Experimental study of thermal management system for cylindrical Li-ion battery pack using thermal interface material

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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

The commercialization of electric vehicles is one of the remedies for climatic change and pollution. Because of the Lithium-ion battery's sensitivity to temperature, thermal management is required to enhance the safety, cycle life, and performance. Moreover, the arrangement of cells and the configuration of the module also play a vital role. Owing to the high power requirements in vehicles, charging and discharging a large battery bank at higher rates pose a risk of thermal runaway. Hence, a fully functional battery thermal management system is one of the integral elements of modern-day automobiles. The ability of thermal grease as a thermal interface material has been investigated along with different variations. The grease-contained box has been used as an alternative to PCM for the first time in a battery thermal management context. Firstly, the available BTMS including active, passive, and hybrid approaches were reviewed. Then a baseline condition of the research was established, which was the effect of no cooling on battery performance at distinct rates. After that, the cooling effect of thermal grease was elaborately presented. Lastly, a complete system with grease and copper tubes was studied comparatively. With a fully functional thermal system, an average drop of 20.4 ℃ was recorded at a 2C rate, followed by 13 and 12.4 at 1.5C and 1C rates respectively. The analysis showed that for significant heat removal, a heat sink with thermal interface material is required. Another point inferred is that an interfacial air gap has an adverse effect on the thermal performance of the battery. Therefore, the presence of thermal grease has opened a new avenue in thermal management. The appropriate configuration of cells and careful selection of thermal compounds can produce exceptionally controlled results.

Keywords: Li-ion battery, cylindrical battery, battery thermal management systems, Thermal interface material, Silicone Thermal grease, copper tubes

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1. "Experimental Study Of Thermal Management System For Cylindrical Li-ion Battery Pack Using Thermal Interface Material", **Zain Ul Abidin**; Naseem Iqbal; Tayyaba Noor; Majid Ali, Journal of Energy Storage (Under-review).

List of Abbreviations/Nomenclature

TIM	Thermal Interface Material
BTMS	Battery Thermal Management Systems
EVs	Electric Vehicles
HEVs	Hybrid Electric Vehicles
TG	Thermal Grease
LIB	Lithium Ion Battery

CHAPTER 1 INTRODUCTION

1.1 Introduction

The surge in environmental and health complications due to reliance on conventional fuels has become a significant concern in recent years. The transition from internal combustion engines to electric vehicles has become inevitable. The commercialization of electric vehicles requires an effective energy storage mechanism. Lithium-ion batteries are the most commonly used storage system because of their comparative advantages like high energy density, higher voltages, recyclability, and long cycle life [2].

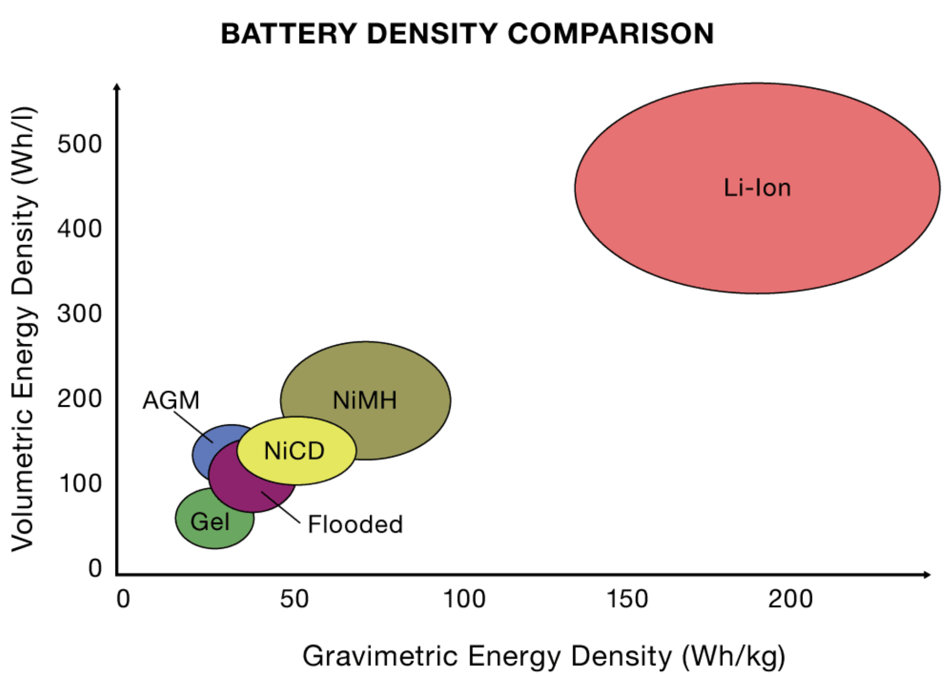

Figure 1.1 Lithium-Ion Battery advantages

LiBs are temperature sensitive [1]. Owing to the range anxiety and high-power requirements, a huge number of cells are connected in series and parallel in a module. When cells are subjected to fast charging and discharging, a large amount of heat is produced inside a module, which can lead to capacity fading, battery deterioration, and even thermal runaway.

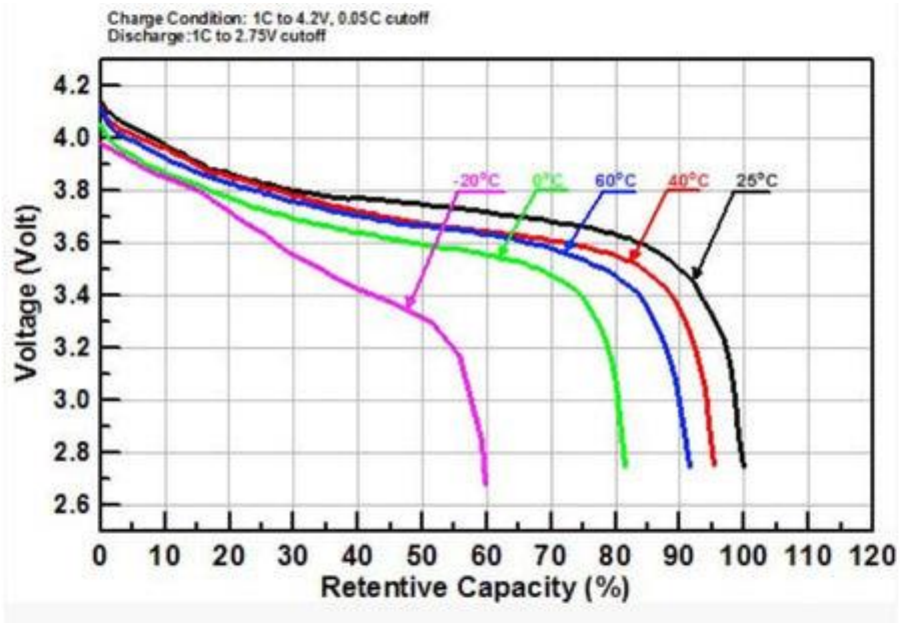

Figure 1.2 Temperature effect on Lithium ion Battery Capacity

To ensure the proper functioning of lithium-ion batteries and overcome safety concerns, a resilient battery thermal management system is required. Btms performs two functions: 1) To maintain an operating temperature between a desired range and 2) to keep the temperature difference between cells in a module should be within 5 ℃. Generally, BTMS employs certain cooling techniques to regulate temperature. Active, Passive, and hybrid cooling methods are commonly used in btms. Active Cooling requires a power source for operation [3] and includes Air cooling [4], liquid cooling, and Peltier cooling. Air Cooling is lightweight and simpler in design but due to the low conductivity of air, it is not suitable for high-current applications. While liquid has a better heat transfer coefficient and efficiency but structural complexity becomes a challenge in some cases and requires a substantial amount of active power. On the contrary, in passive cooling external power is not required and Phase change materials are usually employed in this context because of their low cost and easy controllability. PCM usage for thermal management was first suggested by Hallaj and Selman [5]. However, the hurdle with PCM is low thermal conductivity and energy density, which require some enhancements and modifications. Because of these impediments hybrid cooling system has gained a lot of recognition. It is a combination of active and passive cooling. A lot of different combinations and configurations of hybrid cooling systems are available for battery thermal management. Xin Ge et al has made a hybrid system containing PCM, Silicone grease, and liquid cooling. Thermal grease has been used in the air gap filler between PCM and aluminum tubes containing liquid circulating around the system [6]. This paper will focus only on passive cooling techniques. The passive cooling technique discussed in this paper is Thermal grease (Thermal compound) cooling. It is commonly employed as an air gap filler in several electronics like CPU and GPU. It is a thermal interface material that is usually placed in between the heat source and sink. In this work Thermal grease is used as a heat transfer material and copper pipes have acted as a heat sink. The effect of grease has been studied at different C-rates and temperatures have been recorded as a function of current.

1.2 Battery Operations

The operating temperature range of Li ion cell is 25 to 40. To ensure proper functioning, temperature should be kept in this range. Because the reaction kinetics on either temperature zone would be unusual. Similarly, temperature uniformity across the cells is a performance determining factor. During operation, temperature among cells should not differ by more than 5 ℃ for long cyclic life [17], [25], [26]. Electrical imbalance caused by high temperature difference leads to improper capacity retention, which ultimately affects module performance. [27], Fig 1.3 and fig 1.4 shows the optimum battery temperature range with pros and cons

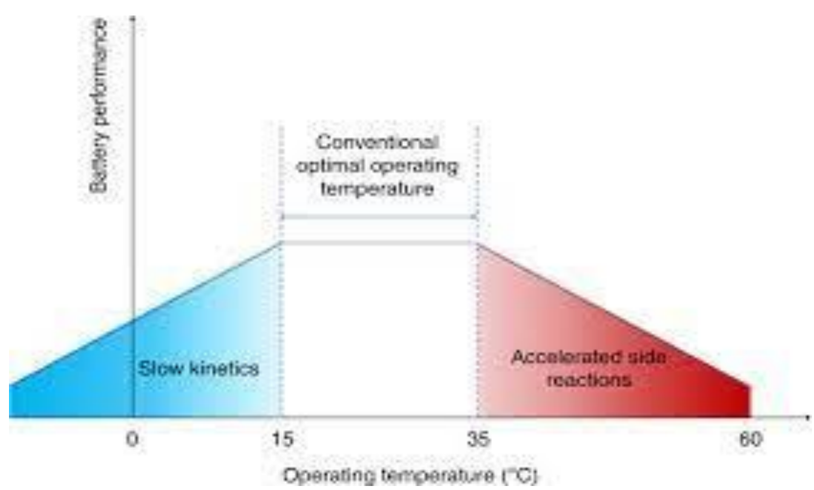

Figure 1.3 Effect on the performance of Li-ion cell with increase and decrease in temperature

Fig. 1.4 illustrates the high temperature processes which could prove fatal for Li-ion based system. Thermal runaway could be initiated by working in temperature condition beyond 100 ℃.

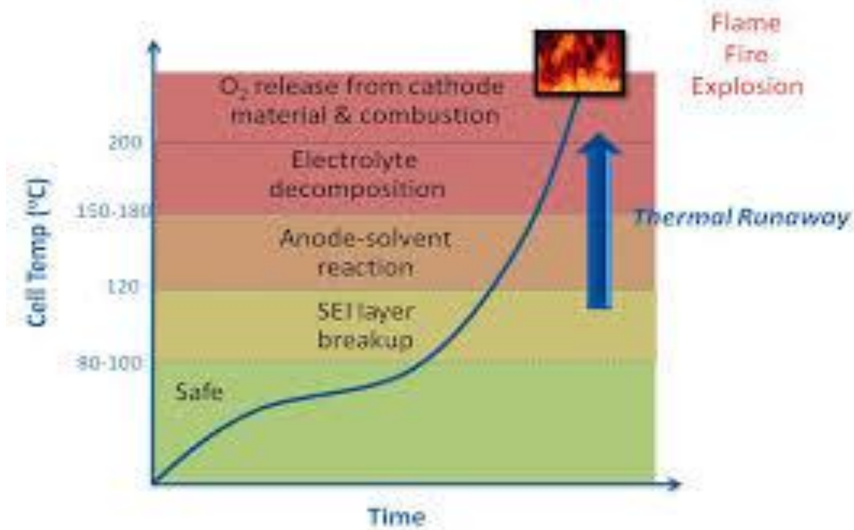

Figure 1.4 Effects on battery chemistry with change in operational temperature

1.3 Battery Thermal Management Systems

Battery can be thermally managed in two ways. One technique is the modification in battery's chemistry. Other way is to remove and regulate heat produced during operation in a module [29]. Temperature regulation externally requires monitoring of cell's temperature and, temperature difference the among cells [30]. To ensure battery safety, either of these two management methods should be employed. Different Cooling method are used in the context of external thermal management. It helps to regulate temperature within operating range of battery [31]. So, For proper functioning of battery, a resilient BTMS is required along with battery pack [29].

To search for reliable cooling techniques, various cooling systems and different configurations have been studied [32]. The temperature can be precisely controlled with the help of BTMS [33], [34]. Two types of cooling methods are common 1) Active Cooling 2) Passive cooling. The first one is comprised of liquid cooling, air cooling and refrigerant cooling are widely adopted for BTMS [35], [36]. In such system, water or air is used as a heat transfer fluid but requires power to transfer heat and usually employed in situations where fast heat dissipation is required. The latter one consists of PCM cooling and thermal interface material cooling, usually employed because of its low cost and easy control [37]. Passive cooling is also preferred because of simpler construction and no power requirements. But to cater increasing power requirement, another approach common is hybrid cooling, which is a combination of cooling techniques mentioned above, usually used to impart more flexibility and adaptability to BTMS[38].Similarly different configurations of BTMS has also been studied to find the appropriate orientation of cells so that heat could be dissipated in an effective ways [23]. A previous study found that using identical cell-spacing efficiently reduces the temperature differences among the cells [35]. For low power applications passive cooling is suitable. Thermal grease cooling has been used as a thermal interface material for BTMS. TIMs provide heat transfer pathways to heat sink and fill air gaps between heat source and heat sink.

1.3.1 Thermal Grease Cooling

Thermal grease is used for thermal management of electronic components and widely used in CPUs and GPUs. The weakest point in heat dissipation cycle is the contact point between heat source and heat sink. Thermal interface materials come into play here. They fill the gap between the two components, which otherwise would be filled with air that acts as a thermal insulator.

Two types of Thermal Grease are commonly used in research. One is metal oxide grease and the other is silicone based grease. The former one has metal such as silver or aluminum as a main ingredient along with some additives like silicone and other metal oxide. It has a high thermal conductivity among all greases but it is also an electrical conductor because of presence of metal particles. The latter one has a silicone as base material along with some other additives like metal oxides. But, the advantage of this grease is thermal insulation which makes it feasible to be used in an electronic components, where short circuit could cause catastrophe. There are also other types of greases available with varying thermal conductivity but they are less common.

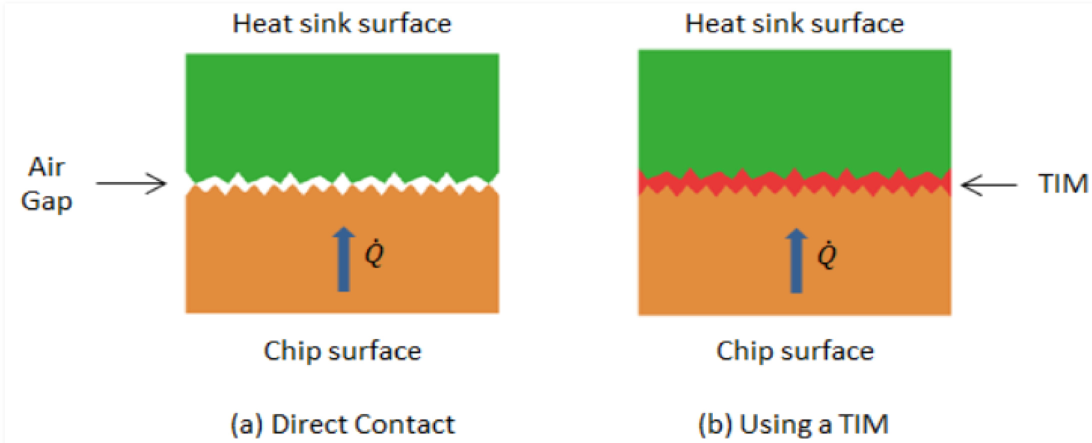

Figure 1.5 Comparison of Heat transfer with and without TIM

1.3.2 Thermal Grease and Copper tubes

Thermal interface materials itself are not enough to cool down a system. It just fills a space between heat source and sink. To complete a system, we need some heat sink to dissipate the heat away. Copper tubes have been used in this regard. The TIM will fill the void spaces between the two elements, which otherwise would be filled by air, and will provide pathways for heat to be dissipated by copper tubes. The contact area between Thermal grease surrounded cells and the copper tubes will produce a significant effect in heat dissipation. The flat-faced faced copper tube will aid more in removing heat compared to the cylindrical one. A lot of research has been conducted to find the appropriate configuration of heat sink to be used in BTMS. In general, copper tube enclosure provides better heat dissipation.

Thermal grease is very convenient to be used in the thermal management of electronics as well as for power generating sources as it serves its function of filling void spaces when used as a thermal interface material. Moreover, it can be adopted in any structural orientation as it has gel-based nature. A hybrid system consisted of liquid cooling system has proved that using thermal grease between cells and cooling pipe has made a significant temperature drop as it has increases a contact area between the two elements[44].

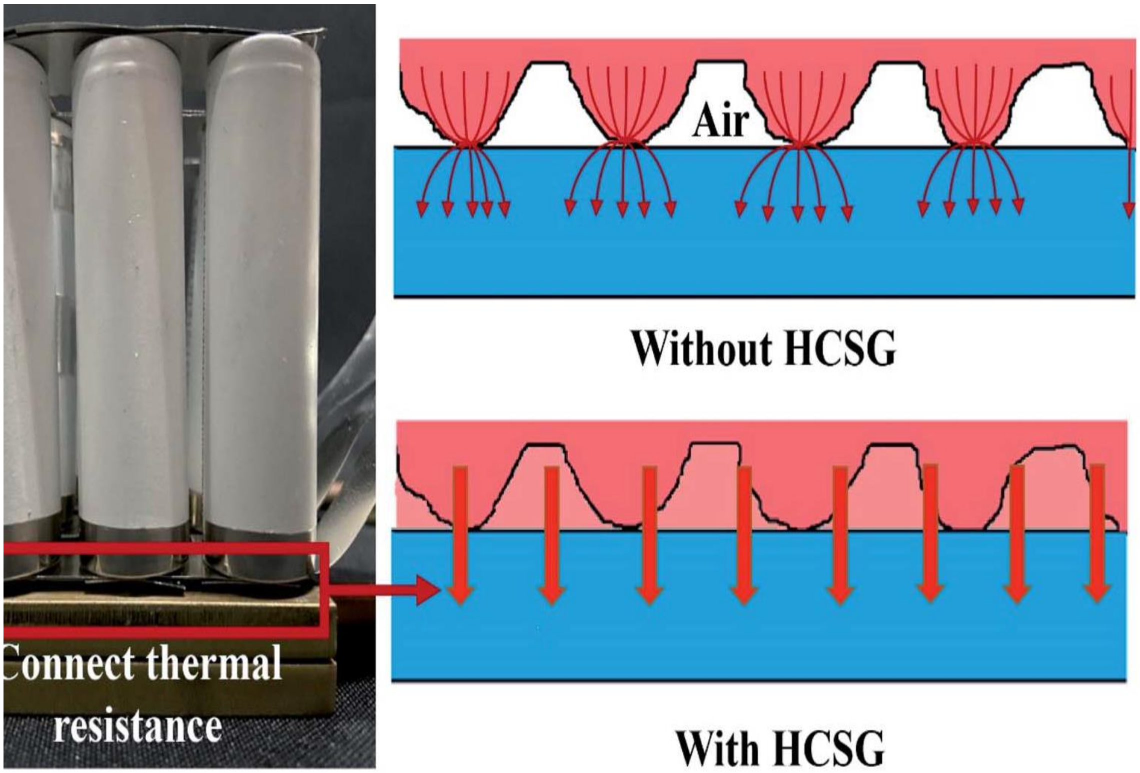

Figure 1.6 Battery pack assembled with Thermal Grease materials for thermal management

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 system

Cooling Technique	**Advantages**	**Disadvantages**
Air Cooling	Structure is simple	Less cooling efficiency
	Cost is low	Cost is high for large volume
	Passive cooling	Easily affected by environment
Phase Change Material	Simple	Low Thermal Conductivity
	No maintenance is required	Cost of maintenance and replacement is high
	Even Temperature distribution	Suitable for low temperature
Liquid Cooling	Even temperature distribution	Complicated structure
	Better cooling efficiency	Maintenance cost is high
	Cooling performance is stable	Active energy is required
Hybrid System	Efficiency is high	Costly
	Suitable for harsh conditions	Complex configuration
	Highly even distribution of Temperature	Active energy is required
	Excellent heat transfer rate	More space requirement

1.4 Problem Statement

Different charge and discharge rates render uneven temperature distribution within the battery pack due to which safety concerns arise.

1.5 Objective of Study

To maintain battery temperature within the optimal range for the desired operation and to reduce overall battery heat, which will increase battery life and reduce maintenance costs.

Summary

This chapter was about the energy demand trends in the world. We have also seen different battery thermal management techniques available in the business. Moreover, the objectives and problem statements have also been discussed.

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CHAPTER 2 LITERATURE REVIEW

2.1 Thermal Management of batteries

When the batteries are charged and discharged at high rates, the electrochemical reactions become fast. The ion within the cells have high kinetic energy, when they strike with other ions, their energy is dissipated in the form of heat because of which battery is thermally excited. This scenario is evident when such action occurs in high power battery. BTMS becomes useful to maintain the battery temperature within optimal range. Such system performs two functions: Regulating the peak temperature and dissipating the additional heat. Another function performed by the system is maintaining uniform temperature distribution among cells and keeping it to less than 5℃ .

2.1.1 PCM and Air cooling based battery thermal management

In this research, PCM based battery thermal system was combined with air-cooling. Xie et al made a novel PCM integrated with air based system. The results showed that hybrid system has produced better results compared to simple air cooling system. 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 airflow. 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].

2.1.2 Liquid based thermal management

In this study liquid based cooling system was used to fulfill the thermal management demands. The important factor like direction of coolant flow, dimensions, flow rate of fluid was investigated numerically. The U shaped flow channels were suggested so that the cells should be cool down from lateral and bottom surface. Several Different models were used to find the better orientations as shown in fig 2.1. The results showed that Case where fluid is flowing in the direction from top to bottom in same direction is the most optimum BTMS design. Moreover, the dimension of cells in an array has the highest impact on temperature difference than the maximum temperature of a cell.

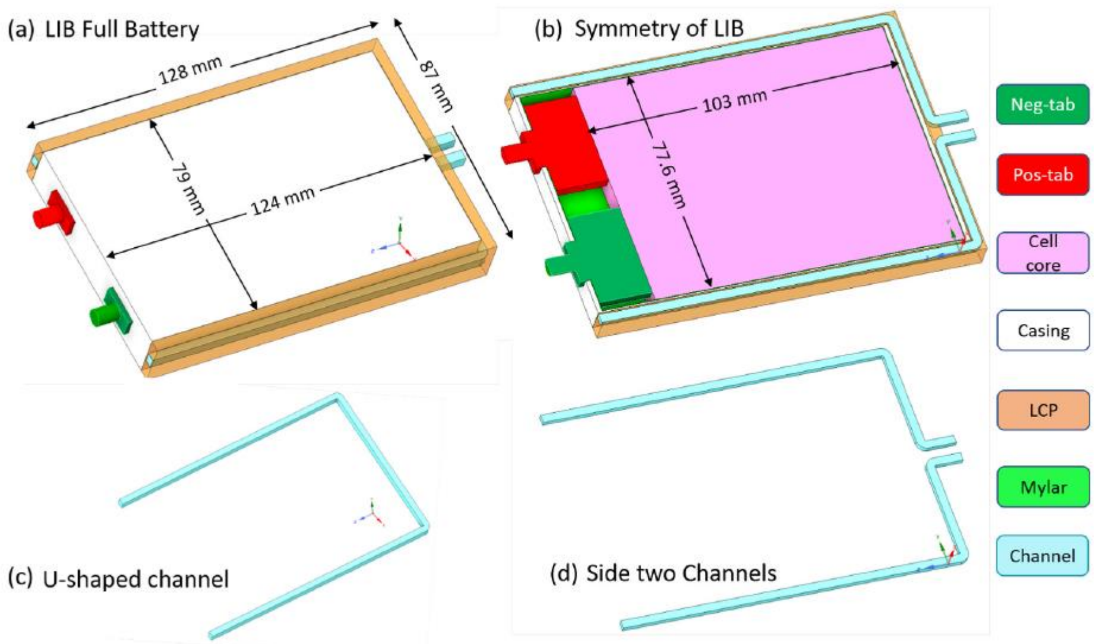

Figure 2.1 Liquid cooled system orientation

2.1.3 Thermal Grease based hybrid system

The proposed system consisted of Li-ion batteries, aluminum element for conduction and U shaped micro heat pipe array with cold plates. The two rows carried U type MHPA, which can siphon heat from the interior of the battery to exterior. Two liquid channels were constructed on both sided of batteries which acted as a heat exchanging fluid. Aluminum conduction element were used between batteries and MHPA to increase the contact area. Thermal Grease served the purpose of making proper contact between components.

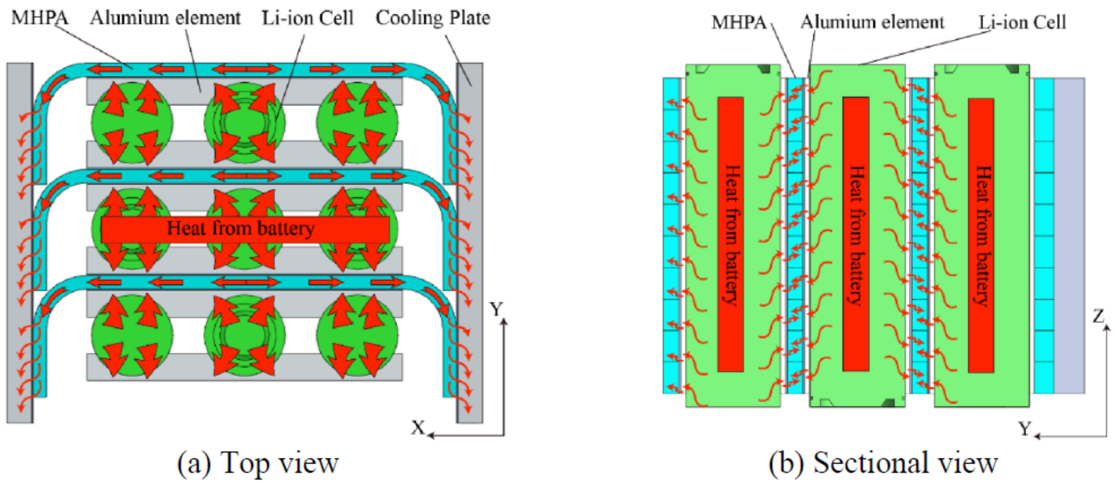

Figure 2.2 Thermal Grease Based Hybrid System

The results showed hybrid system with MHPA and liquid cooling is an effective thermal management technique for cylindrical cells [15].

2.1.4 Heat Pipe and PCM based Hybrid

Heat pipe is a device that is fluid filled vacuum and transmits heat via liquid to vapor phase change. HP has some comparative advantages in terms of design flexibility, better conductivity and low maintenance, which has made it a good alternative for thermal management as passive cooling system. PCM usually has low thermal conductivity, coupling it with HP is a better configuration for battery-based system. In such case, PCM absorbs heat and same amount of heat is partially transferred to HP evaporator. Then heat is rejected into atmosphere through condenser either by natural or forced cooling.

Huang et al., studied the effect of HP-PCM based hybrid system. The results showed that temperature of such system can be maintained around 50 ℃. Zhou et al. took an advantage of PCF immersion cooling capacity and combined it with HP. The result proved that this system is meeting every requirement of safety, long cycle life and long operation.

Table 2.1 Thermal Greases with properties

Type	Material	Properties
Metal Based Grease	Silver	Excellent heat as well as electrical conductor.
	Aluminum	
Liquid Metal Based Grease	Gallium	Smooth and fast heat transfer but may react with aluminum component.
Ceramics Based Grease	Ceramics	Electrical insulator, affordable, and easy to apply.
Carbon Based Grease	Carbon fibers	Good density, electrical insulator, and longer lifespan.
Diamond Carbon Based Grease	Diamond powder	Good heat transference, non-capacitive, and low viscosity.
Silicone Based Grease	Silicone	Spreads evenly, good density, electrical insulator, and better thermal conductivity.

Summary

This phase contains a literature review of existing Battery thermal management system i.e., Active, Passive etc. a comparison between different Thermal Greases is represented in the form of table at the end of this chapter.

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CHAPTER 3 EXPERIMENTATION

3.1 Li-Ion Cells

The cylindrical Lithium-ion batteries (INR18650HG2 3000mAH, 3.6V) have been used for thermal testing. Cell holder brackets (for 18650) cells have been used to mount cells so that the negative terminal wires should not get affected inside a module as shown in fig.3.1.

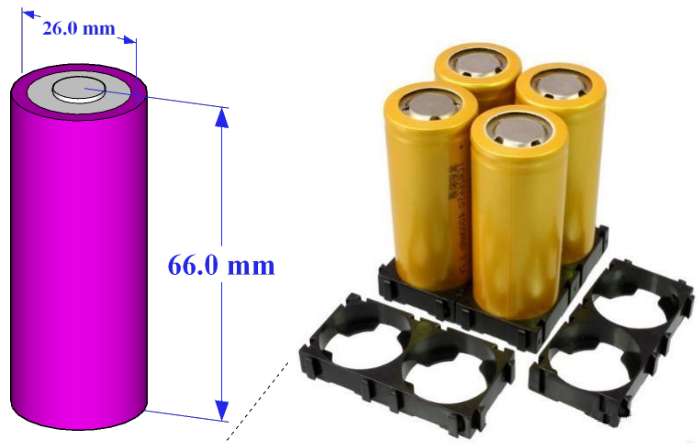

Figure 3.1 18650 Li-ion cells and cell spacers

Table 2.1 Li-Ion Cells Specification

Specification	Nominal Capacity (Ah)	Nominal Voltage (V)	Max Charge Current (A)	Operating Temperature (℃)
Li-ion INR 18650	3.00	3.6	20	-20-+75

3.2 Temperature Measurement

Temperature measurements have been captured with k-type thermocouples as shown in fig. 3.2. K type thermocouple are made up of nickel and chromium. It has a temperature range of -200 to 1260 ℃.

Figure 3.2 K-Type thermocouple for temperature measurements

3.3 Thermal Grease

Silicone Thermal Grease (HY510) is a semiconductor thermal interface material used in electronics like CPUs and GPUs because it fills air gap properly between heat source and sink. It has thermal conductivity around 1.93 W/m-k. It is safe to use. It is affordable and electrically insulated.

3.4 Battery Pack

3.4.1 Casing

The module casing was made up of Acrylic sheet of 2mm thick with dimensions 105*105*105 mm to fit 8*18650 Li-ion batteries, as shown in fig. 3.3.

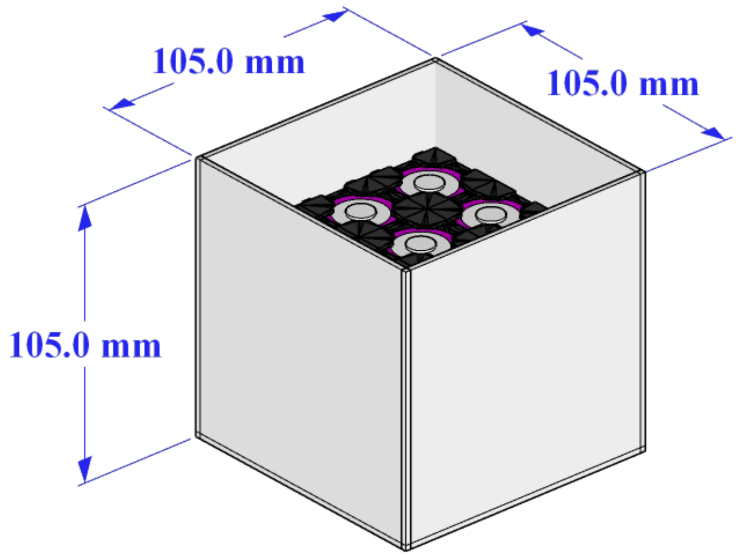

Figure 3.3 BTMS Module Casing

3.4.2 Battery pack configuration

In the experiment, 8 cells were arranged in the square configuration. The module was designed to conduct experiments at the cell level, owing to the availability of eight channels in the battery analyzer. Two cells were present in the first array and three cells in the second and third arrays respectively as shown in Fig 1. Three K-type thermocouples were attached axially to the middle of cells 3,4, and 6 respectively. so that the heat produced at the surface of a cell should be measured. Three cells out of eight cells are of prime importance. Cell 4 is the middle cell, Cell 3 is the one surrounded by three other cells, and Cell 6 is surrounded by two cells. The Rest of the cells are present in a nearly symmetrical way and the value of one cell would be analogous to another cell present in a symmetric position.

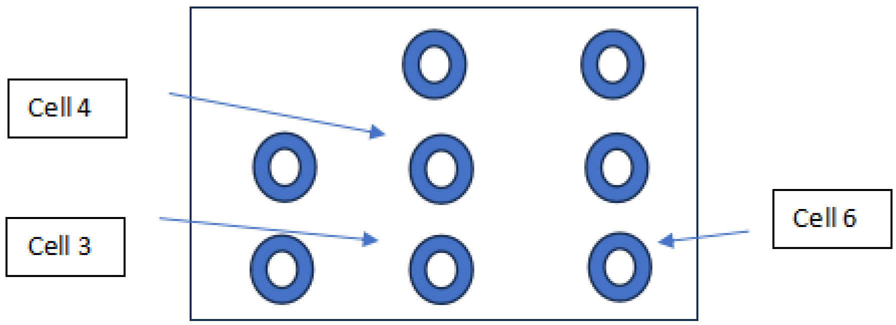

Figure 3.4 Thermocouple positions in battery pack

Each cell in an array is equally spaced at a distance of 1mm. The module is an acrylic box with 8 cells and copper tubes. The heat generation has been measured in three cases 1) Without any cooling system 2) With Thermal Grease as thermal interface material and copper tube 3) With a higher quantity of Thermal Grease.

Figure 3.5 Assembled battery pack with eight 18650 Li-ion cells

3.5 Battery Analyzer

To analyze the battery pack MTI corporation (BST8-3 eight-channel battery analyzer) with rating of 30 A, and 5V having gold-plated pins was used for the best connection, shown in fig. 3.6. There are two ways to connect cells with battery analyzer. One is external connection using probes and other is internal connection using pins configured internally. Computer can control each channel of the analyzer independently and each channel has independent constant voltage and constant current source. These channels are 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 Lutron BTM-4208SD 12-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 Temperature measuring Data Logger

3.7 Experimental Setup

The experimental setup consists of 8*18650 Li-ion cells, an acrylic box, and eight thermocouples each connected axially to the middle part of 18650 cells. Thermocouples were connected to a data logger to measure each cell's temperature as a function of current over some specific time. The battery analyzer was connected externally to each individual's cell through positive and negative probes respectively. These probes provided current to each cell and the effect of current on temperature was recorded. Before, starting the experiment, the temperature of each cell was measured to ensure temperature uniformity across the cells. The experimental setup consists of a battery pack, a battery analyzer, and data logger.

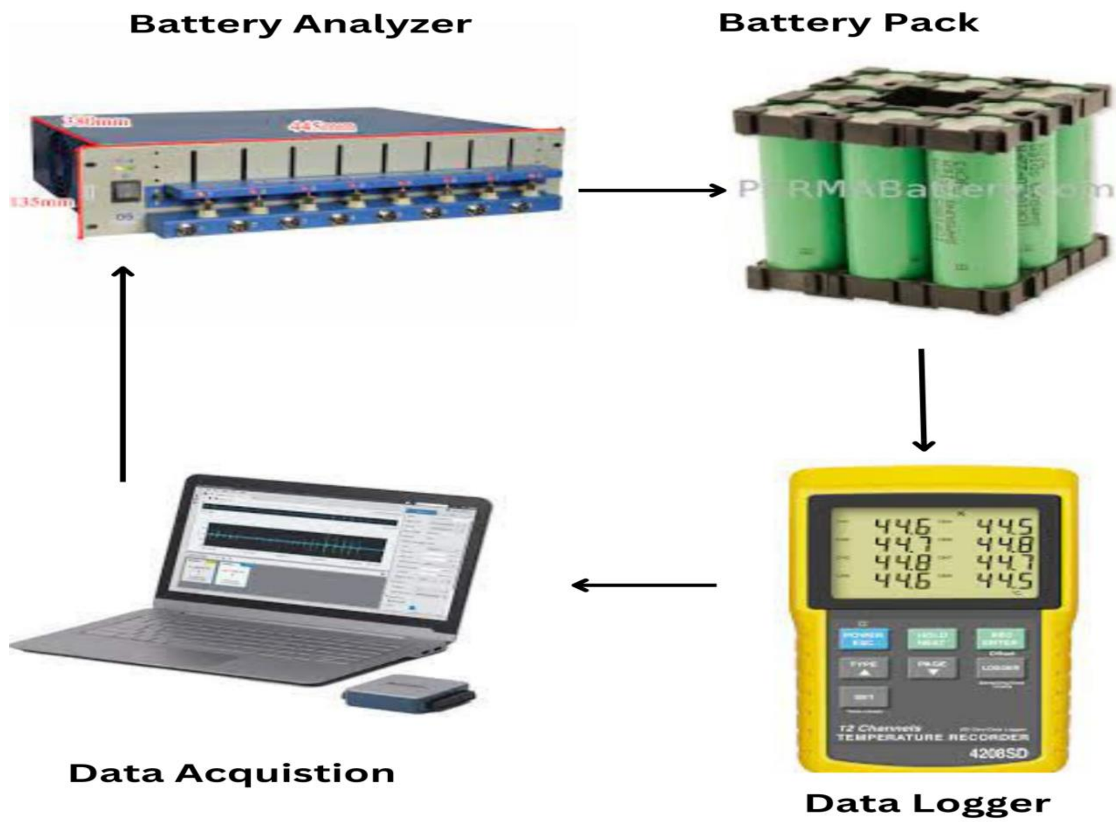

Figure 3.8 Experimental setup of BTMS

The first experiment was conducted at the standard conditions provided in the official datasheet of 18650 to verify the capacity and other parameters of the cells. The cells were charged with 1500 mA constant current, 4.2 V constant voltage, and 50 mA end value as per the standard condition. Similarly, the cells were then discharged at 600 mA and 2V to verify the rated capacity.

Summary

This chapter contains the information about cells configuration inside a module and discusses the entire experimental setup and information flow cycle. In addition, the major components of the setup has also been discussed.

References

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CHAPTER 4

METHODOLOGY

4.1 Methodology

Firstly, an array of eight 18650 cells were made. Each cell was tested individually using battery analyzer internal channels under standard condition. This exercise was for verification of its rated capacity. Each cell was connected with its own thermocouple. Three configurations were used for testing purpose. Every cell in a module was subjected to charge and discharge at three distinct C rates i.e., 2, 1.5 and 1 C. In first series, temperature of each cell was captured without employing any cooling solution. This series of experiment served the purpose of drawing baseline condition. Then battery module was filled with thermal grease, which acted as a thermal interface material. In this scenario, heat sink was not used, just to see the effect of TIM only. Then module was subjected to same conditions as the base condition and temperature of each cells was analyzed at different C rates. Lastly, the final configuration was the addition of heat sink in the grease filled box, to observe the effect of complete heat transfer cycle. Then fully functional battery pack went through same standardized conditions. Temperature behavior of cells was recorded for three different scenario and plotted at different C rates. Fig. 4.1 shows the schematic diagram of methodology:

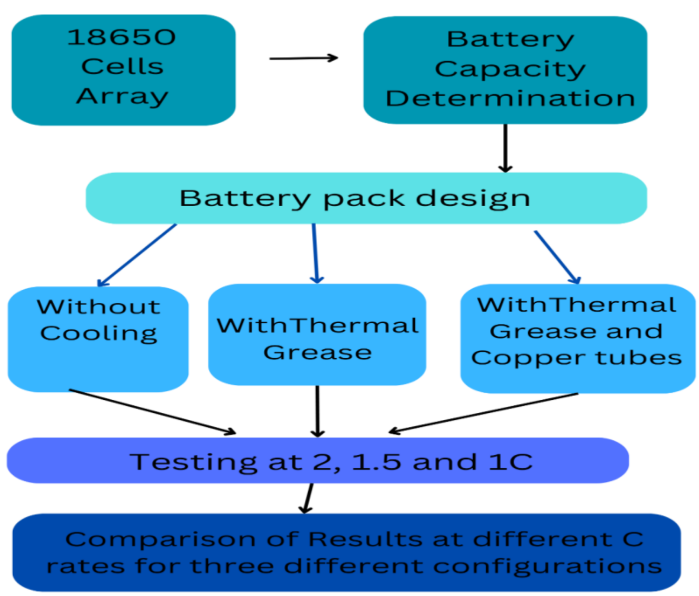


Figure 4.1 Battery Pack Experimental Scheme

4.2 Charging and Discharging Without Cooling

In the first test series, the cells within module were charged and discharged at three different C rates i.e. 2, 1.5 and 1C without any cooling material. Temperature profiles were captured for three cases. The remaining two test series were computed using the same conditions and the results were inferred relative to this base test series.

4.3 Charging and Discharging With Thermal Grease

The second series were conducted in the same way as of baseline. The module was filled with thermal grease. The structural orientation and conditions were the same. The effect of thermal interface material on cell's temperature profile was observed at three distinct C rates..

The TIM fills the air gap present between heat source and sink. It provides heat a transference path to heat sink. In the absence of thermal compound, the air will take its place, would act as thermal insulator, and will add heat into system instead of removing from it. With thermal grease, a decent temperature reduction was observed at distinct C rates. The test were conducted in the configuration shown in fig 4.2.

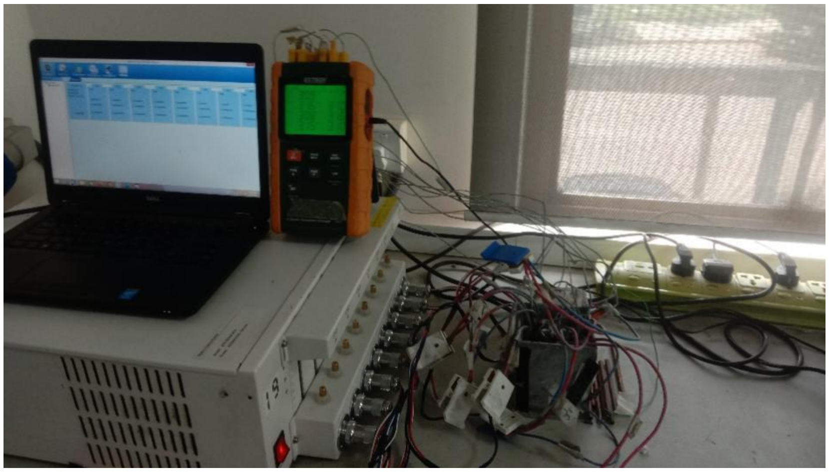


Figure 4.2 BTMS Experimental configuration

4.4 Charging and Discharging with Thermal Grease and Copper Tubes

This experiment was the last configuration of this research test series. In this case, Battery box was filled with grease, which was used as TIM and copper tubes were used as a heat sink. Silicone thermal grease (HY510) is used as thermal compound. HY510 contains a silicone as base material with some metal oxide additives. It has thermal conductivity of 1.93 $W/_{mK}$. as shown in fig. 4.3, it was inserted into an acrylic leak-proof container containing Li-ion cells. Cells were dipped into thermal compound. The experimental conditions were the same. Readings were recorded for three different C rates and the temperature profile of each rate was analyzed for every cell in a configuration.

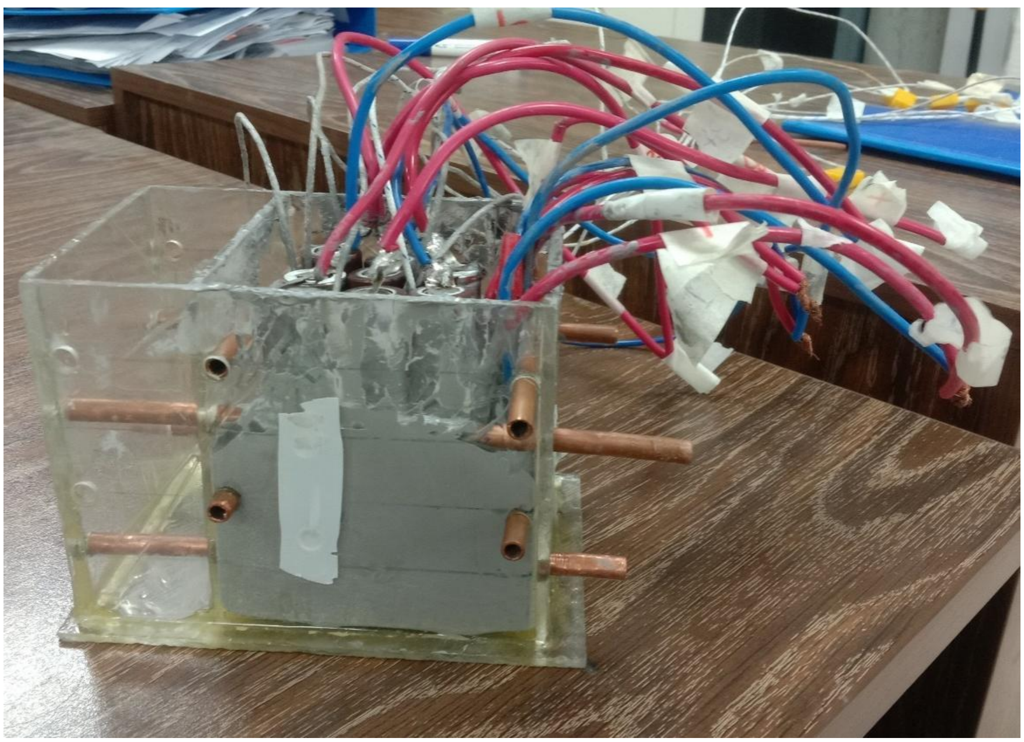


Figure 4.3 Battery Pack with Thermal Grease and Copper tubes

Summary

This chapter was about the methodology we devised to conduct experiments at different C rates for cylindrical cell based BTMS. Different Thermal management orientations have been discussed here.

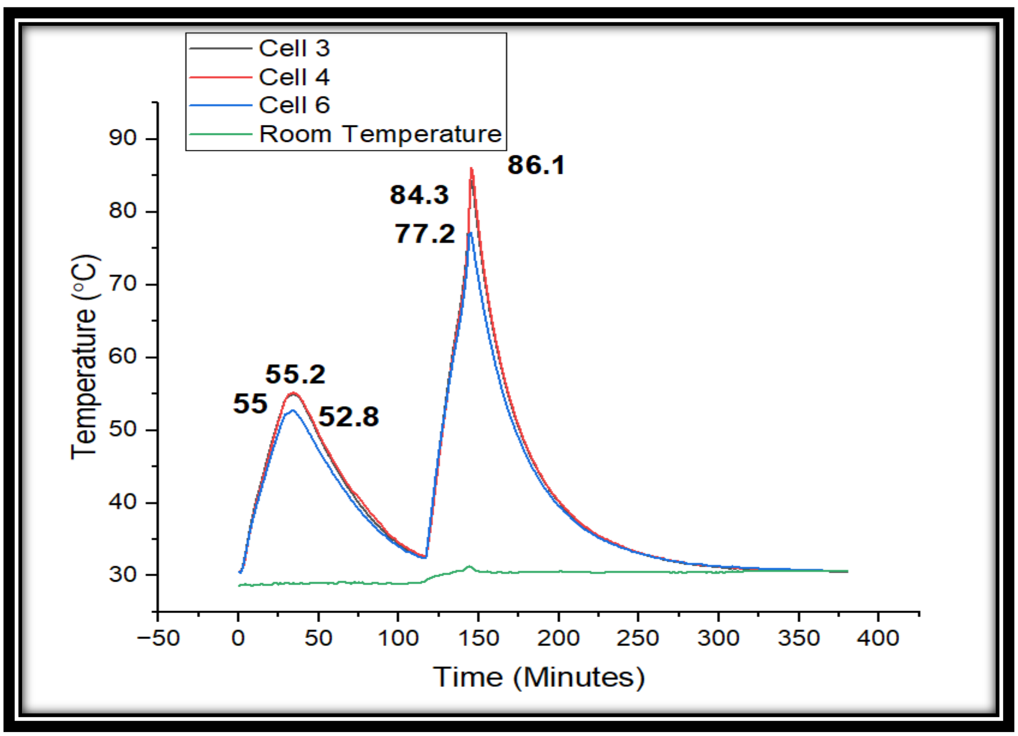
References

[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.

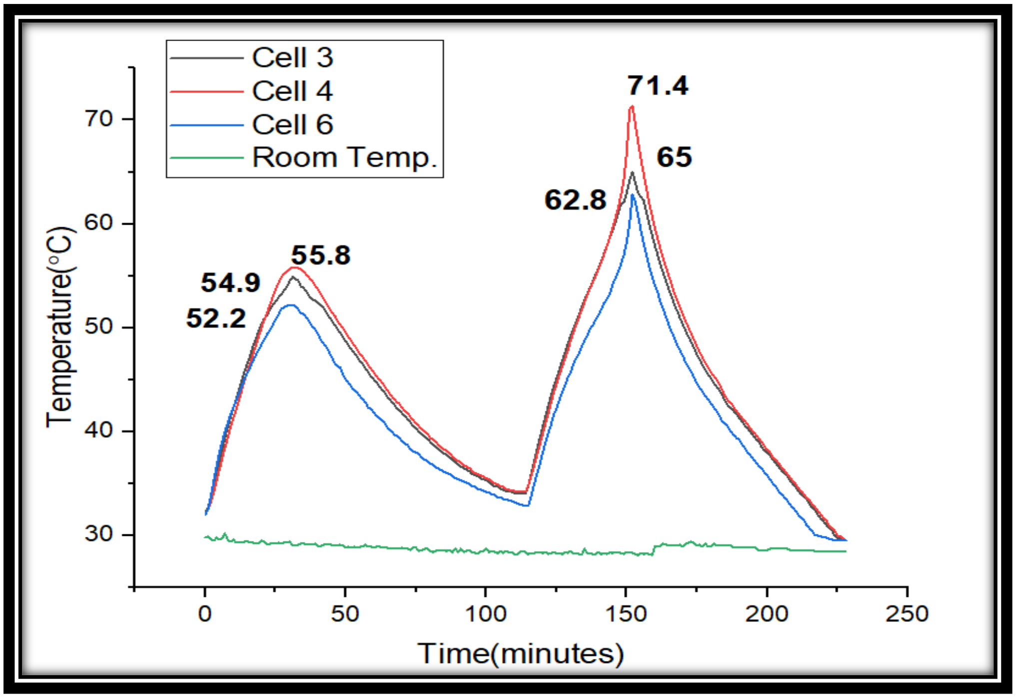
CHAPTER 5 RESULTS AND DISCUSSION

5.1 Battery pack testing without cooling

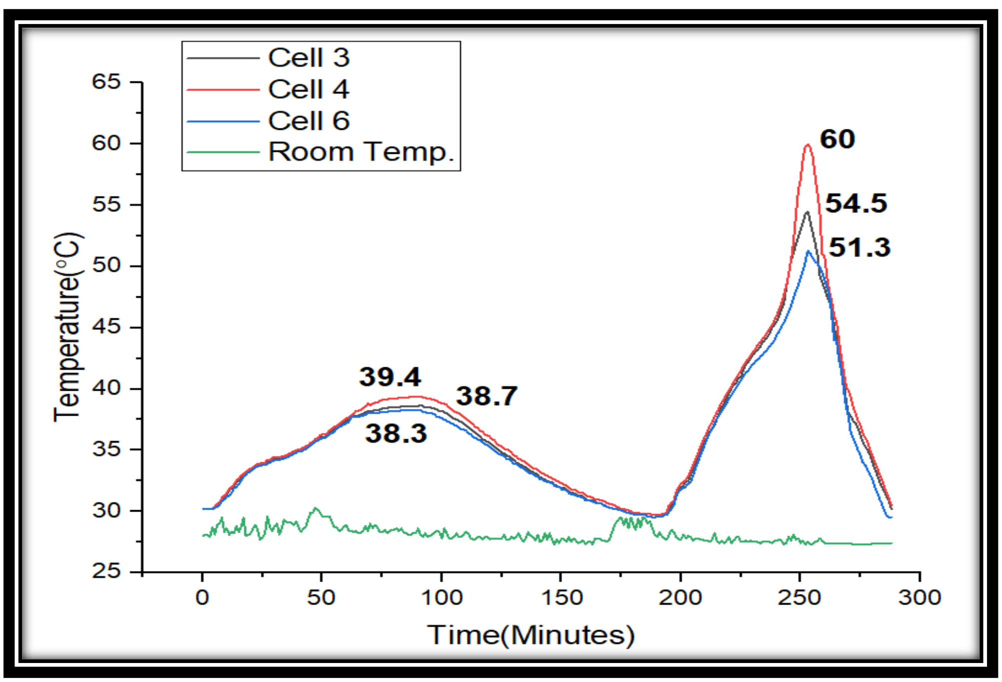
When the battery pack was subjected to charge and discharge conditions according to the above-prescribed parameters without cooling for three different C-rates i.e., 2C, 1.5C, and 1C rates, the thermocouple attached to Cell 3, Cell 4, and Cell 6 respectively, showed trends captured in Fig.5.1. It can be noted that without cooling the maximum discharge temperature at 2C rate for Cell 4 went up to **86.1** ℃ with square arrangements of eight cells. Similarly, at 1.5C and 1C rates have gone up to **71.4**℃ and **60**℃ respectively. Table 5.2 shows the temperature values of three cells.



(a)



(b)

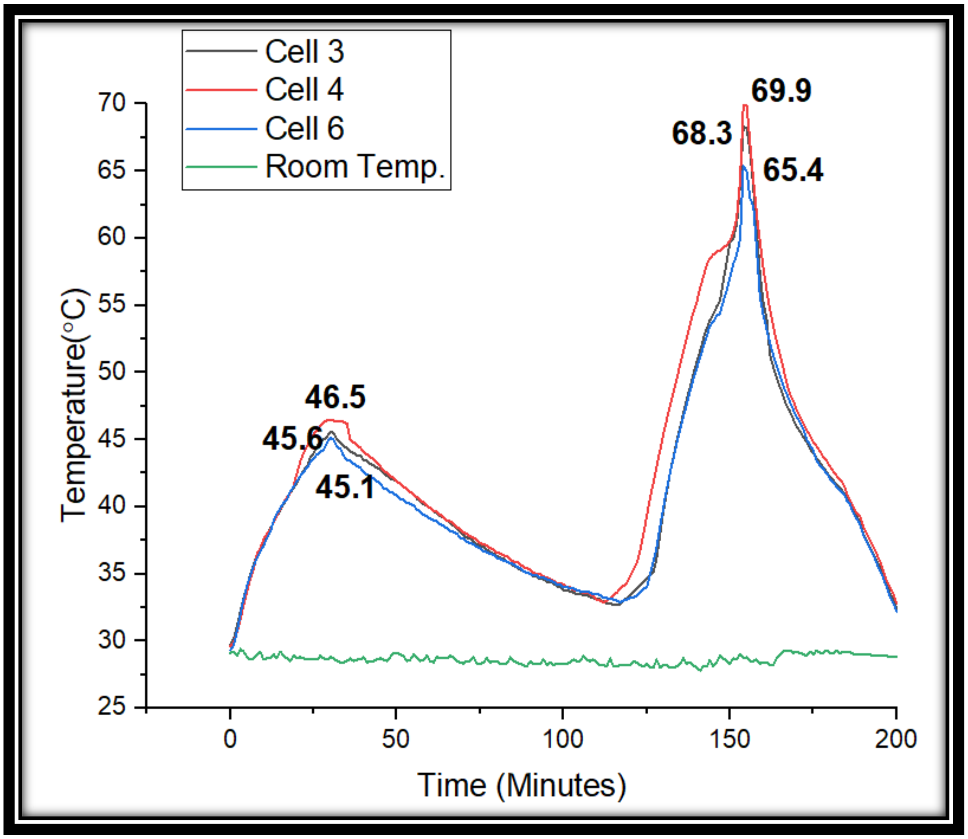


(c)

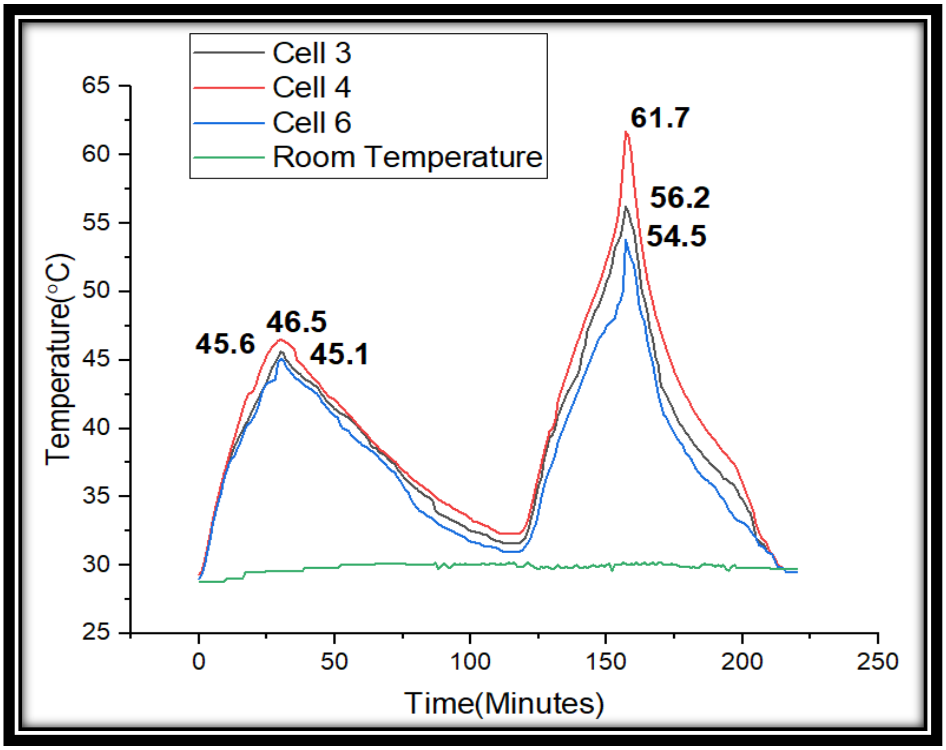
Figure 5.1 Charge and Discharge Temperature Behavior without cooling at (a) 2C rate (b) 1.5C rate (c) 1C rate

5.2 Testing with Thermal Grease and without Copper Tubes

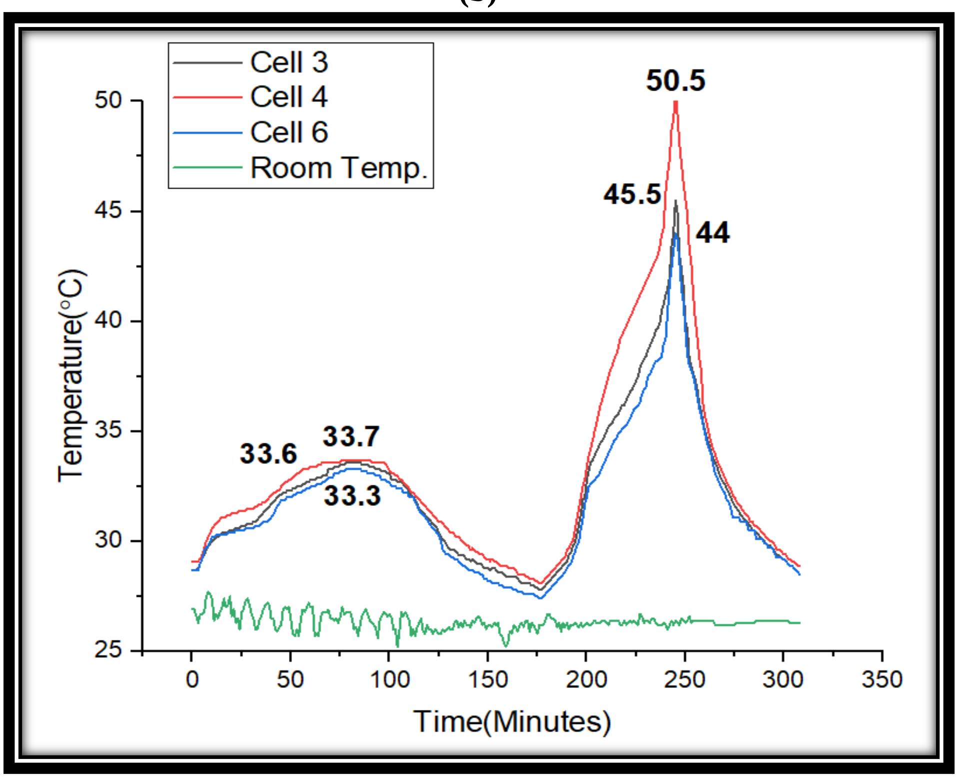
The battery pack with the same orientation was used for this variant of the experiment. In this case, only the cooling material was the thermal interface material. Copper tubes were not used in this variation. The purpose was to observe the effect of the heat sink on heat dissipation. The same prescribed input parameters were used for three distinct C rates. The Temperature rise because of the input current given by different C rates was tracked. The temperature behavior of each cell at different C rates was plotted as shown in Fig.5.2. Cell 4 showed a temperature reduction to **69.9** ℃ at a 2C rate. Similarly, the temperature drop for Cell 3 and Cell 6 at the 2C rate was **68.3** ℃ and **65.4** ℃ respectively. It can be deduced that the complete cycle of heat transfer requires thermal interface material, which is thermal grease in this case and heat sink. The absence of a heat sink has rendered an offset in temperature values compared to the configuration with copper tube. An average temperature difference of 4.2℃ was observed between the two cases at a 2C rate. Similarly, for 1.5C and 1C rates, a difference of 3.3℃ and 2.4℃ was recorded respectively. It can be hypothesized that the heat sink is a necessity of a Thermal management system and makes it more environmentally friendly.


Cell 3
Cell 4
Cell 6
Room Temp.
69.9
68.3
65.4
46.5
45.6
45.1
Temperature(°C)
Time (Minutes)
70
65
60
55
50
45
40
35
30
25
0
50
100
150
200

(a)



(b)

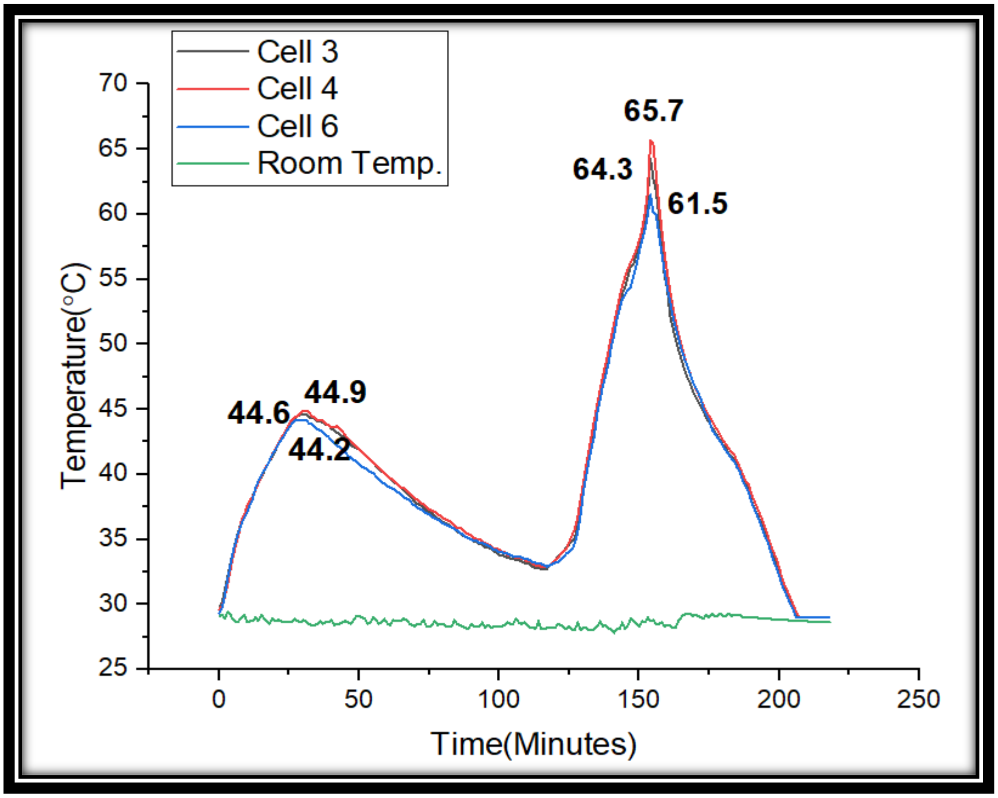


(c)

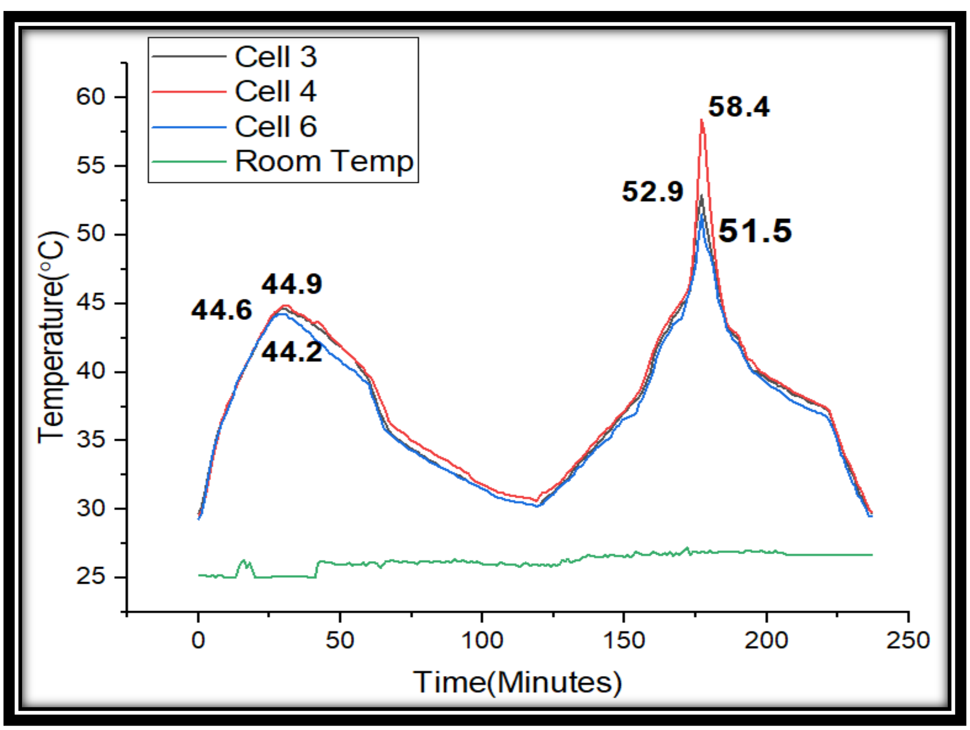
Figure 5.2 Charge and Discharge Temperature Behavior with Thermal Grease without copper tubes (a) 2C rate (b) 1.5C rate (c) 1C rate

5.3 Testing with Thermal Grease and Copper tubes

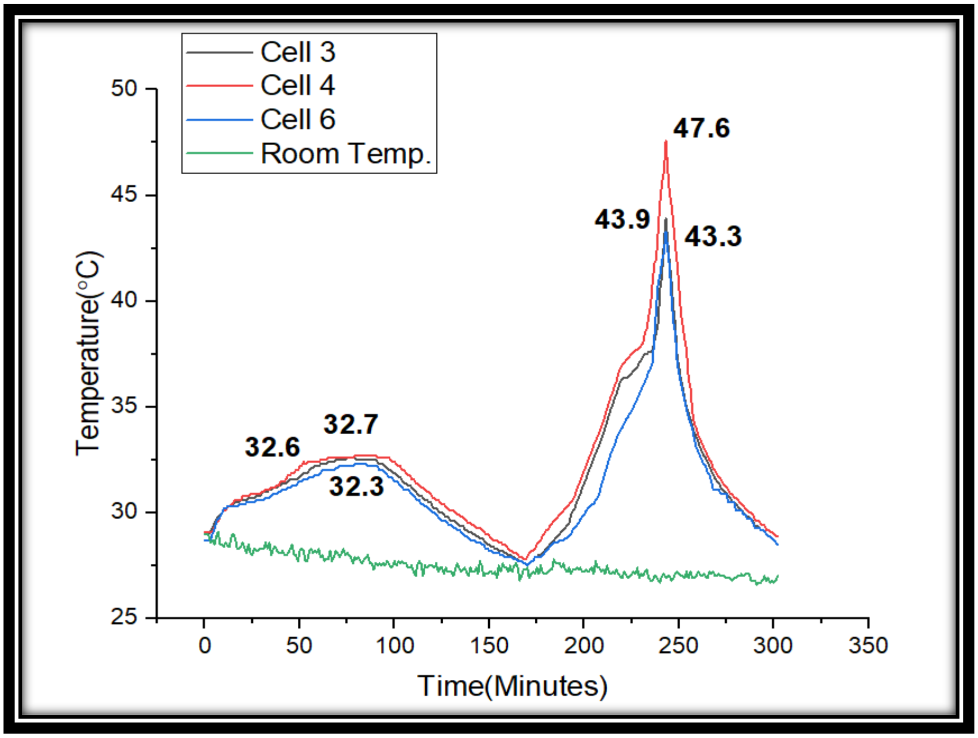
The same battery pack was filled with thermal grease surrounded by copper pipe. The grease used here is HY-510 as mentioned in Table 5.1. It was then subjected to the same conditions as the baseline experiment at 2C, 1.5C, and 1C rates. The temperature profiles captured by the respective thermocouples are shown in Fig. 5.3. It can be observed that the temperature at the 2C rate for cell 4 dropped down to **65.7**℃. Similarly, at 1.5C and 1C rates, it came down to **58.4**℃ and **47.6**℃. Table 5.2 shows the comparative temperature values of the three cells. It can be inferred that by using grease as a cooling material, a decent reduction in temperature has been achieved easily. It has provided a transference path to the heat generated in the system and led it to heat sink, which then dissipated heat into the environment. In the absence of grease, air would act as a heat transfer medium and it has low thermal conductivity, which would lead to thermal insulation instead of conduction. Similarly, without a heat sink, the heat dissipation cycle will not be completed and will result in some temperature addition as discussed in the above case.


Cell 3
Cell 4
Cell 6
Room Temp.
65.7
64.3
61.5
44.6
44.9
44.2
Temperature(°C)
Time(Minutes)
70
65
60
55
50
45
40
35
30
25
0
50
100
150
200
250

(a)


Cell 3
Cell 4
Cell 6
Room Temp
58.4
52.9
51.5
44.6
44.9
44.2
Temperature(°C)
Time(Minutes)
60
55
50
45
40
35
30
25
0
50
100
150
200
250

(b)



(c)

Figure 5.3 Charge and Discharge Temperature Behavior with Thermal Grease and Copper Tubes at (a) 2C rate (b) 1.5C rate (c) 1C rate

5.4 Battery Module Thermal Behavior

To make a robust Battery thermal management system, we analyzed every cell of prime importance which in our case is cells 3, 4, and 5. We made inferences by closely visualizing the temperature-time profile governed by the discharge current rate.

In the case of cell 6, it is the cell surrounded by two other cells in an array. The temperature of this particular cell at a 2C rate went up to 77.2℃. The rise in the temperature of this cell is comparatively low which is due to its position inside a module. Since it is the cell present in the corner. Therefore, it would be the cell with the least cumulative heat generation. Similar is the case with temperature values of Cell 6 at 1.5 and 1 C rates, relatively low values have been recorded in these cases because of the above-mentioned facts. Table 5.2 shows the original values and temperature at different C rates respectively.

In the case where we have employed thermal grease as a heat-transferring material and copper tubes as a heat sink. The reduction in the temperature of Cell 6 is comparatively low because the thermal conductivity of silicone-based grease increases with temperature. Moreover, the conductive heat transfer is dependent on the temperature gradient. The achievable temperature difference is comparably low, so the heat reduction would be low. Thermal grease has dropped down the temperature at a 2C rate to 61.5℃, which is by 15.7℃. This shows the potential of grease as a thermal interface material. The same observation holds true for 1.5 and 1C rate temperature reduction.

Now, in the case of Cell 3, the temperature behavior would be slightly different. It shows a rise in heat generation and dissipation compared to Cell 6 because of its location. It is the cell surrounded by three other cells in an array. The maximum temperature at the 2C rate has reached up to 84.3 ℃ without cooling. The heat generation is higher than Cell 6 because the heat effect of other cells will result in heat accumulation. Similarly, the heat dissipation would be slightly better owing to the higher temperature gradient. The thermal grease will work better in this case. A temperature dip of 20℃ has been observed, and a value dropped to 64.3 ℃ at a 2C rate, which shows the effectiveness of grease as a cooling material. The same holds true for 1.5 and 1C rates. Comparative values have been written in Table 5.2.

Cell 4 is the most important cell in the module and plays a pivotal role in designing a thermal management system. It is a cell surrounded by four other cells. It is the cell with the highest temperature rise because of the high cumulative heat effect. The temperature of 86.1℃ has been achieved without cooling at a 2C rate. The heat dissipation would be highest in this case compared to other cases because the temperature difference would be substantial in this case. The temperature reduction of 20.4℃ was possible with the thermal grease. A precisely controlled value of temperature has been achieved. The temperature profile of a grease-based battery pack is representative of its ability to be used for thermal management and for heat dissipation.

Table 5.3 draws the comparison between the values of three distinct cells recorded at different C rates for a silicone grease-based system surrounded by copper tubes and no cooling system values. The temperature difference between the two conditions has been calculated by subtracting thermal grease values at different C rates with no cooling at the same C rate. It is evident that in Cell 4, which is the middle cell, the value has dropped down 20.4 ℃ at a 2C rate. For Cells 3 and 6, the thermal compound has created a difference of 20 ℃ and 15.7 ℃ at a 2C rate respectively.

Table 5.1 Properties of HY510 thermal grease

Composition	Silicone, Carbon, and Metal Oxide
Thermal Conductivity	＞1.93 W/m-k
Thermal Impedance	＜0.225 C-in^2/W
Specific Gravity	＞2g/ cm^3
Viscosity	1000
Thixotropic Index	280±10 1/10mm
Moment Bore Temperature	-50~300 ℃
Operation Temperature	-30~280℃
Color	Grey

Table 2.2 Comparison of Cells temperature

	Maximum Temperature (℃)		
	Without Cooling	Thermal Grease Cooling without copper	Thermal Grease Cooling with copper
Cell 4			
2C rate	86.1	69.9	65.7
1.5C rate	71.4	61.7	58.4
1C rate	60	50.5	47.6
Cell 3			
2C rate	84.3	68.3	64.3
1.5C rate	65	56.2	52.9
1C rate	54.5	45.5	43.9
Cell 6			
2C rate	77.2	65.4	61.5
1.5C rate	62.8	54.5	51.5
1C rate	51.3	44	43.3

Table 5.3 Different Thermal Management system comparison of cells

The temperature difference between Thermal Management systems relative to no cooling			
Cells	Thermal Grease at 2C and no cooling	Thermal Grease at 1.5C and no cooling	Thermal Grease at 1C and no cooling
Cell 4	20.4	13	12.4
Cell 3	20	12.1	10.6
Cell 6	15.7	11.3	8

Summary

This chapter summarizes the temperature behavior of Cell 4, 3 and 6 at different C rates under different circumstances. The data is presented in tables for comparative analysis.

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CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

A new passive thermal management system has been evaluated and investigated in this research. The potential use of thermal grease as Thermal interface material and its performance has been studied at the cell level. A new aspect of thermal management has been explored. INR18650HG2 cells and HY-510 silicone thermal grease has been used along with copper tubes to build a fully functional battery thermal management system. Maintaining temperature uniformity and limiting operating temperature in a safer range is the primary objective of such a system. Several charging and discharging tests have been conducted at different C rates to study the effectiveness of grease-based cooling systems and their impacts on the thermal performance of cells. To understand the thermal management system, we monitored individual cell temperatures using thermocouples, which were fed into a data logger. The study revealed that the performance of a cooling system depends on the temperature differential of cell and room temperature, the thermal conductivity of cooling material, and the uniformity of thermal interface material across the cells inside a module. It is evident that Cell 4 would have the highest heat generation because of the cumulative effect of neighboring cells and it has the highest heat dissipation because of the highest temperature difference with environment compared to other cells. The temperature reduction observed on Cell 4 at 2C rate is around 20.4℃. Similarly at 1.5 and 1C rate, the temperature dropped by 13 and 12℃ respectively.

It can thus be concluded that thermal interface material like Thermal grease has the potential to be used in thermal management systems. TIM has been used as an alternative of PCM for the first time in thermal management context. The proposed technique falls under passive cooling method. The challenge lies in the application of the grease to the system and maintaining the uniformity of material. Moreover, the thermal conductivity limits its usage. The performance of such a system can be enhanced by increasing the heat transfer ability of the material (conductivity). Furthermore, to make a versatile and resilient battery thermal management system, a hybrid approach with an active cooling system would be the ultimate solution.

6.2 Recommendations

Thermal management is very critical topic especially in the context of electric vehicles. This problem becomes evident where ambient environment is comparatively high. A fully functional BTMS should be resilient enough to survive in any condition. Thermal grease is a potential candidate for thermal management. This thermal compound has been tested in variety of different orientation. There are few challenges, which are associated with such thermal interface material. The recommendations would throw a light on them. It is suggested that: .

- The Thermal conductivity of grease should be increased. In this way the results would be much more better.
- A hybrid system should be built on a top of this existing system. This approach will render excellent results.
- A proper orientation of module and configuration of cells should be studied.
- Maintaining a uniform thickness of layer and volume of grease is necessary to achieve excellent results, so a method should be devised to deposit a proper layer.
- Coupling thermal grease with PCM based system could produce exceptionally outstanding results.

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Zain Ul Abidin

Appendix 1-Publications

Experimental study of thermal management system for cylindrical Li-ion battery pack using thermal interface material

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Abstract

The commercialization of electric vehicles is one of the remedies for climatic change and pollution. Because of the Lithium-ion battery's sensitivity to temperature, thermal management is required to enhance the safety, cycle life, and performance. Moreover, the arrangement of cells and the configuration of the module also play a vital role. Owing to the high power requirements in vehicles, charging and discharging a large battery bank at higher rates pose a risk of thermal runaway. Hence, a fully functional battery thermal management system is one of the integral elements of modern-day automobiles. The ability of thermal grease as a thermal interface material has been investigated along with different variations. The grease-contained box has been used as an alternative to PCM for the first time in a battery thermal management context. Firstly, the available BTMS including active, passive, and hybrid approaches were reviewed. Then a baseline condition of the research was established, which was the effect of no cooling on battery performance at distinct rates. After that, the cooling effect of thermal grease was elaborately presented. Lastly, a complete system with grease and copper tubes was studied comparatively. With a fully functional thermal system, an average drop of 20.4 ℃ was recorded at a 2C rate, followed by 13 and 12.4 at 1.5C and 1C rates respectively. The analysis showed that for significant heat removal, a heat sink with thermal interface material is required. Another point inferred is that an inter-facial air gap has an adverse effect on the thermal performance of the battery. Therefore, the presence of thermal grease has opened a new avenue in thermal management. The appropriate configuration of cells and careful selection of thermal compounds can produce exceptionally controlled results.

Keywords

Li-ion Battery; Thermal Interface Material; Battery Thermal Management; Thermal Grease; Passive Cooling

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