THERMAL ANALYSIS OF LITHIUM-ION BATTERY PACKS AND THERMAL MANAGEMENT SOLUTIONS

THESIS

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By

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Abstract

Lithium ion (Li-ion) batteries have been gaining recognition as the primary technology for energy storage in motive applications due to their improved specific energy densities, charge retention capabilities and long cycling life. However, during utilization, Li-ion cells tend to self-heat due to the effects of internal resistance. In larger battery packs, where cells are typically stacked together and compressed for mechanical stability, a significant amount of heat could be generated. This could lead to an excessive rise in the temperature of the cells, potentially resulting in accelerated degradation.

Therefore, the design and implementation of a thermal management system (TMS) is critical to effectively dissipate the heat generated in a battery pack and ensure that the cells are operating in the desired temperature range specific to the application. In addition, the TMS must be designed to mitigate the non-uniformities in the temperature distributions inside the pack.

The work presented in this thesis carries forward the research in the field of passive thermal management solutions by conducting an experimental study aimed at understanding the feasibility of heat spreading material (HSM) as a mean to reduce the operating temperature and temperature gradients within battery packs.

In order to quantify the effects of thermal imbalance in Li-ion battery packs, a prototyped pack inspired to the application of electric bikes was adopted as a case study. The thermal
and electrical imbalances were characterized through experimental implementation of a battery power profile generated from the analysis of real-world usage data. The effectiveness of the passive heat spreader solution was evaluated based on a comparative study between a pack with the thermal management solution and an unmanaged pack, subject to cooling only by natural convection. The results presented in this work illustrate the influence of the operating temperature range and thermal imbalance on pack performance, charge balancing and degradation.
Dedication

This thesis is dedicated to my father, mother, brother and extended family back home.

They directly influenced my progress in my Masters program and were extremely supportive of every decision taken by me. I appreciate all their blessings and well-wishes which helped me in the completion of my Masters.
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Due to the ever growing concern over the dependence and ever increasing prices of imported oil coupled with environmental pollution and global warming, researchers have spurred into the development of various types of clean energy transportation systems such as Hybrid Electric Vehicles (HEVs), Battery Electric Vehicles (BEVs) and Plug-In Hybrid Electric Vehicles (PHEVs) [18]. The performance and utility of such vehicles is predominantly dependent on the performance and efficiency of the battery pack. The Lithium Ion (Li-ion) battery has been considered as one of the most promising battery technologies as opposed to the other secondary rechargeable batteries due to its improved specific energy densities, capacity and charge retention capabilities and long cycling life. Despite its many favorable characteristics, there is a significant challenge faced by manufacturers in extracting the maximum power utility from a Li-ion battery pack. In order to meet the heavy power demand of EV’s, Li-ion packs are sometimes coupled together in series and parallel combinations which leads to excessive rise in pack temperatures thereby causing significant deterioration to the pack's performance and power supplying capability [24]. The Li-ion packs are also known to generate significant amount of heat during these scenarios thereby leading to potential thermal runaway that could propagate a cell to destruct violently [23]. Therefore, the design and implementation of a successful thermal management system is extremely important.
The primary aim of a thermal management system is to effectively dissipate the heat in a battery pack by ensuring that the batteries are operating in the desired temperature range (specific to the application) while also working towards reducing non uniformities in temperature distributions inside of the pack. A given thermal management system could use a variety of methods for heat dissipation; active methods such as air or liquids for heating and cooling and passive methods such as phase change materials or even heat spreaders[16-23].

The work presented in this thesis carries forward the research in the field of passive thermal management solutions by conducting experimental validations aimed at understanding the feasibility of heat spreader material (HSM) in battery packs. In order to quantify the effects of thermal imbalance on Li-ion cells, a prototyped pack inspired to the application of electric bikes was adopted as a case study. The thermal and electrical imbalance across the cells was characterized through experimental implementation of a battery power profile generated from the analysis of real-world usage data. The effectiveness of the passive heat spreader solution was evaluated based on a comparative study between a pack with the thermal management solution and an unmanaged pack, subject to cooling only by natural convection.

At the onset, Chapter 2 of this thesis presents a state of the art review of the advancements in energy storage devices, particularly that of Li-ion batteries. This chapter describes the thermal issues affecting the battery performance and life and also details the need for effective thermal management. In addition, this chapter provides an extensive literature review with particular focus on the thermal management solutions that have
been published. Next, Chapter 3 presents the analysis for investigating the effects of thermal imbalance on the charge imbalance and degradation of Li-ion cells. This chapter describes first the procedure for experimentally testing the packs, after which the results obtained are post processed. Chapter 4 then details the processed results by quantifying the electro-thermal behavior of the cells through the characterization of these imbalances. Additionally, the effectiveness of the heat spreader material is described in this chapter. The primary goal of this study is to test the feasibility of graphite heat spreader material as a passive thermal management solution. Furthermore, this study aims at obtaining a relation between the effects of thermal and electrical imbalance on the variation of internal resistance, as the cells are aged.
Chapter 2. STATE OF THE ART

2.1 Introduction to Lithium Ion Batteries

The importance of energy conversion and storage devices has increased in today's society primarily due to the demand for stationary and mobile power. In particular, Lithium-ion batteries have attracted attention worldwide due to their high energy density, high efficiency, superior rate capability and long cycling life compared to other secondary batteries. Due to advancements in their technology, lithium ion batteries have been widely used as power sources for portable devices, cordless tools, and laptops since their commercialization in 1991[1].

A typical Lithium ion battery consists of a graphite anode (the negative terminal of the battery) whereas the positive terminal (cathode) is made by a lithium metal oxide. The electrolyte of the battery consists of a solution of a lithium salt in a mixed organic solvent. Figure 2.1 shown below depicts the schematic of a typical cylindrical Li-Ion cell while Figure 2.2 depicts the movement of current ions across the cell terminals. The primary advantage of using such cells, which has also increased their popularity, is that they possess higher volumetric and gravimetric energy density in comparison to the other available rechargeable batteries. The volumetric energy density can be defined as the amount of energy stored in a battery per unit volume, having units of $\text{Wh/l}$. 
Gravimetric energy density, on the other hand, can be defined as the amount of energy present in a battery per unit mass, measured in units of $\text{Wh/kg}$. Figure 2.3 represents a comparison of the various batteries with respect to their volumetric and gravimetric energy densities. It can be observed that, Li-ion batteries provide high values for the above mentioned density characteristics. The larger values of these densities put together translate into smaller and lighter cells which thereby enable the proliferation of portable battery powered electronic devices [4]. Li-ion batteries also possess a no "memory effect" property, typically observed in NiCd batteries which cause them to lose their capacity when exposed to repeated charging after partial discharging. Additionally, Li-ion batteries possess a high voltage and a wide temperature range of operation. Li-ion batteries are also known to have a low self-discharge rate which prevents them from losing charge over a prolonged period of time [5]. While the above mentioned qualities do make Li-ion batteries a commercially viable source of energy, many practical problems can be encountered during their utilization. Some of the major issues affecting lithium ion batteries are that of heat dissipation and thermal runaway. The work presented in this thesis specifically addresses the requirement of having an efficient thermal management system to mitigate the issues affecting the value proposition of Li-ion batteries. Also, this chapter provides an extensive literature review on the thermal management systems already present in battery packs.
Figure 2.1: Typical Cylindrical Li-Ion Battery

1 http://static.ddmcdn.com/gif/lithium-ion-battery-5.jpg
Figure 2.2: Movement of Cell Ions\(^2\)

Figure 2.3: Comparison of Energy Densities of Various Rechargeable Batteries\(^3\)

\(^2\) http://spectrum.ieee.org/images/sep07/images/lithf2.gif

\(^3\) http://ars.els-cdn.com/content/image/1-s2.0-S0013468612005671-gr4.jpg
2.2 Thermal Issues in Lithium Ion Batteries

Lithium ion batteries are used as power sources for a number of applications such as cellular phones, laptops and other electronic devices owing to their advantageous features such as high energy density and high power density. However, the high power density of the lithium ion batteries can be a potential drawback as it can cause the batteries to compromise on the amount of heat lost during energy conversion.

Heat is produced in batteries from three fundamental sources, namely (1) activation losses due to interfacial kinetics (2) concentration losses due to transport of species, and (3) joule heating movement of charged particles causing ohmic losses [5]. Thomas and Newman conducted an extensive study (detailed in [14]) by re-deriving the expression for the heat source in lithium ion batteries presented by Bernardi et al. in [13]. The expression for their derived equation included the following terms (1) reversible entropic heat (2) heat generated by the resistive dissipation (3) mixing heat due to relaxation of concentration gradients in the cell and (4) heat produced by chemical reactions occurring inside of the cell [12]. According to Pesaran et al., the heat generation rate in a cell could be estimated using the following equation.

\[ q = -I \left[ T \left( \frac{dE}{dT} \right) \right] + I(E - V) \quad [W] \quad (2-1) \]

where \( q \), \( I \) and \( T \) are the heat generation rate, current and temperature values respectively. Also, the terms \( E \) and \( V \) represent the open circuit potential and terminal voltage respectively. The first term in (2-1) was from the reversible entropic change from electrochemical reactions and the second term originated from the irreversible effects in
the cell. Pesaran et al. discovered that if the heat generated inside the cell was not accounted for, it would accumulate and store up inside of the system thereby leading to higher temperatures attained during utilization [15].

In order to extract the best possible performance, the cells have to be operated within the optimum temperature range and this effect was studied by K hateed et al. who concluded from their research in [9] that "the electrochemical performance of the Li-ion battery chemistry, charge acceptance, power and energy capability, cycle life and cost are very much controlled by the operating temperature". According to [10], the preferred temperature range providing maximum power capability and acceptable thermal aging is between 20°C and 40°C for Li-ion cells and the temperatures must be limited to a certain value between 50 °C and 60 °C in order to maintain the cell in a safe temperature zone and prevent accelerated aging. Nelson et al. conducted studies to analyze power requirements and optimal operating conditions in HEV's and found that Li-ion batteries are limited to an operating temperature of 45 °C to prevent any drastic cycle life reduction [18].

Another important feature that requires due consideration is that of the temperature non-uniformity that develops in battery packs as they are aged. Thermal imbalance in cells affects the performance of battery systems significantly. According to the Arrhenius equation, the rise in cell temperature causes an exponential growth in the battery reaction, thereby causing the cells at higher temperature to degrade more quickly than those at lower temperatures. The consequence of this degradation is the shortening of the lifetime of the entire battery pack. According to Mahamud and Park, the lifespan of the Li-ion cell
reduces by about two months for every degree of temperature rise in an operating
temperature range of 30 - 40 °C. Thus, the thermal imbalance in cells must be
compensated for by a management system in order to prolong the life of the battery.

Additionally, high operating temperatures have been shown to affect capacity/power
fade. The capacity fade can be defined as the loss of capacity of cells as they accumulate
large number of cycles through multiple iterations of charging and discharging. Elevated
temperatures generally promote degradation, thereby resulting in rapidly declining
capacity [7].

Ramadass et al. conducted capacity fade tests on Sony US18650 cells with a rated
capacity of 1800 mAh and cycled these cells under four different temperatures, namely
25, 45, 50 and 55 °C. They conducted the tests by charging the cells at a constant current
of 1A until the cell potential reached a value of 4.2V and then held the cells constant until
the current dropped to a value of 50 mA. The results obtained from the study depicted
that an increase in temperature led to an increase in capacity fade of the 18650 lithium
ion cells. Some of the key observations they made were that the cells lost 31% and 36%
of their initial capacity after conducting 800 charge-discharge cycles at 25 °C and 45 °C
respectively while the corresponding capacity fades were up to the order of 60% after
putting in 500 cycles at 50°C and 70% after conducting the same tests at 55°C. They
observed that the decrease in cell capacity was due to the increase in resistance at both
electrodes. Figure 2.4 represents the discharge curves for the cells cycled at different
temperatures during the test where RT stands for the room temperature [7]. The
abbreviations, for example 490-55, depict the number of cycles (490) and the temperature
at which the cells were aged (55 ℃). Also, Li and Su in their study of lithium ion batteries discovered that the cycle life is about 3223 cycles at 45℃ but at 60℃, the cycle life reduces to 1037 cycles [17]. Hence, it can be observed that keeping the temperatures within a suitable range is important for the cells to prevent capacity fade which can be achieved by employing an effective thermal management system.

Figure 2.4: Discharge curves of Sony 18650 cells cycled at various temperatures [7]

Another major issue influencing lithium ion batteries as a result of increasing temperatures is that of thermal runaway. Thermal runaway in batteries occurs during heat-generating exothermic reactions triggered by elevated temperatures that raise the overall temperature even further and potentially trigger more deleterious reactions. It can also be a source of rapid increase in the internal resistance of the battery if the heat generated is not dissipated effectively [5].

Chen and Evans carried out a thermal analysis of lithium ion batteries during cycling, with the help of a mathematical model. The objective of this test was to understand the
implication of rising temperature on thermal runaway in the batteries. The modeling results indicated that the battery temperatures during normal operation were unlikely to reach the onset temperature of thermal runaway. However, the continuous cycling under high C rates would lead to a significant heat accumulation by localizing the heat source thereby reaching the onset of the thermal runaway temperature. This reiterates the fact that it is necessary to keep the temperature of the battery within operating range so as to not cause thermal runaway during cycling [8].

The thermal issues affecting lithium ion batteries, discussed above, bring to light the major safety concerns that need to be accounted for while implementing lithium ion batteries. It can thus be concluded that "effective heat dissipation and thermal runaway are the major concerns in the commercialization of lithium ion batteries for high power applications" [9]. Therefore, an effective thermal management system is required in order to optimize the performance of the battery pack by (1) maintaining battery temperature within operating range and (2) reducing temperature non-uniformity in battery packs. A thermal management system would ensure that the cell temperatures are kept in the operating range so as to provide sufficient power capability while also ensuring temperature uniformity within cells so as to prevent degradation and faster aging of cells. The next chapter discusses in detail the available thermal management systems and provides an extensive literature review on the various types of thermal management methods such as active cooling and passive cooling.
2.3 Thermal Management Systems

The primary aim of a thermal management system (abbreviated as TMS in this document) is to regulate temperatures evenly inside a battery pack and keep them well within the desired operating range. A thermal management system present within battery packs should typically consist of the following characteristic features (1) a favorable environment for all the cells to operate within the optimum temperature range in order to optimize the battery performance and life and (2) should work towards reducing the temperature non-uniformity amongst the different cells in order to minimize the electrical imbalance [16]. Pesaran et al from their research recognized that an effective TMS must also be light-weight and compact so as to not add any additional volume or space to the battery pack, and it must also possess low parasitic power and be cost effective in order for it to be easily implemented and maintained. From their study, it was then concluded that an ideal thermal management solution should possess capabilities of maintaining the desired uniform temperature by ensuring rejection of heat during hot climates and addition of the same during cold climates. Additionally, an ideal TMS should be capable of providing ventilation in case the battery were to generate potentially hazardous gases during the course of utilization [16].

Thus, a thermal management system has to be efficiently designed and implemented within Li-ion battery packs. The design of an effective thermal management system is dependent on many factors such as the heat generation rate of the cells, the efficiency of its energy and then temperature dependent sensitivity of performance. The design of the TMS also influences the choice of heat transfer medium which is inherently dependent on
the type of management system. The different types of thermal management system can thus be classified as the following (1) **Active** cooling TMS, wherein a built-in source provides the heating at cold temperatures and cooling at hot temperatures respectively, and (2) **Passive** cooling TMS, a system in which the ambient environment surrounding the batteries is used. Pesaran *et al.* conducted an in-depth study into the various types of thermal management control systems and concluded that battery pack thermal management could be achieved by implementing air or liquid systems, using thermal storage phase change material, by insulation, or by using a combination of the above mentioned active or passive methods.

The use of air cooling for thermal management of batteries can be considered to be one of the simplest methods of heat dissipation primarily due to the size and cost limitations. Another form of thermal management solution involves that of using liquid cooling, in which heat transfer is achieved by either submerging cells in a dielectric fluid for electric contact, by placing discrete tubing around the modules or by placing the modules on a heat sink [20]. However, studies conducted show that air as a heat transfer medium is not as effective as heat transfer by liquid due to the lower conductivity of air and due to its limited heat capacity per unit volume [19]. Nelson *et al.* conducted a comparative study between the two methods of cooling, air cooling and cooling with a silicone transformer fluid designed for high temperature. From their study, they determined that the air coolant is less effective than the transformer fluid in removing heat from the cell surface. The other disadvantages noted in the case of air cooling was that there was a requirement for larger cross sections in the flow passages to and from the supply and exit manifolds, a
subsequently larger temperature rise across the cells and an extensive need for parallel air flow channels to all the modules [21]. Furthermore, Wu et al., from their investigation of the heat dissipation design for Li-ion batteries, also observed that at stressful and abusive conditions during high discharge rates and temperatures, the air-cooling was not found to be effective. During such temperatures exceeding 40°C, the non-uniformity of the temperature distribution could not be avoided and this further led to electrical imbalance within the cells. Pesaran et al., conducted a comparative study on a 12V, 6 cell HEV valve regulated lead acid (VRLA) module using the air and liquid (oil) cooling methods and observed that the module in the oil-cooling case was reaching steady state much more quickly, apart from staying cooler, than the air-cooling case owing to the higher thermal conductivity of the liquid. It can thus be concluded, from the above presented literature, that the usage of a liquid cooling system is more beneficial than that of an air-cooling system for Li-ion batteries.

The goal of an ideal thermal management system is to effectively maintain the battery pack temperature at an optimum temperature while also regulating the temperature distribution in the pack. However, from a physical stand-point, an ideal TMS is also expected to satisfy the above needs within a reasonable space (volume), weight and cost [22]. While there are advantageous to the usage of the active TMS, such as air and liquid cooling, these methods inherently make the overall system bulkier, more complex and expensive due to the usage of accessories such as blowers and pumps. Also, there's a potential safety hazard associated with the usage of liquid cooling systems as they have to be sealed in order to prevent any form of leakage during utilization. Keeping the above
factors in mind, a new technique of thermal management was first demonstrated by Khateeb et al. and later patented by Al-Hallaj and Selman based on phase change material (PCM) for battery management [24]. This passive method of thermal management was designed and implemented to determine whether PCM could be used as a feasible replacement over the conventional management systems (air/liquid cooling). They analyzed the thermal effects of Li-ion batteries using the methods of thermal modeling and experimental analysis and found that the phase change material (passive) system proved to more effective than the active air cooling TMS.

This new innovative technique in [25], presents a detailed procedure on the tests conducted by Khateeb et al. A Li-ion battery pack using two modules of eighteen cylindrical 1.5 Ah Panasonic 18650 cells was incorporated. This pack was to be used inside a Zappy electric scooter model no. 02815B by replacing the existing 12V, 18 Ah lead acid battery pack. The pack was arranged in a manner such that the startup current and voltage requirements of the scooter were met. Simulations were run on the above battery pack for which the heat generation rate was obtained from an accelerating rate calorimeter (ARC), a device used to measure the amount of heat generated by cells during charging and discharging. The air-flowing in between the cells was assumed to be naturally convective with a heat transfer coefficient of 5 W/(m-K) as the pack was completely covered from all sides. The simulation was run for a total of three charging and discharging cycles and it was observed that the temperature of the cell at the center showed a tremendous rise of 45 ℃ whereas the cell that was directly exposed to the forced air convection rose by 35 ℃. This large increase in temperature also added a
temperature gradient of 20°C between the air flowing around the cell at the center and cell exposed to forced cooling. This simulation proved that by just using air-cooling as a thermal management solution, there was a safety risk involved as the Li-ion cells were prone to possible thermal runaway.

Thus, a passive thermal management system using Paraffin wax as a phase change material was implemented. By running simulations on this new TMS alone, it was observed that due to the poor thermal conductivity of paraffin wax, the heat dissipation capability of the PCM was ineffective as there was uneven temperature distribution inside the pack. In order to overcome the low thermal conductivity effects, aluminum foam was added to the PCM inside the pack. This treatment showed a significant increase in thermal conductivity of the thermal foam while also decreasing the temperature rise of the Li-ion module by 25°C. However, this method proved to be ineffective in the long run as the PCM was completely melting when the battery pack was exposed to the three continuous charge-discharge cycles. In order to overcome this problem, aluminum fins were added and proved to be effective in controlling temperature rise during the three cycles by ensuring uniformity in temperature distribution during operation.

A proof of concept study was done by Khateeb et al. (detailed procedure in [9]) in which the experimental validation of the phase change material for the electric scooter was published. The experimental study investigated tests conducted for four different battery modules such as (1) Li-ion cells by themselves, (2) cells with phase change material only, (3) cells with aluminum foam only and (4) a composite mixture of PCM and Al-foam. The testing was conducted at various C rates that ranged from slow to fast charging and
discharging rates. The experimental validation yielded the following results and observations. The Li-ion cells in the absence of any aluminum or phase change materials showed a temperature rise of 16°C, which brought to the light the extreme importance of using thermal management material in such systems. The addition of aluminum foam by itself brought about a 50% reduction in temperature rise to 8°C. In the standalone case where only PCM material was used, there was a large temperature drop however an unfavorable thermal environment for the battery was created due to the poor thermal conduction of PCM causing slow dissipation of heat to the surroundings. The mixture of Al-foam and PCM brought about a temperature rise of only 6°C and was found to be effective in preventing thermal runaway.

In recent times, new methods of thermal management solutions for dissipating heat generated in a battery have been gaining significance. One particular example is that of using graphite based heat spreaders. Graphite heat spreaders have been used in various applications for electronic cooling especially with appliances where heat flux density is low and the available space is limited such as display panels, cell phones, laptops and cameras [26]. Natural graphite is typically found in a polycrystalline form containing hexagonal arrays of carbon. The carbon atoms are bonded in basal planes (flat layers) that possess weak Van Der Waals forces between them. Thus, the graphite structure is able to exhibit favorable heat spreading properties such as structural anisotropy and high thermal conductivity. The thermal conductivity is extremely high and can vary from 140-1500 W/(m·K) into the plane of the sheet while having a 3-10 W/(m·K) range in the perpendicular direction [27]. A detailed analysis containing experimental and simulation
study evaluating effectiveness of flexible graphite materials was conducted by Khasawneh et al. in [26] and [30]. The work conducted was on a Li-ion battery pack consisting of 10 series connected A123-ANR26650 cells typically used in power tool applications. First, a base pack made of ABS plastic only was modeled and simulated in COMSOL Multiphysics®. Tests were conducted by synthesizing a current profile obtained from statistical analysis of the typical usage patterns in a Dewalt power tool. All the tests were performed by initially placing the battery pack in an environmental chamber that was pre-set to a value of 24 °C. The results obtained showed that the pack temperatures at the three different locations were validated by the FEM model and the error in accuracy was found to be within a reasonable limit. However, it was observed that the heat rejection capability of the plastic material led to a temperature rise of about 14 °C, which was highly unfavorable for a Li-ion battery pack.

Thus, a thermally managed pack was built using the eGRAF® SPREADERSHIELD™ SS300-0.51 heat spreader. The heat spreader material was characterized by a high thermal conductivity of 300 W/(m-K) into the plane of the sheet and a value of 4.5 W/(m-K) through its thickness. The simulations were run for three other scenarios apart from the baseline pack presented above (1) grid configuration of graphite heat spreaders, (2) heat spreaders folded around each cell and (3) graphite pack extended through cover with fins added to extract heat and dissipate to ambient surroundings. The temperature distribution uniformity was the driving goal behind running simulations for the different scenarios, and the forced air convection was modeled on the pack surfaces with a flow velocity of 3 m/s. The different thermal management solutions were evaluated by
considering the most abusive cases of high current demand and event duration from the statistical analysis values collected in the prototyping test. The simulation results obtained for the above three cases of thermal management solutions depicted that in case (1) there wasn't any significant difference than the baseline pack primarily due to an ineffective influence of the graphite heat spreader around the cells. This scenario was not preferred as there were localized cold spots that caused the uniformity in the pack temperature to worsen. They observed that in cases (2) and (3) there was an extremely effective dissipation of the heat as the peak temperature values were reduced, while there was a significant improvement in the temperature uniformity in the pack. It was thus concluded that there was an effective dissipation of heat that was distributed over a large surface area which led to declining values of temperatures for cases (1), (2) and (3) by 2.5°C, 5.3°C and 8.5°C respectively.

In addition, Taylor et al. demonstrated the use of flexible graphite heat spreaders by comparing the results obtained against similar aluminum heat spreaders. The first test was conducted on two 80W 115V Kapton™ strip heaters that were used to simulate behavior similar to that of batteries under steady state conditions. The test setup consisted of resistance temperature detectors for monitoring the temperatures of the liquid coolant apart from thermocouples placed on the heaters to monitor surface temperatures. The heat spreaders were placed around the batteries to transfer heat from the faces of the cell to the liquid cooled tubing. It was observed that use of graphite heat spreaders resulted in lower peak temperatures by approximately 30% as the higher thermal conductivity of graphite was more effective in transferring heat to the coolant tubes. In addition to the steady state
tests, the simulated batteries were then subjected to 21W of heat to characterize the transient thermal performance. Nine thermocouples were attached to the surface of the cell under the heat spreaders and the thermocouple data and thermal images were recorded at the end of every 10 seconds throughout the duration of testing. It was observed that the graphite solution was able to decrease temperature gradients by 25% and peak temperatures by 30% in comparison to the aluminum heat spreader. The graphite material used was 20% lighter than the aluminum spreader and was found to increase the specific energy of the pack [33].

The above published literature review documents the importance of the heat spreading capabilities of graphite and this thesis explores the same by experimentally analyzing the effectiveness of a graphite spreader for Li-ion packs typically used in electric bikes (E-bikes).

2.4 Conclusion

The importance of using Lithium ion batteries has been gaining recognition in recent times owing to their intrinsic features such as high energy-to-weight ratio, no memory effect and low self-discharge rate. As a consequence, the development of clean-energy transportation vehicles has improved significantly. However, certain key issues still pose a significant challenge to manufacturers of which the primary difficulty arises from achieving the most ideal battery performance due to the effects of thermal imbalance in the packs. The heating effects associated with Li-ion batteries are mainly due to rise in temperatures during high powered cycles and potential thermal runaway causing reduction in cell life. The rise in temperatures is associated with increasing heat
generation due to conversion from electrical to chemical energy. Both factors significantly affect a battery pack's efficiency and long-term utility. Thus, it is important to use thermal management systems in order to ensure that batteries operate within an optimum range while also reducing temperature variations within the packs.

The thermal management systems are classified as active, where-in heating or cooling is provided by an external source such as a pump or blowing fan or classified as passive, in which the thermal management system only uses the ambient environment. However, novel techniques involving the usage of phase change materials and graphite based heat spreaders are proving to be effective in thermally managing battery packs without making the system more bulky.

This thesis is oriented towards the experimental analysis of a graphite heat spreader in Li-ion battery packs typically used in electric bikes. The advantage of using such spreaders is the thin, compact and lightweight design that can be easily manufactured and potentially serve as a low cost solution to high-powered battery applications.
Chapter 3. THERMAL ANALYSIS OF AN ELECTRIC BIKE PACK:

EXPERIMENTAL SETUP AND POST PROCESSING

This chapter presents an experimental study conducted to understand the effects of thermal imbalance on the charge imbalance and degradation of Li-ion cells. A 36V Li-ion battery pack designed for electric bike applications was adopted as a case study. Two prototype battery packs were built for testing, by assembling ten pouch-style Li-ion cells connected in series. Owing to the space and weight limitations of such packs, a passive thermal management solution based on graphite heat spreaders was implemented in one of the packs to provide a comparison with an unmanaged pack (simply subject to convection with ambient air). The characterization of the thermal and electrical imbalance across the cells was conducted by implementing a battery power profile generated by the analysis of real-world usage data from a bike equipped with a GPS tracking system. First, this chapter presents a physical description of the packs being tested, followed by the experimental setup detailing the instrumentation and fabrication of the prototype packs. After which, the procedure for testing the packs and the post processing of the experimental data is presented.
3.1 Description of the Prototype Battery Packs

The prototype packs built for this study were inspired to a commercial battery pack typically used in electric bikes (E-bikes). Manufactured by eZee Bike™, the pack has nominal voltage of 36V, nominal capacity of 14Ah and a maximum discharge current of 20A. Figure 3.1 illustrates the battery pack shape and Figure 3.2 shows the location of the pack on the bike, namely under the seat.

The aforementioned case study was chosen due to its relevance in various applications as well as for the potential to use passive thermal management solutions. E-bike battery packs have higher rated performance parameters, with capacities in the range of 10Ah and pack voltages exceeding 36V. Additionally, the packs are cost effective and readily available to purchase. Furthermore, the constraints on volume and weight impose considerable limitation to the choice of thermal management solutions that could be applied to such a system.
The study conducted was aimed at understanding the effects of the thermal imbalance on the charge imbalance and degradation of Li-ion cells. This was accomplished by prototyping two identical battery packs inspired by the design of the E-bike pack.

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Prototyping new packs in place of using commercial packs allowed for more flexibility in the control of the current and power output, as well as in the balancing and assessment procedures due to the absence of a traditional battery management system (BMS).

The prototype packs were packaged into plastic boxes similar to the one shown in Figure 3.1, designed using SolidWorks® and later prototyped with a 3D printer. Figure 3.3 depicts one of the boxes for the packs that were used for experimental testing. The boxes were also designed with slits through the top casing for allowing the heat spreaders to reject heat outside of the pack through an interface with an external aluminum heat sink. The heat sink used for this application was the AAVID THERMALLOY™ 766203B04000. Figure 3.4 depicts one of the prototyped packs with the heat sink bolted on top.

![Figure 3.3: Overview of the Box Designed for the Prototype Battery Pack](image)
The two prototyped packs were assembled by connecting ten prismatic LiFePO$_4$-8081238 3.2V 10Ah Tenergy cells in series. The cells were chosen to match the power and voltage capabilities required for an electric bike application. Another favorable feature was the high aspect ratio of these cells (82mm W x 240 mm L), which implies that considerable thermal gradients could be present between the tabs and the sealed ends of the cells during usage. This would help analyze the distribution of temperature across the cells and characterize the thermal imbalance in the pack. Table 3.1 summarizes the specifications of the cells that were obtained from the datasheet.
Table 3.1: Specifications of the LiFePO$_4$-8081238 Tenergy Cells$^6$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Voltage</td>
<td>3.2</td>
<td>V</td>
</tr>
<tr>
<td>Nominal Capacity</td>
<td>10</td>
<td>Ah</td>
</tr>
<tr>
<td>Dimension</td>
<td>8.2 x 82 x 240 (T x W x L)</td>
<td>mm</td>
</tr>
<tr>
<td>Weight</td>
<td>280</td>
<td>g</td>
</tr>
<tr>
<td>Storage Temperature</td>
<td>20 ~ 55</td>
<td>°C</td>
</tr>
<tr>
<td>Tabs Material</td>
<td>Aluminum/Nickel</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.5: Tenergy 3.2V 10 Ah Cells $^7$

Each pack had the ten cells taped and held firmly together by bolting through the tabs with the aid of plastic sleeves that were manufactured to prevent the tabs from shorting each other. Figure 3.6 depicts the assembly of the unmanaged pack with the plastic sleeves (shown in black).

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$^6$ [http://www.jameco.com/Jameco/Products/ProdDS/2144294.pdf](http://www.jameco.com/Jameco/Products/ProdDS/2144294.pdf)

$^7$ [http://www.tenergy.com/30207](http://www.tenergy.com/30207)
The other prototyped pack was then fitted with a passive heat spreader material. The material chosen for this pack is the eGRAF® SPREADERSHIELD ™ SS400-0.51 P1GP1A1 [30]. The heat spreader is characterized by a very high in plane thermal conductivity (400W/m-K), and a thickness of 0.51 mm for improved bend radius. The heat spreaders are coated with P1 PET material possessing a high dielectric strength (2800V) to ensure that the electrically conductive graphite would not create potential short circuits between the Nickel tabs on the front and back side of the cells. The pack with thermal management solution was then fully assembled by sandwiching the heat spreader material in the spacing between each cell as shown in Figure 3.7.

Figure 3.6: Prototyped Pack Assembly - Unmanaged Pack
Each battery pack was fitted with individual cell voltage sensors and nine T-type thermocouples installed at various locations through the pack to provide indications on the cell temperature distribution. The cells were then placed in the prototyped boxes as shown in Figure 3.8 which depicts a top view of the unmanaged pack and Figure 3.9 in which the assembled spreader material is interfaced with the casing cover just before the managed pack is sealed.
Figure 3.8: Unmanaged Pack after Full Assembly

Figure 3.9: Thermally Managed Pack - Fully Assembled
3.2 Description of the Experiments

3.2.1. Experimental Apparatus

After prototyping and assembly, the two packs were prepared for initial characterization and testing. The thermocouples were fabricated in-house and placed at the different locations as depicted in the schematic shown in Figure 3.10. The notation C1-C10 represents the cells arranged in ascending order, while TC refers to the thermocouple present at that location. In particular, TC 2, TC 5 and TC 8 were placed at the central location in between the cells.

Figure 3.10: Schematic of the Prototyped Pack with Thermocouples (Top View)
The equipment used for testing the packs includes two 6’9” wind tunnels made of foam board, built by GrafTech and shown in Figure 3.11. The wind tunnels provide the ability to control the air flow over the battery packs, reproducing conditions similar to the usage of an actual E-bike battery pack. The wind-tunnels were designed for assembly as they came apart in two sections and were also fitted with plastic half-inch egg crates at each end in order to straighten the blowing air.

![Wind Tunnel Ducts](3.11)

The opposing ends of the wind-tunnels were fitted with San Ace 120 DC fans (P/N: 9SG1212P1G01), with rated speeds in the range of 3800-11500 rpm and weighing approximately 460g\(^8\). The fans were wired to a switch board which was used to control the fan speed, as shown in Figure 3.12. The velocity of the air at the center of the wind tunnels was monitored through a Pitot tube.

\(^8\) [http://db.sanyodenki.co.jp/product_db/cooling/dfan/group_pdf/1348654131.pdf](http://db.sanyodenki.co.jp/product_db/cooling/dfan/group_pdf/1348654131.pdf)
The input pack power profile utilized during the tests was designed to achieve very realistic usage conditions for an E-bike battery pack. To this extent, velocity and altitude profiles were obtained from the GPS tracker of a professional cyclist and processed to obtain a time varying power profile that was imposed on the packs. The primary objective of adding the fans to the experimental setup was to simulate the velocity of air corresponding to the relative wind speed as seen by the E-bike pack. The initial calibration of the fan was accomplished with the help of a manometer and a Pitot tube, as shown in Figure 3.13.

Figure 3.12: San Ace Fan (L) with wired Switchboard (R)
After instrumentation of the packs for voltage and temperature measurements, a 50A/50mV shunt resistor was connected to the circuit in order to measure the current flowing through each pack. A shunt is a low resistance precision device that measures the current from the voltage drop created by these currents across the resistor. Using the Ohm's law, this voltage drop corresponds to a proportional current value that was collected and passed onto to the amplifying circuit.
The amplifying circuit consisted of two Dataforth™ SCM7B40 isolated analog voltage input modules. Figure 3.14 shows a top sided view of the shunt resistors wired to the circuit with the Dataforth modules. The modules amplify the incoming voltage values in the range of ±50mV to an output value in the range of 0 to 10V. The modules were connected to the USB data acquisition hardware as described in the next section of this chapter.

3.2.2. Battery Cycling and Data Acquisition

Upon completion of the experimental setup, the data acquisition (DAQ) system was setup. The temperature and voltage data was recorded using the National Instruments (NI)™ SCXI-1000 chassis. The voltage leads were mounted to the chassis through the SCXI-1300 voltage module. Data was collected using the National Instruments™ LabVIEW software. Figure 3.16 depicts the user interface of the software. The DAQ software was storing data at a sampling rate of 10 Hz.

The temperature values were also monitored and recorded by the SCXI-1000 chassis. The thermocouple leads were fixed through the NI™ TC-2095 connector module. Figure 3.15 depicts the SCXI-1000 chassis with the mounted voltage and temperature modules.

The current, on the other hand, was recorded using the National Instruments™ USB 6211 data acquisition hardware. The USB DAQ was setup to do the following (1) record and store incoming voltage data from the amplifying circuit and (2) send input signals to the switchboard for controlling the fan speed during discharging. Figure 3.17 shows the USB DAQ connected to the SCXI chassis.
Figure 3.15: NI™ SCXI-1000 Chassis with SCXI-1300 and TC-2095 Modules

Figure 3.16: NI™ LabVIEW Software Interface
Figure 3.17: NI™ USB 6211 DAQ wired to SCXI Chassis

The equipment used for cycling the batteries was the Maccor™ cycler, shown in Figure 3.19. The working mechanism of the Maccor involved cycling the battery packs by delivering specific current or power profiles. The Maccor was connected to the DAQ and the battery packs according to the flow chart shown in Figure 3.18. The circuit was setup using special connectors known as Anderson connectors. The battery pack (B) was wired to the Maccor using these connectors with one terminal passing through the shunt resistor.
3.3 Description of Testing Procedure

3.3.1 Initial Assessment

Before assembling the prototype packs, the twenty cells were characterized by measuring their individual capacity and internal resistances. Each cell was first soaked in an
environmental chamber pre-set to a value of 25°C. An initial capacity test was then conducted by fully discharging the cells and then charging them back up for a total of three times at a 1C rate. The internal resistance values were then recorded with the help of a milliohm-meter. Table 3.2 lists the results obtained from the initial characterization.

<table>
<thead>
<tr>
<th>Cell No.</th>
<th>Serial No.</th>
<th>Capacity (Ah)</th>
<th>Internal Resistance (mΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A11G18-0012</td>
<td>10.670</td>
<td>2.344</td>
</tr>
<tr>
<td>2</td>
<td>A11G18-2291</td>
<td>10.550</td>
<td>1.942</td>
</tr>
<tr>
<td>3</td>
<td>A11G18-2341</td>
<td>10.510</td>
<td>1.969</td>
</tr>
<tr>
<td>4</td>
<td>A11G18-2268</td>
<td>10.460</td>
<td>2.034</td>
</tr>
<tr>
<td>5</td>
<td>A11G18-1437</td>
<td>10.390</td>
<td>1.959</td>
</tr>
<tr>
<td>6</td>
<td>A11G18-0613</td>
<td>10.370</td>
<td>1.767</td>
</tr>
<tr>
<td>7</td>
<td>A11G18-1275</td>
<td>10.340</td>
<td>2.042</td>
</tr>
<tr>
<td>8</td>
<td>A11G18-1673</td>
<td>10.330</td>
<td>2.089</td>
</tr>
<tr>
<td>9</td>
<td>A11G18-0390</td>
<td>10.320</td>
<td>2.069</td>
</tr>
<tr>
<td>10</td>
<td>A11G18-1685</td>
<td>10.300</td>
<td>1.931</td>
</tr>
</tbody>
</table>

Mean: 10.424 2.014
Std. Deviation: 0.121 0.148

<table>
<thead>
<tr>
<th>Cell No.</th>
<th>Serial No.</th>
<th>Capacity (Ah)</th>
<th>Internal Resistance (mΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>A11G18-1100</td>
<td>10.300</td>
<td>1.757</td>
</tr>
<tr>
<td>12</td>
<td>A11G18-0496</td>
<td>10.290</td>
<td>2.150</td>
</tr>
<tr>
<td>13</td>
<td>A11G18-1272</td>
<td>10.240</td>
<td>2.051</td>
</tr>
<tr>
<td>14</td>
<td>A11G18-0265</td>
<td>10.230</td>
<td>2.009</td>
</tr>
<tr>
<td>15</td>
<td>A11G18-0016</td>
<td>10.170</td>
<td>1.899</td>
</tr>
<tr>
<td>16</td>
<td>A11G18-0422</td>
<td>10.040</td>
<td>2.097</td>
</tr>
<tr>
<td>17</td>
<td>A11G18-0721</td>
<td>10.010</td>
<td>2.194</td>
</tr>
<tr>
<td>18</td>
<td>A11G18-0444</td>
<td>9.987</td>
<td>2.008</td>
</tr>
<tr>
<td>19</td>
<td>A11G18-0315</td>
<td>9.963</td>
<td>2.300</td>
</tr>
<tr>
<td>20</td>
<td>A11G18-1280</td>
<td>9.963</td>
<td>2.057</td>
</tr>
</tbody>
</table>

Mean: 10.119 2.052
Std. Deviation: 0.140 0.152
Cells 1-10 were grouped together as one pack and cells 11-20 as the other by matching the maximum and minimum values of internal resistances, as shown in Table 3.3. The percent difference values were found to be lesser than 2%.

<table>
<thead>
<tr>
<th>Cells</th>
<th>Max. Resistance (mΩ)</th>
<th>Min. Resistance(mΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>2.300</td>
<td>1.757</td>
</tr>
<tr>
<td>11-20</td>
<td>2.344</td>
<td>1.766</td>
</tr>
<tr>
<td>Percent Difference (%)</td>
<td>1.91</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Table 3.3: Comparison of Resistances

To facilitate post processing and analysis of test results, an initial characterization was conducted on one of the twenty cells to define the open circuit voltage (OCV) curve as a function of the battery state of charge (SOC). The curve was generated by conducting an in-house characterization test similar to that of the Hybrid Pulse Power Characterization Test (HPPC) from the Freedom CAR Battery Test Manual. First, the procedure was initialized by discharging the cell at a constant current 1C rate to its cutoff voltage of 2.0V. The cell was then charged to a 95% SOC by subjecting it to a 1C rate for a total of nineteen times in which each profile was programmed to increase the state of charge by 5%. A fifteen minute rest phase was placed at the end of the discharge as well as each charge profile during this procedure. During the rest phase the voltage asymptotically approaches a steady state value. This value at the end of each rest phase was assumed to be the open circuit voltage for each specific state of charge.

---

condition. The detailed procedure for obtaining the open circuit voltage and state of charge has been described in the Data Analysis section of this chapter (see 3.4.1).

Similarly, the procedure shown above was repeated for discharging the cell by 5% each time to bring down the state of charge to 0%. The charging and discharging curves shown in Figure 3.20 were obtained using this procedure and the average of these curves was taken to obtain the actual OCV vs. SOC curve which is used extensively for the post processing of the experimental results.

![OCV vs. SOC Curves](image)

**Figure 3.20: OCV vs. SOC Curves**
3.3.2. Aging Protocol

The load profile adopted for the aging tests was generated from real world usage data of a bike fitted with a GPS tracking system [29]. Figure 3.21 and Figure 3.22 illustrate the time varying velocity and altitude profiles that were taken from the cyclist data. A road load analysis was conducted to calculate the power demand at the wheel by taking into account the effects due to the aerodynamic drag, tire rolling resistance, inclination of road (grade) and inertia. The bike and rider parameters used for the analysis were standard values used and are listed in Table 3.4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontal Area</td>
<td>A</td>
<td>1.15</td>
<td>m^2</td>
</tr>
<tr>
<td>Drag Coefficient</td>
<td>C_d</td>
<td>0.42</td>
<td>–</td>
</tr>
<tr>
<td>Tire Rolling Coefficient (Asphalt Road)</td>
<td>C_r</td>
<td>0.004</td>
<td>–</td>
</tr>
<tr>
<td>Bike + Rider Mass</td>
<td>M</td>
<td>90</td>
<td>kg</td>
</tr>
<tr>
<td>Effective Mass for Inertia</td>
<td>M_{eff}</td>
<td>94.5</td>
<td>kg</td>
</tr>
<tr>
<td>Density of Air</td>
<td>\rho</td>
<td>1.226</td>
<td>m^3</td>
</tr>
<tr>
<td>Acceleration due to Gravity</td>
<td>g</td>
<td>9.81</td>
<td>m/s^2</td>
</tr>
</tbody>
</table>

Table 3.4: Bike and Rider Data

Figure 3.21: Velocity Profile of the Cyclist

Figure 3.22: Altitude Profile of the Cyclist
The aerodynamic drag is a type of resistive force experienced by air that resists its motion through another fluid that consists of forces due to air pressure acting on the body in motion and forces due to surface friction [28]. For this application, the power consumed due to the aerodynamic drag was calculated using (3-1).

\[
P_{\text{aero}} = \frac{C_d \cdot A_{\text{front}} \cdot \rho \cdot V^3}{2} \quad \text{[W]} \tag{3-1}
\]

where \( V \) is the velocity measured in m/s

The rolling resistance of the tires can be defined as the energy lost due to friction at the contact point between the tire and road, as well as to the deformation of the tire. This resistance can be affected by a number of factors such as the pressure in the tire, the diameter of the tire and its tread as well\(^{11}\). The power due to the tire rolling resistance was calculated as follows:

\[
P_{\text{rolling}} = C_r \cdot M \cdot g \cdot V \cdot \cos(\alpha) \quad \text{[W]} \tag{3-2}
\]

where \( \alpha \) is the road inclination angle measured in radians.

The inclination angle value was obtained from the analysis of the velocity and altitude profiles. First, the altitude variation \( \Delta H \) was obtained by determining the gradient of the altitude-time profile. Next, the gradient of the velocity profile integrated over time was used for determining the horizontal distance variation \( \Delta D \). The inclination angle \( (\alpha) \) as a function of the biker's path was then obtained from the equation shown in (3-3).

\(^{11}\) http://www.schwalbetires.com/tech_info/rolling_resistance
The resistance due to the road grade was then calculated as:

\[ P_{\text{grade}} = M \cdot g \cdot V \cdot \sin(\alpha) \quad [W] \tag{3-4} \]

Finally, the inertial effects were taken into account by considering the effective mass of the entire system, which was assumed 5% higher than that of the bike and rider's mass. The other term that was factored into the inertial effects was that of change in velocity, leading to the expression:

\[ P_{\text{inertia}} = M_{\text{eff}} \cdot \frac{dV}{dt} \cdot V \quad [W] \tag{3-5} \]

where \( \frac{dV}{dt} \) is the rate of change of velocity, also known as the acceleration \([ \text{m}/\text{s}^2] \).

The sum of the power terms due to each of the four factors is representative of the power demand at the wheel, given by the expression in (3-6). The calculation of each term generated a time-varying power profile that was implemented during the discharging phase of the testing procedure.

\[ P_{\text{wheel}} = (P_{\text{aero}} + P_{\text{rolling}} + P_{\text{grade}} + P_{\text{inertia}}) \tag{3-6} \]

After generating the power demand at the wheel, the next step was to calculate the power consumption by the battery. This was achieved by factoring in the mechanical efficiency
of the gears as well as the electrical efficiency of the motor. For calculation of the power demand of the battery, the datasheet was referenced to obtain the rated performance values of the cells listed in Table 3.5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Cell Voltage</td>
<td>$V_{pack}$</td>
<td>3.2</td>
<td>V</td>
</tr>
<tr>
<td>Nominal Pack Capacity</td>
<td>$C_{pack}$</td>
<td>10</td>
<td>Ah</td>
</tr>
<tr>
<td>Max. Discharge Current</td>
<td>$I_{max}$</td>
<td>20</td>
<td>A</td>
</tr>
<tr>
<td>Max. Burst Discharge Current</td>
<td>$I_{maxb}$</td>
<td>30</td>
<td>A</td>
</tr>
<tr>
<td>Nominal Electrical Efficiency</td>
<td>$\eta_{el}$</td>
<td>.80</td>
<td>–</td>
</tr>
<tr>
<td>Nominal Mechanical Efficiency</td>
<td>$\eta_{m}$</td>
<td>.95</td>
<td>–</td>
</tr>
</tbody>
</table>

The power demand from the battery ($P_{battery}$) was determined by making a few assumptions. First, the mass of the bike was increased by 20 kg along with a 10% increase in aerodynamic drag. The fraction of electrical assist ($E_{assist}$) provided by the battery was set to equal 60% to allow the state of the charge of the batteries to always stay positive. Lastly, the pack voltage was determined by multiplying the individual cell voltage by 10 to account for the series arrangement of the cells. The expression shown in (3-7) was then used to determine the power demand of the battery pack.

$$P_{battery} = \frac{E_{assist} \cdot P_{wheel}}{\eta_{el} \eta_{m}}$$

(3-7)
However, to account for the maximum rated power performance ($P_{\text{max}}$) of the cells, the battery power had to be trimmed accordingly. The maximum rated power was given by the following equation:

$$P_{\text{max}} = V_{\text{pack}} \cdot I_{\text{maxb}} \quad (3-8)$$

The battery power values that were found to exceed this threshold were replaced by the corresponding values of the maximum power. Figure 3.23 depicts the power at the wheel and the power due to the battery in the top portion of the graph. The bottom portion depicts a comparison between the power demand from the battery and the maximum rated power of the cells.
3.3.3. Implementation

The battery power profile generated in Figure 3.23 was then programmed into the Maccor to discharge the packs. Figure 3.24 shown below depicts the user interface of the software with the programmed commands.
The testing protocol was setup in a manner such that the cycling for each day began with a brief five second rest followed by a constant current (CC) charge at 1C. The charging phase was followed by a two hour rest period. The end of this rest period began the start of the discharging phase in which the power profile was incorporated. During the discharge, the fans mounted at the ends of the wind tunnels were triggered to simulate the velocity of the air seen by the pack corresponding to the battery power at that instant of
time. Upon culmination of the discharge, a brief thirty minute rest followed and the above procedure was repeated to put in effectively five cycles per day for each pack.

At the end of the discharge phase of the last cycle in each day, the data acquisition software was programmed to allow the packs to rest an additional four hours to restore the temperatures back to ambient conditions at 25°C. Additionally, this period was set as a benchmark for comparing the parameters of the packs. After designing the testing protocol for the packs, the profile shown in Figure 3.25 depicting the time varying current was generated.

![Figure 3.25: Current Profile for Both Packs](image-url)
The testing protocol was constructed keeping in mind the realistic approach towards designing the experiments. The user of the bike would typically plug in the vehicle to be charged after utilization. However, a thirty minute rest phase was added primarily for the calculation of battery parameters to facilitate post processing of the experimentally collected data.

In a real life scenario, the period after charging would be followed by a period of idling for the battery pack until the bike was re-utilized. This idling period was simulated by adding a two hour rest phase. The addition of this phase was to allow the pack temperatures to stabilize as well as to accelerate the testing procedure.

To ensure that the packs were cycled according to the testing protocol, a method of using the thermocouples as a switch was implemented. The voltage values from the SCXI chassis were monitored by the Maccor and if the value of any cell reached a peak threshold of 3.6 V or a minimum of 2.0 V, the thermocouple switch would open. This would trigger the Maccor to cut off the current input to the packs. Apart from ensuring that the test protocol was being followed, this was done in order to prevent the cells from overheating or overcharging.

3.4 Post Processing and Analysis of Results

At this stage, the setup for testing was complete and the packs were ready to be cycled. After testing the packs for a few days to demonstrate repeatability, the following voltage and temperature profiles were obtained. Figure 3.26 and Figure 3.29 shown below depict these profiles for the thermally managed pack, also referred to as Pack 1 whereas Figure 3.27 and Figure 3.30 depict the same for the unmanaged pack, also known as Pack 2.
Figure 3.26: Plot of Time-varying Voltages for Pack 1

Figure 3.27: Plot of Time-varying Voltages for Pack 2
By isolating a single cycle for a given cell as shown in Figure 3.28, the following observations were made. The voltage profile would initially rise during charging, until the weakest cell would trigger the peak value of 3.6V. At this point, the current value was set to zero and the voltage was observed to follow a relaxation path by exponentially decaying throughout this rest phase. The voltage at the end of this phase was shown to approach a steady state value, which was used for the accurate determination of the open circuit voltage and state of charge parameters. It was then observed that the voltage profile followed a decaying trend, similar to the power profile which was implemented.

Figure 3.28: Current and Voltage Plot of a Cycle for a Cell
during the discharge. At the end of the discharge, the voltage was observed to relax by exponentially growing back towards a steady state value.

Figure 3.29: Plot of Time-Varying Temperatures for Pack 1
It was observed from Figure 3.30 that one of the thermocouples (TC9) had failed during cycling. This might have taken place due to faulty wiring or external damage to the insulation of the thermocouple. Hence, for the post processing of the experimental data, the entire dataset corresponding to this thermocouple was removed.
The current and temperature plots were isolated for a single cycle and thermocouple as shown in Figure 3.31. During the charging phase, it was observed that the temperature would rise and attain a peak value, after which it began cooling down during the resting phase. The temperature was then found to rise again during the discharge, however this rise was found to be less prominent in comparison to the rise observed during charging. The goal of this study is to characterize the effects of thermal imbalance and since the rise in temperature was highly conspicuous during charging, the forthcoming data analysis is oriented towards determination of battery parameters in this region mainly.
3.4.1. Data Analysis for Aging

In order to experimentally characterize the effects of electrical and thermal imbalances, battery metrics such as the open circuit voltage and the state of charge had to be determined first. The open circuit voltage (OCV) of a battery is defined as the difference in electrical potential across the terminals of a battery when disconnected from a circuit. The state of charge (SOC) is equivalent to a gas gage for batteries which describes how filled the batteries are at a given point of time. An additional characteristic feature, the internal resistance is an important parameter in determining the degradation of batteries and is a function of the state of the charge, the current and the C-rate. For the determination of the open circuit voltage and state of charge, the following procedure was followed.

First, the offset in the current profile was corrected from each day of testing and then filtered using a 1st order Butterworth low pass filter (LPF). Next, the relaxation voltage of each cell during the rest phases was isolated. Figure 3.32 and Figure 3.33 represent the voltages during rest phase 1 and rest phase 2 for a single cycle from one day of testing.
<table>
<thead>
<tr>
<th>Time [sec]</th>
<th>Voltages [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 3.32: Voltages During Rest Phase After Charging for One Cycle**

**Figure 3.33: Voltages During Rest Phase After Discharging for One Cycle**
Then, the steady state value attained by these voltages was approximated to be the open circuit voltage for that particular state of charge condition. For the analysis, the exponentially decaying voltage during rest phase 1 was considered first. The analysis from here on describes the calculation by isolating a single cell, for illustrative purposes only. Figure 3.34 depicts the relaxation curve for Cell 3 with the red circle denoting the approximated open circuit voltage for this cell.

![Figure 3.34: Voltage During Rest Phase 1 for Cell 3](image)

Using the generated curves correlating the OCV and the SOC in section 3.3.1, the state of charge at that instant of time was obtained. In order to determine the open circuit voltage throughout the cycle, the method of Coulomb Counting was used. This method entails the
determination of the state of charge by integrating the current over the time domain, represented by the equation shown in (3-9).

\[
SOC = SOC_0 + \frac{1}{Ah} \int I \, dt
\]  

(3-9)

where: \(SOC_0\) is the state of charge at end of rest phase 1 and \(Ah\) represents the nominal capacity of the battery.

The SOC's corresponding to each point were determined as shown in Figure 3.35 and reinserted into the curves to output the corresponding values of the open circuit voltage. Figure 3.36 depicts the calculated open circuit voltage for the charging portion of the cycle. As expected, the SOC value of this cell rises from a low percentage to a higher percentage during charging and approaches a steady state value during the rest phase.
Figure 3.35: State of Charge During Charging Phase

Figure 3.36: Open Circuit Voltage for Charging Phase
Next, the rest phase after the discharging was considered and the exponentially growing voltage for one cell was isolated, as shown in Figure 3.37. The method used for the determination of the state of charge and open circuit voltage during this region was similar to that of the charging. However, the coulomb counting method was applied backwards in this case and the curves shown in Figure 3.38 and Figure 3.39 were obtained. Since the pack was being discharged, the curves were observed to decrease to a low SOC and as the rest phase was triggered, the SOC was observed to relax to a steady state value.

![Figure 3.37: Voltage During Rest Phase 2 for Cell 30](image-url)
Figure 3.38: State of Charge During Discharging Phase

Figure 3.39: Open Circuit Voltage for the Discharging Phase
For each cycle, the open circuit voltage and state of charge were determined in a similar manner. Since the method of coulomb counting is considered to be inaccurate due to the accumulation of error as the cycle’s progress, the state of charge value was reset at the end of each resting phase using the method shown above. Figure 3.40 shown below depicts the state of charge for a cycle from one day of testing and Figure 3.41 depicts the open circuit voltage for the same.

Figure 3.40: State of Charge for a Cycle from One Day of Testing
The procedure shown above was implemented for every cell through each cycle present in both packs. Figure 3.42 and Figure 3.43 represent the state of charge for Pack 1 and Pack 2 respectively whereas Figure 3.44 and Figure 3.45 depict the open circuit voltages for the managed and unmanaged pack respectively.
Figure 3.42: State of Charge - Pack 1 (Managed)

Figure 3.43: State of Charge - Pack 2 (Unmanaged)
Figure 3.44: Open Circuit Voltage - Pack 1 (Managed)

Figure 3.45: Open Circuit Voltage - Pack 2 (Unmanaged)
3.4.2. Data Processing Approach

During the post-processing of the results, there was significant variability observed in the data collected from the acquisition software. Since the cells were connected in series, the root causes of this variability can be attributed to a given number of reasons. First, differences in cell manufacturing as evidenced during initial characterization which depict an imbalance in the capacity and internal resistance values. Second and more importantly, imbalances associated with the equipment and instrumentation errors on account of a non-perfect current cycle. The above effects compound into a progressive imbalance in the residual charge for each cell, which in turn results into an overall reduction of the useful pack capacity. Hence, this variability was adjusted for using the procedure shown below.

The averaged internal resistance for pack 1 was isolated and plotted as shown in Figure 3.46. The detailed analysis and interpretation of these results has been presented in section 4.3 of this document.
The drift due to initial imbalance was considered over the first seventy-five cycles of testing. The values were individually adjusted for by using a first order best-fit curve to determine the slope and intercept values corresponding to each cell. Table 3.6 and Table 3.7 depict the same for the two packs respectively and Figure 3.47 depicts the best-fit lines corresponding to each cell in Pack 1.
Table 3.6: Initial Imbalance Values – Pack 1

<table>
<thead>
<tr>
<th>Cell No.</th>
<th>Slope</th>
<th>Intercept [Ω]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.649E-06</td>
<td>1.169E-02</td>
</tr>
<tr>
<td>2</td>
<td>9.575E-07</td>
<td>9.844E-03</td>
</tr>
<tr>
<td>3</td>
<td>1.063E-06</td>
<td>1.030E-02</td>
</tr>
<tr>
<td>4</td>
<td>7.972E-07</td>
<td>1.038E-02</td>
</tr>
<tr>
<td>5</td>
<td>2.473E-06</td>
<td>9.839E-03</td>
</tr>
<tr>
<td>6</td>
<td>3.610E-06</td>
<td>8.933E-03</td>
</tr>
<tr>
<td>7</td>
<td>1.374E-06</td>
<td>9.815E-03</td>
</tr>
<tr>
<td>8</td>
<td>6.588E-07</td>
<td>9.963E-03</td>
</tr>
<tr>
<td>9</td>
<td>3.381E-06</td>
<td>1.022E-02</td>
</tr>
<tr>
<td>10</td>
<td>3.956E-06</td>
<td>1.023E-02</td>
</tr>
</tbody>
</table>

Table 3.7: Initial Imbalance Values – Pack 2

<table>
<thead>
<tr>
<th>Cell No.</th>
<th>Slope</th>
<th>Intercept [Ω]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.867E-06</td>
<td>9.875E-03</td>
</tr>
<tr>
<td>2</td>
<td>1.053E-06</td>
<td>1.018E-02</td>
</tr>
<tr>
<td>3</td>
<td>6.086E-06</td>
<td>9.076E-03</td>
</tr>
<tr>
<td>4</td>
<td>2.052E-06</td>
<td>8.883E-03</td>
</tr>
<tr>
<td>5</td>
<td>1.375E-06</td>
<td>9.201E-03</td>
</tr>
<tr>
<td>6</td>
<td>4.467E-07</td>
<td>9.137E-03</td>
</tr>
<tr>
<td>7</td>
<td>1.089E-06</td>
<td>9.359E-03</td>
</tr>
<tr>
<td>8</td>
<td>7.481E-07</td>
<td>8.648E-03</td>
</tr>
<tr>
<td>9</td>
<td>4.434E-06</td>
<td>1.079E-02</td>
</tr>
<tr>
<td>10</td>
<td>3.129E-06</td>
<td>9.907E-03</td>
</tr>
</tbody>
</table>
The adjusted resistance values were then calculated by subtracting the slope variation across each cycle and the resistance values averaged over the first seventy-five cycles. Finally, the averaged value from the first day of testing was added to give the absolute resistance values. This corrected plot is depicted in section 4.2 of this document and is used to correlate the effects of thermal and electrical imbalance across the two packs as they accrue larger cycles.
Chapter 4. THERMAL ANALYSIS OF AN ELECTRIC BIKE PACK:

DESCRIPTION OF ANALYZED RESULTS

This chapter summarizes and analyzes the data generated from the extensive experimental characterization of the prototyped battery packs for electric bike applications. The scope of the analysis is to evaluate the impact on performance, balancing and life of thermal management solutions based on graphite heat spreading materials. After establishing procedures for evaluating output metrics and parameters in the regions of interest, a detailed interpretation of the thermal and electrical imbalances for the two prototype packs is presented. The thermal imbalance is first characterized by evaluating the maximum temperature of each thermocouple throughout the seventy five days of testing. Additionally, the values for the temperature increment during the charging phase are evaluated over the total number of amp-hours accumulated by the two packs. Next, a correlation between the thermal imbalance and internal resistance is investigated by conducting an energy balance for the two battery packs, based on the experimentally collected data. The electrical imbalance is then characterized by calculating the open circuit voltage and state of charge parameters at critical locations in the test procedure. A final assessment study was then conducted to evaluate the nominal capacity and internal
resistance of each cell after the aging campaign, by comparing the results to the values measured before testing

4.1 Analysis of Pack Thermal Imbalance

The effects of the cell-to-cell thermal imbalance within each prototype pack were calculated by determining the maximum temperature and the temperature rise ($\Delta T = T_{\text{max}} - T_{\text{min}}$) during the charging phase of each pack.

The plots showing the maximum temperature reached during the charging portion of each cycle are summarized in Figure 4.1 for Pack 1 and Figure 4.2 for Pack 2. In both figures, the temperature values have been plotted in relation with the cumulative Amp-Hours (Ah) on each pack.

![Figure 4.1: Maximum Temperatures During Charging - Pack 1](image)
From the aforementioned plots, it can be immediately observed that minor fluctuations in the temperature values for the two packs are present throughout the entire aging campaign. This can be attributed to the absence of active control of the ambient temperature (the tests were conducted in an air-conditioned room). Additionally, cycle 1 in each pack is observed to read lower values compared to the remaining cycles, due to the fact that the first cycle of each day of testing begins with the pack rested at ambient temperature. Therefore, a cycle is needed in order to stabilize the pack temperature to nominal values.

For the entire duration of the testing, Pack 2 displays larger values in the peak temperatures and a larger spread between the different thermocouples. Based on the
locations of the thermocouples, described in Figure 3.10, it is possible to conclude that a moderate thermal gradient exists across the cells in the unmanaged pack, hence the cells at the center experience nominally higher temperature conditions than the cell located at the extremes. On the other hand, the managed pack presents a more uniform distribution of temperature values. The importance of the thermal management system is evident in Figure 4.3 and Figure 4.4, where the mean value and standard deviation of the measurements from the thermocouples located in each pack are shown. Here, the mean values of the temperature readings corresponding to each pack were observed to follow a similar trend while maintaining significant difference in temperatures. It is possible to observe that the SD values illustrate an increasing trend for both packs.

Figure 4.3: Comparison of Mean Temperature Readings for Both Packs
The unmanaged pack exhibits a higher imbalance from the onset of testing and the deviation in the values is more pronounced and non-uniform. As the cells are subjected to a larger number of cycles and subsequently larger Amp-Hours, the temperature effects became more evident in the case of Pack 2. The mean value and SD plots give a preliminary indication that the thermal management material is effective in maintaining uniformity in temperatures across the pack. This is evidenced by a 4°C drop in the mean and a < 0.1°C variation in standard deviation. In order to better quantify the advantages of using the graphite heat spreaders as a passive thermal management solution, the effects of thermal imbalance were further analyzed by plotting the
temperature differences as illustrated in Figure 4.5 and Figure 4.6 for Packs 1 and 2 respectively.

Figure 4.5: Temperature Difference During Charging - Pack 1
Figure 4.6: Temperature Difference During Charging - Pack 2

Figure 4.7: Plot of Mean for Temperature Differences - Both Packs
The above-mentioned plots indicate a similar increasing trend as that of the maximum temperatures. From Figure 4.7, it can be noticed that Pack 2 displays higher values of temperature rise, than the thermally managed pack, hence the use of heat spreading materials is effective in maintaining not only lower peak temperatures but also in reducing the temperature rise during charging. The temperature rise observed in the above figures can be explained as a consequence of Joule heating that occurs during the charging phase.

This effect can be recognized by assuming the behavior of the cells to be represented by a first order equivalent circuit model. However, since each pack was subjected to a constant C-rate during the charging, the behavior of the battery is approximated as that of a zeroth order model instead. This is possible due to the losses being ohmically dominated in this region. Figure 4.8 depicts the said model which is illustrated by the expression shown in (4-1).

![Zeroth Order Equivalent Circuit Model of a Battery](image)

\[ V = V_{oc} - IR \]  

(4-1)
where $V$, $V_{oc}$ and $I$ represent the cell terminal voltage, open circuit voltage and current in the pack respectively, while $R$ denotes the internal resistance in each cell. Due to the same C-rate being applied, it can thus be inferred that the rate of heat generation in this region is directly proportional to the internal resistance of the battery. Hence, the increase in the temperature variation for both packs can be attributed to the varying internal resistance, as the cells accrue larger number of cycles. In order to quantify the increasing internal resistance, the procedure described in the next section of this chapter was followed.

4.2 Internal Resistance

The internal resistances of the cells in each pack were calculated by conducting an energy balance for the entire battery system. The energy balance was governed by the equation represented in

\[(4-2)\]

\[Q_{th} + Q_{chem} = Q_{elec} \tag{4-2}\]

where $Q_{th}$, $Q_{elec}$ and $Q_{chem}$ represent the thermal, electrical and chemical energy terms respectively, having the units of W-hr. The individual terms were quantified by taking the integral over the entire charging phase as described in equations \((4-3)\) - \((4-5)\). Figure 4.9 through Figure 4.14 depict first the chemical energy for the two packs followed by the corresponding electrical and thermal energy plots of each pack respectively.
\[ Q_{\text{chem}} = \int I \cdot V_{\text{oc}} \, dt \] \hspace{1cm} (4-3)

\[ Q_{\text{elec}} = \int I \cdot V \, dt \] \hspace{1cm} (4-4)

\[ Q_{\text{th}} = \int I \cdot (V - V_{\text{oc}}) \, dt \] \hspace{1cm} (4-5)

Figure 4.9: Chemical Energy During Charging - Pack 1
Figure 4.10: Chemical Energy During Charging - Pack 2

Figure 4.11: Electrical Energy During Charging - Pack 1
Figure 4.12: Electrical Energy During Charging - Pack 2

Figure 4.13: Thermal Energy During Charging - Pack 1
The aforesaid plots representing the thermal energy for the two packs depict an increasing trend with Pack 2 possessing a scattered distribution. The increase in thermal energy, which is also representative of the heat generation, can be traced back to the effects of Joule heating as described by the equivalent circuit model in (4-1). The advantage of using the heat spreading material can be recognized by the steady and marginal variation illustrated in Figure 4.13.
From the SD plot summarized in Figure 4.15, it can be ascertained that there is no significant difference in the behavior of the two packs until accumulation of about 2000 [A-h]. The thermal energy in the unmanaged pack is then observed to digress, potentially due to the effects of aging, and then ramp up around 3500 [A-h] where a cell is suspected to have failed. The ramifications of a potential cell failure are also visible in the chemical and electrical energy plots, which cause the values to stray from their original path. The significance of this cell failure was investigated further by generating the values of internal resistance for each cell. The internal resistance in this region was calculated by equating (4-5) with the equation shown in (4-6). This term was used for generating the averaged internal resistance ($\bar{R}_{ch}$) during this phase.
The averaging was done in order to account for the various uncertainties present in the experimental setup. Due to instrumentation errors, the current recorded in each pack was found to be extremely noisy. Hence, it was difficult to isolate the same location in the different cycles for the accurate calculation of the internal resistances. In addition to this, the different cells began with an initial imbalance in state of charge values and during the charging, the state of the pack was governed by a single cell that triggered the voltage limit first. This led to inaccuracy in determination of the resistance as the SOC values were observed to vary on a cycle-to-cycle basis. The plots illustrated in Figure 4.16 and Figure 4.17 for Pack 1 and Pack 2 respectively, were then obtained.

\[ Q_{th} \approx R_{ch} \int I^2 dt \]  

(4-6)

Figure 4.16: Internal Resistance During Charging - Pack 1
From the aforementioned plots, the behavior of the internal resistance is recognized to be proportional to that of the thermal energy. The mean values of the internal resistances for each pack are in the range of 11-12 [mΩ] at the beginning of the tests and from Figure 4.18, the relatively similar divergence in the two packs is observed. From the SD plot illustrated by Figure 4.19, the effects of aging are distinguishable in the range of 2000-3500 [A-h] where the unmanaged pack exhibits a sharp rise in comparison to the managed pack which possesses a relatively flat slope. The heat spreader material is found to be effective in maintaining uniformity in internal resistance values, in other words the effect of Joule heating is minimized in this region. The gradual and steady rise of internal resistance can also be correlated to the moderate increase in temperatures across a cell.
thereby validating the claim that the heat spreading material is effective in mitigating effects of thermal imbalance. Also, the heat spreader demonstrates the ability to mitigate the likelihood of cells departing from their natural course, as observed in the case of Pack 2. This distinct quality helps sustain the performance of the pack in the long run as the effects of cell-to-cell differences on overall aging of the pack can be mitigated.

Upon accumulation of approximately 3500 [A-h], the effects of degradation are discernible in Pack 2. The explicit growth in resistance of cell 9 indicates an internal failure. This emphasizes the fact that the digression of values in the energy and temperature plots is due to the effects of this failure. Hence, a relationship between the thermal imbalance and its codependency on the internal resistance is established. The impact of this failure is examined further by evaluating the effects of electrical imbalance in the next section of this chapter.
Figure 4.18: Plot of Mean for Internal Resistances - Both Packs

Figure 4.19: Comparison of Standard Deviation for Internal Resistances in Both Packs
4.3 Effects of Electrical Imbalance

This section analyzes the effects of electrical imbalance in the two packs and establishes a correlation between the open circuit voltage, state of charge and internal resistance.

From the procedure described in section 3.4.1, the open circuit voltage was calculated for each cell at the end of the charging phase. Figure 4.20 and Figure 4.21 depict these plots for Pack 1 and Pack 2 respectively.

The open circuit voltages are observed to decrease progressively for both packs. This behavior can be attributed to the variation in internal resistance of each cell in both packs. The cells grouped together in each pack began with an initial imbalance due to the fact that there was no active balancing performed. Consequently, this led to each cell possessing a different rate of growth in internal resistance. Since, the charging phase is governed by a single cell triggering the threshold voltage of 3.6V, the remaining cells are forced to endure lesser charge which subsequently precipitates a reduction in their overall SOC. This effect is compounded over the repeated charge-discharge cycles which results in the decaying trend observed in the aforementioned figures. However, the trends observed in these figures also take into account the effects of instrumentation error and non-perfect current cycle. This was corrected by using the procedure detailed in section 3.4.2. Hence, the actual variation in open circuit voltages of the two packs is summarized in Figure 4.22 and Figure 4.23 for the managed and unmanaged pack respectively.
Figure 4.20: Open Circuit Voltage, End of Charging - Pack 1

Figure 4.21: Open Circuit Voltage, End of Charging - Pack 2
Figure 4.22: Absolute Open Circuit Voltages - Pack 1

Figure 4.23: Absolute Open Circuit Voltages - Pack 2
From the standard deviation plots illustrated in Figure 4.24, the effects of variation in internal resistance can be examined. In the region of growth specified earlier, a significant deviation in open circuit voltages of Pack 2 is observed. In contrast, the heat spreader is found to mitigate the deviation in OCV values by maintaining a balanced and minimal growth throughout the aging process.

The behavior at the end of cycle life in Pack 2 is characterized by the degradation effects encountered by cell 9. The accelerated rise in internal resistance of this cell consequently results in a higher overall charge imbalance in the pack. The correlation between the internal resistance and open circuit voltages can thus be acknowledged. However, to fully substantiate this, the region after the discharging phase was also analyzed.
The imbalance was evaluated by determining the state of charge values for each cell at that location. The SOC values in this region were determined using the method described in section 3.4.1 from the exponentially growing voltages. Following a process similar to that of the OCV, the drift in SOC’s was corrected and plotted as shown in Figure 4.25 and Figure 4.26 for Pack 1 and Pack 2 respectively. The plots illustrate a decreasing trend for both packs. This deviation can attributed to a number of reasons such as (1) increasing amp-hours per cycle, (2) depreciating minimum voltage and (3) variation of internal resistance.

![Figure 4.25: Absolute State of Charge, End of Discharge - Pack 1](image-url)
Owing to the imposed power profile during discharge, the amount of watt-hours going into each pack were equivalent. As a consequence, the amount of amp-hours extracted from each pack were found to increase, as shown in Figure 4.27, thereby resulting in the depreciating minimum voltage, shown in Figure 4.28.
Figure 4.27: Amp-Hours During Discharging

Figure 4.28: Minimum Voltage During Discharging
The preceding factors coupled with the increasing variation in internal resistance described earlier incite an overall reduction in the state of charge due to the higher demand of chemical energy. This reduced state of charge attests to the fact that there is an overall reduction on a cycle-to-cycle basis as the subsequent charge-discharge cycle covers a lower range of SOC values. Hence, the interconnection between the variation in internal resistance and electrical imbalance is corroborated.

As an additional comparison, the state of charge values at the end of each day's four hour rest period were also calculated. The imbalance due to initial drift was adjusted for the two packs and the absolute SOC's were plotted as shown in Figure 4.29 and Figure 4.30.

![Figure 4.29: Absolute SOC, End of Day - Pack 1](image-url)
From the above-mentioned plots, a decreasing trend is observed in the state of charge values. The thermally managed pack is characterized by a consistent reduction except in the case of Cell 7 in which the SOC drops swiftly. The unmanaged pack on the other hand is governed by the degradation effects exhibited by the failed cell 9. Due to the reasons for failure described above, the remaining cells in the pack were prevented from being charged up to their potential and hence the curves are observed to nose-dive by bringing down the SOC to approximately 10%.
From the standard deviation plot summarized in Figure 4.31, the two packs exhibit similar behavior until the 64th day after which the effects of aging coupled with the rising internal resistance in cell 9 led to values in Pack 2 completely digressing from its actual course. This is further evidenced by the fact that the 64th day corresponds to the region where each pack had accumulated 3500 [A-h]. The influence of internal resistance on the electrical imbalance of a pack is thus reinforced. The next section provides a summary of the factors affecting the variation in internal resistance.

4.4 Factors Influencing Variation of Internal Resistance

The analysis of the experimental data was conducted by individually characterizing the thermal and electrical imbalances and correlating each aspect to the variation of internal resistance.
resistance. The mutual dependency between the imbalances and internal resistance is summarized by the flow chart shown in Figure 4.32.

The initial characterization of the batteries was accomplished by grouping twenty cells into two packs based on their measured capacity and internal resistance values. Despite the grouping of relatively similar cells, an initial imbalance was existent due to the fact that no active charge balancing was performed. This disparity led to a variation in charge imbalance at the onset of testing. This electrical imbalance, as shown in section 4.3, entails a variation in state of charge, a factor that strongly influences the internal resistance. The influence of internal resistance, on the other hand, is evident through the progressive deviation of the state of charge values in each subsequent charge-discharge cycle. Thus, a co-dependency between the electrical imbalance and internal resistance is recognized. Also, the internal resistance was shown to affect the charge imbalance based on the first order equation illustrated in \((4-1)\). Additionally, the varying internal resistance induces a larger thermal imbalance as evidenced by the deviation in temperature plots. The increase of these parameters was attributed to the effect of Joule heating. The accumulation of cycles by the packs was also observed to influence the internal resistance. From Figure 4.19, in the region between 2200-3500 [A-h], there is a steady surge of internal resistance values in Pack 2 before the effects of cell failure influence the behavior of the remaining cells in the pack.

Hence, it can be concluded that there exists a strong dependence between the thermal imbalance, charge imbalance and degradation of the packs as each of these factors influence and are influenced by the variation in internal resistance.
Figure 4.32: Factors Affecting Growth of Internal Resistance
4.5 Characterization of Batteries - Post Aging

Post disassembly, the twenty cells were subjected to a characterization test similar to the one described in section 3.3.1 of this document. However, the results of the capacity tests were deemed inconclusive due to the minor deviation observed in the state of charge values prior to the effects of cell failure experienced by Pack 2.

Additionally, the internal resistance of one cell in each pack was found to be immeasurable due to the physical abnormalities detected at the end of the experimental testing. The resistance readings of the remaining cells were recorded and tabulated along with the corresponding values measured prior to aging, as shown in Table 4.1 and Table 4.2 respectively.

<table>
<thead>
<tr>
<th>Cell No.</th>
<th>Internal Resistance (mΩ)</th>
<th>Percent Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-Aging</td>
<td>Post-Aging</td>
</tr>
<tr>
<td>1</td>
<td>2.344</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>1.942</td>
<td>2.707</td>
</tr>
<tr>
<td>3</td>
<td>1.969</td>
<td>2.958</td>
</tr>
<tr>
<td>4</td>
<td>2.034</td>
<td>2.986</td>
</tr>
<tr>
<td>5</td>
<td>1.959</td>
<td>2.411</td>
</tr>
<tr>
<td>6</td>
<td>1.767</td>
<td>2.210</td>
</tr>
<tr>
<td>7</td>
<td>2.042</td>
<td>3.026</td>
</tr>
<tr>
<td>8</td>
<td>2.089</td>
<td>2.762</td>
</tr>
<tr>
<td>9</td>
<td>2.069</td>
<td>2.617</td>
</tr>
<tr>
<td>10</td>
<td>1.931</td>
<td>2.413</td>
</tr>
<tr>
<td>Mean</td>
<td>2.014</td>
<td>2.676</td>
</tr>
</tbody>
</table>
Table 4.2: Comparison of Results, Post Aging - Pack 2

<table>
<thead>
<tr>
<th>Cell No.</th>
<th>Internal Resistance (mΩ)</th>
<th>Percent Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Aging</td>
<td>Post-Aging</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.757</td>
<td>2.066</td>
</tr>
<tr>
<td>2</td>
<td>2.150</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>2.051</td>
<td>2.853</td>
</tr>
<tr>
<td>4</td>
<td>2.009</td>
<td>2.813</td>
</tr>
<tr>
<td>5</td>
<td>1.899</td>
<td>2.542</td>
</tr>
<tr>
<td>6</td>
<td>2.097</td>
<td>2.729</td>
</tr>
<tr>
<td>7</td>
<td>2.194</td>
<td>3.754</td>
</tr>
<tr>
<td>8</td>
<td>2.008</td>
<td>3.232</td>
</tr>
<tr>
<td>9</td>
<td>2.300</td>
<td>76.480</td>
</tr>
<tr>
<td>10</td>
<td>2.057</td>
<td>4.650</td>
</tr>
<tr>
<td>Mean</td>
<td>2.052</td>
<td>3.080</td>
</tr>
</tbody>
</table>

From the above-mentioned tables, the growth of internal in the two packs is confirmed. However, the managed pack is defined by a more uniform and stable rise as evidenced by the 35% average percent difference. The unmanaged pack on the other hand depicts variations in the range of 60-70% excluding the effects of cell 9 in which the cell shows a more than significant growth. The failure of cell 9 is evident from the percent difference readings. The tabulated results thus reiterate the claim that the heat spreader material is effective in maintaining consistency in the variation of internal resistances on a cell-to-cell basis throughout the course of testing.

4.6 Conclusion

The effects of thermal and electrical imbalance coupled with the growth in internal resistances were each analyzed individually to corroborate a correlation between them.
The thermal imbalance was characterized by comparing the peak temperatures and temperature variations in the two packs. The thermal management material was found to be effective in reducing the peak temperatures by approximately 4°C while also maintaining a uniform and stable growth throughout the course of testing. In addition, the spreader material was effective in reducing the maximum temperature variation by 1°C, an effect that ensures uniform aging of the cells relative to the unmanaged pack. After this, the internal resistances were quantified by conducting an overall energy balance analysis for each cell. The heat spreader material was found to be proficient in reducing the growth of internal resistances thereby ensuring mitigation of the effects due to Joule heating. A mutual dependency between the thermal imbalance and growth of internal resistance was established. Additionally, the spreader material was also responsible for indirectly mitigating the effects of cell-to-cell differences on overall aging of the pack which is a feature that can help sustain the pack performance in the long run. The effects associated with the charge imbalance were then studied by determining the open circuit voltage and state of charge parameters at the end of the charging and discharging phases respectively. The behavior of the cells was characterized by an overall subjugation of SOC values. This was attributed to the absence of a traditional BMS in the packs and the testing procedure which was governed by the first cell reaching the threshold value set during charging. The effect was compounded over repeated charge-discharge phases also due to the significant influence of the growing internal resistance. Similarly, the initial charge imbalance was found to induce variations in the internal resistance thereby confirming the interdependency between the two. In conclusion, heat spreaders are
effective as low cost thermal management solutions to alleviate the effects of cell-to-cell variations on overall aging thereby facilitating pack performance in the long run.
Chapter 5. CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

Lithium-ion batteries are widely used in electronic appliances owing to their high efficiency, superior power capability, light-weight and low self-discharge rate. A typical Li-ion battery consists of a positive electrode (the cathode), a negative electrode (anode) and an electrolyte. Much like any other electrochemical device, the conversion of energy from chemical to electrical is associated with an energy loss, according to the second law of thermodynamics. This loss of energy results in rising temperatures inside the packs which affect the overall performance and life-cycle of the batteries.

The thermal issues associated with these energy losses were examined in this thesis. First, a detailed literature review was presented on Li-ion batteries and the thermal issues affecting it. In the interest of resolving these issues, a thermal management system is required to ensure that the battery temperature is kept within its operating range and also to maintain uniformity in temperature variations across the cells in a pack. An extensive summary of the thermal management systems in published literature was then documented. The different types of thermal management solutions such as active methods, using air or liquid cooling and passive techniques such as heat spreader and
phase change materials were also presented in this thesis. The work done in this thesis was an experimental study aimed at understanding the effects of electrical imbalance and thermal imbalance on the variation in internal resistance, as battery packs were aged. In addition, the effectiveness of graphite heat spreaders as a thermal management solution was evaluated. A Li-ion pack inspired to the design of a commercial pack typically used in E-bikes was chosen as the case study. The E-bike pack was chosen due to its higher rated performance parameters, cost effectiveness and the potential to use thermal management solutions. Additionally, the packs were prototyped in order to gain full access to control the current and power outputs due to the absence of a traditional BMS. In order to model the tests realistically, real-world usage data was analyzed for the synthesis of a power profile that was employed to discharge the packs during the testing procedure.

A comparative study was then conducted by assembling one of the two packs with graphite heat spreaders sandwiched between the ten cells connected in a series arrangement. An aluminum heat sink was bolted on top of the two packs while ensuring interface contact with the heat spreaders in the managed pack. The electro-thermal behavior of the packs was characterized by running progressive charge-discharge cycles with adequate zero current rest periods placed in between for the accurate calculation of battery parameters. The analysis of the results was done by individually quantifying the effects of thermal and electrical imbalances and corroborating a correlation with the variation in internal resistance, for the entire duration of the aging campaign.
The processed results depict that the heat spreading material is effective in reducing pack average temperatures by 4°C due to the highly conductive properties of the material. Additionally, the heat spreading material was found to minimize variations in temperatures from cell-to-cell by reducing the overall non-uniformity in temperatures. The management material was effective in reducing temperature rise up to 1°C. This distinct quality is beneficial to improving performance of a battery pack and extracting maximum utility from it. The internal resistance parameter was then quantified for each cell by conducting an energy balance for the entire battery system. The calculation was averaged due to the variations of SOC's on a cycle-to-cycle basis and due to instrumentation errors resulting in noisy current data. Compelling indications were found to suggest that there exists a strong correlation between the thermal imbalance and growth of internal resistance. In addition, the heat spreading material was found to mitigate the growth of resistance values thereby weakening the effects due to the ohmic losses. Additionally, the spreader material was effective in mitigating the effects of cell-to-cell differences on the overall aging of the pack. The material was also observed to diminish the likelihood of resistance values in the cells departing abruptly from their natural course.

The electrical parameters, on the other hand, depicted trends in their behavior that were governed by the variation in internal resistances thereby confirming the correlation between the two. The state of charge values in a cycle were found to decrease at the end of each charge-discharge phase. This was due to the absence of a traditional BMS and due to the behavior of a single cell in the pack, with the highest resistance rate, exceeding
the voltage threshold. The thermal management material ensured a relatively uniform deviation of these values during the course of testing. It was thus concluded that the effects of electrical and thermal imbalances were strongly governed by the growth of internal resistance in the packs. Additionally, each of these imbalances was found to influence the variation in internal resistance as the cells were aged. Lastly, the heat spreading material is an effective low-cost solution for mitigating the effects of aging on a cell-to-cell basis that can help sustain pack performance in the long run.

5.2 Future Work
The work presented in this thesis carries forward the research in the field of heat spreading materials as passive thermal management solutions. This thesis focused on the experimental analysis of Li-ion batteries and in order to get a more thorough understanding of the effects of heat spreaders, the development and validation of a 3D Finite Element Model (FEM) is required. The finite element model would help identify key parameters such as the rate of heat generation and dissipation in the two packs that could help further the credibility of heat spreaders. In addition, the characterization of the electro-thermal behavior in the two packs can be extended using this model.

The growth in internal resistance of the unmanaged pack was shown to be quite significant and in order to predicate this failure, material characterization studies can be performed by cutting open those cells and analyzing them in detail.

Another possible suggestion for future work, would be to change the configuration of the heat spreaders by using a horse-shoe type configuration which would allow for larger thermal contact between the spreaders and the cell in all directions. This would help gain
a better understanding of the effects of using heat spreading material and possibly help quantify the pack behavior in a more detailed manner.

Since E-bikes are already in commercial use in many countries worldwide, the analysis presented in this thesis could further the use of light-weight passive thermal management solutions, such as heat spreaders.
Bibliography


