ling, and L. Huang, "Influence of phase change material dosage on the heat dissipation performance of the battery thermal management system," *J. Energy Storage*, vol. 41, no. November 2020, p. 102849, 2021, doi: 10.1016/j.est.2021.102849.

[2] M. M. El Idi, M. Karkri, and M. Abdou Tankari, "A passive thermal management system of Li-ion batteries using PCM composites: Experimental and numerical investigations," *Int. J. Heat Mass Transf.*, vol. 169, p. 120894, 2021, doi: 10.1016/j.ijheatmasstransfer.2020.120894.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

A new experimental bench has been established in this research to investigate the thermal characteristics of a Li-ion battery at the cell scale. IFR-26650 cells were used. $Na_2SO_4 \cdot 10H_2O$ was used to design and optimize a passive BTMS. The objective is to keep the cells' temperature uniform and within a safe operating temperature range. Number of charge and discharge experiments were performed to study the impact of cooling techniques on thermal performance of Li-ion cells. To study the performance of BTMS, the temperature of the cells was monitored continuously. The results revealed that the cell surface temperature is affected by numerous factors, including current rate, charge and discharge cycle duration, and ambient temperature. The influence of active cooling and passive cooling were separately investigated.

The maximum temperature, temperature difference and the temperature rise rate of the cells with no cooling are the highest. In this study, the cooling performance of an air-cooled BTMS is enhanced by improving the system's flow pattern. It has been discovered that fan cooling helps to dissipate the heat generated by the cells. However, the uneven temperature distribution among cells limits its performance. Research revealed that using $Na_2SO_4 \cdot 10H_2O$ as a PCM not only enhances the cooling performance of BTMS but also minimizes the temperature difference among cells.

6.2 Recommendations

The thermal management of a larger battery pack with a high capacity can be a hard task to achieve in which the temperature of the battery pack can go higher than the current research conducted. In areas where the average summer temperature is higher than 40 ℃, which can ultimately increase the risk of battery optimum temperature operations. Similarly, battery pack thermal pack certain other issues regarding use of certain materials, which can be a difficult task to achieve for this purpose in light to our research conducted it is recommended that:

- Battery packs with a large number of cells will be constructed with certain arrangements in order to be tested under similar conditions.
- Battery packs should be tested at higher C-rates.
- Battery pack with different types of cells (different sizes and battery materials) should be tested to get better viable research that which material to choose in almost every kind of battery pack.
- Certain different PCM materials with melting point higher than of sodium sulfate decahydrate should be tested on larger battery packs at different C-rates to have a proper viability of using PCM as source of cooling for batteries.
- PCM materials should be experiment with some additives such as copper chips to increase the thermal management of cells and battery pack.

Acknowledgments

All praise to Allah Almighty, who gave me the strength to successfully complete this dissertation. Completion of MS Degree has been a challenging, yet interesting journey filled with life lessons. As my research has been completed, I would like to take this opportunity to express sincere gratitude to my supervisor **Dr. Naseem Iqbal** for the continuous support and guidance throughout the MS program and research. I would also like to thank my guidance and evaluation committee: **Dr. Ghulam Ali**, **Dr. Hassan Abdullah**, **Dr. Mustafa Anwar** and **Dr. Majid Ali** for their valuable feedback and insights which added value to this research.

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Muhammad Waqas Nazar

Appendix 1-Publications

Thermal Management of Li-ion Battery by Using Active and Passive Cooling Method

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Abstract:

To enhance the safety of Li-ion batteries, it is crucial to understand their behavior when exposed to high temperature. The structural arrangement and identical cell spacing with use of proper thermal management system are key aspects related to safety of Li-ion batteries. In this study a battery pack was constructed by using nine 26650 Li-ion cells, which are discharged on 1C rated and series of experiments conducted on different battery pack thermal management systems including air cooling and PCM based thermal management of battery pack to evaluate the effects of thermal management on the performance of the battery pack. Inorganic phase change material sodium sulphate decahydrate was used to evaluate the thermal management of battery pack. The results show the hike in temperature of battery pack of about 10 ℃ in normal air-cooling operation of battery when discharged at 1C rate, as in comparison with forced air cooling the maximum temperature hike was about 7 ℃ and in PCM based thermal management system was the temperature hike was up to 4.4 ℃. each monitored cell temperature was also analyzed for each thermal management system. With the help of simple modeling, it shows the maximum temperature hike on normal operation for the battery can be reduced up to about 4.2 ℃ and by 6.4 ℃ by using forced air cooling and PCM based thermal management system respectively. It was also analyzed that PCM based thermal management systems does not show any sharp hike in temperature of battery pack cell, which indicated that PCM used properly thermally managing the battery heat. On comparison between these three systems, it clearly shows that PCM based thermal

management system having sodium sulphate decahydrate as PCM shows the best result in thermal management of battery pack which can be the potential candidate for future electric vehicles battery pack.

Keywords: Li-ion battery, cylindrical battery, Battery Thermal Management, Air cooling, Phase change materials

Journal: Journal of Energy Storage (IF=6.583) (Under-Review)