Design, development and analysis of a battery electric vehicle energy storage system

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**DESIGN, DEVELOPMENT AND ANALYSIS OF
A BATTERY ELECTRIC VEHICLE ENERGY
STORAGE SYSTEM**

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**SCHOOL OF MECHANICAL AND AEROSPACE
ENGINEERING**

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DESIGN, DEVELOPMENT AND ANALYSIS OF A BATTERY ELECTRIC VEHICLE ENERGY STORAGE SYSTEM

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Abstract

The significance of Lithium-Ion Battery technology in the electric vehicle industry has been undoubtedly impactful. The massive advantage of the improved energy-to-weight, power-to-weight ratio and the lengthened battery lifespan over the existing Nickel-variants and lead-acid batteries had leapfrogged the electric vehicle to become on par with the combustion engine vehicle in terms of performance and reliability.

The lithium-ion battery cell can be charged or discharged but the conversion of energy from the stored chemical energy to useable electrical energy comes with an efficiency rating or energy loss which manifests as heat energy, causing temperature rise in battery cells. Excessive rise in temperature can cause battery explosion or fire. It is therefore critical that the battery pack is safe from such temperature rises.

The focus of the thesis was to design, analyse and manufacture the battery pack to the temperature control requirements of the NTU BEV (Battery Electric Vehicle). The thermal packaging design was designed to extract the waste heat arising from the batteries undergoing energy conversion process. The thermal cooling system was broken down into two essential heat flow paths: 1) through cell connectors and 2) through cooling channels. The cooling system evaluation proceeded with the initial one-dimensional heat transfer calculations. This involved basic heat transfer analysis and manual calculations to ensure the pack will be fit for the purpose of powering the BEV.

Once results were tabulated and cooling capacity was found to be adequate, the subsequent more detailed thermal simulation using ANSYS CFD and heat transfer FLUENT software was carried out. The heat transfer analysis enabled a more detailed understanding of airflow paths and temperatures within the battery pack. Several performance assumptions were made to analyse for heat dissipation performance of the cooling system. After the simulation confirmed the feasibility of the pack design, the detail CAD and manufacture was carried out. A complete module was made for testing.

The physical battery module assembly was then instrumented with a large number of thermistors throughout the pack. An experimental programme was carried out to measure the temperature during discharge and charge process.

Data from experimentation confirmed that the temperature inside the battery module at 1C discharge were well within the prescribed range of the cells. With active cooling by centrifugal fans, a uniform temperature was maintained with small differentials ($< 5\text{ }^{\circ}\text{C}$) across the pack while overall battery temperatures continued to increase to a maximum of 30°C at the center of the module.

For the current thermal management scheme, a forced convection flow rate of 4-8 m/s at 25°C is desired to keep the maximum cell temperature below 45°C under discharge/charge load of 1C rate. At higher C-rates, further analysis was carried out using extrapolation techniques. They showed that at 3C, a flow rate of 15.5 m/s is needed.

This project enabled a deeper understanding of the ability of forced air convection cooling utilised in battery packs for an electric vehicle environment. The requirements of a battery pack are very stringent, therefore the need to

understand a wide range of multidisciplinary engineering topics was required to evaluate the battery pack.

Keywords: Lithium-ion batteries; Thermal analysis; Energy Storage System; Battery Electric Vehicle

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List of Abbreviations

General	
3D	3 Dimensional
Ag	Silver
BEV	Battery Electric Vehicle
BMS	Battery Management System
BMU	Battery Management Unit
CAD	Computer Aided Design
CAN	Controller Area Network
CFD	Computational Fluid Dynamics
CID	Current Interrupt Device
CMU	Cell Management Unit
Cu	Copper
DOD	Depth of Discharge
EiG	Energy Innovation Group
ESS	Energy Storage System
ERI@N	Energy Research Institute @ NTU
EV	Electric Vehicle
FYP	Final Year Project
HEV	Hybrid Electric Vehicle
HTC	Heat Transfer Coefficient
ICE	Internal Combustion Engine
LCO	Lithium Cobalt Oxide
Li-Ion	Lithium-Ion
LIB	Lithium-Ion Battery
LMO	Lithium Manganese Oxide
LTO	Lithium Titanium Oxide
MAE	Mechanical and Aerospace Engineering
MIT	Massachusetts Institute of Technology
NCA	Nickel Cobalt Aluminium
NiCd	Nickel Cadmium

NiMH	Nickel Metal Hydride
NMC	Lithium Nickel Manganese Cobalt Oxide
NREL	National Renewable Energy Laboratory
NTU	Nanyang Technological University
OCV	Open Circuit Voltage
PHEV	Plug-in Hybrid Electric Vehicle
SOC	State-of-Charge
TBD	To Be Determined

List of Symbols

General symbols

A	Surface area (m ²)
a	Width of duct opening (m)
b	Height of duct opening (m)
c_p	Specific heat (J/kg. K)
E	Cell potential (V)
D_h	Hydraulic diameter (m)
f	Friction factor
g	Fin gap (m)
$\dot{g}$	Heat generation rate (W/m ³)
h	Convective heat transfer coefficient (W/m ² .K)
H	Fin height (m)
I	Current (A)
k	Thermal conductivity (W/m.K)
L	Length of duct (m)
Nu	Nusselt number
p	Perimeter (m)
Pr	Prandtl number
Q	Heat (W)
Ra	Rayleigh number
Re	Reynolds number
S	Cells in series
T	Temperature (K) or (°C)
t	Thickness of fin (m)
V	Voltage (V)
ν_{ol}	Volume (m ³)
ν	Mean velocity in pipe (m/s)

Greek symbols

β	Coefficient of volume expansion (1/K)
μ	Dynamic viscosity (kg/m.s)
ρ	Density (kg/m ³)
ν	Kinematic viscosity (m ² /s)
η	Fin efficiency

Sub-/Super-script

°	Degree
battery	Battery
A	Flow A, cooling channel
air	Air property
B	Flow B, cell connector
bb	Bus bar
C	Flow C, end plate
cc	Cell connector
cell	Battery cell
ep	End plate
f	Film temperature
fins	Heatsink fins
base	Heatsink base
oc	Open circuit

Chapter 1: Introduction

This introductory chapter will elaborate on the objectives of this research study, the research importance and motivation, the scope of the thesis and lastly the presentation format.

1.1. Research objectives

The performance of batteries depends critically on the reliability and longevity of the cells which is linked to the battery's thermal performance. Analysing thermal design of a developed battery module can be achieved by simulation analysis and experimental testing. The present work utilises these methods to predict the performance of thermal management systems at actual operating conditions. The objectives of the thesis are summarized below:

- To develop an in-depth understanding of the heat transfer interactions between the lithium ion battery cells and the developed thermal cooling design for a battery module through the use of design calculations, simulation and experimental testing.
- Test the combined efficiency for the cooling fan and thermal design of the battery module under battery discharge and charge conditions. The system must be able to remove heat from the cells to a maximum of 3C discharge rate.
- Higher discharge rates (2C and 3C) shall be checked for feasibility by performing the heat transfer simulation.
- Assess the ability of the battery module thermal design to remove heat from higher discharge rates up to 3C through thermal simulation.

To provide the experimental data required for the validation of the battery module thermal design, a physical module was designed and manufactured to perform the battery testing close to real-world operating conditions. The battery test setup consists of an electrical load to discharge the cells, a fabricated thermal chamber for simulating constant temperature conditions and a data acquisition unit to capture the temperature readings all around the battery module.

1.2. Research importance and motivation

Lithium-ion cells are fast becoming the prevailing choice for industries requiring high performance energy sources but inherent safety issues of lithium battery operation have not been fully resolved. The safety issues are primarily related to the cell being easily damaged/destroyed by heat and a cause of fire and explosion.

Thermal failure has been identified to be the root cause of most lithium battery incidents [1], therefore it is important to improve upon the thermal management of lithium by battery packaging design. Thermal failure refers to the cells undergoing cell degradation through excessive uncontrolled self-heating chemical reactions and causing thermal explosion of the cell.

Thermal management of lithium battery cells in Energy Storage System (ESS) is crucial and are mission critical to several applications such as; aerospace (space satellites and aeroplanes), automotive (hybrid and electric vehicles), military (armoured vehicles and robotics) and tele-communication systems.

Considering the ever-increasing desire of the automotive industry for a more reliable, low-cost and efficiently packaged ESS, passively cooled thermal

management systems is a first choice as a viable alternative to active cooling devices such as liquid cooling or phase change cooling systems.

Passive/semi-passive cooling is more economical and reliable, well suited for power electronic applications. It also serves as a sustainable solution because it requires low power draw on the system.

A complete engineering solution for electronic components involves mechanical, electrical and thermal interactions. The design of a BEV energy storage system has the same principles, a compromise has to be reached between discrete connections.

The main driver of this research is to develop an effective heat management system for a lithium battery pack for the Nanyang Technological University's (NTU) Battery Electric Vehicle (BEV) which is shown in Fig. 1.1. It is an Electric Vehicle (EV) designed for city driving and test bedding platform for future research. The BEV requires an energy storage solution that is capable of delivering electrical power large enough for constant start-stop driving conditions and driving cycles of the Singapore road network whilst maintain an acceptable battery temperature.

Figure 1.1: NTU Plug-in Battery Electric Vehicle

In an electric vehicle application setting, space is a constraint, therefore cells are densely packed. This presents challenges in the layout of the cooling system and electrical wiring harness. The battery system experiences highly erratic discharge loads which are dependent on the driving route, road traffic conditions and driver behaviour. Yet, a suitably designed thermal management system must ensure optimal vehicle operation and prevent cell failure that give rise to fire/explosion.

The current public domain research does not contain any in-depth studies on applied thermal cooling management for lithium cells in densely packaged configuration. Thus, a package comprising of thermal simulation studies can be correlated with controlled experiments to understand the diverse interactions that goes on when the battery cells undergo discharge/charge.

1.3. Research scope

The goal of this project is to design and develop a battery module for an electric vehicle application that will satisfy or operate well within the operating requirements of a lithium battery pouch cell. The justifications will be presented in the form of thermal analysis simulation and experimental study on the forced air cooling system of the battery module.

To meet the simulation objectives, the 3-dimensional CAD model assembly has to be simplified to reduce computation efforts and yet retain an accurate representation of the actual prototype. The simulation will analyse for steady-state thermal analysis for battery discharge process. The airflow within the battery module is divided into three separate paths for analysis.

An experimental study is conducted on the discharging and charging of the prototype battery module held in a thermally controlled chamber. Both the simulation and experimental study has to be performed under identical conditions experienced in an actual electric vehicle's operation. The results should provide a reasonable estimation of thermal dynamics inside the battery module assembly.

1.4. Thesis structure

The thesis will be structured according to the following chapters:

Chapter 1: Introduction of the research importance along with the motivation and objectives.

Chapter 2: Literature review of battery technology and its safety mechanisms, specifically lithium-ion batteries. Battery management systems and an introduction to electric vehicles are introduced.

Chapter 3: NTU's Battery Electric Vehicle project is presented along with the BEV's energy storage design and development described in detail, with emphasis on the cell cooling design.

Chapter 4: Air flow and heat transfer coefficients are presented by Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) simulation.

Chapter 5: Experimental testing of battery module are described and results presented.

Chapter 6: Summary, the challenges faced and future recommendations.

Chapter 2: Literature Review

This chapter covers the introduction of batteries, in particular the lithium cell. Technical battery terms are discussed as well. The highlight of this chapter is the lithium ion cell safety, as well as using a Battery Management System to monitor and control cell temperatures, also covered are battery vehicle technology.

2.1. Battery cell background

A cell holds energy stored in the chemical form, it is the smallest individual electrochemical unit that produces a voltage based on its inherent cell chemistry.

2.1.1. Primary and secondary batteries

Cells can be classified as primary or secondary batteries. Primary cells are typically alkaline cylindrical cells and button sized lithium cells. Primary cells are non-rechargeable and of single-use only. Secondary cells are rechargeable which refers to batteries that can have their electrical charge restored by applying a reverse voltage. The cell chemistries that can be recharged are Lead-Acid (Pb), Nickel Metal Hydride (NiMH), Nickel Cadmium (NiCd), and some variations of lithium batteries.

2.1.2. Basic battery terms

Physical properties: Figure 2.1 illustrates the terms used to describe the physical battery parts.

- The cell is the core component of any energy storage system; it is a basic building block to make a battery pack.

- Cells that are electrically connected in series or parallel, forms a battery module.
- Multiple battery modules are then fitted together to form a battery pack. The battery pack provides the necessary energy and power to propel the electric vehicle.

Figure 2.1: Modular parts of an energy storage unit [2]

A cell can be described by its electrical properties, voltage (V), current (A), internal resistance (Ω) and power (W) which are described below:

- Voltage:

The voltage of a cell measured between the cell terminals without load is the Open-Circuit Voltage (OCV). The cell voltage measured with an electrical load present is called terminal voltage (V).

- A cell internal impedance/resistance determines its current carrying capability.

When current flows through the cell, there is a voltage drop across the Internal Resistance (IR) of the cell which decreases the terminal voltage of the cell during discharge $V = OCV - IR$. A low internal resistance allows high currents. It is measured in (Ω).

- A battery State of Charge (SOC) is a measure of available energy over total cell capacity expressed as a percentage (%).
- Battery Depth of Discharge (DOD) indicates the percentage (%) of energy discharged over total cell capacity (0% DOD equals to 100% SOC).
- A cell contains stored charge quantified in Ampere-hours (Ah), which refers to the quantity of charge that the battery is rated to hold. This is the cell nominal capacity; it can be interpreted as a cell being able to deliver X amperes over one hour.
- C-rate refers to the X rate of a cell current measured based on cell capacity. A 20 Ah cell that can produce 20 A for 1 hour is represented as 1C. The same cell can deliver 100 A at 5C rate for 12 minutes.
- Battery power is measured in Watts (W), it is the multiplication of V and I of a cell.
- Battery total energy storage capacity is termed as Watt-hours (Wh), simply by multiplying nominal voltage (V) with nominal capacity (Ah).

A complete glossary of battery specifications and terminology are given in Appendix A.

2.1.3. Working principle of an electrochemical cell

Inside the cell are four key components: anode (negative electrode), cathode (positive electrode), electrolyte and separator shown in Figure 2.2.

Figure 2.2: Electrochemical cell structure [3]

When a battery cell is at full charge, there is a surplus of electrons on the anode giving it a negative charge and a deficit on the cathode giving it a positive charge resulting in a potential difference (in volts) when measured across the cell [4]. The discharge process happens when the cell terminals are connected with an electrical load, negatively charged electrons are released from anode and flows through the external circuit to the cathode. At the same time, positively charged lithium ions stored in the negative electrode dissolve in the electrolyte, migrates to the positive electrode. At the positive electrode, the electrons recombine with the Li^+ ions and are stored in the molecular structure of the active material. An electrical current is thus generated. The electrochemical reaction is completed and the current flows from the battery positive terminal to through the load to the battery negative terminal. The charging process is the exact reverse of the discharge process, whereby the lithium ions are stored back into the anode. An overall diagram of a cell's electron movement in relation to the electronic components (load and charger) is provided in Appendix A.

2.1.4. Battery performance metrics

Batteries are energy sources, and that they can be designed to provide large bursts of power in a short duration or supply a sustained power over a longer

length of time. Large burst of energy/current relates to the battery's (specific power) whereas the endurance of a battery is rated by (specific energy).

- Specific power (W/kg) is the amount of power obtained per kilogram of battery.
- Power density (W/m³) is the maximum available power per unit volume.
- Specific energy (Wh/kg) is the amount of electrical energy stored for every kilogram of battery mass. Interchangeable terms are: gravimetric energy density.
- Energy density (Wh/m³) is the amount of electrical energy stored per cubic metre of battery volume. An alternative term would be volumetric energy density.

Ragone plots are used for characterising battery performance; power and energy are compared, both in terms of weight (kg) or volume (m³). Typical Ragone plots for various battery types are plotted as specific power versus specific energy, however if certain application or industries emphasizes more on volume, then power density plot against energy density are used. Examples are hearing aid devices and land based static application where weight is less of a concern than volumetric space available.

Figure 2.3 is a Ragone plot in logarithmic scale of various battery types and energy sources in terms of specific energy versus specific power. Super capacitors are high in specific power and low in specific energy as they are capable of producing instantaneous high power delivery but they are not able to store much energy. Fuel cells are the direct opposite of super capacitors; they can store large amounts of energy but they can only output a small quantity of power each time.

The yellow starred icon on the chart indicates the future target of lithium-ion cells for electric vehicle applications. A high-power battery is useful in an application where instantaneous acceleration power is required; e.g. in Hybrid Electric Vehicle (HEV) as the electric motor often used to assist the combustion engine. A high-energy battery is useful in Battery Electric Vehicle (BEV) and Plug-in Hybrid Electric Vehicle (PHEV) applications where the vehicles run solely on electrical energy for a long driving distance. Having both high power and high energy for a lithium ion cell would put the electric vehicle in a better standing to challenge the internal combustion engine.

Figure 2.3: Ragone plot of specific energy vs specific power of different battery types [5]

2.2. The lithium battery

Amongst different types of rechargeable batteries, Lithium-ion (Li-ion) battery cells are of interest to commercial and military applications due to their high specific energy (~ 180 Wh/kg), high energy density (~ 400 Wh/L), high

operating cell voltage (up to about 4 V), and low self-discharge rate (around 5-8%) and long life.

Commercial Lithium Ion Batteries (LIB) was invented by American Professor John Goodenough in 1979 [6]. He made a lithium battery with Lithium Cobalt Oxide (LiCoO_2) as the positive electrode (cathode) and lithium metal as the negative electrode (anode). Today, most lithium battery applications such as portable electronic gadgets contain LiCoO_2 as the cathode. A list of available cathodes is given in Table 2.1.

The invention of the lithium battery has made a significant impact, opening up the many possibilities of different lithium battery research areas. LIB is a broad classification to cover the various chemistries of the positive electrode/cathode. The negative electrode/anode is typically lithium-graphite, which was pioneered by Professor Rachid Yazami in 1980 [7].

Lithium is the lightest of all metal elements, it has high electrochemical potential [8] and large specific energy per unit weight. These characteristics of the lithium element makes it a highly reactive material. High reactivity means that the element is unstable and just a small chemical reaction is needed to trigger or release large amounts of energy.

2.2.1. Cell makeup and working mechanism

Lithium-ion cells function differently from the electrochemical cell; they produce electrical power through an intercalation process rather than a redox reaction. Firstly, lithium ion cells are made up of four functional components; the anode, cathode, electrolyte and separator. The cathode is made of lithium-metal oxides or phosphates and the anode is typically made from graphite. The

electrolyte is a mixture of organic carbonates containing lithium enables lithium-ions to travel between the positive and negative electrodes. To allow the transport of electricity, the cathode is placed on highly conductive aluminium foil, the anode on copper foil. Figure 2.4 shows the internal construction of a pouch cell; a long separator sheet is folded length-wise to separate each anode and cathode layers. A pouch cell will have multiple anode and cathode pairs that collectively form the bulk of a cell's nominal capacity.

Figure 2.4: Construction method for a typical pouch cell [9]

Ion intercalation process is defined as the movement of the lithium-ions migrating between anode and cathode. Lithium-ions gets removed from the anode and inserted/intercalated into the cathode during discharge process and the process is reversed when the cell is charging.

2.2.2. Cell chemistries

The term 'Li-ion' encompasses a range of different chemistries, with each chemistry offering a different mix of cost, durability, performance, and safety. Table 2.1 compares the different lithium battery chemistries. Not all chemistries are deployed in the automobile industry, electric vehicles favour the overall good

performing chemistries, e.g. Nickel-Manganese-Cobalt (NMC), Nickel-Cobalt-Aluminium (NCA) and Lithium Iron Phosphate (LiFePO₄) variants.

Selecting a cell chemistry suitable for electric vehicles depends on a few properties: specific power, specific energy, safety (risk of fire), operating temperatures, the number of charge/discharge cycles, cost and weight.

Table 2.1: Lithium-ion battery characteristics, by chemistry [10]

	Lithium cobalt oxide (LiCoO ₂)	Nickel, cobalt and aluminum (NCA)	Nickel-manganese-cobalt (NMC)	Lithium polymer (LiMn ₂ O ₄)	Lithium iron phosphate (LiFePO ₄)
Energy Wh/kg or L	Good	Good	Good	Average	Poor
Power	Good	Good	Good	Good	Average (lower V)
Low T	Good	Good	Good	Good	Average
Calendar life	Average	Very Good (if charge at 4.0 V)	Good	Poor	Poor above 30°C
Cycle life	Average	Very good (if charge at 4.0 V)	Good	Average	Average
Safety*	Poor	Poor	Poor	Average	Good
Cost/kWh	Higher	High	High	High	High
Maturity	High	High	High	High	Low

2.2.3. Cell geometry and applications

There are several specific cell formats made for lithium batteries shown in Figure 2.5, the first image shows a cylindrical cell casing most commonly used in laptop batteries. The next cell format is the prismatic cell, the robust outer shell is well suited for stationary applications such as backup power units. The third cell format is the pouch cell, this is the most efficient packaging design compared to the previous two formats due to the flat rectangular profile that makes battery pack design straightforward.

Figure 2.5: Lithium cell formats available [2]

Within the electric vehicle industry, all three formats are used by various automotive companies and small-firms specialised in Internal Combustion Engine (ICE) to EV conversion of gasoline cars. Pouch cell formats are the most commonly used in electric vehicles. The attributes of the cell formats in the mechanical design of energy storage systems are listed in Appendix A, Table A.2.

2.3. Lithium cell failure modes

The best method to keep lithium ion batteries operating normally and efficiently is to understand what, why and how cells can fail. Battery controls can then be developed to prevent the failures and provide early warning signals to highlight the fault to the operator. Failures occur because of inherent cell design faults, poor control of manufacturing processes, cell aging, uncontrolled operations, and abuse. Proper battery controls can only avoid uncontrolled operations, slow down cell aging and prevent cell abuse but it is not able to mitigate the first two failure modes.

2.3.1. Aging

Cell performance gradually deteriorates irreversibly with time due to unwanted chemical reactions and physical changes to the active chemicals. The cell breakdown produces undesirable effects such as:

- Increase in cell internal impedance: a higher resistance value translates to more energy lost as waste heat and a larger voltage drop across the cell.
- Reduction in cell capacity: as more and more active chemicals become unusable, the lesser the energy conversion reactions can form.

Ning and Haran [11] have shown that cells operating at elevated temperatures experience accelerated battery ageing, in which the electrolyte decomposes and cause cell capacity reduction. This is shown in Figure 2.6, the cell degraded the fastest with high discharge rates after 300 test cycles.

Figure 2.6: Capacity fade of lithium batteries under different discharge rates

[11]

2.3.2. Uncontrolled operations and cell abuse

Uncontrolled operations refer to events that may happen unexpectedly, such as a car crash leading to physical cell deformation, puncture of cell or short circuit of the cell. The cell can abruptly fail when operated beyond their rated specifications. This includes cell short circuiting, over discharging, over charging and usage of cell at extreme temperatures. This is defined as lithium cell abuse. By operating the cells out of the specification range, the chemical reactions cause the cells to heat up abnormally. The heated cell leads to overheating conditions, which then causes cell failures.

2.3.3. Cell failure

The cell can fail in a number of ways:

- Unable to produce any power, not responding to charging, measures 0 volts at the cell terminals.
- Highly reactive reactions, cells generating heat but the heat is not removed as quickly. The contained cell heat causes accelerated cell heat generation and it becomes self-sustaining. The result is cell thermal runaway; the cell components breaks down and causes a fire or explosion.

2.4. Understanding lithium battery thermal runaway

Thermal runaway is considered the greatest threat to lithium battery safety. Once the cell experiences thermal runaway and start to burn, the best solution is to wait for the lithium content to burn to depletion.

2.4.1. Battery thermal runaway

In order to extract the best possible performance from lithium battery, the cells have to work strictly within the optimal temperature range specified by the manufacturer. If this limit is exceeded, the cell undergoes thermal runaway. This term is explained as accelerated cell self-heating condition and becomes uncontrollable. The heat would propagate to surrounding cells, creating a chain reaction of adjacent cell thermal runaways and cause subsequent damage such as melting or combustion of surrounding plastic components. This was confirmed by Khateed et al [12] with laboratory test results of a Li-ion battery designed for electric scooter applications.

A highly heated cell only occurs if the safety measures employed to remove the internal heat has failed to intervene. The exact temperature for the beginning of thermal runaway varies with cell size, cell design and cell materials [13]. Figure 2.7 shows a simplified graph of the rate of temperature rise during a cell thermal runaway. The chart plots the three stages of the battery cell self-heating rate, with the rate of cell heating versus cell temperature rise. At stage 1, the cell undergoes discharge/charge process, and the cell produces a fairly constant cell self-heating rate. The cell then experiences cell abuse or unexpected conditions.

At stage 2, if the heat generated by the chemical reactions cannot be removed fast enough, this leads to a further increase in temperature and self-sustaining uncontrolled chain of exothermic reactions are triggered.

Finally, for stage 3, the cell is now in thermal runaway mode, the chain reactions cause further acceleration of the reaction kinetics. The catastrophic self-accelerated degradation of the cell can spontaneously burn/combust, meltdown

its plastic shell and create a fire. Toxic gases are also released into the air through the process, it includes carbon monoxide and other hydrocarbons compounds [2].

Figure 9. Cell self-heating rate during forced thermal ramp test of Li-Ion Gen 2 chemistry: anode = MCMB | electrolyte = 1.2 M LiPF₆ in EC:PC:DMC | cathode = LiNi_{0.8}Co_{0.05}Al_{0.05}O₂ | separator = Celgard 2325 trilayer.⁶⁰

Figure 2.7: Thermal Runaway in Three Stages [13]

Figure 2.8 shows a cylindrical lithium ion cell's thermal runaway plot: the rate of temperature rise versus cell temperature. The cell was forced into thermal runaway by heating up the cell body. At stage 3, the rate of temperature increase hit the peak and begins to fall but the temperature continues to increase due to the thermal explosion still on-going. The cell would take a long time to completely burn off itself unless the fire is put out by starving the fire's oxygen supply.

Figure 2.8: Cell temperature rate of rise versus cell temperature for the full experiment duration. [14]

2.4.2. Combating thermal runaway

Heat is generated intrinsically in lithium ion cells during usage. As long as the thermal control module keeps the cell cooled sufficiently to confine it to the specified temperature range and the rate of heat removed is always greater than the rate of heat generated by the cells, then the battery pack is considered well protected from thermal runaway. Thus, the risk of lithium battery fire or explosion is greatly reduced.

2.4.3. Heat generation phenomenon

Research from the National Renewable Energy Laboratory (NREL) [15] highlights a marked increase in heat generation rate when lithium cells are

assembled as a battery module shown in Figure 2.9. This is caused by lack of cooling capacity as the module are densely packed together decreasing paths for heat dissipation. The graph explains that, as the discharge current increases, the heat generated by per cell in the battery module starts to diverge from the single cell heat generated curve. The increments are shown to be more than 30% over the single cell comparison. This highlights the fact that thermal design cannot be based solely on the experimental temperature data gathered for a single cell, and it might lead to overheating in a battery pack.

Figure 2.9: Increase in heat generation rate of battery module versus individual cell [16]

2.4.4. Cell cooling

Various research has shown that cell heat generation cannot be assumed to be homogeneous or constant throughout the cell body, especially at higher discharge rates [17]. As for lower discharge rates, the cell heat generation rate is

uniform, the temperature variation is within $\pm 1^\circ\text{C}$, with the exception of the positive cell terminal exhibiting a slightly higher value as shown by Teng [18] in Figure 2.10. Cell cooling is a definite requirement at higher current draw, and a cooling device to cool the cell tabs should be explored.

Figure 2.10: Simulated cell temperature distributions at 90% Depth of Discharge [18]

Kotub et al [19, 20] showed that the benefits of cell cooling in Figure 2.11 contributed to the cell's low internal resistance to the operation of the cell at its optimum temperatures. Bandhauer [21] also concluded that low cell internal resistance equates to higher battery efficiency, which results in more extractable electrical power.

Figure 2.11: Internal resistance of a NMC battery cell versus discharge current and SOC [19]

2.5. Battery pack architecture

The battery pack architecture is illustrated in Figure 2.13; these includes safety devices protecting the cells from thermal failure and they are divided into three tiers. The multi-tier system is explained in sub-sections, which are the Cell Management Unit (CMU) and Battery Management Unit (BMU).

Figure 2.12: Safety levels present in a battery pack

2.5.1. Battery cell level

The safety features found in this level is typically developed by the cell manufacturer, the commercial cells would have most of the safety devices installed, and these are as follows:

2.5.1.1. Current Interrupt Device (CID)

The Current Interrupt Device protects against over-current by interrupting the internal electrical connection when the internal pressure exceeds specified limits. This safety cut-off mechanism is a one-time device that permanently disables the cell. This is shown in Figure 2.13.

Figure 2.13: Cylindrical cell with pressure vent (disk vent) and interrupt device [22]

2.5.1.2. Cell pressure vent

Cell pressure vent are used as pressure relief to allow the safe release of gas if excessive pressure builds up within cells. It activates if the internal cell pressure exceeds a pre-set value. This feature prevent injury that could be caused by sudden bulging or bursting of a battery cell. Figure 2.13 is an image of a cylindrical cell with cell level safety features built-in.

2.5.1.3. Current Limiting Fuses

The battery cells inside the Tesla Motors: Model S sedan vehicle has a short length of wire acting as a fuse. The fuse is indicated in Figure 2.14, it breaks off when abnormal high current passes through the cell.

Figure 2.14: Tesla battery cell fuse [23]

2.5.2. Battery module level

At the module level, the safety features are designed to monitor a group of cells to prevent excessive temperature increase.

2.5.2.1. Cell Management Unit (CMU)

The CMU is explained together with the Battery Management Unit (BMU) as part of the Battery Management System (BMS) in Chapter 2, Section 5.3.2.1.

2.5.2.2. Intumescent coating

Tesla Motor's battery cells (shown in Figure 2.15) are coated with an intumescent outer layer which isolates and prevents thermal runaway from affecting any adjacent cells. Intumescent is defined as is a substance that swells as a result of heat exposure. The material absorbs the heat created by the cell and starts to swell. The swelling engulfs the heated cell, protecting adjacent cells from absorbing the heat of the first cell. The secondary purpose is to seal up the heated cell, preventing chances of fire.

Figure 2.15: Tesla Motors patented cell assembly with an outer layer of intumescent material [24]

2.5.3. Battery pack level

The battery pack is the highest level, the controls used at this stage prevents a catastrophic thermal failure of the whole pack. A battery management system is installed to cut power and isolate the cells from the load or other electrical systems connected to the pack. As a result, the entire vehicle is cut-off from power supply, and emergency responders can safely rescue the vehicle occupants.

2.5.3.1. Current Limiting Fuses

Current limiting fuses are used at the pack level to cut off power to the traction motor when the current has exceeded. These fuses such the one in Figure 2.16 are typically a one-time use, and not resettable in the event of a blown fuse. It ensures the electric vehicle will not be able to restart.

Figure 2.16: High voltage, high current fuse (250 A) [25]

2.5.3.2. Battery Management System (BMS)

The Battery Management System is an electronic system that provides many functions mentioned earlier, they are divided into primary and secondary functions:

Primary Functions (cell protection):

- Monitors and controls the charging and discharging of cells
- Prevent over current draw
- Cell balancing, to ensure all cells maintain the same voltage at all conditions
- Cell cooling, to activate the cooling fans to keep temperature in check
- Evaluate the battery pack in terms of: SOC, temperature, voltage and current
- Provide electrical connection interrupt to prevent cell damage

Secondary Functions (communication):

- Communicate with other vehicle systems such as battery charger, motor controller, climate controls and thermal management systems
- Reports all the data to an external communication device through the Controller Area Network (CAN) Bus communication line.
- CAN Bus is a two wire, serial communications bus which is used for networking of intelligent sensors and actuators

- Display visual and audio warning to driver
- Provide diagnosis reports to the vehicle management system
- Data logging of errors and cell vitals

2.5.3.2.1. Cell Management Unit (CMU)

The CMU does the cell balancing, cell voltage and temperature measurement and communicates between CMUs in other battery modules as well as between the BMU. The cell modules contain a number of temperature sensors to detect critical temperatures. These sensors are connected with the thermal management in order to prevent over temperature in the battery system.

2.5.3.2.2. Battery Management Unit (BMU)

The BMU handles the higher-level controls and computational work. This includes communication with other vehicle systems, provide cell diagnosis function, control the cooling fans and provide the high voltage disconnection. It also records temperature data and any system faults from the BMS.

2.5.3.2.3. System topology

The BMS mentioned in this chapter uses a distributed cell management topology. It means that there is a master control board (BMU) that connects to multiple slave units (CMU) which monitors and balance the cells. The master control board refers to the BMU, and the cell board refers to the CMU. The non-distributed topology would mean that one main control board can control all the cells directly.

The selection of topology depends on the demands of cell packaging, preference of wire management method, cost and ease of installation.

2.6. Thermal behaviour of battery cells

In addition to the earlier section of battery literature review, reference study articles are included here for constructive discussion purposes, so as to highlight the positives and negatives related to the research papers.

2.6.1. Lithium cell thermal model

Peyman et al [26], investigated for battery thermal behaviour using a three-dimensional thermal model and determined that the cells only showed small variations of temperature along the thickness of the cell body.

The graph shown in Figure 2.17 is the experimental data of voltage versus DOD, provided by the cell manufacturer [27]. The cells used is of the same brand and cell model (EiG ePLB-Co20B) in the BEV battery pack design. The red data plot are the voltage open circuit potentials of the cell, it can be used to calculate the cell's internal resistance in Chapter 3: heat transfer calculations.

Figure 2.17: EiG Co20B cell voltage versus Depth of Discharge [26]

2.6.2. Cooling performance of indirect liquid cooling systems for lithium-ion battery packs

Teng et al [28] conducted simulation on indirect cooling of the cell bodies. Heat was conducted away from the cells using 1.5 mm thick aluminium plates attached to a cold plate located at the bottom of the battery module. The aluminium plates act as a heat transfer bridge between the cells and the cold plate, it is also a heat spreader to even out the heat distribution. Figure 2.19 illustrates the thermal design for the indirect cooling system, showing the heat spreader cooling fins and bottom cold plate. Although the cell maximum temperature differential is 5.2°C, the results for a 4 C discharge rate, indirect cooling meets the battery cooling system design criteria: $T_{\text{cell,max}} \leq 55\text{ }^{\circ}\text{C}$ and $\Delta T_{\text{cell,max}} < 8\text{ }^{\circ}\text{C}$.

Figure 2.18: Simulated temperature distribution for indirect cooling [28]

2.6.3. Force air cooling of a battery module

Heesung Park [29] developed a forced air cooling system for HEVs. Different flow patterns within the cooling passage was analysed. The air passage was also varied in their inlet and outlet dimensions to find the optimised power for cooling fan energy utilisation.

The results in Figure 2.19 and 2.20 show that Type IV passage airflow design produced better results than types I to III. Comparing Type III and V designs, Type V has an additional vent hole located above the air passage which caused an even lower thermal resistance. The author terms it as pressure relief ventilation effect. The power consumption for operating fan is also improved due to air pressure relief (Type IV = 47W, Type V = 27W). The findings in this

study can be used as a design guideline for the battery cooling system in electric vehicles.

Figure 2.19: Airflow patterns for 5 different configurations [29]

Figure 2.20: Temperature distribution for 5 simulated air passage [29]

2.6.4. Effect of battery cooling air gap and flow rates

L. Fan et al [30] examined the fin gap spacing between cells in the module in detail. He evaluated constant gap spacing of 1mm to 5mm, even and uneven gap spacing and changing flow rates of a 3mm constant gap spacing. He found that higher flow rates and smaller gap spacing in the cooling channels produced a

lower maximum temperature rise and the temperature distribution also achieved more uniformity in the cells as seen in Figure 2.23. Uneven gap spacing tests showed that further optimisation can be performed to find the ideal individual gap dimension with respect to the flow rates used.

Although the various gap spacing is simulated by Computational Fluid Dynamics (CFD), whether manufacturing capabilities or standard parts can achieve the small 1 mm gap spacing is questionable. The cost versus performance would not allow such a battery module design to be manufactured. A better approach would be to regulate the air flow rate to determine the best compromise between low cell temperatures and cooling fan power consumption.

Figure 2.21: PHEV air-cooled module; (a) actual battery module, (b) CFD mesh model [30]

Three-dimensional temperature distributions (unit: °C) within the cells after 600 s for one-side cooling design with various gap spacing values at $V = 20.4 \text{ m}^3 \text{ h}^{-1}$.

Figure 2.22: Temperature distribution within cells with varying air gaps [30]

2.6.5. Temperature distribution of battery module at 3C discharge rate

Jaeshin et al [31] accessed the natural and forced convection cooling for battery discharge at 3C. Figure 2.23 shows the simulation model result, the cell temperature for natural convection did not rise more than 51 °C at the hottest region. This ascertains the notion that battery cells do not require complicated liquid cooling systems to function within cell temperature limits.

Figure 2.23: Simulation of 3C discharge with natural convection cooling [31]

The author also compared forced convection of different volumetric flow rates. The results are shown in Figure 2.24, with the lowest air flow, the cell temperatures did not exceed the critical operating temperature. The battery module tested was a stacked eight-cell unit, therefore a more densely packed module would yield a different result.

Figure 2.24: Simulation results for 3C discharge at different flow rates [31]

2.6.6. Uneven temperatures at cell terminals

Uddin et al [19] investigated the surface temperature map of the battery cell terminals being heated up during cell discharge test at 2C. The NMC cell in Figure 2.25 shows one of its battery terminal experiencing a higher heat concentration. This is because the negative and positive terminals of the cell use two different materials. The positive tab connection is made from aluminium material, while the negative tab is copper material. Aluminium has greater electrical resistivity than copper, thus the positive terminal is heating up more than the negative terminal.

Figure 2.25: Battery cell discharge test at 2C for a NMC cell [19]

2.6.7. Temperature rise of cells at 1C, 2C and 3C discharge under adiabatic conditions

Taheri et al [26] presented a three-dimensional thermal model simulating the EiG ePLB Co20B cell's characteristics as shown in Figure 2.26. It has charts shown for each discharge rate, the plot is temperature (K) versus DOD, and the start temperature is 298K (25°C). From the temperature plots, the cell can sustain 1C and 2C discharge continuously with minimal HTC of $h=1\text{W/m}^2\cdot\text{K}$ and not exceed the cell specification of 323K. For a typical forced convection cooling, the HTC would be more than $20\text{W/m}^2\cdot\text{K}$, the results showed that the temperature rise of a cell at 3C is around 15°C. This suggests that the cells would not encounter cell overheating from higher discharge rates if the HTC is greater than $20\text{W/m}^2\cdot\text{K}$.

Figure 2.26: Temperature variation vs Depth of Discharge shown for 1C, 2C and 3C discharge rates [26]

2.6.8. Effects of lithium ion battery charging algorithm

Schuster et al [32] highlights the effect of Constant Current – Constant Voltage (CC-CV) charging algorithm in Figure 2.27; as the cell starts to charge, the power feeding back into the cell is at constant current, until the SOC reaches 80%, then the charging algorithm switches to constant voltage where the current is seen to be decreasing and the temperature reaches a plateau. The 80% to 100% SOC

range takes place as the battery is near full capacity, and the term can be likened to the ‘trickle charge’ effect common for secondary battery charging.

Figure 2.27: CC-CV observations [32]

2.7. Introduction to electric vehicle technology

An Electric Vehicle (EV) is a vehicle primarily driven by electric traction motors with a constant supply of electrical energy coming from energy stored on-board. Electric vehicles are not new products in the automotive industry, the very first electric vehicles in the 1830s used non-rechargeable batteries [33]. Later through the years, they were fitted with lead acid battery packs which made them very hefty and severely range limited, coupled with the high ownership cost, EVs were not popular back in those days.

Thereafter, nickel batteries were developed and introduced into EV battery packs, but the limiting parameter was the energy value of the batteries compared

to fossil fuels. The energy generated at the shaft for nickel batteries still did not surpass the net calorific energy value created at the shaft for fuels. Figure 2.28 compares the energy of lead acid batteries to fuel energy; nickel batteries have similar specific energy values to lead acid by comparison.

Figure 2.28: Comparison of energy conversion of petrol and lead acid battery
[33]

2.7.1. Types of electric vehicles

The types of electric vehicle are shown in Figure 2.29, in the increasing order of degree of electrification.

In Hybrid Electric Vehicle (HEV) systems, the electrical drive train (battery pack powering an electric motor) is combined with an internal combustion engine with its fuel tank as primary energy storage. The battery in HEV systems can only be recharged by electric motor generator with energy from regenerative braking or from the combustion engine.

For the Plug-in Hybrid Electric Vehicle (PHEV) the battery pack, it receives charge directly from the electrical grid.

As for Battery Electric Vehicle (BEV) systems, the battery pack is the only energy storage and a large electric motor serves as the vehicle propulsion system.

Figure 2.29: Degree of hybridisation for electric vehicles [34]

Other energy storage systems exist for electric vehicles; however, their technology have not yet fully mature which makes it unsafe or unreliable. In other cases, the market adoption rate is low due to the high initial and running costs. Figure 2.30 provides a list of alternative energy sources used in electric vehicles.

Figure 2.30: Alternative energy sources for EVs

2.7.2. Challenges for battery electric vehicles

The industry for electric vehicles has only recently been in the public spotlight due to the huge popularity of Tesla Motors: Model S [35] and other major automotive manufacturers that have developed and marketed EVs for the mass consumers. The success for the electric vehicle industry is far from assured, as consumer perceptions of the practicality, functionality, and the potential advantages of EVs remain largely mixed in areas such as cost, savings, convenience, travel range, and charging infrastructure [36].

2.7.3. Battery manufacturing costs

Electric vehicle makers have approximated that around 25 percent of an EV's cost goes into building the battery pack. Energy storage technology is the single largest expense for any battery electric vehicle. When the Nissan Leaf debuted, its lithium-ion battery pack accounted for one-third of the cost of the entire vehicle [37]. For the Tesla Motors Model S, it is less than US\$310 per kWh. This number is expected to improve to below US\$120 per kWh by 2030 as studies suggest [38].

Most of the consumer's worries revolve around the battery pack, the challenge is to improve battery technology so that the EV has a much further travel range.

Future improvements are still to come in terms of battery chemistries or battery combinations which can allow for faster charging times, thereby reducing inconvenience. Energy and power density will also be increased significantly, which influences driving range and vehicle performance. Ultimately it benefits the driver/owner, as he gets to enjoy cost savings over a combustion engine vehicle.

2.7.4. Specific hazards of electric vehicles

Thaler and Watzenig [2] highlighted that: “Crash safety for batteries means that an accident does not cause dangerous voltages, vent gas, heat or fires, which could harm the environment, passengers, pedestrians or rescue teams. This can be accomplished by the battery design itself, together with structural protection measures implemented during the vehicle integration”. This is the guidance for all engineers involved in battery pack design.

Batteries have a huge energy content stored on-board, but it is not very much different from the fuel tank of combustion engine cars. Electric-vehicle battery packs are made of hundreds to thousands of battery cells, each of which contains a flammable liquid electrolyte, so is a tank full of gasoline. The additional hazards come from the high voltage electrical contact, which is certain to electrocute a person or an emergency response personnel.

Battery disasters will result in serious consequences as mentioned by Thaler, thus many organisations and governing bodies have come up with standardized safety and abuse procedures for batteries, especially usage of batteries in electric vehicles. These procedures will ensure that the electric vehicle has most of the dangers mitigated with risk control measures developed for the electric vehicle.

Many automotive makers implement multiple stages of safety controls to remove the danger/hazard at the first warning signal.

2.7.5. Automotive battery safety test procedures

Several test standards exist worldwide for the testing of electric vehicle and for the Energy Storage System (ESS) in particular. As highlighted by the German testing and certification provider, TÜV SÜD AG [39], in Table 2.2 shows the specific United Nations Economic Commission for Europe (UNECE) Regulation No. 100, revision 2, safety requirements imposed for electric vehicles. These mandatory tests subject the battery pack to “off-normal” conditions that might be expected to occur. There is mechanical battery testing in which the single battery cell is tested for failure by puncture, impact, compression, tensile and torsional loads. The electrical battery testing is done by over-charging, over-discharging and operating in abnormal conditions such as excessive heat or extreme cold temperatures. The physical battery pack or battery modules are mounted in the vehicle to be crash tested and also subjected to weather-proof testing for water leaks or lightning strikes.

Table 2.2: Safety and abuse tolerance test procedures for ECE R 100.02 [40]

Testing requirements in ECE-R100 revision 2	
1	Vibration
2	Thermal shock and cycling
3	Mechanical shock
4	External short circuit protection
5	Mechanical integrity
6	Fire resistance
7	External short circuit penetration
8	Overcharge protection
9	Over-discharge protection
10	Over temperature protection

Table 2.3 lists the available testing standards implemented worldwide for electric vehicles. The list is non-exhaustive, several standards organisation are refining the existing procedures and others are drafting new protocols for electric vehicles to follow.

Table 2.3: List of organisations for electric vehicle standardisation

Organisation and governing bodies	
UNECE ECE-R100	United Nations Economic Commission for Europe
SAE J2464	Society of Automotive Engineers
IEC 62660-02	International Electrotechnical Commission
ISO/CD 12405-2	International Organization for Standardization
EUCAR	European Council for Automotive R&D
USABC	United States Advanced Battery Consortium

Chapter 3: Design and development of BEV Battery Pack

This chapter presents the background to the NTU BEV which is followed by the details of the battery pack. The vehicle conceptualisation process and vehicle performance calculation details are first briefly introduced followed by the design and development of the battery module.

The focus of this chapter is the design of the cooling system of the battery module. The cooling system is required to extract the heat generated by all the pouch cells and maintain cell temperature within the manufacturer's specified operating range.

3.1. Description of NTU's Battery Electric Vehicle

Under the supervision of Professor Ng Heong Wah, a project group consisting of 4th year students embarking on their Final Year Project (FYP) come together to Research and Develop (R&D) an urban electric vehicle named Nanyang Venture 7, pictured in Figure 3.1.

This Battery Electric Vehicle is built and housed inside Innovation@MAE Laboratory under the School of MAE. Figure 3.2 and 3.3 shows the battery pack location, mounting the battery pack underneath the vehicle enables a lower centre of gravity, provides better space and packaging optimisation for other vehicle components and also reduces the chances of battery damage upon frontal impacts or rear end collisions.

Figure 3.1: CAD model of NTU BEV (Isometric View)

Figure 3.2: CAD model of NTU BEV (battery pack mounting)

Figure 3.3: NTU BEV: Nanyang Venture 7 (with battery pack)

The electric vehicle project commenced in the year 2012 with a small team of students developing vehicle system components such as chassis, suspension, braking, electric powertrain and ergonomics.

Throughout the years of development, the NTU BEV had transformed from a 3-Dimension (3D) Computer Aided Design (CAD) model into a complete welded steel structure with its mechanical components installed in. Figure 3.4 to 3.6 showcases the CAD images while Figure 3.7 and 3.8 are photos of the NTU BEV fitted with its components.

Figure 3.4: CAD model of NTU BEV (Front View)

Figure 3.5: CAD model of NTU BEV (Side View)

Figure 3.6: CAD model of NTU BEV (Top View)

Figure 3.7: NTU BEV in the unpainted stage

Figure 3.8: NTU BEV covered with blue automotive paint

3.1.1. Project progression and specifications

This project was approached with a low-cost yet functional concept, and this aligns which allows the project students to grasp the working fundamentals of an electric car easily. The details of the battery electric vehicle are listed in Table 3.1, the design specifications of the EV was determined at the commencement of the project and the project progressed through the years, is illustrated as a diagram in Figure 3.9.

Figure 3.9: NTU BEV project completion progress chart

Table 3.1: NTU BEV specifications

Powertrain		
Drive layout		Mid-mounted motor
Power	Rated	24 kW continuous
	Maximum	100 kW
Max torque		169 Nm @ 600 Amps
Motor		NetGain WarP 9 series wound brushed DC
Motor controller		Evnetics Soliton Jr.
Energy Consumption		
City driving cycle		100 km/charge
Performance		
Top speed		90 km/h
Acceleration from 0 – 90 km/h		12 secs
Transmission		
Driveline layout		Rear-wheel drive
Single speed fixed gear ratio		2.36
Final gear ratio		4.10
Body		
Modified Honda S2000 front and rear sub-frames with 4130 chromium-molybdenum alloy steel chassis		
Length		3650 mm
Width		1750 mm
Height		1450 mm
Wheelbase		2400 mm
Ground clearance		130 mm
Track width	Front	1490 mm
	Rear	1550 mm
Drag coefficient (Cd)		-TBD
Kerb weight		1000 kg
Seating capacity		2 + 2
Weight distribution % F / R		48 / 52
Turning circle		10.79 m
Wheels		16 x 7J ET 45
Tires		205/45R16

Mechanicals		
Brakes	Front	300 mm, Ventilated disc
	Rear	281 mm, Solid disc
Steering		Rack and pinion, electric power assisted
Suspension	Front	Double wishbone setup
	Rear	Double wishbone setup
Propulsion Battery		
Battery type		EiG ePLB Co2oB prismatic pouch cell
Cell chemistry		Lithium ion polymer, Li(NiMnCo)O ₂ cathode
Power rating		16,352 kWh
Cell configuration		56 in series, 4 in parallel
Nominal pack voltage		204.4 V
Total pack capacity		80 Ah
Cooling		Closed volume air-cooled

3.2. Design process of battery pack

Critical vehicle parameters were calculated based on the required vehicle performance (such as acceleration and cruising range). These, in turn, are used to derive the battery pack capacity, battery voltage and current draw. The vehicle packaging process also explored the suitable volume within the chassis to house the battery pack.

3.2.1. Initial vehicle parameters

A design scenario was developed to define the initial requirements such as vehicle dimensions and weight for the preliminary calculations of vehicle performance. A user profile of a typical daily Singapore driver detailed in Table 3.2 is based on the design scenario documented in Appendix B. Further details such as the shape, styling and size of the vehicle were loosely interpreted through the design scenario.

Table 3.2: BEV driver user profile

User Profiling	
Age	30 - 40
Number of children	2 kids below 10 year-old
Driver Gender	Male
Seating Arrangement	2+2
Number of Doors	3
Driving Range	Medium to long
Purpose	Primary: Ferry Secondary: Working/Leisure/Shopping
Time of Usage	Peak hour
Area of Usage	City & urban

Parameters such as top speed, acceleration time, distance per battery charge were derived from the following criteria:

- Journey starts somewhere in the eastern part of Singapore to the workplace located in the western part of Singapore (a selected worst case scenario, shown on map in Figure 3.10)
- Journey is during the early morning peak hour with the fastest travel time
- Battery energy provision for twice the driving range
- User to recharge vehicle at workplace or at home whenever possible

Figure 3.10: Distance journey from point A to point B; using (www.gothere.sg)

Additional vehicle data was included into the vehicle parameters in Table 3.3; the vehicle concept was then idealised as a subcompact city car, the body proportions, along with the tire sizing, the top speed and acceleration time were estimated so that the vehicle performance can be calculated.

Table 3.3: Concept Vehicle initial vehicle parameters

Vehicle component	Specification	Metric data
Tire size	16 inch wheels	600 mm (diameter)
Vehicle dimensions	Length	3500 mm
	Width	1600 mm
	Height	1700 mm
	Wheel base	2200 mm
Top speed	90 km/h	25 m/s
Acceleration time	(0-90 km/h)	12 s
Vehicle weight	Fully laden with 4 passengers	1600 kg
Driving wheels	Rear wheel drive	NA

Vehicle performance was based on vehicle tractive effort to overcome rolling resistance, aerodynamic drag, gradient (slope) resistance and acceleration force. The vehicle tractive effort was matched to a suitable electric motor coupled to a gearbox to step-down the motor rpm to accommodate to the ideal vehicle road speed and acceleration time. The major vehicle components such as motor, gearbox, suspension, steering were purchased upon design confirmation. The final hurdle was to be the design of the battery pack for the vehicle which is the focus of this thesis.

3.3. Design requirements

The process of designing the battery pack follows the flowchart in Figure 3.12. The problem is first specified, followed by the setting of requirements of the battery pack. The next step is to generate 3D concepts of the battery pack by

brainstorming exercises. The concepts produced at the design stage was evaluated by a selection matrix with cost, ease of assembly, electrical insulation, compactness, cooling design for cells and weight as selection criteria.

Figure 3.11: Battery module design process

The design criteria for the battery pack are as follows:

- A centralised location to allow battery connections to be of short wire lengths.
- The battery pack should be easily removed as multiple modules, which are lightweight for one-man to carry.
- A low centre of gravity and preliminary crash safety features

- Modular design where multiple or repeated components can reduce fabrication complexity, and lower overall machining costs.
- Efficient air cooling via forced or natural convection so that the entire battery pack to achieve acceptable cell temperatures.
- Safety features such as high voltage protection using appropriate insulation materials.
- To maintain control over pack parameters by a Battery Management System and Thermal Control Module.
- To achieve the power requirements of the vehicle traction drive rated at:
  - >170 Volts, to account for voltage drop during acceleration/heavy loads
  - Provide for peak acceleration power of 100 kW
  - Cruising velocity current draw to consume about 1 C discharge rate

In order to meet the predicted performance goals in terms of power and energy storage numbers in Table 3.4, the appropriate cell had to be chosen for the pack. This is accomplished in the next section.

Table 3.4: Battery performance numbers

Electric vehicle and battery data	Representation
Electric motor input voltage	> 170 Volts
Acceleration current	600 Amperes
Constant velocity current (@ 90 kmh)	75 Amperes
Battery capacity	16 kWh
Battery pack weight	< 250 kg

3.3.1. Cell selection

The selection process begins by narrowing down the list of commercially available cells. Some cells are barred by country export restrictions and others

suppliers require a large Minimum Order Quantity (MOQ). The final selection criteria are operational safety and longevity of the cells procured. With all the considerations taken into account, the chosen battery cell was the EiG ePLB-Co20B cell (www.eigbattery.com). The battery cells were acquired in the year 2015 with the financial assistance of ERI@N. The selected battery cell specifications are listed in Table 3.5:

Table 3.5: EiG ePLB-Co20B cell specification [27]

Single cell parameters		
Brand	Energy Innovation Group (EiG), South Korea	
Model	ePLB-Co20B	
Chemistry	Lithium Ion Polymer	
Cathode	Li(NiMnCo)O ₂ based	
Anode	Graphite based	
Mechanical characteristics		
Thickness	7.2 mm	
Width	129 mm	
Length	217 mm	
Weight/cell	428 grams	
Form factor	Aluminium foil pouch cell packaging	
Electrical characteristics		
Nominal voltage	3.65 V	
Rated capacity	20 Ah	
Specific energy	174 Wh/Kg	
Energy density	370 Wh/L	
Operating conditions		
Upper voltage limit	4.15 V	
Lower voltage limit	2.5 V	
Max discharge current	100 A (continuous, 5C)	200 A (< 5 seconds, 10C)
Max charge current	10 A (0.5C)	
Operating temperature	-30 ⁰ C to +55 ⁰ C	

Figure 3.12 shows the orthographic 2-dimensional drawing of the battery cell while Figure 3.13 list the cell's discharge curve specification curve at various discharge rates. The area under each curve denotes the available power for a given discharge rate, a higher current draw (5C) causes a larger voltage drop across the cell, and thus actual output power is less than a cell undergoing a 1C discharge.

Figure 3.12: EiG Co20 cell dimensions [27]

Figure 3.13: Cell discharge curve at multiple C-rates [27]

3.3.2. Pack sizing

This section presents the calculation on battery packaging; i.e. the number of series or parallel cell connections required to attain the battery pack target capacity. Using the targeted drivetrain requirements from Table 3.4. The cell configuration is generated in Table 3.6. The weight will be evaluated later as the design of the structural housing has yet to be decided.

The cells are arranged in either series (S) or parallel (P) connections. More cells in series increase the overall pack voltage, while cells in parallel multiply the pack current. The nomenclature of cell order arrangement is shown by an example of a 3S4P battery which indicates there are 3 cells are in Series with 4 in Parallel:

- The total cell count is $3 \times 4 = 12$ cells.
- The pack voltage would be $3.65\text{V} \times 3 = 10.95\text{V}$.
- The pack capacity would be $20\text{Ah} \times 4 = 80\text{Ah}$.
- Battery pack power rating would be $10.95\text{V} \times 80\text{Ah} = 0.876\text{kWh}$

Table 3.6: Selected cell configuration for battery pack sizing

Configuration	Performance goals:			
	Nominal voltage	Acceleration current	Constant velocity current	Power rating
	> 170 Volts	~ 600 Amperes	~ 75 Amperes	~ 16 kWh
56 in series 4 in parallel <u>224 cells in total</u>	56 x 3.65V = 204.4V ✓	4 x 20Ah = 80Ah 80Ah x 10C = 800A ✓	75A / 80Ah = 0.9375C $\approx$ 1C ✓	204.4V x 80Ah = 16,352kWh ✓

The cell arrangement of 56S4P was selected due to several reasons justified below:

- Comparing with Table 3.4, the higher voltage of 204.4V vs 170V for the electric motor is to account for voltage drop across the cells when a load is applied.
- The motor maximum current draw during acceleration is 600A, and the cell had 10C discharge capability, thus the battery pack is capable of producing 800A for a few seconds during vehicle acceleration.
- The cruising speed current draw is estimated at 75A, with the combined cell capacity at 80Ah, the continuous current draw required is < 1C discharge.

Therefore, the pack is sufficiently sized for the vehicle.

3.3.3. Space constraints

From the above, the battery pack volume was allocated so the task is to design in all the additional components besides the cells that was allocated for the battery pack. Figure 3.14 below is the available volume. The green edges are

designated as the battery pack back-plate mounting flange. The all-around flange serve as structural connection points to locate and mount the battery pack to the spaceframe beneath the BEV. Figure 3.15 shows an estimate of the pack dimensions.

Figure 3.14: Designated battery pack volume

Figure 3.15: Estimated dimensions for battery packaging design

Given the available space, the decision was made to divide the allocated volume for the battery pack into seven battery modules. This can be observed in Figure 3.16, in addition, some areas were earmarked for the air ducting to channel forced air flow into the modules. The remaining space had to be allocated for electrical wiring harness. Module 1 to 6 are standard propulsion module where module 7 is for accessory power.

Figure 3.16: Proposed component allocation within available battery pack volume

3.3.4. Structural constraints

This subsection details the design process for the battery casing, which collectively includes the baseplate, top cover, and structures that will secure the cells in place.

The base and structure of the battery pack was made of high-strength steel (AISI 4130), with thickness of 3mm. This will protect the battery pack from road debris. It also has higher stiffness compared to aluminium.

The following drawing illustrates the concepts drawn in SolidWorks: Figure 3.17 is showing an early concept of the packaging and arrangement of the battery modules, where the design of the module was assessed for feasibility and to pinpoint any possible design faults.

Figure 3.17: Early concept for proposed fibreglass top cover and steel baseplate

Figure 3.18 showcases the concept of having a walled battery housing, however the idea was discarded because the walls needed a large border around the perimeter and it would impede the air duct packaging design. Furthermore, the welding of the wall segments does not guarantee a watertight seal and warpage due to welding heat of the battery casing may be a problem.

Figure 3.18: Early concept of battery pack structural housing (welded steel walls)

Figure 3.19 and 3.20 depicts the final concept of the battery pack housing, including the top cover and the connection interfaces for electrical wiring and cooling ducting.

Figure 3.19: Final concept of battery housing (Front Side View)

Figure 3.20: Final concept of battery housing (Rear Side View)

3.3.5. Battery Management System

The Tritium IQ Battery Management System (www.tritium.com.au) was selected because it was designed specifically for lithium cell chemistry. This system uses the master and slave distributed control configuration, a mainboard provides the higher-level control algorithm while multiple cell boards are used to monitor the individual cell voltage, current and temperatures. The BMS is configured to the specific cell parameters so that the cells are allowed to function at its maximum potential. Figure 3.21 and 3.22 shows the BMS boards.

Figure 3.21: Battery Management Unit (BMU)/master board

Figure 3.22: Cell Management Unit (CMU)/slave board

3.4. Conceptual design of cell packaging in each module

The design of the cell packaging is discussed in this section. From the pack sizing discussed previously, a total of 224 cells were used to achieve the 56S4P configuration. The battery pack was divided into 7 parts, which allowed the large cell batch to be further repacked into smaller sizes. Table 3.7 and Figure 3.23 illustrates the cells divided into battery modules. The subsequent chapters and description of the battery module design follows the naming convention explained in Figure 3.23.

Table 3.7: BEV battery pack detailed configuration layout

Propulsion Battery (packaging specification)			
Cell arrangement for 1 module	4 cells in parallel = 1 sub-module		
	8 sub-modules connected in series		
	29.2 V	80 Ah	2.336 kWh
Module arrangement for full battery pack	7 modules in series forms the full battery pack		
	204.4 V	80 Ah	16.352 kWh

Figure 3.23: Battery cell grouping terms inside a module

3.4.1. Cell to cell connections

The design for connecting 4 parallel cell tabs can be seen in Figure 3.24. The cell terminals are inserted through the machined copper cell plates which has slots to allow the tabs to pass through. The tabs are then folded inwards and the top plate is screwed together with the cell plate using 4 screws, sandwiching the cell tabs and providing electrical contact with all four cells.

Figure 3.24: Cell connector assembly installation steps (shown without screws)

Figure 3.25 shows the array of cell connectors that attaches to the insulated plastic back plate. The back plate prevents the cell connectors from moving around thereby causing a short circuit. This is especially important as the cells are very densely stacked together, an electrical short can cause the cells to heat up and lead to thermal runaway.

Figure 3.25: Copper cell connector plates secures the cell tabs to the plastic support plate for assembly

To achieve the required module voltage, the cell terminals were connected in series, from the positive terminal of one cell to the negative terminal of the adjacent cell bus bar. Figure 3.26 illustrates the connection setup in detail. Copper bus bars bridge the positive and negative terminals together, as seen in Figure 3.27.

Figure 3.26: Positive to negative cell terminal connection order to join the cells in series

Figure 3.27: 3D view of the cell connectors assembled

3.5. Cooling design concept for battery pack

This section covers the overall concept for the battery pack cooling. Since the cooling method is forced air cooling, air channels are required to route air flow from a centralised fan intake from outside the battery pack. The design relies on positive pressure air flow to move the cooling air, as each of the battery module presents a resistance and the ducting have curved 90-degree bends which causes some pressure drop. Figure 3.28 shows one of the early concepts with the cooling fans integrated as part of the battery pack. It was discarded due to the space constraints underneath the vehicle.

Figure 3.28: Early concept of integrated cooling fans within the pack

Figure 3.29 presents the top view of the cooling concept design, the batteries are cooled by an incoming fan unit positioned at the front end of the car (not shown), and an external section of air duct guides the cool air into the battery pack. The air channels distribute the air into the battery modules in equal portions.

Figure 3.29: Top view of air ducting layout in light blue

Figure 3.30 shows the bounding box volume (shown in light blue) given for the ducting design.

Figure 3.30: Proposed routing design for air ducts (in blue)

The final air ducting concept is drawn in Figure 3.31, the blue arrows denote the intake air, the orange arrows is the air flow passing through the battery module and the red arrows are the exhaust exits to surrounding air.

Figure 3.31: Top view of battery pack with final layout of air ducting

In Figure 3.32, an initial CFD simulation was carried out to find out the air distribution within the ducting. This is the proposed 3D CAD model as depicted in Figure 3.30 earlier.

Figure 3.32: Initial assessment of air flow within the duct

Figure 3.33 shows the 3D CAD image of the ducting system. The ducts will be fabricated by 3D printing methods, as it offers the ability to make complex parts that are impossible to machine by conventional methods.

Figure 3.33: 3D render image of ducting channels

3.6. Forced cooling concept for battery module

The idea was to utilise forced air-cooling as the active cooling solution for the battery module. The trade-off is the gain in weight attributed to the heatsink fixtures needed for active cooling while reducing the design complexity of the cooling system.

3.6.1. Cooling of cell body (Path A)

The pouch cell has 6-sides, of which, two have the largest surface area (front and back), and the remaining 4 edges has negligible. Therefore, the thermal design developed has aluminium cooling channels to dissipate the heat generated by the cells that remove heat from the front and back surface. The first design concept was to use the heat pipe coupled to a heat spreader to wick the heat away from the cell body and to the heatsink. The design can be seen in Figure 3.34 and 3.35, the concept was rejected due to the cost of procuring the custom-made heat pipes.

Figure 3.34: Heat pipe design concept (view 1)

Figure 3.35: Heat pipe design concept (view 2)

The final design for fabrication is represented in Figure 3.36 and Figure 3.37. The heat transfer flow is outlined into two flow paths, Path A is heat removed from the cell front and back surfaces while Path B removes heat from the cell tabs. Path B is discussed in detail in the following section.

Figure 3.36: Cooling channels denoted in yellow, 16 square air passages per plate

Heat generated from the battery cell then travels to the cooling channels. The cooling channels extend through the lengthwise of the battery module and forced convection is applied. The arrows in blue indicates the inlet cooling air while the red arrows are the exhaust air.

Figure 3.37: 3D view of cooling channels emphasised within battery module assembly

3.6.2. Cooling of cell terminals (Path B)

The cell's electrical tabs are designated cooling path B. For any electrical components; whenever a current pass through an electrically conductive object, power is lost through the inherent electrical resistivity of the material as waste

heat. The early concepts designed to draw away the heat from the cells are shown in Figure 3.38 to 3.40, the first idea was to have a machined copper heatsink that doubles as cell connectors for the sub-module battery. The first concept in Figure 3.38 was costly to fabricate, thus a stacked concept was derived from the previous concept in Figure 3.39 and 3.40.

Figure 3.38: First design of 2-in-1 cell connector

Figure 3.39: Stacked cell connector design

Figure 3.40: Early concept of stacked cell connectors machined from copper material

The final design made use of the heatsink concept and by purchasing a standard aluminium heatsink with similar dimensions removed the need to fabricate the heatsink and reduced the total battery module cost. Figure 3.41 displays the side view of the 2-in-1 cell connector/heatsink. The copper plates are bonded to the finned aluminium heatsink with epoxy thermal adhesives after machining and flat finishing of the mating surfaces.

Figure 3.41: Copper Cell Terminal Connector with Aluminium Heatsink

Figure 3.42 shows the cell connectors are housed within a walled chamber, there is an inlet opening and exit port for the cooling air to pass through.

Figure 3.42: Cell terminals heat transfer concept

3.7. Heat transfer analysis

Design verification is carried out to ascertain that the battery module heat extraction system is reliable. One-dimensional heat conduction analysis was carried out to determine the thermal efficiency of forced air convection from the cell onto the connector heatsinks and via cooling channels. The heat transfer calculation solves for the temperature at the cell surface, at discharge of 1 C, 2C and 3C. The amount of heat dissipated by the cell connectors and cooling channels are calculated, to prove that the cooling design can function as intended to keep the cell temperature within -30°C to $+55^{\circ}\text{C}$ as stipulated by the cell specifications.

3.7.1. Flow path identification

Figure 3.43 shows the front view of the battery heat transfer model, the symmetry planes drawn allow the model to be reduced in size for computation. The symmetry boundaries are suitable for this battery module as the heat sink features are common for all across the cells.

Figure 3.43: Front view of battery CAD model showing symmetry planes for idealisation

The apportioned battery model in the green bounding box from Figure 3.43 is shown in orthographical 3-views in Figure 3.44.

Figure 3.44: Simplified heat transfer model for calculation and simulation

Figure 3.45 illustrates the air flow paths within the battery module, there are two distinct paths, which are labelled as Flow A, B and C. Flow A is airflow through the cooling channels, Flow B is the air flow pass the cell connectors and Flow C is the airflow through the end plate. Heat is generated from the cell bodies (4 cells located at the top and the 2 cells below the cooling channel).

Figure 3.45: Flow labelling of cooling system

3.7.2. Cell heat generation

The heat generation model presented by Bernardi [41], which has been widely cited in the field of lithium battery research is used. It assumes that the temperature of the battery is uniform throughout the cell body.

$$\dot{g}_{cell} = \frac{I}{\mathcal{V}} \left[(V_{oc} - V) - T \frac{dV_{oc}}{dt} \right] \quad \text{Eqn. 3.1}$$

Where:

- $\dot{g}$ = Cell heat generation, W/m³
- I = Operational current, A
- V = Operational voltage, V
- $\mathcal{V}$ = Battery volume, m³
- V_{oc} = Open Circuit Potential (OCP) of the battery, V
- t = Time, s

- The term $I(V_{OC}-V)$ denotes the irreversible heat due to cell over-potential (electrode polarization). It is the mechanical side-effects (of the redox process) by which isolating barriers develop at the interface between electrode and electrolyte [21].
- The transient term: $I.T(dV_{OC}/dt)$ refers to the reversible heat caused by entropy change of electrochemical reactions [41, 42]. Chen, Wan and Wang [43] also determined that the derivative: dV_{OC}/dt is a very small constant value (0.0002 V.k^{-1}) and can be neglected.
- When evaluated without dV_{OC}/dt , the equation is essentially $Q=I^2R$, where $I(V_{OC}-V)$ is a derivative of $I.R$.
- Battery volume is taken from the cell specification, which is $\mathcal{V} = 0.195 \text{ m} \times 0.125 \text{ m} \times 0.007 \text{ m} = 1.70625 \times 10^{-4} \text{ m}^3$.
- V_{OC} and V is obtained from the experimental data chart in Figure 3.46 provided by the cell manufacturer (EiG). V_{OC} is the experimental potential (voltage) of the electrode recorded using a high impedance voltmeter at zero current draw. V is the corresponding voltage for different discharge rates (0.5C, 1C, 2C, 3C, 5C).

Figure 3.46: Experimental data to find V_{oc} and V versus Depth-of-Discharge for different discharge conditions in C-rate. [44]

- The useable range of DOD for the cell is confined from 0% to 80% to preserve battery life. Therefore 80% DOD is selected to be the worst possible scenario.

After reducing Bernardi's equation (Eqn. 3.1), the cell heat generation rate is computed for 1C, 2C and 3C which is shown in Table 3.8:

$$\dot{g}_{cell} = \frac{I}{V} (V_{oc} - V) \quad \text{Eqn. 3.2}$$

$$\dot{Q} = \dot{g}_{cell} \times V = I(V_{oc} - V) \quad \text{Eqn. 3.3}$$

Table 3.8: Cell heat generated at various C-rates

Heat Generation			
Discharge rate	Single cell		Six cells
1C	$\dot{g} = 14 \text{ kW/m}^3$	$Q = 2.388 \text{ W}$	$Q = 14.328 \text{ W}$
2C	$\dot{g} = 46 \text{ kW/m}^3$	$Q = 7.848 \text{ W}$	$Q = 47.088 \text{ W}$
3C	$\dot{g} = 90 \text{ kW/m}^3$	$Q = 15.356 \text{ W}$	$Q = 92.137 \text{ W}$

3.7.2.1. Cell temperatures

Temperature of the cell at different discharge rates is taken from Peyman, et al [26] and presented in Table 3.9. They are applied to the following heat transfer analysis. Further details of the temperature simulation are given back in Literature Review, Chapter Two, section six.

Table 3.9: Cell surface temperature at 1C, 2C and 3C discharge rates

T _{cell} at 80% DOD for different discharge rates	
1C	311 K (38°C)
2C	319 K (46°C)
3C	326 K (53°C)

3.7.3. Assumptions for heat transfer calculation

The list of assumptions for the hand calculations are listed below:

- The cells are treated as a lumped mass body, and the total heat generated is the multiple of 6 cells.
- Only uniform cell heat generation, no temperature gradients in the cells.
- There is negligible heat generation i.e. adiabatic condition at the sides of the battery cell, $Q = 0$.
- Heat transfer by conduction and forced convection only, no radiation due to low temperature difference.
- The flow of air is evenly distributed in each flow channel.
- Density, kinetic viscosity and other physical properties of air are dependent on temperature.

3.7.4. Cooling fan power

The centrifugal blower fan has been sourced for this project, as no datasheet was available for reference, air speed and power consumption were measured to be used in the design calculations. Table 3.10 lists the fan data measurements.

Table 3.10: Cooling fan specifications

Blower fan data	
Voltage	12 V
Max current draw	10 A
Rated power	120 W
Maximum flow rate	8 m/s

3.7.5. Heat transfer calculation

Figure 3.47 shows the schematic of the heat transfer problem, red arrows denote the cell heat generated, purple arrows indicate forced convection flow, blue arrows indicate natural convection and green dashed lines are the adiabatic boundaries ($Q=0$).

- A steady-state analysis is assumed, therefore heat flow by conduction through the metal bodies are negligible.
- Flow A is to resolve the heat flow by forced convection through the 16 cooling channels modelled as heat transfer through non-circular pipes.
- Flow B is to solve the heat flow by forced convection through the cell connector heatsinks.
- Flow C is the natural convection heat flow through the end plate surface.
- Fan speed was set at 8m/s for forced convection.
- Ambient temperatures are assumed to be 25°C (298K)

Figure 3.47: Schematic of battery cell heat transfer

Figure 3.48 includes additional dimensions for the length of the cooling channel and cell connectors.

Figure 3.48: Additional dimensions in mm for heat transfer model

The heat transfer equation is considered as parallel heat transfer and it is written as:

$$Q_{Total} = Q_A + Q_B + Q_C \quad \text{Eqn. 3.4}$$

$$Q_A = h_A A_A (T_{cell} - T_{\infty}) \quad \text{Eqn. 3.5}$$

$$Q_B = h_B A_B (T_{cell} - T_{\infty}) \quad \text{Eqn. 3.6}$$

$$Q_C = h_C A_C (T_{cell} - T_{\infty}) \quad \text{Eqn. 3.7}$$

Where:

- Q_{Total} = Total battery module cooling capacity, W
- Q_A = Heat flow through Cooling Channel (Flow A), W
- Q_B = Heat flow through Cell Connector (Flow B), W
- Q_C = Heat flow through End Plate (Flow C), W
- T_{cell} = Temperature of cell surface, K
- T_{∞} = Temperature at surrounding, K
- h_A = Heat transfer coefficient of cooling channel, W/m². K
- A_A = Surface area of cooling channel, m²
- h_B = Heat transfer coefficient of cell connector, W/m². K
- A_B = Surface area of cell connector, m²
- h_C = Heat transfer coefficient of end plate, W/m². K
- A_C = Surface area of end plate, m²

3.7.5.1. Flow A heat transfer

The heat transfer flow in the cooling channels is to be determined by flow inside a non-circular pipe. There are 16 cooling square ducts within the cooling channel, therefore the calculation of one square pipe is multiplied by 16x to find h_A . Solving for Flow A:

$$Q_A = h_A A_A (T_{cell} - T_{\infty}) \quad \text{Eqn. 3.5}$$

Film temperature is determined by the average of cell temperature and ambient temperature using Eqn. 3.8. The properties of air at 31.5°C film temperature is interpolated from the properties table in Appendix E and listed in Table 3.11.

$$T_f = \frac{(T_{cell} + T_{\infty})}{2} = \frac{(311 + 298)}{2} = 304.5 \text{ K} = 31.5 \text{ }^{\circ}\text{C} \quad \text{Eqn. 3.8}$$

Table 3.11: Air properties at film temperature of 31.5°C at 1 atm

Properties	Air @ 31.5°C
Density, ρ	1.15829 kg/m ³
Thermal conductivity, k	0.025991 W/m.K
Dynamic viscosity, μ	1.8789 x 10 ⁻⁵ kg/m.s
Kinematic viscosity, ν	1.6221 x 10 ⁻⁵ m ² /s
Prandtl number, Pr	0.72778

To determine hydraulic diameter, D_h :

$$D_h = \frac{2ab}{a + b} = \frac{2 \times 0.007 \times 0.006}{0.007 + 0.006} = 0.00646 \text{ m} \quad \text{Eqn. 3.9}$$

Where:

a = Width of duct opening, m

b = Height of duct opening, m

The Reynolds number is defined as:

$$Re = \frac{\mathcal{V} D_h}{\nu} = \frac{8 \times 0.00646}{1.6221 \times 10^{-5}} = 3186.75 \quad \text{Eqn. 3.10}$$

Where:

$\mathcal{V}$ = Mean velocity in pipe, m/s

ν = Kinematic viscosity, m²/s

Table 3.12: Reynolds number flow range

$Re < 2300$	laminar flow
$2300 \leq Re \leq 10,000$	transitional flow
$Re > 10,000$	turbulent flow

From Table 3.12, the flow is taken to be turbulent in the smooth tube and the correlation used is the *second Petukhov equation* [45] for the Nusselt number relation.

Determining friction factor, f :

$$f = (0.790 \ln Re - 1.64)^{-2} = 0.04464 \quad \text{Eqn. 3.11}$$

The Nusselt number is given as:

$$Nu = \frac{h_A D_h}{k} = \frac{(f/8)(Re - 1000)Pr}{1 + 12.7 \left(\frac{f}{8}\right)^{0.5} (Pr^{\frac{2}{3}} - 1)} = 10.845 \quad \text{Eqn. 3.12}$$

Where:

k = Thermal conductivity of air, W/m.K

The HTC for Flow A is derived from Nusselt number:

$$\therefore h_A = \frac{Nu \cdot k}{D_h} = 43.626 \text{ W/m}^2 \cdot \text{K}$$

The surface area for the duct is calculated as:

$$A_A = pL = 2(a + b)L = 2 \times (0.006 + 0.007) \times 0.125 \quad \text{Eqn. 3.13}$$

$$A_A = 0.00325 \text{ m}^2$$

Where:

p = Perimeter of duct, m

$L =$ Length of duct, m

The heat flow for Flow A is solved, taking into account the 16 square ducts:

$$\begin{aligned} Q_A &= h_A A_A (T_{cell} - T_{\infty}) \\ &= 43.626 \times (16 \times 0.00325) (311 - 298) \\ Q_A &= 29.491 \text{ W} \end{aligned} \quad \text{Eqn. 3.5}$$

3.7.5.2. Flow B heat transfer

The heatsink equation by Teertstra et al [46] is used to calculate Flow B. There are two heatsinks sectioned in half, so the calculated surface areas will be multiplied by 3x. The cell tabs are part of the cell, therefore cell heat generation is considered in the cell tabs. The heat transfer equation for the cell connectors are given as:

$$Q_B = h_B A_B (T_{cell} - T_{\infty}) \quad \text{Eqn. 3.6}$$

The properties are the same value from Table 3.12 (at 31.5°C and 1atm), and air speed is 8m/s. The modified channel Reynolds number ($0.26 < Re < 175$) is defined as:

$$Re^* = Re \cdot \frac{g}{L} = \frac{\rho \mathcal{V} g}{\mu} \cdot \frac{g}{L} = \frac{1.184 \times 8 \times 0.0017^2}{1.849 \times 10^{-5} \times 0.038} = 38.960 \quad \text{Eqn. 3.15}$$

Where:

$\rho =$ Density of air, kg/m³

$\mathcal{V} =$ Velocity of air, m/s

$g =$ Fin gap, m

$\mu =$ Dynamic viscosity, kg/m.s

$L =$ Heat sink length, m

Finding for Nusselt number,

$$Nu = \frac{h_B g}{k} = \left[\left(\frac{Re^* Pr}{2} \right)^{-3} + \left(0.664 \sqrt{Re^*} \cdot Pr^{1/3} \sqrt{1 + \frac{3.65}{\sqrt{Re^*}}} \right)^{-3} \right]^{-1/3}$$

$$Nu = 4.498$$

Eqn. 3.16

Where:

k = Thermal conductivity of air at 31.5°C, W/m.K

The HTC for flow B is calculated as:

$$\therefore h_B = \frac{Nu \cdot k_{air}}{g} = \frac{4.498 \times 0.25991}{0.0017} = 68.777 \text{ W/m}^2 \cdot K$$

Evaluating fin efficiency, η :

$$\eta = \frac{\tanh(mH)}{mH} = \frac{\tanh(22.011 \times 0.009)}{22.011 \times 0.009} = 0.8176$$

Eqn. 3.17

$$m = \sqrt{\frac{2h}{k_{alu}t}} = \sqrt{\frac{2 \times 68.777}{167 \times 0.0017}} = 22.011$$

Eqn. 3.18

Where:

H = Fin height, m

k = Thermal conductivity of aluminium = 167 W/m.K [47]

t = Thickness of fin, m

The surface area of heatsink is defined as:

$$A_B = \eta A_{fins} + A_{base} \quad \text{Eqn. 3.14}$$

$$A_{fins} = 12(0.009 \times 0.038) + 6(0.0017 \times 0.038)$$

$$A_{fins} = 4.4916 \times 10^{-3} \text{ m}^2$$

$$A_{base} = 4(0.0017 \times 0.038) + (0.012 \times 0.038)$$

$$A_{base} = 7.144 \times 10^{-4} \text{ m}^2$$

$$A_B = (0.8176 \times 4.4916 \times 10^{-3}) + 7.144 \times 10^{-4}$$

$$A_B = 0.0131 \text{ m}^2$$

Where:

A_{fins} = Total finned area of heatsink, m^2

A_{base} = Total area of non-finned heatsink, m^2

We can find for Q_B at the cell connector heatsink:

$$Q_B = h_B A_B (T_{cell} - T_{\infty})$$

$$Q_B = 11.767 \text{ W} \quad \text{Eqn. 3.6}$$

3.7.5.3. Flow C heat transfer

Flow C is solved by natural convection cooling of a horizontal flat plate:

$$Q_C = h_C A_C (T_{cell} - T_{\infty}) \quad \text{Eqn. 3.7}$$

The characteristic length is identified as:

$$L_c = \frac{A_C}{P} = \frac{0.195 \times 0.125}{(2 \times 0.195) + (2 \times 0.125)} = 0.03808 \text{ m} \quad \text{Eqn. 3.15}$$

Where:

A_C = Surface area of flat plate, m^2

P = Perimeter, m

Using the properties of air at film temperatures in Table 3.12 (at 31.5°C and 1atm), and air speed is 8m/s, the Rayleigh number in this case is:

$$Ra_L = \frac{g\beta(T_{cell} - T_{\infty})L_c^3}{\nu^2}$$

$$Ra_L = \frac{9.81 \times 0.00328 \times (311 - 298) \times 0.03808}{1.6221 \times 10^{-5}^2}$$

Eqn. 3.16

$$Ra_L = 87935.404$$

$$\beta = \frac{1}{T_f} = 0.00328$$

Eqn. 3.17

Where:

β = Coefficient of volume expansion, 1/K

g = Gravity, 9.81 m/s²

Finding for Nusselt number:

$$Nu = \frac{h_c L_c}{k} = 0.54 Ra_L^{1/4} = 9.298$$

Eqn. 3.18

Where:

k = Thermal conductivity of air at 31.5°C, W/m.K

Therefore, the HTC of the end plate is:

$$h_c = \frac{k}{L_c} Nu = \frac{0.025991 \times 9.298}{0.03808} = 6.345 \text{ W/m}^2 \cdot \text{K}$$

Finding the area of flat plate:

$$A_c = 0.195 \times 0.125 = 0.0244 \text{ m}^2$$

Final step to find Q_c :

$$Q_c = h_c A_c (T_{cell} - T_{\infty})$$

$$Q_c = 2.011 \text{ W}$$

Eqn. 3.7

3.7.6. Results

With Flow A and B's forced convection air speed at 8m/s and Flow C using natural convection cooling, the ratio of cooling performance is compared; Flow A : Flow B : Flow C. The results are: 0.682 : 0.272 : 0.046, from these design calculations, it can be said that Flow A (cooling channels) contributes 68% of the total heat dissipation power, and Flow C (end plate) cooling can be neglected as 2W of cooling is not substantial.

The sum of cooling power produced by both flow system is 43.269W, the current air speed at 8m/s is capable of cooling the cells at 1C but not sufficient to remove the heat from the cells at 2C. Table 3.13 lists down the increase or decrease in flow rate needed to remove the heat at 1C, 2C and 3C respectively.

Table 3.13: Calculating of flow rate needed for various discharge rates

Discharge rates	Flow rates needed	Resultant combined cooling power
1C	3.1 m/s	14.817W > 14.328W
2C	8.9 m/s	47.249W > 47.088W
3C	21.7 m/s	92.205W > 92.137W

The preliminary design calculations have been performed and results show that the cooling design is working, thus the battery module design is passed and approved for fabrication. The fabrication and assembly of the battery module is detailed in Appendix C, the Bill of Material (BOM) is included, together with the exploded assembly drawings and 2D part drawings. The next stage is the heat transfer simulation to validate the calculations as the assumptions may have been over exaggerated or some critical details ignored.

Chapter 4: Finite Element Heat Transfer

Analysis for Battery Module

The preliminary design calculations for heat transfer of cooling functions carried out in the previous chapter showed a viable design. However, as the design developed by CAD modelling progressed, more complexities in the geometry emerged that some of the original assumptions became less valid.

Therefore, a full FEA heat transfer analysis is performed on the battery module to analyse its thermal behaviour using the commercially available software package, ANSYS FLUENT (www.ansys.com). The 3D CAD model assembly previously developed in SolidWorks was pre-processed into a finite element thermal assembly model.

The ANSYS FLUENT's K-epsilon viscous ($k-\epsilon$) model with enhanced wall treatment is applied to the computational domain. This model is a two-layer approach for enhanced wall treatment widely used for simple heatsink or flat plate simulations. This enables the viscosity-affected near-wall region to be fully resolved up to the viscous sublayer.

The heat transfer simulation is a combined CFD and FEA problem solved by software iterative process. The energy model is coupled with the heat transfer flow model to solve for temperature in the pouch cells. The heat transfer model is meshed and the initial boundary conditions set identical to Chapter 3.7: Heat transfer analysis. The simulation results of cell temperatures were compared against flowrates and discussed.

4.1. FEA idealisation

Because of the ANSYS's academic license limitations, the cooling channel and the cell connectors have to be decoupled into separate models for thermal analysis. This decoupling process is documented in Chapter 3.7: Flow path identification. The heat transfer model assembly was reduced further due to difficulties encountered during the meshing process. The following sub-sections describes the idealisation work done for Flow A, B and C.

4.1.1. Flow A heat transfer model

Figure 4.1 shows the heat transfer model: a) before applying symmetry condition, b) after applying symmetry. The cell tabs were removed for this Flow A part of the study. The individual battery cells were modelled as combined bodies for simplicity.

Figure 4.1: Flow A idealisation a) full model, b) symmetry condition applied

The final heat transfer model mesh is given in Figure 4.2a, and Figure 4.2b shows boundary mesh refinement in the air volume to improve the heat transfer accuracy.

Figure 4.2: Flow A meshed model a) overall structure, b) close up of cooling channel

4.1.2. Flow B heat transfer model

Flow B heat transfer model is shown in Figure 4.3, the duplicate heatsink features were kept intact so as to evaluate the subsequent heatsink temperatures after the airflow had been heated up.

Figure 4.3: Flow B heat transfer model a) CAD model, b) meshed model

4.1.3. Flow C heat transfer model

Flow C was removed from the simulation as the cooling capacity provided by natural convection cooling at the end plate was marginal (<5% contribution) as shown by the design calculations. As a result, the cooling at end plate is modelled as an adiabatic wall boundary condition ($Q=0$).

4.2. Boundary conditions

Flow velocity inlet of 4, 6, and 8 m/s and pressure outlet boundary conditions are used for the CFD calculations. The outlet boundary condition for the flow field is fixed at 1 atm. The inlet and outlet boundary conditions for the temperature field are the fixed air temperature of 25 °C and the free boundary condition, respectively. The boundary conditions follow the illustration in Figure 3.47.

The heat transfer analysis was conducted under 1C, 2C and 3C discharge rate with the corresponding constant heat generation numbers in Table 3.8. The pouch cell was assigned density, specific heat and thermal conductivity values in Table 4.1, which was obtained from Taheri and Bahrami [44]. The properties of air, copper and aluminium were also provided in Table 4.1.

Table 4.1: Fluid and material properties

Properties		Air @25°C	Copper	Aluminium	Cell
Density, ρ	kg/m ³	1.184	8978	2719	2213.96
Specific heat, c_p	J/kg.K	1007	381	871	1250
Thermal conductivity, k	W/m.K	0.02551	387.6	202.4	26.57
Dynamic viscosity, μ	kg/m.s	1.849e-05	-	-	-

4.3. Results and discussion

The heat transfer simulation study is performed for Flow A and B, the results are presented and discussed in Chapter 4.31 and 4.32 respectively. The effects of forced cooling are compared with discharge rates of 1C, 2C and 3C.

4.3.1. Analysis of Flow A

This section comprises of the simulation results for Flow A, the cell temperature distribution is investigated for uniformity within the cell body at different discharge rates for steady state heat transfer analysis.

4.3.1.1. Flow characteristic of cooling channel

Figure 4.4 shows the cross-section of the cooling channel with the temperature contour applied across the ZX plane at steady state 1C discharge with 8m/s flow velocity. The even spacing of the cooling channels produced uniform cell temperatures at the adjoining cell surfaces as shown in Figure 4.5 in the X and Z axes.

Figure 4.4: Temperature contour of cooling channel at 8m/s, 1C discharge

Figure 4.5: Temperature contour of cell surface at 8m/s, 1C discharge

4.3.1.2. Flowrate of 4, 6 and 8 m/s, 1C discharge

Figure 4.6 shows the temperature contour for Flow A half-sectioned at the cooling channel, at 8m/s and 1C discharge. The temperature for the cell nearest to the cooling channel is the lowest at 302.42K, compared with the cell furthest away from the cooling channel which is the highest temperature 302.90K, the $\theta=0.433\text{K}$. this indicates that the cooling channel design works well for cooling the large cell surface area and also up to the thickness of four battery cells.

Figure 4.6: Temperature contour of cell cross-section at 8m/s, 1C discharge

Table 4.2 below shows the temperature uniformity of the cells during discharge at different flow rates. The calculated θ value are all within 0.5K, this indicates that the cooling rate is sufficient at low speeds (4m/s) and cell temperature uniformity was very good. Furthermore, there is good agreement with the design calculations made in Chapter 3.7.5, where the calculated T_{cell} was 311K, and the simulation result is 302.9K. Figure 4.7 and 4.8 shows the contour plot for flow rates of 6m/s and 4m/s respectively.

Table 4.2: Maximum temperature deviation with varied flowrates at 1C

Flow rate (m/s)	$\theta, (T_{\max} - T_{\min})$ (K)	$T_{\max}$ (K)
8	0.433	302.903
6	0.470	304.020
4	0.534	306.448

Figure 4.7: Temperature contour of cell cross-section at 6m/s, 1C discharge

Figure 4.8: Temperature contour of cell cross-section at 4m/s, 1C discharge

The HTC of the cooling channel for 1C discharge rate at 8m/s flow rate is shown in Figure 4.9, where the $HTC=47.11 \text{ W/m}^2\cdot\text{K}$. The value derived from the simulation is close to the HTC value from the design calculation of $43.626 \text{ W/m}^2\cdot\text{K}$.

Figure 4.9: Heat Transfer Coefficient plot for 1C discharge, 8m/s flow rate

4.3.1.3. Flowrate of 4, 6 and 8 m/s, 2C discharge

Flow A is analysed with the increase in discharge rate to 2C. The first observations made with Figure 4.10 was the maximum cell temperature was at 314K (41°C), it was still below the critical operating temperature of 55°C. This indicated that the cooling system had more cooling capacity than the cell heat generation. This was the opposite for the design calculations for 2C discharge rates, which called for an increase in flow rate to 8.9m/s to balance the energy equation. Table 4.3 tabulates the cell temperature deviation at 2C, as a direct comparison to Table 4.2, the difference in the cell temperature deviation of 2C over 1C is an average of 1K. Figure 4.10, 4.11 and 4.12 shows the plots for 8, 6 and 4 m/s flowrates respectively.

Table 4.3: Maximum temperature deviation with varied flowrates at 2C

Flow rate (m/s)	$\theta, (T_{\max} - T_{\min})$ (K)	$T_{\max}$ (K)
8	1.308	314.109
6	1.544	317.782
4	1.736	325.759

Figure 4.10: Temperature contour of cell cross-section at 8m/s, 2C discharge

Figure 4.11: Temperature contour of cell cross-section at 6m/s, 2C discharge

Figure 4.12: Temperature contour of cell cross-section at 4m/s, 2C discharge

4.3.1.4. Flowrate of 8, 10 and 12 m/s, 3C discharge

The cooling design is evaluated at 3c discharge, at 8m/s as shown in Figure 4.13. The temperature reached at the hottest cell is 329.5K (56.5°C), and the value exceeds the specified cell temperature of 55°C. This meant that 8m/s air flow is insufficient and a higher flowrate of 10 and 12m/s was included in the revised simulation. The revised values are given in Figure 4.14, in which the cell temperature did not go over 325K (52°C).

Table 4.4: Maximum temperature deviation with varied flowrates at 3C

Flow rate (m/s)	$\theta, (T_{\max} - T_{\min})$ (K)	$T_{\max}$ (K)
8	2.595	329.514
10	2.732	325.055
12	2.658	321.793

Figure 4.13: Temperature contour of cell cross-section at 8m/s, 3C discharge

Figure 4.14: Temperature contour of cell cross-section at 10m/s, 3C discharge

Although the flowrate of 10m/s is sufficient, it is not safe to operate the cells near its limits. A flowrate of 12m/s was added to the analysis in Figure 4.15, the cell temperature is at 321.8K (48.8°C). A margin of >5°C was achieved with 12m/s, but a higher margin of >10°C was preferred. The graph in Figure 4.16 plots a projected fan speed curve with additional simulation data of 14m/s and fitted with a high order polynomial. The fan speed required for the target temperature of 318K (45°C) is 15.5m/s.

Figure 4.15: Temperature contour of cell cross-section at 12m/s, 3C discharge

Figure 4.16: Temperature vs air speed for 3C discharge

4.3.2. Analysis of Flow B

The results of Flow B are discussed in this section, the concept of cooling the cell terminals is new and the benefits of cooling them is investigated in this thesis. From the design calculations in Chapter 3.7, there appears to be a substantial amount of heat generated at the cells. The focus of discussions is on the heat dissipated by the cell connectors.

4.3.2.1. Simulation anomaly

It was found that the cell connector, Flow B, was not able to produce the heat output as per the design calculations. Using ANSYS FLUENT, the cell tabs were assigned the property of aluminium (positive current collector tabs) and the temperature at the cell tabs are the unknown. In the design calculations, it was assumed that the cell temperature was also generated at the ends of the cell terminals. That was the only differentiation between the calculations and simulations.

It is believed that the design calculation's assumption was incorrect. In the simulation, the cell tabs were modelled with the cross-sectional area as thin heat flux surfaces as shown in Figure 4.17. This was considered the correct modelling approach to solve the heat transfer problem by conduction through the cell tabs then onto the cell connectors.

Figure 4.17: Heat flux assigned to cell tab surfaces

The heat transfer simulation is performed and the results of the cell connector is reported as follows. Although the heat flux is measurable in the results in Figure 4.17, there were no temperature rise found in the heatsinks, the cell tabs measured 298K (25°C) room temperature. The heat flux surfaces could not produce heat fast enough to fill the thermal mass of the heatsinks and cell connectors.

Figure 4.18 shows the temperature rise at a sectioned heatsink across its length. The contour plot has been exaggerated to show the change in temperature but the temperature is still constant at 298K.

Figure 4.18: Temperature rise of cell connectors at 8m/s, 1C discharge

4.3.2.2. Cooling effect of heatsinks at higher discharge currents at low flowrates

The cell connector setup was tested for 3C discharge and 4m/s flow rate to determine if there were any noticeable changes. However, the end results remained the same as in Figure 4.18, therefore the conclusion made was the copper connectors and aluminium heatsinks had large thermal mass that absorbed all the heat output from the cell tabs and temperature was normalised very quickly. The cross-sectional area of the cells tabs was also relatively small compared to the aluminium heatsink dimensions, which may have caused the heat load disparity.

With the simulation completed, the effects of varying the fan speeds during the discharge process is known. For the cell body cooling effects, the rate of cooling is constant due to the straight cooling channel geometry developed for cooling the cell surface area. For the cell connector terminal cooling, the results have

shown that the cooling performance offered by the heatsinks were not useable, considering the heat flux at the cell tabs could not transfer heat effectively to the heatsinks.

The cooling strategy to adopt is of high fluid velocity entering the cooling channels. The cell connectors cooling mechanism have to be looked further in detail, the experiments in the next chapter should provide some answers to assist in the understanding of the cell connector cooling design.

Chapter 5: Experimental Work

This chapter covers the experimental testing of the battery cells and battery module under charging and discharging conditions at different C-rates in order to gather temperature data so as to understand the effects of air flow rates going into the cooling channels and heatsinks. The experiments serve to confirm the heat transfer calculations performed in Chapter 3.7. The experiment data is also to compare with the CFD and FEA heat transfer simulations in Chapter 4 to get an idea of the accuracy of the heat transfer analysis. Functional test was also performed to assess the handling safety of the battery module by testing for voltage leak to the battery housing. The experiment apparatus is first described, followed by the experimental setup and finally, the results and discussion concludes this chapter.

5.1. Equipment and apparatus

This section describes in detail, the equipment used to test the battery module. It consists of a test rig, load device, battery charger, handheld measuring devices and a data acquisition system.

5.1.1. Test rig

Figure 5.1 shows the test setup to measure the temperature of the cells. Two cooling fans channel air through the inlet ducts into the battery module to cool the cell body and cell tabs. The battery module is then placed inside a test chamber to maintain an enclosed space similar to the battery compartment in the vehicle in order to replicate the condition. A top cover which is not shown in the photo, fully seals up the battery module. The positive and negative wire

terminals of the battery module are connected to an electronic load for discharge tests or a battery charger for charging shown in Figure 5.2. The thermistors attached to the cell surfaces are connected to the external data acquisition system that records the temperature readings. A schematic diagram of the test setup is shown in Figure 5.3.

Figure 5.1: Layout of test rig

Figure 5.2: a) DC electronic load module, b) DC battery charger

Figure 5.3: Schematic diagram of test rig

5.1.1.1. Test chamber

A temperature controlled enclosure is fabricated to isolate the module for thermal testing. This is because the module is housed in an enclosed space in the actual battery pack, and the test chamber replicates this scenario with full insulation at all 6 surfaces. The actual enclosure can be found in Appendix G. Holes are made in the test chamber for the electrical wiring and fan ducting to enter or exit the enclosure. Any gaps between the holes and wiring were sealed

off with insulation material used for the test chamber to improve the experiment temperature results.

5.1.1.2. Cooling fans

The blower fan used in this experiment was rated at 12V, 120W (www.denso.com) shown in Appendix G. The flow rate of the fan is controlled by regulating the fan's DC input current. Two fans were used in the experiment to force air into the cooling channels and cell terminals of the battery module respectively. Automotive cone air filters (www.knfilters.com) were installed at the fan inlet to filter the air.

5.1.1.3. 3D printed inlet and outlet air ducts

Two sets of connecting adapters were designed in SolidWorks (www.solidworks.com) CAD software. The adapters join the fan's outlet to the cooling system's inlet. These fan duct design have a smooth transition from a circular inlet to a rectangle outlet. Figure 5.4 shows the 3D CAD model, and the actual fan ducts made by additive manufacturing process due to the complex internal and external shapes. Figure G.5 in Appendix G shows the installation of the duct into the test chamber.

Figure 5.4: Cross-sectioned CAD model of fan ducts

5.1.2. Electrical load

Two types of electrical load banks were used in the experiments: resistive and electronic load banks.

5.1.2.1. Resistive load bank

The single cell experiment uses wire wound resistor banks (www.vishay.com) shown in Figure 5.5 to provide a dissipative heat load to discharge the cells at 20A. The positive and negative terminals of the cell connect to the two ends of the resistor bank, closing the electrical circuit would trigger a discharge current. The resistance of a resistor bank is $0.54\ \Omega$, and three units wired in parallel provides the resistance value:

$$R_{Total} = \left(\frac{1}{R} + \frac{1}{R} + \frac{1}{R} \right)^{-1} = \left(\frac{1}{0.54} + \frac{1}{0.54} + \frac{1}{0.54} \right)^{-1} = 0.18 \, \Omega$$

Figure 5.5: Wire wound resistor banks

5.1.2.2. Electronic load module

The battery module's nominal capacity is 80Ah, and to discharge at 1C, it would require an electrical load capable of drawing 80A continuously. The electronic load used in the experiment is the Chroma programmable AC/DC electronic load module model no. 63804 (www.chromausa.com) shown in Figure 5.2a, is rated for 4.5kW/45Amps/350Volts maximum. Two units were operated in parallel to draw a combined current of 80A (1C).

5.1.3. Battery charger

A large battery charger is used to charge the battery module to 100% SOC. The 7.2 kW DC charger: Manzanita Micro PFC30XM (www.manzanitamicro.com) shown in Figure 5.2b. The charger is capable of providing 30 Amperes of direct current (DC) power to recharge the battery module. The maximum rate of charge for the battery module is defined as the charging input current divided by the battery module's nominal capacity: 30 A / 80 Ah = 0.375 C rate.

5.1.4. Data acquisition system

An analogue data acquisition system was used to collect a large number of temperature probe points with adjustable sampling rate for streaming continuous data. A schematic diagram is shown in Figure 5.6, the system was created with an Arduino programmable-microprocessor (www.arduino.cc) connected to nine Multiplexers Integrated-Circuit (IC) chip (www.ti.com). Each Multiplexer chip controls a maximum of 16 temperature sensor inputs. The setup has the ability to record 144 temperature inputs, 120 are designated for the cell surface temperatures and the remaining inputs were used to measure the cell connector temperatures at the heatsinks. For the experiment, the polling rate was set to collect temperature readings every 1 minute. The code of for this data logging programming is available in Appendix F. The self-built system is shown in Figure 5.7.

Figure 5.6: System diagram of data acquisition system

Figure 5.7: Data acquisition system pictured with microprocessor, Integrated Circuit (IC) chip and wiring setup

Figure 5.7 shows the thermistors installed inside the battery module, then it was wired out and plugged into the prototyping breadboard. The generic thermistors used are rated at $10K\Omega$ from Murata (www.murata.com), capable of 0.1% accuracy (Figure 5.8).

Figure 5.8: Murata thermistors, NTC $10K\Omega$

Figure 5.9: Thermistor locations on single cell

The photo in Figure 5.9 shows the five attachment points of the thermistors on a cell surface. 5 thermistors are sandwiched in-between cell-to-cell (2nd and 3rd cell) and also 5 sensors on each of the surface of the two outermost cells, making a total of 15 sensors in a sub-module as described in Figure 5.10. The 8 sub-modules are then listed in alphabetical order; A – H as depicted in Figure 5.11. A total of 120 thermistors were placed onto cell bodies.

Figure 5.10: Cell stack numbering layer order

Figure 5.11: Sub-module numbering order

Figure 5.12 illustrates the numbering system used to identify individual thermistors in Table 5.1. An example for calling out a thermistor no. 1 located in Set A, Layer 1 would be: SA-L1-1.

Figure 5.12: Thermistor identification code call-up

Table 5.1: Thermistor identification system

Battery module		
Sub-module	Stack layer	Thermistor number
A - H	L1 – L3	1-5

Thermistors were also placed at the copper cell connectors to measure the temperature rise in the cell terminals. Figure 5.13 shows the placement location of thermistors from T1 to T16.

Figure 5.13: Cell connector thermistor locations

5.1.5. Handheld devices

A list of electrical handheld devices is used to measure voltage, resistance, current, temperature and flow velocity. A digital multi-meter measures the

voltage and resistance of any given two electrical contact point. A current clamp meter measures the flow of current in and out of the battery cells. A temperature thermometer gun captures the temperature value of a specific spot surface. Lastly, flow velocity measurement is by an air flow meter that measures the speed of the air going through the measurement probe.

Figure 5.14: a) Hot wire IR thermo-anemometer, b) Clamp meter, c) Digital multi-meter, d) Infrared temperature gun

5.1.5.1. Air Flow and Temperature probe tool

Figure 5.14a shows the air flow measurement tool used is the Sentry ST732 hot wire infrared-thermometer/anemometer (www.graigarinstruments.com). The probe is inserted through an opening hole into the inlet and outlet air duct to record air speed in m/s and temperature in °C.

5.1.5.2. Current clamp meter

The Fluke 317 Clamp Meter (www.fluke.com) shown in Figure 5.14b is a current sensor for measuring the current going in or out of the module. It is measures DC current and it has a zeroing feature. The purpose of using the clamp meter

is to confirm the current draw of the discharge or charge process by directly measuring the wire leads.

5.1.5.3. Multi-meter

The Fluke 115 Digital Multi-meter (www.fluke.com) shown in Figure 5.14c is used to measure the voltage or resistance value between the two probe points. The multi-meter is used as a secondary verification tool to monitor the voltage of the cells to ensure the cells do not go over voltage or under voltage which could lead to overheating and cell damage.

5.1.5.4. Infrared thermometer

A Tenma 72-823 Non-contact Digital Laser IR Infrared Thermometer (www.farnell.com) is a point and shoot temperature measurement device shown in Figure 5.14d. It is used to measure cell surface temperatures during the single cell discharge test.

5.2. Single cell discharging test

The first experiment is a cell thermal characterisation by discharge test at 0.5C and 1C in natural convection cooling mode. The purpose of this test is to provide actual cell temperatures for comparison in Chapter 3.7: Heat transfer calculation. By gathering temperature data through actual experiments, we are provided with a better understanding of the cell and to provide credibility to the literature research study used.

The purpose of this experiment is to measure the temperature rise and temperature distribution of the cell surface and at the cell tabs. This cell discharge experiment of 0.5C and 1C, is conducted in a draft-free environment

at ambient air temperature ($T=25\text{ }^{\circ}\text{C}$). As a safety precaution, the cell is discharged to 80% DOD, so as to prevent damage to the cell.

5.2.1. Procedure

The experiment is conducted with the list of steps as follows:

- 1) Charge the cell to full capacity at 4.15V, 100% SOC
- 2) Place the test cell standing vertically as seen in Figure 5.15. Use cell holders with minimal contact to the cell surface to keep it upright.

Figure 5.15: Battery cell positioned in vertically up direction

- 3) Connect the positive and negative terminals to the resistor bank to start the discharge at 20A (1C).
- 4) Use a non-contact infrared digital thermometer gun to measure the cell temperatures at the locations as indicated in Figure 5.16.

Figure 5.16: Temperature measurement location points

- 5) Record the temperatures every minute and plot the results.
- 6) Allow cell to discharge until 80% DOD and disconnect the resistor bank.
- 7) Repeated the test sequence for a fully charged cell, with the resistor banks re-wired to draw 10A (0.5C) from the cell.

5.2.2. Results and discussion

The battery cell test data is used to plot the temperature rise against DOD for different discharge rates. The graphs are then compared and analysed in the following sub-sections.

5.2.2.1. Single cell discharge at 1C and 0.5C, natural convection

Figure 5.17 shows the cell temperature plot versus DOD of all the measured points, the densely-packed data range indicates that the cell temperature is uniformly distributed throughout the cell body at 1C. The temperature rise was $\Delta 8^{\circ}\text{C}$ at 80% DOD, overall cell temperature did not exceed manufacturer's specification of 55°C . It was observed that the cell tabs were of higher temperatures compared to the cell body, and especially the positive tab throughout the discharge process. Locations 4 and 5 of the cell registered lower

temperatures, whereas the center of the cell body, ‘Front 3’ and ‘Rear 3’ had similar values with ‘Front 1, 2’ and ‘Rear 1, 2’, this indicates the upper cell body heated up more evenly than the bottom cell portion. This uneven heat generation is more evident in the case of higher discharge rates.

Figure 5.17: Temperature vs Depth of Discharge for 1C; cell surfaces and cell tabs

Figure 5.18 shows the comparison for the cell discharge test at 0.5C, it has the same vertical axis range to highlight the difference in temperature rise. The two graphs exhibit the same behaviour; higher temperatures at the cell tabs and the upper cell body. The graph shows a flat temperature gradient, and the temperature range is wider, this could be caused by the low sensitivity of the temperature gun at close to room temperature.

Figure 5.18: Temperature vs Depth of Discharge for 0.5C; cell surfaces and cell tabs

5.2.2.2. Mean cell temperatures at 1C vs 0.5C discharge

The discharge rates of 0.5C vs 1C is given in Figure 5.19, the temperatures are represented as an average, because the upper and lower values have a difference of only $<1^{\circ}\text{C}$. The graph shows the 1C discharge cell temperature rise by 7°C whereas the 0.5C discharge resulted in less than 3°C increase. The two red lines are positioned as best fit straight line for the rate of temperature rise, this indicates the cells are experiencing constant heat generation along 30% DOD to 70% DOD.

Figure 5.19: Discharge rate of 1C and 0.5C with average temperature versus Depth of Discharge

5.2.2.3. Maximum temperature of cell at 1C discharge

In Figure 5.20, the front and back surfaces exhibited the same temperature for all of the measurements, whereas the cell tab temperatures show slightly higher temperatures. This finding is in agreement with the literature review that the cell terminals experience a higher temperature and reiterates the observation made earlier in Figure 5.17, where the lower part of the cell shows lower temperatures and the cell tabs have higher temperatures.

Figure 5.20: Maximum temperature of individual cell location at 1C discharge

It can be concluded that the cell tested at 0.5C and 1C discharge rate encountered a gradual and uniform temperature increase within the cell body, and the rate of temperature rise is not high enough to produce temperature imbalance in the cell body. The cell tabs have slightly higher temperatures which can be attributed to the electrical currents flowing through the restrictive cell tabs and creating waste heat. From the temperature data gathered, it can be seen

that the cell temperature distributions were uniform throughout the cell surfaces, including the front and back surfaces. Temperatures at the cell tabs were observed to be higher than the cell surfaces, indicating that current flow through the tabs causes the electrical constriction and as a result, increased heating at the tabs.

5.3. Battery module charging and discharging test

This section illustrates the experiments conducted to measure the cell temperature distributions across the battery module with a fixed load and with different cooling conditions. Experiment 3 would provide a clearer picture of the state of health of the cell (i.e. cell temperature) inside the module when subjected to discharging or charging. The effects of airflow velocity with respect to the temperature rise in the cells is examined, this is to find the optimum cooling efficiency so that the battery cooling system does not draw unnecessary battery power. The data collected serves as a guideline for implementing a fan speed control system to vary the cooling power according to the cell temperatures. A charging test is performed under natural convection to evaluate the need to apply forced air cooling during charging. This would allow better charging power efficiency if the cell temperatures are maintained within specified temperature limits. Lastly, the experiment observations will be used to confirm the design calculations and heat transfer simulation results in the previous chapters.

This experiment will measure the cell temperatures in between cell layers and the cell connectors. Cooling fans will be used to provide internal forced

convection to the cell bodies and cell connectors. This test is performed by charging and discharging the battery module at 0.375C and 1C respectively. In addition, natural convection will be applied to the charging process.

5.3.1. Procedure

The steps taken to conduct the experiments are ordered as such:

- 1) Charge the battery module to full capacity (100% SOC) and cut-off at module voltage of 33.2V.
- 2) The electrical load is connected to the batteries to discharge 80A (1C).
- 3) Cooling fans are concurrently activated to provide forced air flow.
- 4) The battery is discharged continuously until the temperature rise has reached a constant value.
- 5) The setup is repeated for each experiment variant (3a -3c) shown in Table 5.2 at full charge capacity (100% SOC).
- 6) Experiment 3d starts with the battery module at 20% SOC and charged to full capacity. Temperature is monitored for the charge process.

The fan speeds are the only controlled variable in this test, varying at flow rates of 4, 6 and 8 m/s. The airspeeds are measured at the straight inlet duct sections using the anemometer.

Table 5.2: Variations of experiment

Experiment	Air speed (m/s)	Type of test
3a	4	1 C discharge
3b	6	
3c	8	
3d	0	0.375 C charge

5.3.2. Results and discussion

The battery module is placed under discharge and charge tests to collect the temperature data and various comparisons are made: At the cell level, the temperature distribution of a cell surface is looked at in detail. At the sub-module level, the temperature uniformity of all the sub-modules were evaluated. The cooling flow rate of the battery module and the cooling performance of the cell connectors were discussed in this section.

5.3.2.1. Erroneous data

An issue was encountered with the data acquisition system when carrying out the experiments, there were several thermistors failing midway through the tests, and a temperature value could not be recorded. The fault was due to the soldered electrical wire connections breaking causing intermittent connections. The failure rate of the thermistors occurred at were typically 1 out of 5 within a cell layer, and a total of 5 layers were found faulty. The decision was made to discard the damaged thermistor's data and generate the graphs based on the average of cell layer data.

5.3.2.2. Peak temperature of sets A-H

Figure 5.26 is a 1C discharge plot of peak temperature of all the averaged sub-modules, set A-H, along the direction of air flow as indicated in Figure 5.18. The highest temperature reached at the cell body is Set H. This is because Set H is located at the end of the module, the air in the cooling channel is already heated up due to the heat transfer of the first 6 cell sets. Set B, E, G lies in between two cooling channels, thus the temperature of the cells recorded a lower value compared to the other cell sets which only had access to one cooling channel.

The rate of temperature rise from A, B, C to D, E, F and G, H are fairly linear, which suggests that the cell heat generation is equal among the cells.

Figure 5.21: Peak temperature of sub-modules at end of 1C discharge for 4m/s

5.3.2.3. Cooling efficiency of battery module

Cooling efficiency is defined as cooling fan power draw versus temperature delta rise above ambient. Airflow is the only variable in the test, discharge rate is kept constant at 1C and the battery module is set to discharge, with the temperatures monitored closely. Airspeed is proportional to the fan power draw measured in Watts. Table 5.3 lists the ratio of fan power drawn, to the heat dissipated in air, at airspeeds of 4 and 8 m/s. Heat dissipated is calculated by $\dot{Q} = C_p \cdot \rho A v \cdot \Delta T$ where C_p is Specific heat of air, $\rho A v$ is mass flow rate, and ΔT is the temperature difference at the air inlet and outlet.

The resulting ratio is 0.0506 for 4m/s and 0.0564 for 8m/s. This means that the cooling fan draws 0.0506W for every 1W of cell cooling provided. And the 8m/s airflow consumes $\frac{0.0564-0.0506}{0.0506} = 11.55\%$ more fan power to provide a better temperature delta of 3.9°C. This suggests that a balance can be achieved between battery cell cooling and fan energy consumption.

This test had been conducted at 1C discharge rate, there could be a possibility that higher airspeed is best suited for higher discharge rate. A multi variable approach could be implemented to evaluate the best cooling efficiency when finding for the ideal fan speed for different discharge rates.

Table 5.3: Cooling efficiency of battery module

Air speed (m/s)	Temperature rise above ambient (°C)	Fan power (W)	Heat dissipated in air (W)	Ratio
4	4.7	74	1461.19	0.0506
8	3.9	137	2424.95	0.0564

The temperature result from the air forced through the module at two flow rates are shown in Figure 5.22 and 5.23. The effect of flow rate on the forced air concept can be seen, the distribution of cell temperatures became less dispersed with increased flow rate of cooling air from 4m/s to 8m/s.

Figure 5.22: Temperature versus time plots at 1C discharge for 4m/s

Figure 5.23: Temperature versus time plots at 1C discharge for 8m/s

Figure 5.29 compares the mean temperatures of the two flow rates, there was a temperature drop of 0.6°C (from 29.6°C to 29.0°C). The two flow rates started to diverge at the 15 minutes' mark, and the 4m/s flow rate settled into constant temperature slightly later than the 8m/s flow rate by 3 minutes (8m/s @ 21 minutes' vs 4m/s @24 minutes).

Figure 5.24: Comparison of rise in temperature at flow rates of 4m/s vs 8m/s

5.3.2.4. Charging test at 0.375C, no airflow

The plot in Figure 5.30 records the temperature rise during charging test at 0.375C under natural convection for the Set H cells (rear end of battery module). Temperature stability is observed at the end of the charge process and no more heat generation has occurred after the charging current has cut-off. The temperature rose until 32.5°C peak and temperature remains constant briefly before decreasing. The 100% charge cut-off occurred at the 118 minute mark indicated in the orange box, however the temperature rise maintained at 32.5°C at the 100 minute mark. This time difference is the effect of CC-CV charging algorithm as discussed in Chapter 2, Section 6.8.

Figure 5.25: Plot for 0.375C charge, no airflow

5.3.2.5. Temperature variation within a battery cell

The heat generation within a sub-module (set 'H') is observed in this test, the deviation of temperature range occurred was minimal (0.19°C) during the 1C discharge testing at 4 m/s. All the three layers of thermistors (15 sensors) exhibited no distinct temperature deviations when discharged at 1C, as it can be seen in Figure 5.26. Thus, it is inconclusive to determine that the cell terminal tabs were experiencing higher temperatures, however a higher discharge rate might present a different outcome.

Figure 5.26: Temperature distribution as per 3 layers of thermistors (Set H)

5.3.2.6. Cell connector cooling comparison

The next evaluation would be the cooling performance of the cell connector design. The cell connectors are compared using the flow rate of 4, 6 and 8 m/s. Figure 5.27 show the temperature difference between the averaged cell connectors and averaged cell bodies. It can be seen that at higher flow rates, the

temperatures are identical, and at lower flow rates (4m/s), the temperature at the cell connectors were higher. This is attributed to flow constriction at the cell connectors, the copper bus-bars and thermistor wiring obstructed the airflow within the cell connector cooling volume as seen in Figure 5.28. Projected polynomial trend lines suggests that a higher flow rate applied to the cooling system might not produce any better results as the curve has reached a plateau. A linear cooling fan curve would also be possible, further tests on higher flowrates is required to verify it.

Figure 5.27: Temperature of cell connector vs cooling flowrate

Figure 5.28: Flow restriction of Set G and H

5.3.2.7. Cell temperatures at sub-module center

The cell temperatures at the centroid of the sub-module (Set A-H) are checked to see if they are significantly higher than the lowest cell temperature in the module. With reference to the thermistor numbering system, the points of interest are SA-L2-3, SB-L2-3, SC-L2-3, ... SH-L2-3. Their maximum values are compared against thermistor no. SB-L1-4 shown in Figure 5.29. The temperature difference observed is $<1^{\circ}\text{C}$ with the hottest cell temperature (SH-L2-3). The cooling channels were effective in dissipating heat, as the thermistors in Set B, E, and G (SB-L2-3, SE-L2-3, SG-L2-3) all recorded a lower value than the other Sets (A, C, D, F, H).

Figure 5.29: Highest cell temperatures compared with lowest value

The tests carried out on the battery module have been very useful, the temperatures of the battery module at 1C discharge is well below the cell specification limit of 55°C even at low flow rates. The cooling channels were proven to be effective at removing cell heat generation, and the pouch cells had showed to respond well to high cooling velocities.

5.4. Battery module functional test

Function test is carried out to ascertain that the structure of the battery module is electrically insulated from the live high voltage connections and checked for high voltage leak to the battery housing. If high voltage leak is detected on the housing, then it is a serious safety breach because the high voltage is transmitted through the housing and can electrocute any person handling the battery module.

An insulation resistance test instrument shall be connected between the live parts to any electrically conductive part of the battery module that is not a high voltage connection. The isolation resistance is measured and the voltage level measured should be a zero value.

5.4.1. Procedure

The experiment shall be conducted following the steps listed below:

- 1) Ensure that the battery is charged and a voltage is measurable from the battery positive and negative terminals (see Figure 5.30). This value is recorded as V_b .

Figure 5.30: Reading battery voltage

- 2) By measuring the points depicted in Figure 5.31. Start by measuring the points in green using the multi-meter. The ground connection will be the battery module housing. Record the value as the first voltage reading; V_1 . Thereafter measure the points in red, recording the value as the second reading; V_2 .

Figure 5.31: Measuring for high voltage leak to ground [40]

- 3) Comparing the three voltage readings; V_1 should not have the same value as V_2 and V_b . V_1 and V_2 should read a zero value on the multi-meter.
- 4) Once it is ascertained that the battery module does not have any voltage leakage to the housing, the battery module passed the insulation resistance test.

5.4.2. Results and discussion

The multi-meter measured 0 volts on both readings (V_1 and V_2) with the battery module housing as ground, which indicates that the basic isolation resistance test results were successful (as seen in Figure 5.32). The battery module had a proper electrical insulation design that isolated the live high voltage parts from the module housing. This test fulfils the mandatory high voltage safety requirement of the battery module put forth during the packaging design stage.

Figure 5.32: DC Voltage measurement between the battery module housing and battery terminals

Chapter 6: Conclusion and Future Work

This chapter serves to summarise the work done on the design and development of the battery module, with the cell cooling design as the main focus in this study. Problems surfaced during the battery module experimental testing process are discussed, and recommendations for future work are given in detail.

6.1. Summary

For battery electric vehicles, forced air cooling for battery is a preferred option due to compactness, low cost, and design flexibility. This thesis has developed packaging design of a battery module that includes design for forced air flow for the cooling of battery cells. Its thermal design performance was confirmed by conducting steady state one-dimensional heat transfer calculations, followed by heat transfer analysis simulation and battery module charge/discharge experiments.

The thermal characteristics of a pouch cell was studied by carrying out experiments with discharge of 0.5C and 1C and with start temperature of 25°C. It is found that for the pouch cells, the maximum cell temperature occurs near the cell terminals. The tests also found good agreement with the literature reviewed and deemed to be credible in the published data for their work done on pouch cells. Their heat transfer data were then used for the design calculations.

The battery cooling analyses conducted covered the cooling system design, forced convection flow distributions in the battery pack using battery heat generation equation for 1C, 2C, and 3C continuous discharge.

Simulation results demonstrated that forced air cooling performed well at higher airspeeds due to the turbulent flows in the cooling channels. The data collected can be used as a guideline to optimise the fan speed and power consumption for the battery cooling system. The extrapolated results also showed that a higher air flow rate is able to remove the heat generated at 3C discharge.

The experimental results for the 4 m/s and 8 m/s flow rates suggests that the amount of thermal cooling gains from the higher flow rate is minimal, furthermore the battery cooling fan input power has doubled. This indicates that a high air flow, low current discharge equates to higher parasitic electrical load draw from the BEV battery system. Higher air speeds will be beneficial to higher current loads, and the BMS can setup to ramp up the fan speeds when high current loads are detected.

The experiments show that higher flow rate on the forced air concept causes the distribution of cell temperatures to be less dispersed with increased flow rate of cooling air from 4m/s to 8m/s.

The battery charging test proved that the maximum charging rate of 0.375 C is safe without cooling the cells as the cell temperature did not reach the cell upper temperature limit of 55°C.

The cell connector with the heat sink design does have some merits, a higher temperature was detected at the cell terminal tabs during the experiments in comparison to the cell body. Thus, the cooling of cell connectors supplemented the main cell body cooling function.

Lastly, the cell body temperature showed only marginal differences within one layer of 5 thermistors on the cell surface area. Thus, it can be said that the thermal profile is very uniform and any cell surface temperature imbalance is negligible.

6.2. Challenges faced

The issues faced with a self-built data acquisition program were errors in the temperature data recorded. The errors were caused by wiring issues during the assembly of the battery module. The large amount of wiring coupled with fragile thermistor wiring leads resulted in breakage of wires which could be detected only after assembling and testing of the battery module. As each thermistor had a pair of wire to attach to the monitoring system, the task of identifying the damaged wire ends became twofold.

6.3. Future work

This thesis focused on the numerical calculation, thermal simulation and experimental analysis of the BEV battery module. This is to fully assess the capability of the thermal management system and understand the effects of introducing cooling functions and controlling the temperature of the battery cells within prescribed safe limits. The following points are the proposed future work to improve the battery pack design:

- Develop and integrate a cooling fan logic that vary fan power depending on discharge/charge loads.
- An electric vehicle drive cycle could be implemented to simulate the actual driving electrical load condition so that transient thermal

conditions can be captured as research data to analyse the performance of densely packed pouch cells.

- Another possibility would be to incorporate an electro-thermal finite element model which can fully replicate a battery cell's thermal behaviour in the simulation. However, high performance computer systems would be needed as this requires the battery cell to be introduced into the simulation process and each cell would need to be meshed.
- Troubleshoot the data acquisition system to remove the temperature calibration errors and thereafter scale it down into a single circuit board design. The system can then be incorporated into the battery pack to gather temperature data during the on-road electric vehicle test cycles.
- Replace the thermistors with thermocouple as it is a voltage-based temperature measurement rather than the resistive-based thermistor. Resistance values are accumulative throughout the sensor system, electrical trace, wiring and connections. This makes it harder to achieve consistent measurements.
- Obtain a higher current capacity electronic load to perform higher discharge test on the battery module. The experiments would help to find correlations with the simulation results.
- Perform driving test on the BEV with the assembled battery pack to test for actual battery performance.
- Use CFD simulations to optimise the cooling ducts of the battery pack to allow greater airflow into the battery module.
- Redesign the battery module to be lighter and optimise the cooling channels to improve cooling performance with a larger range of flow velocities.

- Re-evaluate the cell connector heatsink design with a more systematic approach (with more accurate experiments, and to vary the designs of cell connector) to quantify the performance of the cell connector cooling concept.

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Appendices

Appendix A - Glossary

Working principle of an electrochemical cell

Figure A.1 provides the overall diagram of a cell's electron movement in relation to the electronic components (load and charger). The blue arrows indicate the direction of negative electron flow through the external electrical hardware while the red arrow shows the direction of lithium ion migration.

Figure A.1: Macro view of (a) discharge process, (b) charge process¹

Cell potential and cell chemistry

A cell's nominal voltage or cell potential, E_{cell} is derived from its electrochemical structure. It is the measure of the potential difference between two half cells in the electrochemical cell. The potential difference is caused by the ability of electrons to flow from one half cell to the other. The flow of electrons is a chemical reaction called: electrochemical oxidation-reduction (redox) reaction. A redox reaction occurs when a certain substance is oxidized, while another is

¹ Lawson, Barrie, Cell Chemistries - How Batteries Work, <http://www.mpoweruk.com/chemistries.htm>, 2005

reduced. During oxidation, the substance loses one or more electrons, and thus becomes positively charged. Conversely, during reduction, the substance gains electrons and becomes negatively charged. The cell potential is determined by the measuring the difference between the potential for the reducing agent to become oxidized and the oxidizing agent to become reduced². The larger the potential difference between the two electrodes is, the greater the EMF of the cell and the greater the amount of energy that can be produced by the cell.

Each electrode potential is measured by the redox reaction process in which one of the half-cell is the standard hydrogen electrode of 0 volts³. Table A.1 shows a sample list of standard cell potentials. Compiling all the electrode potentials with the hydrogen electrode as reference provides a basis for a wide range of calculations and combination/predictions. The base expression for a cell potential is defined below.

$$E_{cell}^{\circ}:$$

1. Measured against standard hydrogen electrode
2. Concentration = 1 Molar
3. Pressure = 1 atmosphere
4. Temperature = 25°C

Table A.1: List of electrode potentials⁴

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² Barrett, et al, The Cell Potential, http://chemwiki.ucdavis.edu/Core/Analytical_Chemistry/Electrochemistry/Voltaic_Cells/The_Cell_Potential

³ Nave, Rod, Standard Electrode Potentials, <http://hyperphysics.phy-astr.gsu.edu/hbase/chemical/electrode.html>, 2012

⁴ Ebbing & Gammon, General Chemistry, 10th Edition, 1990

Strengths of Oxidizing and Reducing Agents	
Cathode (Reduction) Half-Reaction	Standard Potential E^0 (volts)
$\text{Li}^+_{(\text{aq})} + \text{e}^- \Rightarrow \text{Li}_{(\text{s})}$	-3.04
$\text{K}^+_{(\text{aq})} + \text{e}^- \Rightarrow \text{K}_{(\text{s})}$	-2.92
$\text{Ca}^{2+}_{(\text{aq})} + 2\text{e}^- \Rightarrow \text{Ca}_{(\text{s})}$	-2.76
$\text{Na}^+_{(\text{aq})} + \text{e}^- \Rightarrow \text{Na}_{(\text{s})}$	-2.71
$\text{Zn}^{2+}_{(\text{aq})} + 2\text{e}^- \Rightarrow \text{Zn}_{(\text{s})}$	-0.76
$2\text{H}^+ + 2\text{e}^- \Rightarrow \text{H}_2$	0.00
$\text{Cu}^{2+}_{(\text{aq})} + 2\text{e}^- \Rightarrow \text{Cu}_{(\text{s})}$	0.34
$\text{O}^{3+}_{(\text{g})} + 2\text{H}^+_{(\text{aq})} + 2\text{e}^- \Rightarrow \text{O}_{2(\text{g})} + \text{H}_2\text{O}_{(\text{l})}$	2.07
$\text{F}_{2(\text{g})} + 2\text{e}^- \Rightarrow 2\text{F}^-_{(\text{aq})}$	2.87

The following equation is used to find the voltage of a cell which is the potential difference between two individual electrode potentials.

$$E^0_{\text{cell}} = E^0_{\text{red,cathode}} - E^0_{\text{red,anode}}$$

E^0_{cell} is the standard cell potential

$E^0_{\text{red,cathode}}$ is the standard reduction potential for the reduction half reaction occurring at the cathode

$E^0_{\text{red,anode}}$ is the standard reduction potential for the reduction half reaction occurring at the anode

The calculation of a standard cell potential for copper (Cu) and silver (Ag) is explained below:

Oxidation half cell of the redox equation:

The reduction half cell:

Sum of the chemical equations:

The simplified equation becomes:

The computed cell potential is:

$$E^\circ_{\text{Cell}} = E^\circ_{\text{Red,Cathode}} - E^\circ_{\text{Red,Anode}}$$

$$E^\circ_{\text{Cell}} = 0.800\text{V} - 0.340\text{V}$$

$$E^\circ_{\text{Cell}} = 0.460\text{V}$$

From Table A.1, the half-cell potential of Lithium electrode is -3.04V, its high value forms the foundation to enable the development of cells with higher voltage. Higher voltage cells are preferred as the battery pack designer can reduce the number of series cells to achieve the target pack voltage.

Mechanical attributes of three cell formats

Table A.2: Comparing cell formats for design packaging purposes

Attributes	Cell Formats		
	Cylindrical	Prismatic	Pouch
Mechanical stability of cell	Good, metal casing	Good, rigid plastic casing	Poor, thin and soft aluminium foil envelope
Packaging efficiency	Wasted space due to round profile	Good, easy to stack	Good, easy to stack
Inactive weight vs Active weight	Large inactive weight	Small inactive weight	Negligible inactive weight
Safety	Good, has cell level fuse	Adequate, has built-in vents	Bad, flimsy form factor
Cell shape, ease of cell cooling	Round, complex	Large plastic casing, mixed	Thin rectangular block, easy
Single battery cell capacity	< 5 Ah	5 - 200 Ah	> 5 Ah
Electrical tab connections	Spot welded nickel strips	Threaded hole for bolt	Clamped, spot welded or soldered tabs
Require specific cell orientation	None	Vertically upright, due to the vent holes	None

Technical battery terms

Kindly provided by Massachusetts Institute of Technology

A Guide to Understanding Battery Specifications

MIT Electric Vehicle Team, December 2008

A battery is a device that converts chemical energy into electrical energy and vice versa. This summary provides an introduction to the terminology used to describe, classify, and compare batteries for hybrid, plug-in hybrid, and electric vehicles. It provides a basic background, defines the variables used to characterize battery operating conditions, and describes the manufacturer specifications used to characterize battery nominal and maximum characteristics.

Battery Basics

- **Cell, modules, and packs** – Hybrid and electric vehicles have a high voltage battery pack that consists of individual modules and cells organized in series and parallel. A cell is the smallest, packaged form a battery can take and is generally on the order of one to six volts. A module consists of several cells generally connected in either series or parallel. A battery pack is then assembled by connecting modules together, again either in series or parallel.
- **Battery Classifications** – Not all batteries are created equal, even batteries of the same chemistry. The main trade-off in battery development is between power and energy: batteries can be either high-power or high-energy, but not both. Often manufacturers will classify batteries using these categories. Other common classifications are High Durability, meaning that the chemistry has been modified to provide higher battery life at the expense of power and energy.
- **C- and E- rates** – In describing batteries, discharge current is often expressed as a C-rate in order to normalize against battery capacity, which is often very different between batteries. A C-rate is a measure of the rate at which a battery is discharged relative to its maximum capacity. A 1C rate means that the discharge current will discharge the entire battery in 1 hour. For a battery with a capacity of 100 Amp-hrs, this equates to a discharge current of 100 Amps. A 5C rate for this battery would be 500 Amps, and a C/2 rate would be 50 Amps. Similarly, an E-rate describes the discharge power. A 1E rate is the discharge power to discharge the entire battery in 1 hour.
- **Secondary and Primary Cells** – Although it may not sound like it, batteries for hybrid, plug-in, and electric vehicles are all secondary batteries. A primary battery is one that can not be recharged. A secondary battery is one that is rechargeable.

Battery Condition

This section describes some of the variables used to describe the present condition of a battery.

- **State of Charge (SOC)(%)** – An expression of the present battery capacity as a percentage of maximum capacity. SOC is generally calculated using current integration to determine the change in battery capacity over time.

- **Depth of Discharge (DOD) (%)** – The percentage of battery capacity that has been discharged expressed as a percentage of maximum capacity. A discharge to at least 80 % DOD is referred to as a deep discharge.
- **Terminal Voltage (V)** – The voltage between the battery terminals with load applied. Terminal voltage varies with SOC and discharge/charge current.
- **Open-circuit voltage (V)** – The voltage between the battery terminals with no load applied. The open-circuit voltage depends on the battery state of charge, increasing with state of charge.
- **Internal Resistance** – The resistance within the battery, generally different for charging and discharging, also dependent on the battery state of charge. As internal resistance increases, the battery efficiency decreases and thermal stability is reduced as more of the charging energy is converted into heat.

Battery Technical Specifications

This section explains the specifications you may see on battery technical specification sheets used to describe battery cells, modules, and packs.

- **Nominal Voltage (V)** – The reported or reference voltage of the battery, also sometimes thought of as the “normal” voltage of the battery.
- **Cut-off Voltage** – The minimum allowable voltage. It is this voltage that generally defines the “empty” state of the battery.
- **Capacity or Nominal Capacity (Ah for a specific C-rate)** – The coulometric capacity, the total Amp-hours available when the battery is discharged at a certain discharge current (specified as a C-rate) from 100 percent state-of-charge to the cut-off voltage. Capacity is calculated by multiplying the discharge current (in Amps) by the discharge time (in hours) and decreases with increasing C-rate.
- **Energy or Nominal Energy (Wh (for a specific C-rate))** – The “energy capacity” of the battery, the total Watt-hours available when the battery is discharged at a certain discharge current (specified as a C-rate) from 100 percent state-of-charge to the cut-off voltage. Energy is calculated by multiplying the discharge power (in Watts) by the discharge time (in hours). Like capacity, energy decreases with increasing C-rate.
- **Cycle Life (number for a specific DOD)** – The number of discharge-charge cycles the battery can experience before it fails to meet specific performance criteria. Cycle life is estimated for specific charge and discharge conditions. The actual operating life of the battery is affected by the rate and depth of cycles and by other conditions such as temperature and humidity. The higher the DOD, the lower the cycle life.
- **Specific Energy (Wh/kg)** – The nominal battery energy per unit mass, sometimes referred to as the gravimetric energy density. Specific energy is a characteristic of the battery chemistry and packaging. Along with the energy consumption of the vehicle, it determines the battery weight required to achieve a given electric range.

- **Specific Power (W/kg)** – The maximum available power per unit mass. Specific power is a characteristic of the battery chemistry and packaging. It determines the battery weight required to achieve a given performance target.
- **Energy Density (Wh/L)** – The nominal battery energy per unit volume, sometimes referred to as the volumetric energy density. Specific energy is a characteristic of the battery chemistry and packaging. Along with the energy consumption of the vehicle, it determines the battery size required to achieve a given electric range.
- **Power Density (W/L)** – The maximum available power per unit volume. Specific power is a characteristic of the battery chemistry and packaging. It determines the battery size required to achieve a given performance target.
- **Maximum Continuous Discharge Current** – The maximum current at which the battery can be discharged continuously. This limit is usually defined by the battery manufacturer in order to prevent excessive discharge rates that would damage the battery or reduce its capacity. Along with the maximum continuous power of the motor, this defines the top sustainable speed and acceleration of the vehicle.
- **Maximum 30-sec Discharge Pulse Current** – The maximum current at which the battery can be discharged for pulses of up to 30 seconds. This limit is usually defined by the battery manufacturer in order to prevent excessive discharge rates that would damage the battery or reduce its capacity. Along with the peak power of the electric motor, this defines the acceleration performance (0-60 mph time) of the vehicle.
- **Charge Voltage** – The voltage that the battery is charged to when charged to full capacity. Charging schemes generally consist of a constant current charging until the battery voltage reaching the charge voltage, then constant voltage charging, allowing the charge current to taper until it is very small.
- **Float Voltage** – The voltage at which the battery is maintained after being charge to 100 percent SOC to maintain that capacity by compensating for self-discharge of the battery.
- **(Recommended) Charge Current** – The ideal current at which the battery is initially charged (to roughly 70 percent SOC) under constant charging scheme before transitioning into constant voltage charging.
- **(Maximum) Internal Resistance** – The resistance within the battery, generally different for charging and discharging.

Appendix B - NTU-BEV Design Story

The team have come together, discussed and pieced together the design story that is customised for the Singapore market. The method used was the 5 Ws and 1 H (who, what, where, when, why, how).

The narrative starts off with a young working professional who drives to work daily, his other primary purpose is to send his spouse to work. With two different venues to drive to, he would require sufficient energy from the fuel source to last him through until he arrives at his workplace. The roads along the way is often jam packed with vehicles at the time of journey, thus the vehicle must be driveable in comfort and not stress out the driver or occupants.

The young professional would prefer a stylish looking car, and he would not mind paying for a better specification model. He would also consider greener alternatives like electric cars, hybrids.

As for the weekends, the young couple would like to do shopping at various megamalls or even the occasional trip to neighbouring country, Malaysia. Therefore the ability to store all the possible shopping bags inside the boot is considered important.

The ideal car should last for at least 5 years of ownership and if possible, still remain as a suitable car when the young couple decides to have children. Thus there would be a requirement of rear seats that can be occupied by babies to young children, or even the occasional hitch-a-ride friend, though it remains a compact car.

Appendix C - Design and Fabrication of Battery Module

2D drawings of battery module

BOM LEVEL																			
LV										PART NO	NAME / DESCRIPTION	RI	QTY	Unit Cost	UD	REF ID	MI	SUPPLIER	SUPPLIER PIN
0										410-0003_HeatSink_WA412108_RS(Schalfer)	Heat Sink WA412108 (100x23x11.5)	A	1	\$ 39.40	EACH			BS (Schalfer)	410-0003
1										WFTTSX103FA2E100	Thermisto NTC 10K OHM 1%	A	128	\$ 0.90877	EACH			Electronics	430-5530-10
1										Electrolube Epoxy Thermal Adhesive 24 h Cure, 75 ml Syringe	Epoxy Thermal Adhesive (Syringe)	A	1	\$ 58.35	EACH			BS (Electrolube)	725-8971
1										BFE10-10_Cross Recased Flat Head Machine Screw_M3 x L10_MISUMI	M3 x L10 Hexagon Socket Flat Head Countersunk Screws	A	70						
1										MSF53-8_FlatEndSetScrew_M3xL6_MISUMI	M3xL6 Hexagon Socket Set Screws	A	10						
1										BFB10-8_Countersunk Screw_M3xL8_MISUMI	M3 x L8 Hexagon Socket Flat Head Countersunk	A	18						
1										09108.02_003_MPE_ThermalPad	100 x 100 x 3 Thermal Pad	A	16						
1										BFB10-8_CrossRecessedFlat Head Machine Screw_M3xL8_MISUMI	M3 x L8 Hexagon Socket Flat Head Countersunk Screws	A	8						
1										SPW16-M6_Spring Washer_MISUMI	M6 Spring Washer	A	4						
1										SPW16-M6_Plan Washer_MISUMI	M6 Plain Washer	A	4						
1										SLBNF6_HeadNut_M6_MISUMI	M6 Nut	A	4						
1										SPW13_Plan Washer_M3_MISUMI	M3 Plain Washer	A	65						
1										SSCB3-12_Buttn Head Cap Screw_M3xL12_MISUMI	M3xL12 Buttn Head Hexagon Socket Cap Screw	A	48						
1										SSCB3-20_Buttn Head Cap Screw_M3xL20_MISUMI	M3xL20 Buttn Head Hexagon Socket Cap Screw	A	17						
1										SSLV3_Spring Washer_M3_MISUMI	M3 Spring Washer	A	65						
1										thin nut chartered grade 8.8 (hexagon thin nut ISO 4035 - M3 plain washer small grade 8.8 ISO (washer ISO 7082 - 3)	Hexagon Thin Nut M3	A	4						
1										MSUMIWC33-12	M3 Plain Washer	A	4						
1										PEK33-8_Reem Socket Head Cap Screw HexSocket_M3xL8_MISUMI	hexagon socket head cap screw M3xL12 (w/ M3 nut)	A	4						
1										SETG35-27-SC10_M3-M3_MISUMI	PEEK Hexagon Socket Head Cap Screws M3 x L8	A	4				MISUMI		
1										SLSBW16-22_HeadPost_M3xL22_MISUMI	Circular Posts - One End Male Thread - M3 x M3 x L27	A	6				MISUMI		
1										SLSBW16-22_HeadPost_M3xL22_MISUMI	Hexagon Posts - One End Male Thread - M3 x L22	A	4				MISUMI		
1										SLSBW16-22_HeadPost_M3xL15_MISUMI	Hexagon Posts - One End Male Thread - M3 x L15	A	4				MISUMI		
1										1385526 (DN16303 B) Threaded Insert - M3_BOSCHARD	BOSCHARDEN 1036 Threaded Insert M3 article no. 1385526	A	64	\$ 13.06	EACH		BOSCHARDEN Unit - 100PCS		
1										NPTH-2-0144-RIT	Cable Tie Holder	A	8				ESSENTRA (for RICHCO)		
1										41108_FusionMagnaLugStraightLug_14800_QuickCable	Straight Lug 14" 20 Quick Cable	A	20	\$ 5.25	EACH		FASTENAL Singapore		
1										Arduino Mega 2560 Board	Arduino Mega 2560 Board	A	6						

Figure C-1: Exploded assembly of battery module

Figure C-2: Exploded assembly of battery pack

Drawn	20/12/2014	Approved	20/12/2014	Legal Owner	Samuel Ho	Sufyan	Part Description	091.06.03_BusBarConnectors	Qty	1	Third Angle Projection
Title Battery Electric Vehicle 091 - Populair Battery (prototype 01)											
Material Copper C1100											
Treatment Sn Plating (10-30nm)											
Scale 1:1											
Sheet 2 of 2											

Battery module 3D model

Figure C-3: Box structure of module

Figure C-4: Aluminium cooling plate with pass through channels

Figure C-5: 3D battery module assembled (front and side view)

Battery pack 3D model

Figure C-6: Finalised concept of battery housing (Front Side View)

Figure C-7: Finalised concept of battery housing (Rear Side View)

Assembly process of battery module

Figure C-8: Module base plate underside

Figure C-9: Module base plate topside

Figure C-10: Module side plate 1

Figure C-11: Module side plate 2

Figure C-12: Module front and back plate

Figure C-13: Module intermediate plates

Figure C-14: Assembled module housing

Figure C-15: First set of parallel cells added

Figure C-16: Adding of thermistors

Figure C-17: Placing thermal pad on battery cell surface

Figure C-18: Assembling the middle row of cells

Figure C-19: Addition of upper cell cooling plate (view 1)

Figure C-20: Addition of upper cell cooling plate (view 2)

Figure C-21: Securing cooling plates to housing

Figure C-22: Affixing Delrin cell terminal holder (view 1)

Figure C-23: Affixing Delrin cell terminal holder (view 2)

Figure C-24: 2nd row of battery cells inserted

Figure C-25: Completed assembly of 32 battery cells, 8 series and 4 parallel

Figure C-26: Measuring module voltage, axial fan and cooling ducting added

Appendix D - Component Datasheet

Thermistor

NTC Thermistors for Temp. Sensor and Compensation Chip Type

(Part Number) **NC P 18 XH 103 J 03 RB**

q w e r t y u i q Product ID t Resistance

Product ID	
NC	NTC Thermistors Chip Type

Expressed by three-digit alphanumerics. The unit is ohm (Ω). The first and second figures are significant digits, and the third figure expresses the number of zeros that follow the two figures.

wSeries

Code	Series
P	Plated Termination Series

Ex.

Code	Resistance
102	1k Ω
103	10k Ω
104	100k Ω

eDimensions (LgW)

Code	Dimensions (LgW)	EIA
03	0.60g0.30mm	0201
15	1.00g0.50mm	0402
18	1.60g0.80mm	0603
21	2.00g1.25mm	0805

yResistance Tolerance

Code	Resistance Tolerance
D	$\pm 0.5\%$
F	$\pm 1\%$
E	$\pm 3\%$
J	$\pm 5\%$

rTemperature Characteristics

Code	Temperature Characteristics
XC	Nominal B-Constant 3100e3149K
XF	Nominal B-Constant 3250e3299K
XH	Nominal B-Constant 3350e3399K
XM	Nominal B-Constant 3500e3549K
XQ	Nominal B-Constant 3650e3699K
XV	Nominal B-Constant 3900e3949K
XW	Nominal B-Constant 3950e3999K
WB	Nominal B-Constant 4050e4099K
WD	Nominal B-Constant 4150e4199K
WF	Nominal B-Constant 4250e4299K
WL	Nominal B-Constant 4450e4499K
WM	Nominal B-Constant 4500e4549K

Individual Specifications

Structures and other specifications are expressed by two figures.

Ex.

Code	Individual Specifications
03	Standard Type

iPackaging

Code	Packaging
RA	Plastic Taping 4mm Pitch (4000 pcs.)
RB	Paper Taping 4mm Pitch (4000 pcs.)
RC	Paper Taping 2mm Pitch (10000 pcs.)
RL	Paper Taping 2mm Pitch (15000 pcs.)

Battery cell

Creative Power For Future Energy

ePLB C High Energy Product

Technology

Lithium Ion Polymer Battery
Li[NiCoMn]O₂-based Cathode
Graphite-based Anode
High Energy Density
Optimized for PHEV, EV

Product General Specification

Mechanical Characteristics

Model	C020
Length	217,0 ± 1 mm (excluding terminal)
Width	129,0 ± 1 mm
Thickness	7,2 ± 0,2 mm
Weight	approx. 428 g

Electrical Characteristics

Nominal Voltage	3,65 V
Nominal Capacity	20 Ah
AC Impedance (1 KHz)	< 3 mΩ
Specific Energy	174 Wh/Kg
Energy Density	370 Wh/L
Specific Power(DOD50%, 10sec)	2300 W/Kg
Power Density(DOD50%, 10sec)	4600 W/L

Operating Conditions

Charge Conditions :

Recommended Charge Method	CC/CV
Maximum Charge Voltage	4,15 V
Recommended Charge Current	0,5 C Current

Discharge Conditions :

Recommended Voltage Limit for Discharge	3,0 V
Lower Voltage Limit for Discharge	2,5 V
Maximum Discharge Current (Continuous)	up to 5 C Current
Maximum Discharge Current (Peak < 10 sec)	10 C Current

Operating Temperature :	-30°C / + 55°C
Recommended Charge Temperature	0°C / + 40°C
Storage Temperature	-30°C / + 55°C

Cycle Life at 25°C : (1 C Charge / 1 C Discharge, DOD100%)	1000 Cycles to 80% Nominal Capacity

ePLB C020 Performance

CHARGE : CC(0,5C)/CV(4,15V to 0,05C) at 25°C
DISCHARGE : CC to 3,0V at 25°C

HPPC calculated from FreedomCAR Battery Test Manual

CHARGE : CC(1,0C)/CV(4,15V to 0,05C) at 25°C
DISCHARGE : CC(1,0C) to 3,0V at 25°C (DOD100%)

EIG Energy Innovation Group

All specifications are subject to change without notice. For your system requirements, please contact info@eigbattery.com

Battery Management System

Battery pack Management Unit (BMU)

The BMU is a bridge between the CMUs and the vehicle communication bus. It controls the pre-charge and main contactors of the battery pack as well as collating the telemetry data from the nodes and providing a summary to other components on the vehicle CAN bus.

BMU specifications	
Communications	CAN bus to both batteries and vehicle
Contactor Drive	3x 12V 3A, with feedback
Precharge	Resistive (includes fault detection)
Isolation Rating	1kV DC
Dimensions	195 x 55 x 30mm
Mass	150g
Environmental	No enclosure — coated PCB

Cell Management Unit (CMU)

The Tritium CMU suits any lithium cell chemistry of any form factor, as the threshold voltages are user-configurable and a simple wiring harness is used to connect the node to the cells. Each node can monitor between one and eight cells, and is powered from the network, not the cells themselves, so the BMS itself does not contribute to cell leakage and imbalance.

CMU specifications

Cell options	Any lithium chemistry cell
Communications	CAN bus (ribbon cable)
Balance current	250mA
Voltage resolution	1mV
Update rate	Full pack @ 1Hz, MinV/MaxV @ 100Hz
Max system	32 nodes, 256 cells, 1000V
Battery wiring	Simple point-point ribbon, 1-8 cells
Fault detection	Redundant voltage sense, cross checked A/D reference, comms timeouts
Temp accuracy	2°C
Isolation Rating	1kV DC
Dimensions	135 x 55mm (250mA node)
Mass	35g
Environmental	No enclosure — coated PCB

Electronic load

**PROGRAMMABLE AC&DC ELECTRONIC LOAD
MODEL 63800 SERIES**

MODEL 63800 SERIES

Key Features :

- Power Rating : 1800W, 3600W, 4500W
- Voltage Range : 50V ~ 350Vrms
- Current Range :
  - Up to 18Arms, 36Arms, 45Arms
- Peak Current : Up to 54A, 108A, 135A
- Parallel / 3-Phase Function
- Frequency Range : 45 ~ 440Hz, DC
- Crest Factor Range : 1.414 ~ 5.0
- Power Factor Range : 0 ~ 1 lead or lag (Rectified mode)
- CC, CR, CV, CP for DC Loading
- Constant & Rectified Load Modes for AC Loading
- Analog Voltage & Current Monitor
- Timing Measurement for Battery, UPS, Fuse and Breaker tests
- Measurement : V, I, PF, CF, P, Q, S, F, R, Ip+/- and THDv
- Short circuit simulation
- Full Protection : OP, OC, OT protection and OV alarm
- GPIB & RS-232 interfaces

Schaffner aluminium heatsink

WA409/412/432 type heatsinks

Standard profiled heatsinks.

B terminal: natural aluminium; B terminal: black anodised.

Sold as 1 m bars.

	WA409	WA412	WA432
Rth (°C)	2.7	5.4	2.2

WA 412 - 0,43kg/m

Thermal Resistance More Than 1.3°C/W

Battery charger

PFC-20/30/40

EV BATTERY
CHARGER

The Manzanita Micro PFC-20, PFC-30 and PFC-40 chargers share the same size enclosure. With a fully adjustable output voltage for battery packs from 12 to 450VDC and power levels of up to 9.6kW we think you'll agree that there are no other EV battery chargers that are this flexible or powerful in such a small footprint.

There are no input voltage settings to change, simply plug into any AC wall outlet from 100 to 250 volts and 40 to 80 hertz. Current is easily adjustable allowing users to fine tune the unit to pull the maximum amount of amps from whatever outlet is available. Starting in 2011 all PFC-30 and PFC-40 chargers come standard with built-in digital input current meters allowing quick and precise amperage adjustments. The small size, flexible input and output ranges and ease of user adjustable features make Manzanita Micro chargers an exceptional on-board charging solution so your electric vehicle should never encounter a single phase outlet it cannot use. It is no wonder Manzanita Micro chargers are used in electric vehicles in countries all across the globe.

The PFC-20, PFC-30 and PFC-40 series chargers weigh in at approximately 18 pounds (8.2 kg)

The maximum outermost dimensions including foot flanges and protrusions are approximately:
14" L x 10.5" W x 5.75" H (358mm x 264mm x 145mm)

Input Voltage Range : 100 to 240VAC 40-80Hz computer grade pure sine wave

Output Voltage Range : 12 to 450VDC (+/- 1 volt)

Operating Temp Range : -20° F to +120° F (-28.8° C to +48.8° C)

Power Consumption : Up to 9.6kW ~ PFC40 / 7.2kW ~ PFC30 / 4.8kW ~ PFC20

The 20, 30 or 40 nomenclature is indicative of how many amps that charger is rated to draw from the AC line. Unlike some other chargers, this is the rated continuous load and all units are thoroughly tested to their rated limits before leaving Manzanita Micro. Chargers can be set up to accept SAE J1772 communication.

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PFC-20/30/40

EV BATTERY
CHARGER

	PFC-20	PFC-30	PFC-40
Input voltage range	100-250 Volts AC		
Line frequency	40-80 Hz		
Output voltage range	12-450 Volts DC		
Input current range	0.2 to 20 Amps AC	0.2 to 30 Amps AC	0.3 to 40 Amps AC
Standard output	0 to 20 Amps DC	0 to 40 Amps DC*	0 to 40 Amps DC
Output -buck enhanced	0 to 30 Amps DC	0 to 40 Amps DC	0 to 40 Amps DC
Standby current	0.2 Amps DC	0.2 Amps DC	0.3 Amps DC
Air cooling path	In the back, out the front		
Cooling fan control	Thermostat controlled variable speed fans are standard features on air cooled units		
Input cable	#10-3 SO Cable	#10-3 SO Cable	#6-4 SO cable
Input connector	Unterminated	NEMA 14-30	NEMA 14-50
Output cable	#10-3 SO Cable	#8-3 SO Cable	#4-3 SO cable
Output connector	50 Amp Andersen Gray		
Input protection	30 amp 240 volt breaker	30 amp 240 volt breaker	50 amp 240 volt breaker
Output protection (stock)	30 amp 450 VDC clip mount fuse	50 amp 450 VDC stud mount fuse	60 amp 450 VDC stud mount fuse
Output protection (with buck enhancement)	50 amp 450 VDC stud mount fuse	50 amp 450 VDC stud mount fuse	60 amp 450 VDC stud mount fuse
Mounting bolt holes	4 each 5/16 inch		
Charger type	Switch mode PFC		
Topology	Two transistor fly back		
Isolation input to output	None, negative terminal of input bridge rectifier is connected to battery negative		
Charge algorithm	Constant current then constant voltage		
Current adjustment	Front panel knob or optional connection on rear		
Voltage adjustment	Front panel recessed 20 turn trim pot (20 volts per turn) or optional digipot		
Charge timer modes	NO timeout		
	Starts at Constant Current Stage		
	Starts at Constant Voltage Stage		
	Starts when first BMS unit commands it		
Charge timer settings	Zero to 150 minutes in 10 minute increments		
Switching frequency	50 kHz		
Power factor into 400V	Typically >.99		
Efficiency into 400V	Typically >90%		
Full power current ripple (peak to peak)	2X the average DC value		

*All PFC-30 & 40 chargers are buck enhanced so a PFC-30 is capable of moving up to 40A into a low voltage pack but a PFC-40 is better for H.V. packs. Maximum power levels are 4.8kW, 7.2kW and 9.6kW for PFC-20, 30 and 40 respectively. Detailed power input and output graphs are available at: manzanitamicro.com

Appendix E - Tables

Properties of air at 1 atm pressure

Temp. $T, ^\circ\text{C}$	Density $\rho, \text{kg/m}^3$	Specific Heat $c_p, \text{J/kg}\cdot\text{K}$	Thermal Conductivity $k, \text{W/m}\cdot\text{K}$	Thermal Diffusivity $\alpha, \text{m}^2/\text{s}$	Dynamic Viscosity $\mu, \text{kg/m}\cdot\text{s}$	Kinematic Viscosity $\nu, \text{m}^2/\text{s}$	Prandtl Number Pr
-150	2.866	983	0.01171	4.158×10^{-6}	8.636×10^{-6}	3.013×10^{-6}	0.7246
-100	2.038	966	0.01582	8.036×10^{-6}	1.189×10^{-5}	5.837×10^{-6}	0.7263
-50	1.582	999	0.01979	1.252×10^{-5}	1.474×10^{-5}	9.319×10^{-6}	0.7440
-40	1.514	1002	0.02057	1.356×10^{-5}	1.527×10^{-5}	1.008×10^{-5}	0.7436
-30	1.451	1004	0.02134	1.465×10^{-5}	1.579×10^{-5}	1.087×10^{-5}	0.7425
-20	1.394	1005	0.02211	1.578×10^{-5}	1.630×10^{-5}	1.169×10^{-5}	0.7408
-10	1.341	1006	0.02288	1.696×10^{-5}	1.680×10^{-5}	1.252×10^{-5}	0.7387
0	1.292	1006	0.02364	1.818×10^{-5}	1.729×10^{-5}	1.338×10^{-5}	0.7362
5	1.269	1006	0.02401	1.880×10^{-5}	1.754×10^{-5}	1.382×10^{-5}	0.7350
10	1.246	1006	0.02439	1.944×10^{-5}	1.778×10^{-5}	1.426×10^{-5}	0.7336
15	1.225	1007	0.02476	2.009×10^{-5}	1.802×10^{-5}	1.470×10^{-5}	0.7323
20	1.204	1007	0.02514	2.074×10^{-5}	1.825×10^{-5}	1.516×10^{-5}	0.7309
25	1.184	1007	0.02551	2.141×10^{-5}	1.849×10^{-5}	1.562×10^{-5}	0.7296
30	1.164	1007	0.02588	2.208×10^{-5}	1.872×10^{-5}	1.608×10^{-5}	0.7282
35	1.145	1007	0.02625	2.277×10^{-5}	1.895×10^{-5}	1.655×10^{-5}	0.7268
40	1.127	1007	0.02662	2.346×10^{-5}	1.918×10^{-5}	1.702×10^{-5}	0.7255
45	1.109	1007	0.02699	2.416×10^{-5}	1.941×10^{-5}	1.750×10^{-5}	0.7241
50	1.092	1007	0.02735	2.487×10^{-5}	1.963×10^{-5}	1.798×10^{-5}	0.7228
60	1.059	1007	0.02808	2.632×10^{-5}	2.008×10^{-5}	1.896×10^{-5}	0.7202
70	1.028	1007	0.02881	2.780×10^{-5}	2.052×10^{-5}	1.995×10^{-5}	0.7177
80	0.9994	1008	0.02953	2.931×10^{-5}	2.096×10^{-5}	2.097×10^{-5}	0.7154
90	0.9718	1008	0.03024	3.086×10^{-5}	2.139×10^{-5}	2.201×10^{-5}	0.7132
100	0.9458	1009	0.03095	3.243×10^{-5}	2.181×10^{-5}	2.306×10^{-5}	0.7111
120	0.8977	1011	0.03235	3.565×10^{-5}	2.264×10^{-5}	2.522×10^{-5}	0.7073
140	0.8542	1013	0.03374	3.898×10^{-5}	2.345×10^{-5}	2.745×10^{-5}	0.7041
160	0.8148	1016	0.03511	4.241×10^{-5}	2.420×10^{-5}	2.975×10^{-5}	0.7014
180	0.7788	1019	0.03646	4.593×10^{-5}	2.504×10^{-5}	3.212×10^{-5}	0.6992
200	0.7459	1023	0.03779	4.954×10^{-5}	2.577×10^{-5}	3.455×10^{-5}	0.6974
250	0.6746	1033	0.04104	5.890×10^{-5}	2.760×10^{-5}	4.091×10^{-5}	0.6946
300	0.6158	1044	0.04418	6.871×10^{-5}	2.934×10^{-5}	4.765×10^{-5}	0.6935
350	0.5664	1056	0.04721	7.892×10^{-5}	3.101×10^{-5}	5.475×10^{-5}	0.6937
400	0.5243	1069	0.05015	8.951×10^{-5}	3.261×10^{-5}	6.219×10^{-5}	0.6948
450	0.4880	1081	0.05298	1.004×10^{-4}	3.415×10^{-5}	6.997×10^{-5}	0.6965
500	0.4565	1093	0.05572	1.117×10^{-4}	3.563×10^{-5}	7.806×10^{-5}	0.6986
600	0.4042	1115	0.06093	1.352×10^{-4}	3.846×10^{-5}	9.515×10^{-5}	0.7037
700	0.3627	1135	0.06581	1.598×10^{-4}	4.111×10^{-5}	1.133×10^{-4}	0.7092
800	0.3289	1153	0.07037	1.855×10^{-4}	4.362×10^{-5}	1.326×10^{-4}	0.7149
900	0.3008	1169	0.07465	2.122×10^{-4}	4.600×10^{-5}	1.529×10^{-4}	0.7206
1000	0.2772	1184	0.07868	2.398×10^{-4}	4.826×10^{-5}	1.741×10^{-4}	0.7260
1500	0.1990	1234	0.09599	3.908×10^{-4}	5.817×10^{-5}	2.922×10^{-4}	0.7478
2000	0.1553	1264	0.11113	5.664×10^{-4}	6.630×10^{-5}	4.270×10^{-4}	0.7539

Note: For ideal gases, the properties c_p , k , μ , and Pr are independent of pressure. The properties ρ , ν , and α at a pressure P (in atm) other than 1 atm are determined by multiplying the values of ρ at the given temperature by P and by dividing ν and α by P .

Source: Data generated from the EES software developed by S. A. Klein and F. L. Alvarado. Original sources: Keenan, Chao, Keyes, Gas Tables, Wiley, 1984; and Thermophysical Properties of Matter, Vol. 3: Thermal Conductivity, Y. S. Touloukian, P. E. Liley, S. C. Saxena, Vol. 11: Viscosity, Y. S. Touloukian, S. C. Saxena, and P. Hestermans, IFI/Plenum, NY, 1970, ISBN 0-306067020-8.

Empirical correlations for the average Nusselt number for natural convection over surfaces

Geometry	Characteristic length L_c	Range of Ra	Nu
Vertical plate 	L	10^4-10^9 10^9-10^{13} Entire range	$Nu = 0.59Ra_L^{1/4}$ (9-19) $Nu = 0.1Ra_L^{1/3}$ (9-20) $Nu = \left\{ 0.825 + \frac{0.387Ra_L^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{8/27}} \right\}^2$ (9-21) (complex but more accurate)
Inclined plate 	L		Use vertical plate equations for the upper surface of a cold plate and the lower surface of a hot plate Replace g by $g \cos \theta$ for $Ra < 10^9$
Horizontal plate (Surface area A and perimeter p) (a) Upper surface of a hot plate (or lower surface of a cold plate) 	A_s/p	10^4-10^7 10^7-10^{11}	$Nu = 0.54Ra_L^{1/4}$ (9-22) $Nu = 0.15Ra_L^{1/3}$ (9-23)
(b) Lower surface of a hot plate (or upper surface of a cold plate) 		10^5-10^{11}	$Nu = 0.27Ra_L^{1/4}$ (9-24)
Vertical cylinder 	L		A vertical cylinder can be treated as a vertical plate when $D \geq \frac{35L}{Gr_L^{1/4}}$
Horizontal cylinder 	D	$Ra_D \leq 10^{12}$	$Nu = \left\{ 0.6 + \frac{0.387Ra_D^{1/6}}{[1 + (0.559/Pr)^{9/16}]^{8/27}} \right\}^2$ (9-25)
Sphere 	D	$Ra_D \leq 10^{11}$ $(Pr \geq 0.7)$	$Nu = 2 + \frac{0.589Ra_D^{1/4}}{[1 + (0.469/Pr)^{9/16}]^{4/9}}$ (9-26)

Heat transfer equations

$$\dot{g}_{cell} = \frac{I}{V} \left[(V_{oc} - V) - T \frac{dV_{oc}}{dt} \right] \quad \text{Eqn. 3.1}$$

Where:

$\dot{g}$ = Cell heat generation, W/m³

I = Operational current, A

V = Operational voltage, V

V = Battery volume, m³

V_{oc} = Open Circuit Potential (OCP) of the battery, V

t = Time, s

$$\dot{g}_{cell} = \frac{I}{V} (V_{oc} - V) \quad \text{Eqn. 3.2}$$

$$\dot{Q} = \dot{g}_{cell} \times V = I(V_{oc} - V) \quad \text{Eqn. 3.3}$$

$$Q_{Total} = Q_A + Q_B + Q_C \quad \text{Eqn. 3.4}$$

$$Q_A = h_A A_A (T_{cell} - T_{\infty}) \quad \text{Eqn. 3.5}$$

$$Q_B = h_B A_B (T_{cell} - T_{\infty}) \quad \text{Eqn. 3.6}$$

$$Q_C = h_C A_C (T_{cell} - T_{\infty}) \quad \text{Eqn. 3.7}$$

Where:

Q_{Total} = Total battery module cooling capacity, W

Q_A = Heat flow through Cooling Channel (Flow A), W

Q_B = Heat flow through Cell Connector (Flow B), W

Q_C = Heat flow through End Plate (Flow C), W

T_{cell} = Temperature of cell surface, K

T_{∞} = Temperature at surrounding, K

h_A = Heat transfer coefficient of cooling channel, W/m². K

A_A = Surface area of cooling channel, m²

h_B = Heat transfer coefficient of cell connector, W/m². K

A_B = Surface area of cell connector, m²

h_C = Heat transfer coefficient of end plate, W/m². K

A_C = Surface area of end plate, m²

$$T_f = \frac{(T_{cell} + T_{\infty})}{2} = \frac{(311 + 298)}{2} = 304.5 \text{ K} = 31.5 \text{ }^{\circ}\text{C} \quad \text{Eqn. 3.8}$$

$$D_h = \frac{2ab}{a + b} = \frac{2 \times 0.007 \times 0.006}{0.007 + 0.006} = 0.00646 \text{ m} \quad \text{Eqn. 3.9}$$

Where:

a = Width of duct opening, m

b = Height of duct opening, m

$$Re = \frac{\mathcal{V}D_h}{\nu} = \frac{8 \times 0.00646}{1.6221 \times 10^{-5}} = 3186.75 \quad \text{Eqn. 3.10}$$

Where:

$\mathcal{V}$ = Mean velocity in pipe, m/s

ν = Kinematic viscosity, m²/s

$$f = (0.790 \ln Re - 1.64)^{-2} = 0.04464 \quad \text{Eqn. 3.11}$$

$$Nu = \frac{h_A D_h}{k} = \frac{(f/8)(Re - 1000)Pr}{1 + 12.7 \left(\frac{f}{8}\right)^{0.5} (Pr^{\frac{2}{3}} - 1)} = 10.845 \quad \text{Eqn. 3.12}$$

Where:

k = Thermal conductivity of air, W/m.K

$$A_A = pL = 2(a + b)L = 2 \times (0.006 + 0.007) \times 0.125 \quad \text{Eqn. 3.13}$$

$$A_A = 0.00325 \text{ m}^2$$

Where:

p = Perimeter of duct, m

L = Length of duct, m

$$A_B = \eta A_{fins} + A_{base} \quad \text{Eqn.}$$

3.14

$$A_{fins} = 12(0.009 \times 0.038) + 6(0.0017 \times 0.038)$$

$$A_{fins} = 4.4916 \times 10^{-3} \text{ m}^2$$

$$A_{base} = 4(0.0017 \times 0.038) + (0.012 \times 0.038)$$

$$A_{base} = 7.144 \times 10^{-4} \text{ m}^2$$

$$A_B = (0.8176 \times 4.4916 \times 10^{-3}) + 7.144 \times 10^{-4}$$

$$A_B = 0.0131 \text{ m}^2$$

Where:

A_{fins} = Total finned area of heatsink, m²

A_{base} = Total area of non-finned heatsink, m²

$$Re^* = Re \cdot \frac{g}{L} = \frac{\rho \mathcal{V} g}{\mu} \cdot \frac{g}{L} = \frac{1.184 \times 8 \times 0.0017^2}{1.849 \times 10^{-5} \times 0.038} = 38.960 \quad \text{Eqn. 3.15}$$

Where:

ρ = Density of air, kg/m³

$\mathcal{V}$ = Velocity of air, m/s

g = Fin gap, m

μ = Dynamic viscosity, kg/m.s

L = Heat sink length, m

$$Nu = \frac{h_B g}{k} = \left[\left(\frac{Re^* Pr}{2} \right)^{-3} + \left(0.664 \sqrt{Re^*} \cdot Pr^{1/3} \sqrt{1 + \frac{3.65}{\sqrt{Re^*}}} \right)^{-3} \right]^{-1/3} \quad \text{Eqn. 3.16}$$

$$Nu = 4.498$$

Where:

k = Thermal conductivity of air at 31.5°C, W/m.K

$$\eta = \frac{\tanh(mH)}{mH} = \frac{\tanh(22.011 \times 0.009)}{22.011 \times 0.009} = 0.8176 \quad \text{Eqn. 3.17}$$

$$m = \sqrt{\frac{2h}{k_{alu}t}} = \sqrt{\frac{2 \times 68.777}{167 \times 0.0017}} = 22.011 \quad \text{Eqn. 3.18}$$

Where:

H = Fin height, m

k = Thermal conductivity of aluminium = 167 W/m.K [47]

t = Thickness of fin, m

Appendix F - Data Acquisition System

System diagram of Arduino to Multiplexer setup

Arduino code for temperature measurment

[illegible]

```

    // don't do anything more:
    return;
}
Serial.println("card initialized.");
}
//2,3,4,5,6,7,8,9,10
//pin 2 corresponds to first demultiplexer (demux1)
void demux1() //enable pin 2
{digitalWrite(2,LOW);
digitalWrite(3,HIGH);
digitalWrite(4,HIGH);
digitalWrite(5,HIGH);
digitalWrite(6,HIGH);
digitalWrite(7,HIGH);
digitalWrite(8,HIGH);
digitalWrite(9,HIGH);
digitalWrite(10,HIGH);}

void demux2() //enable pin 3
{digitalWrite(2,HIGH);
digitalWrite(3,LOW);
digitalWrite(4,HIGH);
digitalWrite(5,HIGH);
digitalWrite(6,HIGH);
digitalWrite(7,HIGH);
digitalWrite(8,HIGH);
digitalWrite(9,HIGH);
digitalWrite(10,HIGH);}

void demux3() //enable pin 4
{digitalWrite(2,HIGH);
digitalWrite(3,HIGH);
digitalWrite(4,LOW);
digitalWrite(5,HIGH);
digitalWrite(6,HIGH);
digitalWrite(7,HIGH);
digitalWrite(8,HIGH);
digitalWrite(9,HIGH);
digitalWrite(10,HIGH);}

void demux4() //enable pin 5
{digitalWrite(2,HIGH);
digitalWrite(3,HIGH);
digitalWrite(4,HIGH);
digitalWrite(5,LOW);
digitalWrite(6,HIGH);

```

```

digitalWrite(7,HIGH);
digitalWrite(8,HIGH);
digitalWrite(9,HIGH);
digitalWrite(10,HIGH);}

void demux5() //enable pin 6

{digitalWrite(2,HIGH);
digitalWrite(3,HIGH);
digitalWrite(4,HIGH);
digitalWrite(5,HIGH);
digitalWrite(6,LOW);
digitalWrite(7,HIGH);
digitalWrite(8,HIGH);
digitalWrite(9,HIGH);
digitalWrite(10,HIGH);}

void demux6() //enable pin 7

{digitalWrite(2,HIGH);
digitalWrite(3,HIGH);
digitalWrite(4,HIGH);
digitalWrite(5,HIGH);
digitalWrite(6,HIGH);
digitalWrite(7,LOW);
digitalWrite(8,HIGH);
digitalWrite(9,HIGH);
digitalWrite(10,HIGH);}

void demux7() //enable pin 8

{digitalWrite(2,HIGH);
digitalWrite(3,HIGH);
digitalWrite(4,HIGH);
digitalWrite(5,HIGH);
digitalWrite(6,HIGH);
digitalWrite(7,HIGH);
digitalWrite(8,LOW);
digitalWrite(9,HIGH);
digitalWrite(10,HIGH);}

void demux8()

{digitalWrite(2,HIGH);
digitalWrite(3,HIGH);
digitalWrite(4,HIGH);
digitalWrite(5,HIGH);
digitalWrite(6,HIGH);
digitalWrite(7,HIGH);

```

```

digitalWrite(8,HIGH);
digitalWrite(9,LOW);
digitalWrite(10,HIGH);}

void demux9()

{digitalWrite(2,HIGH);
digitalWrite(3,HIGH);
digitalWrite(4,HIGH);
digitalWrite(5,HIGH);
digitalWrite(6,HIGH);
digitalWrite(7,HIGH);
digitalWrite(8,HIGH);
digitalWrite(9,HIGH);
digitalWrite(10,LOW);}

void setPin(int outputPin)
// function to select pin on 74HC4067
{ //digitalWrite(x, HIGH);
PORTC = controlPins[outputPin];
//digitalWrite(x, LOW);
}
void displayData1()

// dumps captured data from array to serial monitor
{
Serial.println();
Serial.println("Values from multiplexer:");
Serial.println("=====111111111111111111111111");
for (int i = 0; i < 16; i++)
{Serial.print("input I");
Serial.print(i);
Serial.print(" = ");
Serial.println(muxValues[i]);
}
Serial.println("=====");
}
void displayData2()
// dumps captured data from array to serial monitor
{Serial.println();
Serial.println("Values from multiplexer:");
Serial.println("=====222222222222222222222222");
for (int i = 0; i < 16; i++)
{
Serial.print("input I");
Serial.print(i);
Serial.print(" = ");

```

```

    Serial.println(muxValues[i]);
}
Serial.println("=====");
}
void displayData3()
// dumps captured data from array to serial monitor
{
    Serial.println();
    Serial.println("Values from multiplexer:");
    Serial.println("=====333333333333333333333333");
    for (int i = 0; i < 16; i++)
    {
        Serial.print("input I");
        Serial.print(i);
        Serial.print(" = ");
        Serial.println(muxValues[i]);
    }
    Serial.println("=====");
}

void displayData4()
// dumps captured data from array to serial monitor
{
    Serial.println();
    Serial.println("Values from multiplexer:");
    Serial.println("=====4444444444444444444444444444");
    for (int i = 0; i < 16; i++)
    {
        Serial.print("input I");
        Serial.print(i);
        Serial.print(" = ");
        Serial.println(muxValues[i]);
    }
    Serial.println("=====");
}

void displayData5()
// dumps captured data from array to serial monitor
{
    Serial.println();
    Serial.println("Values from multiplexer:");
    Serial.println("=====555555555555555555555555");
    for (int i = 0; i < 16; i++)
    {
        Serial.print("input I");
        Serial.print(i);
        Serial.print(" = ");

```

```

Serial.println(muxValues[i]);
}
Serial.println("=====");
}

void displayData6()
// dumps captured data from array to serial monitor
{
Serial.println();
Serial.println("Values from multiplexer:");
Serial.println("=====666666666666666666666666");
for (int i = 0; i < 16; i++)
{
Serial.print("input I");
Serial.print(i);
Serial.print(" = ");
Serial.println(muxValues[i]);
}
Serial.println("=====");
}

void displayData7()
// dumps captured data from array to serial monitor
{
Serial.println();
Serial.println("Values from multiplexer:");
Serial.println("=====777777777777777777777777");
for (int i = 0; i < 16; i++)
{
Serial.print("input I");
Serial.print(i);
Serial.print(" = ");
Serial.println(muxValues[i]);
}
Serial.println("=====");
}

void displayData8()
// dumps captured data from array to serial monitor
{
Serial.println();
Serial.println("Values from multiplexer:");
Serial.println("=====888888888888888888888888");
for (int i = 0; i < 16; i++)
{
Serial.print("input I");
Serial.print(i);

```



```

delay(50);
muxValues[i]=analogRead(A0); // read the vlaue on that pin and store in array
delay(50);
muxValues[i]= log(10000.0*((1024.0/muxValues[i]-1)));
muxValues[i]= 1 / (0.001129148 + (0.000234125 + (0.0000000876741 * muxValues[i] *
muxValues[i] ))* muxValues[i]);
muxValues[i] = muxValues[i]-273.15;
//test
delay(50);
dataFile.print(muxValues[i]);
dataFile.print(",");
}
// display captured data
displayData2();
delay(1000);

//-----

demux3();
for (int i = 0; i < 16; i++){
setPin(i); // choose an input pin on the 74HC4067
delay(50);
muxValues[i]=analogRead(A0); // read the vlaue on that pin and store in array
delay(50);
//test
muxValues[i]= log(10000.0*((1024.0/muxValues[i]-1)));
muxValues[i]= 1 / (0.001129148 + (0.000234125 + (0.0000000876741 * muxValues[i] *
muxValues[i] ))* muxValues[i]);
muxValues[i] = muxValues[i]-273.15;
//test
delay(50);
dataFile.print(muxValues[i]);
dataFile.print(",");}
// display captured data
displayData3();
delay(1000);
//-----

demux34);
for (int i = 0; i < 16; i++){
setPin(i); // choose an input pin on the 74HC4067
delay(50);
muxValues[i]=analogRead(A0); // read the vlaue on that pin and store in array
delay(50);
//test
muxValues[i]= log(10000.0*((1024.0/muxValues[i]-1)));
muxValues[i]= 1 / (0.001129148 + (0.000234125 + (0.0000000876741 * muxValues[i] *

```

```

muxValues[i ]) * muxValues[i]);
muxValues[i] = muxValues[i]-273.15;
//test
delay(50);
dataFile.print(muxValues[i]);
dataFile.print(",");}
// display captured data
displayData4();
delay(1000);
//-----

demux5();
for (int i = 0; i < 16; i++){
setPin(i); // choose an input pin on the 74HC4067
delay(50);
muxValues[i]=analogRead(A0); // read the value on that pin and store in array
delay(50);
//test
muxValues[i]= log(10000.0*((1024.0/muxValues[i]-1)));
muxValues[i]= 1 / (0.001129148 + (0.000234125 + (0.0000000876741 * muxValues[i] *
muxValues[i] )) * muxValues[i]);
muxValues[i] = muxValues[i]-273.15;
//test
delay(50);
dataFile.print(muxValues[i]);
dataFile.print(",");}
// display captured data
displayData5();
delay(1000);
//-----

demux6();
for (int i = 0; i < 16; i++){
setPin(i); // choose an input pin on the 74HC4067
delay(50);
muxValues[i]=analogRead(A0); // read the vlaue on that pin and store in array
delay(50);
//test
muxValues[i]= log(10000.0*((1024.0/muxValues[i]-1)));
muxValues[i]= 1 / (0.001129148 + (0.000234125 + (0.0000000876741 * muxValues[i] *
muxValues[i] )) * muxValues[i]);
muxValues[i] = muxValues[i]-273.15;
//test
delay(50);
dataFile.print(muxValues[i]);
dataFile.print(",");}
// display captured data

```

```

displayData6();
delay(1000);
//-----

demux7();
for (int i = 0; i < 16; i++){
  setPin(i); // choose an input pin on the 74HC4067
  delay(50);
  muxValues[i]=analogRead(A0); // read the vlaue on that pin and store in array
  delay(50);
  //test
  muxValues[i]= log(10000.0*((1024.0/muxValues[i]-1)));
  muxValues[i]= 1 / (0.001129148 + (0.000234125 + (0.0000000876741 * muxValues[i] *
  muxValues[i] ))* muxValues[i]);
  muxValues[i] = muxValues[i]-273.15;
  //test
  delay(50);
  dataFile.print(muxValues[i]);
  dataFile.print(",");
  // display captured data
  displayData7();
  delay(1000);
  //-----

  demux8();
  for (int i = 0; i < 16; i++){
    setPin(i); // choose an input pin on the 74HC4067
    delay(50);
    muxValues[i]=analogRead(A0); // read the vlaue on that pin and store in array
    delay(50);
    //test
    muxValues[i]= log(10000.0*((1024.0/muxValues[i]-1)));
    muxValues[i]= 1 / (0.001129148 + (0.000234125 + (0.0000000876741 * muxValues[i] *
    muxValues[i] ))* muxValues[i]);
    muxValues[i] = muxValues[i]-273.15;
    //test
    delay(50);
    dataFile.print(muxValues[i]);
    dataFile.print(",");
    // display captured data
    displayData8();
    delay(1000);
    //-----

    demux9();
    for (int i = 0; i < 16; i++){
      setPin(i); // choose an input pin on the 74HC4067

```

```

delay(50);
muxValues[i]=analogRead(A0); // read the vlaue on that pin and store in array
delay(50);
//test
muxValues[i]= log(10000.0*((1024.0/muxValues[i]-1)));
muxValues[i]= 1 / (0.001129148 + (0.000234125 + (0.0000000876741 * muxValues[i] *
muxValues[i] ))* muxValues[i]);
muxValues[i] = muxValues[i]-273.15;
//test
delay(50);
dataFile.print(muxValues[i]);
dataFile.print(",");}
// display captured data
displayData9();
delay(1000);
//-----

dataFile.println("");
dataFile.close();
}
else {
Serial.println("error opening datalog.txt");
}}

```

Converter code for calibration of thermistor

```
analogTempConverter | Arduino 1.6.5
File Edit Sketch Tools Help

analogTempConverter$
1 void setup() {
2   // put your setup code here, to run once:
3   float muxValues;
4   Serial.begin(9600);
5 }
6 void loop() {
7   while (Serial.available() == 0);
8   float muxValues = Serial.parseFloat(); //read int or parseFloat for ..float...
9   Serial.println("original number");
10  Serial.println(muxValues);
11  muxValues= log(10000.0*((1024.0/muxValues-1)));
12  muxValues= 1 / (0.001129148 + (0.000234125 + (0.0000000876741 * muxValues * muxValues ))* muxValues);
13  muxValues= muxValues-273.15;
14  Serial.println("converted number");
15  Serial.println(muxValues);
16  Serial.println("");
17  Serial.println("");
18  Serial.println("");
19 }
```


Appendix G - Test Rig System

Thermal enclosure

Figure G-1: Thermal enclosure, pictured with battery module in place

Figure G-2: Close up image of insulation foam and plywood wall

Battery cooling fan

Figure G-3: Cooling fan installed with cone air filter

Inlet and outlet air ducts

Figure G-4: Completed fan ducts made by 3D printing process

Figure G-5: Cooling fan and fan duct installation into test rig