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**AND**

**MECHANICAL ENGINEERING**

# THERMOMECHANICAL ANALYSIS OF ELECTIC VEHICLE BATTERY PACKS

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# ABSTRACT

The Battery Thermal Management System (BTMS) plays a crucial role in Electric Vehicles' (EVs) performance, safety, and longevity. The BTMS controls the battery temperature and prevents overheating or overcooling of the battery, which can lead to reduced efficiency, degradation, and even failure. The BTMS also ensures safe operation of the battery under various environmental conditions and driving scenarios. In recent years, there have been significant advancements in BTMS technology, including the use of advanced materials, improved cooling systems, and more refined control algorithms. These advancements have enabled EVs to achieve longer driving ranges, faster charging times, and improved overall performance. However, the design and implementation of a BTMS for EVs require careful consideration of various factors, such as the size and capacity of the battery, the operating conditions, and the desired performance targets. Moreover, the cost and complexity of the BTMS must be balanced against the benefits it provides. This abstract provides an overview of the design of BTMS in EVs, the recent advancements in BTMS technology, and the key factors that must be considered in the design and implementation of a BTMS for EVs.

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# CHAPTER 1

# INTRODUCTION

## BATTERY THERMAL MANAGEMENT SYSTEM

Battery Thermal Management Systems (BTMS) are essential components of electric vehicle battery packs that regulate the temperature of the battery cells. Maintaining the optimal temperature range is critical for the battery pack’s performance, longevity, and safety. The operating temperature range for the battery pack varies depending on the specific chemistry of the battery cells, so effective BTMS are crucial to ensure optimal performance. BTMS in electric vehicles use either liquid cooling, air cooling, or a combination of both to manage the temperature of the battery pack. Liquid cooling systems can provide more efficient temperature regulation, while air cooling systems are less expensive but not as efficient. Some electric vehicles use a combination of both air and liquid cooling systems to achieve optimal cooling. BTMS in electric vehicles also use thermal management software to optimize the temperature of the battery pack. The software monitors the temperature of the battery pack and adjusts the cooling or heating systems as necessary to maintain the battery pack within the optimal temperature range. Additionally, the software can help to identify hotspots in the battery pack, which can lead to thermal runaway, a potentially hazardous condition where the temperature of the battery pack rises uncontrollably. Effective BTMS are crucial for optimal battery pack performance, longevity, and safety. They can help to reduce the risk of thermal runaway, extend the battery pack's lifespan, and improve the vehicle's overall driving range. As electric vehicles become more popular, the development of more efficient and cost-effective BTMS will be critical to their success.

## 1.1 Importance of BTMS

Thermomechanical design and analysis are important for EV battery packs as they ensure that the battery operates within safe temperature and stress limits. High temperatures can accelerate battery degradation, leading to reduced capacity and shorter lifespan. Excessive stress on the battery pack due to thermal expansion and contraction can also cause mechanical damage and decrease the pack's structural integrity. By performing thermomechanical analysis, engineers can identify potential design issues and address them before the battery is manufactured, ensuring that the battery pack is safe, reliable, and efficient. Proper thermomechanical design and analysis can also improve the battery's thermal management system, which is crucial for maintaining the battery's performance and prolonging its lifespan. Ultimately, this can lead to improved driving range, lower maintenance costs, and increased market competitiveness for EV manufacturers.

### 1.1.1 Safety:

Safety measures for electric vehicles (EVs) are critical, particularly when it comes to the battery packs. During normal operation, these battery packs can generate a substantial amount of heat, and if there is a malfunction or damage, this heat can escalate to an uncontrollable level, causing thermal runaway. In such cases, battery pack failure, fire, or even explosions can occur. the safety of EV battery packs is of utmost importance, and implementing proper thermomechanical design and analysis can help prevent potential risks and ensure the safety of the driver and passengers. It is crucial to educate drivers on battery safety and maintain the vehicle regularly to prevent battery-related accidents.

### 1.1.2 Performance:

Performance is a crucial factor to consider when it comes to electric vehicle (EV) battery packs. The performance of the battery pack is closely related to its temperature, as higher temperatures can significantly impact battery life and decrease the driving range. When the temperature of the battery pack increases, the internal resistance of the battery also increases, leading to a reduction in its capacity to deliver power.

Additionally, higher temperatures accelerate the chemical reactions within the battery, causing degradation of the active materials, which can ultimately lead to a shorter lifespan of the it is essential to optimize the thermomechanical design and analysis of the battery pack. This includes developing advanced thermal management systems that can regulate the temperature of the battery pack and ensure that it operates within an optimal temperature range. By doing so, the battery can maintain its performance, and its lifespan can be extended, resulting in a better overall driving experience for the EV owner.

Furthermore, optimizing the thermomechanical design and analysis of the battery pack can also help to reduce the weight and size of the battery, making it more compact and lightweight. This, in turn, can increase the energy density of the battery, allowing it to store more energy and provide longer driving ranges. Moreover, optimizing the design can also reduce the charging time, making it more convenient for the EV owner.

### 1.1.3 Cost:

Cost is a significant consideration when it comes to electric vehicle (EV) battery packs. Replacing or repairing a damaged battery pack can be an expensive undertaking, and an inefficient battery pack can lead to decreased driving range and increased maintenance costs. Therefore, it is crucial to have proper BTMS to prevent damage and improve battery pack efficiency, resulting in lower maintenance costs over time. Furthermore, the optimization of battery pack design can also lead to cost savings. For instance, developing lightweight and compact battery packs can reduce the overall weight of the vehicle, resulting in increased energy efficiency and longer driving ranges. Additionally, by improving the design of the battery pack, it can be produced more efficiently and at a lower cost.

### 1.1.4 Market competitiveness:

As the popularity of electric vehicles (EVs) continues to grow, the competition in the EV market is intensifying. To stay competitive, EV manufacturers must design and produce battery packs that are not only efficient and safe but also reliable and cost-effective.

One way for EV manufacturers to gain a competitive advantage is by optimizing the thermomechanical design and analysis of their battery packs. By developing advanced thermal management systems, implementing proper charging protocols, and optimizing the design of the battery pack, manufacturers can improve the overall efficiency of the battery pack, leading to longer driving ranges and reduced charging times. This, in turn, can make their EVs more attractive to potential customers and help them stand out in a crowded market.

## 1.2 Terminologies involved

Terminologies related to thermomechanical design and analysis of an EV battery pack:

1. Structural integrity
2. Thermal conductivity
3. Thermal modeling
4. Cyclic aging
5. Battery capacity fade
6. State of charge (SOC)
7. State of health (SOH)
8. Energy density
9. Power density
10. Depth of discharge (DOD)S

### 1.2.1 Structural integrity:

The structural integrity of a battery pack is crucial for the safe and reliable operation of the battery. A battery pack is typically made up of individual battery cells, which are connected together to form a larger unit. The cells are usually enclosed in a protective casing, which is designed to provide structural support and to protect the cells from damage.

One important consideration for the structural integrity of a battery pack is the mechanical strength of the casing. The casing should be strong enough to withstand the forces that can be generated during normal use and in the event of an accident. The casing should also be designed to prevent the cells from being crushed or punctured, which can cause a dangerous short circuit.

Another important consideration is the thermal management of the battery pack. Lithium-ion batteries are known to generate heat during use, and excessive heat can damage the cells and reduce their lifespan. Therefore, the casing should be designed to allow for efficient heat dissipation and to prevent the build-up of heat.

In addition, the electrical connections between the cells and the external circuitry must be secure and reliable. Any loose connections or faulty wiring can cause the battery to fail or to become a fire hazard.

### 1.2.2 Thermal conductivity:

Thermal conductivity refers to the ability of a material to conduct or transfer heat. In the context of a battery pack, thermal conductivity is an important consideration because batteries can generate heat during use, and excessive heat can damage the cells or reduce their lifespan.

The thermal conductivity of the materials used in a battery pack can affect how well the heat generated by the cells is dissipated. Materials with high thermal conductivity, such as copper or aluminum, are good at transferring heat, so they can help to dissipate the heat generated by the cells more efficiently.

The thermal conductivity of the materials used in a battery pack can also affect how hot the battery pack becomes during use. If the materials have low thermal conductivity, the heat generated by the cells may not be dissipated quickly enough, which can cause the temperature of the battery pack to rise. This can be a safety hazard, as high temperatures can damage the cells or even cause the battery pack to catch fire.

Therefore, it is important to consider the thermal conductivity of the materials used in a battery pack when designing and building the pack. Materials with high thermal conductivity should be used in areas where heat dissipation is important, such as the casing or the electrical connections between the cells. Additionally, the design of the battery pack should allow for efficient heat dissipation to prevent the build-up of heat within the pack.

### 1.2.3 Thermal modeling:

Thermal modeling refers to the process of using computer simulations and mathematical models to predict how heat will be generated and transferred within a battery pack. In the context of a battery pack, thermal modeling can be used to design and optimize the thermal management system to ensure that the cells are operating within safe temperature limits.

The thermal modeling process involves creating a mathematical model of the battery pack that includes details such as the size and shape of the pack, the number and arrangement of the cells, the thermal properties of the materials used in the pack, and the conditions under which the pack will be used. This model is then used to simulate the behavior of the battery pack under different conditions, such as different ambient temperatures, discharge rates, and charging rates.

The output of a thermal model can include information such as the temperature distribution within the battery pack, the rate of heat generation by the cells, and the effectiveness of the thermal management system. This data can be used to identify potential hot spots within the pack, optimize the design of the thermal management system, and ensure that the cells are operating within safe temperature limits.

Thermal modeling is an important tool for designing and testing battery packs because it allows designers to evaluate the performance of the pack under different conditions without the need for expensive and time-consuming physical testing. By using thermal modeling to optimize the design of the pack, designers can ensure that the pack will operate safely and reliably over its entire lifetime.

### 1.2.4 Cyclic aging:

Cyclic aging refers to the gradual deterioration of a battery's capacity over time, as a result of repeated charge and discharge cycles. In the context of a battery pack, cyclic aging can occur when the battery pack is used and recharged repeatedly, such as in an electric vehicle or a portable electronic device.

During each charge and discharge cycle, a small amount of the active materials within the battery cells is lost or degraded. Over time, this can lead to a reduction in the capacity of the cells, which can result in reduced performance and shorter battery life. The rate of cyclic aging can depend on a number of factors, such as the chemistry of the battery, the depth of discharge during each cycle, and the temperature at which the battery is operated.

One way to mitigate the effects of cyclic aging is to design the battery pack with a larger capacity than is required for the intended use. This can allow the pack to deliver the required performance even as its capacity gradually degrades over time. Additionally, the charging and discharging cycles can be managed to minimize the depth of discharge and to avoid high temperatures, which can accelerate the rate of cyclic aging.

Cyclic aging is an important consideration in the design and operation of battery packs, particularly in applications where the pack will be subjected to frequent charge and discharge cycles. By understanding the factors that contribute to cyclic aging, designers can optimize the performance and lifespan of the battery pack, and ensure that it meets the requirements of the intended application.

### 1.2.5 Battery capacity fade:

Battery capacity fade refers to the gradual reduction in the maximum amount of charge that a battery can hold over time. In the context of a battery pack, capacity fade can occur as a result of a number of factors, including repeated charge and discharge cycles, exposure to high temperatures, and aging of the active materials within the battery cells.

Capacity fade can be a significant issue for battery packs used in applications such as electric vehicles or portable electronics, where the performance of the battery pack is critical to the operation of the device. As the capacity of the battery pack decreases, the range or operating time of the device may also be reduced, which can impact its usability and functionality.

One way to mitigate the effects of capacity fade is to design the battery pack with a larger capacity than is required for the intended use. This can allow the pack to deliver the required performance even as its capacity gradually degrades over time. Additionally, the charging and discharging cycles can be managed to minimize the depth of discharge and to avoid high temperatures, which can accelerate the rate of capacity fade.

Other strategies for reducing the effects of capacity fade include using battery chemistries that are less prone to capacity fade, and incorporating monitoring systems that can detect and manage the performance of individual cells within the battery pack. By understanding the factors that contribute to capacity fade and implementing strategies to mitigate its effects, designers can optimize the performance and lifespan of the battery pack.

### 1.2.6 State of charge (SOC):

State of charge (SOC) refers to the amount of energy that is currently stored in a battery relative to its maximum capacity. In the context of a battery pack, SOC is typically expressed as a percentage, with 0% representing a fully discharged battery and 100% representing a fully charged battery.

Measuring the SOC of a battery pack is important for ensuring that the pack is operating within safe and optimal conditions. It can also be used to estimate the remaining operating time or range of the device that the battery pack is powering.

There are a number of different methods for measuring SOC, including coulomb counting, open circuit voltage (OCV) measurement, and model-based estimation. Coulomb counting involves measuring the amount of charge that has entered or left the battery during charging and discharging cycles. OCV measurement involves measuring the voltage of the battery when it is at rest, and using this value to estimate the SOC based on a calibration curve. Model-based estimation involves using mathematical models to predict the behavior of the battery under different conditions, and using this information to estimate the SOC.

Accurately measuring the SOC of a battery pack can be challenging, particularly for large or complex battery systems. However, accurate SOC measurement is essential for ensuring the safe and reliable operation of the battery pack over its.

### 1.2.7 State of health (SOH):

State of Health (SOH) refers to the overall health or condition of the battery, including its ability to store and deliver electrical energy compared to its original capacity. SOH is typically expressed as a percentage, with 100% indicating that the battery is operating at its full capacity, and a lower percentage indicating that the battery's capacity has degraded over time due to usage or other factors. Accurately measuring the SOH of a battery pack is important for determining its remaining lifespan and ensuring its safe and efficient operation.

### 1.2.8 Energy density:

Energy density refers to the amount of energy that can be stored in a given volume or mass of the battery. It is typically expressed in units of watt-hours per liter (Wh/L) or watt-hours per kilogram (Wh/kg). A higher energy density means that the battery can store more energy in a smaller volume or mass, which is desirable for applications where space and weight are limited, such as in electric vehicles and portable electronics. However, higher energy density batteries often come at the expense of other characteristics, such as safety, durability, and cost, and finding a balance between these factors is a key consideration when selecting a battery for a particular application.

### 1.2.9 Power Density:

Power density refers to the amount of power that can be delivered by a given volume or mass of the battery. It is typically expressed in units of watts per liter (W/L) or watts per kilogram (W/kg). A higher power density means that the battery can deliver more power in a smaller volume or mass, which is desirable for applications where high power output is required, such as in electric vehicles and power tools. However, like energy density, increasing power density can also come at the expense of other characteristics, such as safety and durability, and finding a balance between these factors is important when selecting a battery for a particular application.

### 1.2.10 Depth of discharge (DoD):

Depth of discharge (DoD) is a key metric used to measure the state of charge (SOC) of a battery pack. It is defined as the ratio of the amount of energy that has been removed from the battery to its total energy capacity. In other words, it represents the percentage of the battery's energy that has been used up at a particular point in time.

DoD is an important consideration when designing and using battery packs because it can have a significant impact on their lifespan and performance. Generally, operating a battery at a high DoD (i.e., discharging it deeply) can reduce its lifespan and increase the risk of failure. This is because deep discharging can cause chemical changes in the battery that can lead to degradation of its performance and capacity over time.

To maximize the lifespan and performance of a battery pack, it is often recommended to operate it within a particular range of DoD. This range may depend on the specific type of battery, the application, and other factors, but generally, it is best to avoid operating a battery at a DoD of 100% or close to it, and instead aim to keep it within a range of 20-80% or so. By controlling the DoD of a battery pack, it is possible to optimize its performance, reduce the risk of failure, and extend its lifespan.

# Chapter 2:

# Comparison Of Key Characteristic of Popular Rechargeable Battery

## 2.1 Lead-acid

Lead acid batteries are not typically used in electric vehicles (EVs) due to several disadvantages, including:

### 2.1.1 Low Energy Density:

Lead-acid batteries have a lower energy density compared to other battery technologies, such as lithium-ion. This means that they require more space to store the same amount of energy, which can be a major drawback in EVs where space is limited. As a result, lead-acid batteries can make the vehicle heavier and negatively impact range and performance.

### 2.1.2 Short Cycle Life:

Lead-acid batteries have a limited number of charge/discharge cycles, which means that they will degrade over time and need to be replaced sooner than other battery types. In comparison, lithium-ion batteries typically have a longer cycle life, meaning they can last for more cycles before needing to be replaced.

### 2.1.3 Slow Charging Time:

Lead-acid batteries have a slow charging time compared to other battery technologies. This means that it takes longer to charge them, which can be a disadvantage in EVs where fast charging is desirable. In contrast, lithium-ion batteries have a faster charging time, making them a more practical choice for EVs.

### 2.1.4 Low Efficiency:

Lead-acid batteries have a lower round-trip efficiency compared to other battery technologies, which means more energy is lost during the charging and discharging process. This can impact the overall efficiency and performance of the EV, and result in decreased range and reduced battery life.

### 2.1.5 Vulnerability to Extreme Temperatures:

Lead-acid batteries are vulnerable to extreme temperatures and can become damaged or even fail in hot or cold conditions. This can be a problem in EVs.

## 2.2 Nickel-cadmium (NiCad)

Batteries are not commonly used in electric vehicles (EVs) due to several disadvantages compared to other battery technologies, including:

### 2.2.1 Memory Effect:

NiCad batteries have a tendency to develop a "memory effect", where the battery only retains a partial charge if it is not fully discharged before being recharged. This can reduce the overall life and performance of the battery, and can be a major drawback for use in EVs.

### 2.2.2 Environmental Concerns:

NiCad batteries contain toxic metals, including cadmium, which can be harmful to the environment if not disposed of properly. This has led to regulations limiting their use in certain applications and has made them less appealing for use in EVs.

### 2.2.3 Low Energy Density:

NiCad batteries have a lower energy density compared to other battery technologies, such as lithium-ion. This means that they require more space to store the same amount of energy, which can be a major drawback in EVs where space is limited. As a result, NiCad batteries can make the vehicle heavier and negatively impact range and performance.

### 2.2.4 Short Cycle Life:

NiCad batteries have a limited number of charge/discharge cycles, which means that they will degrade over time and need to be replaced sooner than other battery types. In comparison, lithium-ion batteries typically have a longer cycle life, meaning they can last for more cycles before needing to be replaced.

### 2.2.5 High Cost:

NiCad batteries are more expensive to produce compared to other battery technologies, which can make them less appealing for use in EVs where cost is a major consideration.

## 2.3 NICKEL-METAL HYDRID

(NiMH) batteries are not commonly used in electric vehicles (EVs) for several reasons:

### 2.3.1 Limited Energy Density:

NiMH batteries have a limited energy density compared to other battery technologies, such as lithium-ion. This means that they require more space to store the same amount of energy, which can be a major drawback in EVs where space is limited. As a result, NiMH batteries can make the vehicle heavier and negatively impact range and performance.

### 2.3.2 High Self-Discharge Rate:

NiMH batteries have a higher self-discharge rate compared to other battery technologies, which means that they lose a significant amount of energy when not in use. This can be a disadvantage in EVs, as the battery needs to be fully charged when the vehicle is in use.

### 2.3.3 High Cost:

NiMH batteries are more expensive to produce compared to other battery technologies, which can make them less appealing for use in EVs where cost is a major consideration.

### 2.3.4 Limited Cycle Life:

NiMH batteries have a limited number of charge/discharge cycles, which means that they will degrade over time and need to be replaced sooner than other battery types. In comparison, lithium-ion batteries typically have a longer cycle life, meaning they can last for more cycles before needing to be replaced.

### 2.3.5 Vulnerability to Extreme Temperatures:

NiMH batteries are vulnerable to extreme temperatures and can become damaged or even fail in hot or cold conditions. This can be a problem in EVs, as the battery is a crucial component of the vehicle and needs to perform reliably in a variety of conditions.

## 2.4 Lithium-ion

(Li-ion) batteries have become the most popular choice for electric vehicles (EVs) due to several advantages they offer over other battery technologies. Some of the reasons why Li-ion batteries are most suitable for EVs include:

### 2.4.1 High energy density:

Li-ion batteries have a high energy density, which means they can store a large amount of energy in a small and lightweight package. This is important for EVs because it allows for smaller, lighter batteries that take up less space in the vehicle, leading to better weight distribution and improved range.

### 2.4.2 High power output:

Li-ion batteries are also capable of delivering high power output, which is important for quick acceleration and high-performance driving.

### 2.4.3 Long cycle life:

Li-ion batteries have a long cycle life, which means they can be charged and discharged many times without significant degradation. This is important for EVs because it means the battery can last for several years, potentially reducing the need for frequent replacement.

### 2.4.4 Low self-discharge rate:

Li-ion batteries have a low self-discharge rate, which means they can hold their charge for a long time when not in use.

### 2.4.5 No memory effect:

Li-ion batteries do not have a "memory effect," which means they can be charged and discharged at any time without affecting their overall performance.

## 2.5 Table of Comparison:

The table of comparison of different battery chemistries is given below.

| | **Specific** Energy (Wh/kg) | **Specific** Power (W/kg) | **Cycles** | **Maximum Depth of Discharge** | **Self-Discharge Rate** | **Availability** |
|---|---|---|---|---|---|---|
| **Lead Acid** | 35-50 | 150-400 | 250-500 | 20-80% | 2-8% per month, some 20- 30%per month | Easily available |
| **Nickel Cadmium** | 30 60 | 80-150 | 900 to1200 | 60-80% | 5-15% per month | Easily available<br>(Chance of Second hand is high) |
| **Nickel Metal Hydride** | 60-80 | 200-300 | 600-1200 | 60-80% | 15-<br>25% per month | Available<br>(But Chance of Second hand is low) |
| **Lithium-Ion** | 120-240 | 200-1000 | 1500-1800 | 100% | 2-10%/month | Available (But Chance of Second hand is low) |

**Figure 2.1**: Table of comparison of Batteries

## 2.6 Why Li-ion batteries are the most suitable?

Li-ion batteries are the most suitable for EVs due to their high energy density, high power output, long cycle life, low self-discharge rate, high operating temperature range, and lack of memory effect. These characteristics make Li-ion batteries an ideal choice for powering EVs and helping to make them a more practical and sustainable mode of transportation.

## 2.7 Impact of operating temperature on lithium-ion batteries

LIBs are susceptible to two types of temperature concerns: the operating temperature exceeds the permissible range, and low- temperature uniformity reduces battery life by causing localized degradation. LIBs must be operated within a narrow temperature range of 15–35˚C as seen in to deliver the optimum performance. When LIBs operate in temperatures outside their operating ranges, their safety, performance, and lifespan will all be impacted. Nonetheless, dreadful ambient conditions like extremely or elevated cold temperatures are inevitable in practical applications. The battery's performance will significantly deteriorate under these adverse conditions due to improper storage or operating temperature. During some extreme conditions, the battery may even suffer a thermal runaway (TR). In this section, the detrimental effects of inappropriate temperature on LIBs to better understand the relevance of

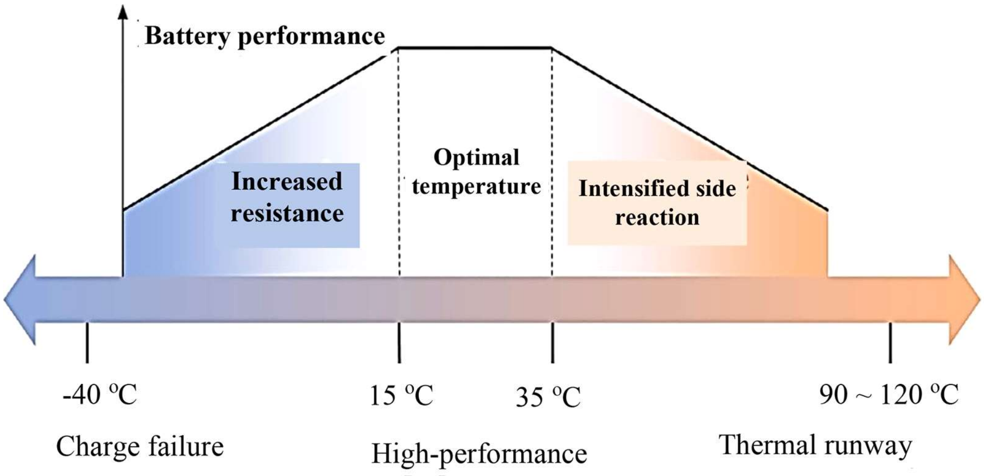


**Figure 2.2**: Temperature range for battery safety-[1]

# Chapter 3

# Types of cooling systems

For battery performance and lifespan, keeping the battery pack within the right temperature range is key. Different battery cooling methods for electric vehicle batteries that are used and the up and downsides of these methods.

## 3.1 Air cooling system:

By running air through the battery pack batteries can be cooled. For example, Nissan uses this technology to cool the batteries of the Nissan Leaf. They circulate the air from inside the car through the battery pack. With this system the batteries can be cooled but can also be heated during cold winter days. A downside to this system is that the temperature of the air inside the vehicle is also the temperature with which the batteries get cooled. When you turn up the heat inside the car because you are cold, the batteries get heated as well. This is sometimes not ideal, especially when high power is requested.

Another way of cooling the batteries with air is by guiding the outside air through ducts to the battery pack in the vehicle. In this case, the temperature of the batteries will fluctuate with the fluctuation of the temperature outside. During hot summer days, the batteries will rise in temperature as well. This is again a problem for high power applications since the risk of overheating the battery increases.

In most low to medium power applications, air cooling is sufficient. The power demanded from the drivetrain is not that high causing the battery temperature to stay around the surrounding temperature. Even when high power is demanded occasionally, air cooling will still be enough because the batteries will have more than enough time to cool down after a short high-power demand. When the demanded power gets higher, the air-cooling system will not be sufficient anymore. Let us look at some other types of cooling systems.

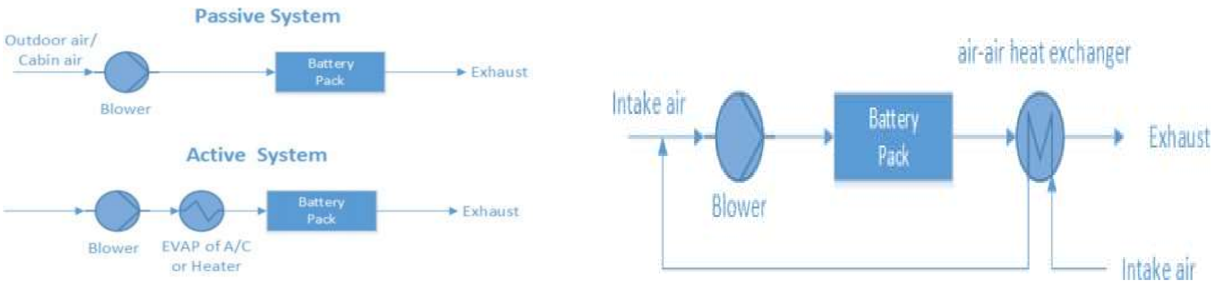


**FIGURE 3.1**. (a) Passive and Active Cooling System Model, (b) Air Cooling System-[2]

## 3.2 Liquid cooled system:

Liquid cooling is the most popular way of cooling a battery pack. A liquid cooling system consists of a lot more components then for example an air-cooling system. These components do make it possible to improve

22 the cooling performance by upgrading the components.

Electric vehicle manufacturers like Tesla and Audi use liquid cooling in their battery packs. This cooling system is a separate cooling system which only cools the battery pack, the motor and controller are cooled with a second liquid cooling system because of the temperature differences between the components. The battery pack needs to stay below 60 degrees Celsius, causing the temperature of the cooling fluid to stay as low as possible. The temperature of the motor and controller can reach temperatures as high as 140 degrees Celsius. When those three components share the same cooling system, the battery pack will be heated by the motor and controller. A separate cooling system for the battery pack is necessary.

Liquid cooling is the most favored solution for almost every battery pack. Whether it is a low power or high-power application, liquid cooling has the most advantages. With low power applications, the battery pack can be nursed so it will always operate at the right temperature. With high power applications the battery pack can be cooled to the maximum. The temperature of the cooling system must be kept as low as possible to enable maximum power for the longest time possible.Besides all these cooling advantages, the battery pack can be heated as well by adding a heating element in the cooling system.

The liquid cooling system of the battery pack and the cooling system of the motor and controller need to be separated. These two cooling systems can occasionally be combined to heat the battery pack when needed by the motor and controller. Tesla uses this method for example. They can heat the battery pack with the heat generated by the motor and controller. This is very useful during cold winter days.

## 3.3 Cooling with heat conducting materials:

Heat conducting materials, such as heat pipes can be used to withdraw heat from the battery pack. This is a slower way of cooling the batteries then when using liquid cooling. Also, metals like aluminium and copper are heat conducting materials. Unfortunately, this way of cooling is only one part of the cooling system instead of a complete one. When using this as the only cooling system, the heat conducting material needs to be very large. The heat conducting material has a certain heat capacity. This is the amount of heat that a material can absorb per weight of the material. For a large withdrawal of heat from the battery pack, the heat conducting material would need to be massive.

This means that this way of cooling will need to be combined with another cooling system such as the two systems mentioned earlier. The heat conducting material will guide the heat to the other cooling system.

## 3.4 Submersion Cooling system:

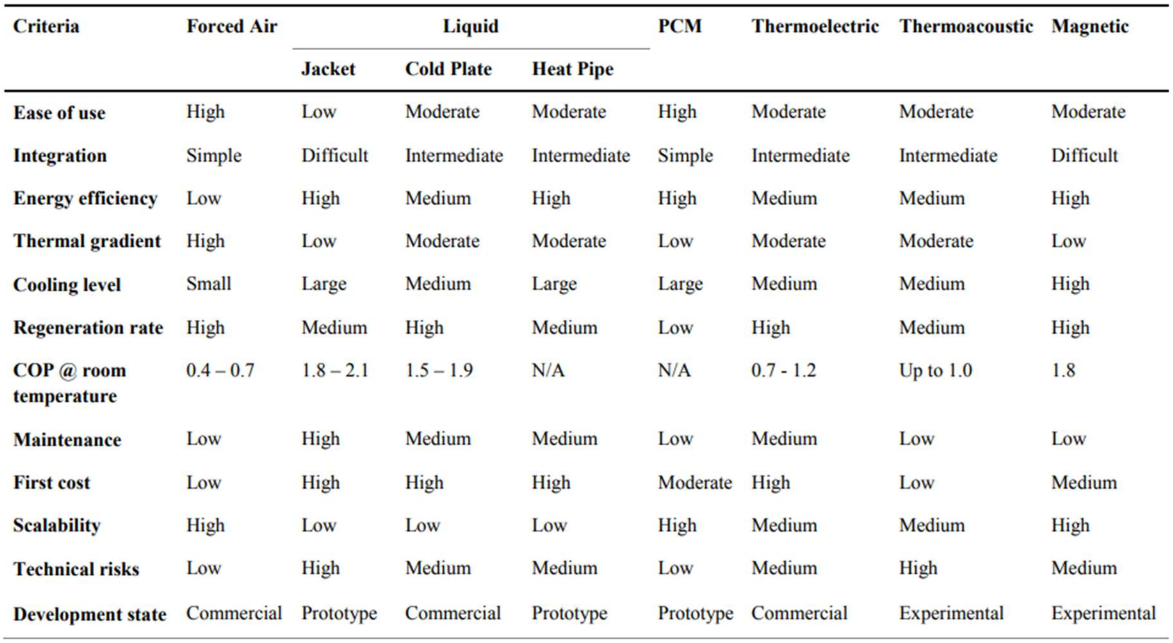
Another way of cooling a battery pack with liquid is to submerge the complete battery pack in the cooling fluid. This technology is already used in the world of supercomputers. However, this method is very expensive.

Another downside is that the amount of fluid used has a certain heat capacity. As explained before, this is the amount of heat that a material can absorb. By submerging the entire battery pack in a fluid, the fluid can only cool as much as the heat capacity allows it to. In other words, the fluid heats up together with the battery pack. The fluid just slows this process down.

In high-power applications this method of cooling will need to be combined with other types of cooling systems. For example, the housing can be made of aluminium which conducts heat very well. When air passes alongside this housing, the battery pack and the fluid inside can be cooled.

## 3.5 Table of comparison:

Tabular comparison of different cooling systems is shown below:



| **Criteria** | **Forced Air** | **Liquid** | | | **PCM** | **Thermoelectric** | **Thermoacoustic** | **Magnetic** |
|---|---|---|---|---|---|---|---|---|
| | | **Jacket** | **Cold Plate** | **Heat Pipe** | | | | |
| **Ease of use** | High | Low | Moderate | Moderate | High | Moderate | Moderate | Moderate |
| **Integration** | Simple | Difficult | Intermediate | Intermediate | Simple | Intermediate | Intermediate | Difficult |
| **Energy efficiency** | Low | High | Medium | High | High | Medium | Medium | High |
| **Thermal gradient** | High | Low | Moderate | Moderate | Low | Moderate | Moderate | Low |
| **Cooling level** | Small | Large | Medium | Large | Large | Medium | Medium | High |
| **Regeneration rate** | High | Medium | High | Medium | Low | High | Medium | High |
| **COP @ room temperature** | 0.4 – 0.7 | 1.8 – 2.1 | 1.5 – 1.9 | N/A | N/A | 0.7 - 1.2 | Up to 1.0 | 1.8 |
| **Maintenance** | Low | High | Medium | Medium | Low | Medium | Low | Low |
| **First cost** | Low | High | High | High | Moderate | High | Low | Medium |
| **Scalability** | High | Low | Low | Low | High | Medium | Medium | High |
| **Technical risks** | Low | High | Medium | Medium | Low | Medium | High | Medium |
| **Development state** | Commercial | Prototype | Commercial | Prototype | Prototype | Commercial | Experimental | Experimental |

**FIGURE 3.2:** Comparison of Batteries-[3]

## 3.6 Why did we choose liquid cooling?

Liquid battery cooling is a highly efficient and effective way to manage the temperature of batteries. Compared to other cooling methods like air, submersion, or phase change material cooling, liquid cooling has several advantages. One key advantage is its higher efficiency. Liquid cooling can absorb more heat than air cooling, thanks to its higher thermal conductivity and specific heat capacity. This means that it can transfer heat more effectively, which keeps the battery at a lower operating temperature.

Another advantage of liquid battery cooling is better thermal management. Liquid cooling can distribute heat more evenly throughout the battery, which reduces hotspots that can cause damage to the battery. This ensures better thermal management and extends the battery's lifespan. In addition, liquid cooling can keep the battery operating at a lower temperature compared to other cooling methods. This reduces the risk of thermal runaway, which can occur when batteries become too hot and cause a fire.

# Chapter 4:

# Design Parameters:

A battery thermal management system (BTMS) is designed to regulate the temperature of a battery system to ensure optimal performance, efficiency, and safety. The following are the key design parameters of a BTMS:

## 4.1 Battery chemistry:

Different battery chemistries have different temperature ranges for optimal performance and safety. The BTMS should be designed based on the specific chemistry of the battery. Since we have chosen li ion batteries due to large number of benefits they have over any alternative battery chemistries available the BTMS should be able to provide temperature range required for optimal performance of li ion batteries.

Proper thermal management of EV batteries (lithium-ion) is essential to maintain adequate and consistent performance of the battery and the vehicle. Excessive temperature will negatively affect an EV’s battery and its performance. Features that can be impacted include its electrochemical system, charge acceptance, power output, safety and life cycle/replacement cost and the vehicle’s driving distance.

From a thermal point of view, there are three main aspects to consider when using lithium-ion batteries in an EV:

- At temperatures below 0°C (32°F), batteries lose charge due to slower chemical reactions taking place in the battery cells. The result is a significant loss in power, acceleration and driving range, and higher potential for battery damage during charging.

- At temperatures above 30°C (86°F) the battery performance degrades, posing a real issue if a vehicle’s air conditioner is needed for passengers. The result is an impact on power density and reduced acceleration response.

- Temperatures above 40°C (104°F) can lead to serious and irreversible damage in the battery. At even higher temperatures, e.g. 70-100°C, thermal runaway can occur. This is triggered when the runaway temperature is reached. The result is a self-heating chain reaction in a battery cell that causes its destruction while propagating to adjacent cells.

The ideal temperature range for an EV’s lithium-ion battery is akin to that preferred by human beings. To keep it in this range, the battery temperature must be monitored and adjusted. A battery thermal management system (BTMS) is necessary to prevent temperature extremes, ensure proper battery performance, and achieve the expected life cycle. An effective BTMS keeps cell temperatures within their allowed operating range.

## 4.2 Operating environment:

The BTMS should be designed to operate within the temperature range of the operating environment. For example, if the battery is used in a cold climate, the BTMS should be designed to maintain the battery's temperature within the optimal range.BTMS is responsible for maintaining the battery cells within a specific temperature range to optimize their performance, extend their lifespan, and prevent safety hazards.

In Pakistan, where the climate ranges from hot and humid to cold and dry, the BTMS must be able to handle a wide range of operating conditions to ensure that electric vehicles are successful. This is particularly important since electric vehicles' batteries are more sensitive to temperature changes than conventional vehicles' batteries.

During the hot summer days in Pakistan, the ambient temperature can rise above 40°C, which can cause the battery cells to overheat and reduce their performance. If the BTMS is not designed to handle these high temperatures, it could result in premature battery failure, reduced range, and even safety hazards such as thermal runaway.

On the other hand, during the cold winter nights in northern areas of Pakistan, the ambient temperature can drop below freezing point, which can cause the battery cells to lose their capacity and reduce their performance. If the BTMS is not designed to handle these low temperatures, it could result in reduced range and premature battery failure.

Therefore, a successful BTMS in Pakistan should be able to handle a wide range of operating conditions, including high temperatures in summers and low temperatures in winters. This requires a sophisticated thermal management system that can regulate the battery temperature within a narrow range, regardless of the ambient temperature.

## 4.3 Thermal insulation:

The BTMS should be designed to prevent heat loss from the battery during operation. This can be achieved through the use of thermal insulation materials or by designing the battery housing to reduce heat transfer.

Thermal insulation is a critical aspect of the battery pack design for electric vehicles in a place like Pakistan. It plays a crucial role in regulating the temperature of the battery pack and preventing it from heating up on hot summer days or cooling below zero in winters in northern areas.

The battery pack is the most critical component of an electric vehicle and is responsible for storing and supplying power to the electric motor. However, the battery pack is sensitive to temperature changes and can significantly affect its performance, efficiency, and lifespan.

In hot summer days in Pakistan, the temperature can rise above 40°C, and if the battery pack is not insulated correctly, it can quickly overheat, leading to reduced performance, premature failure, and even safety hazards. The insulation acts as a barrier that prevents the heat from reaching the battery cells, allowing the battery to function optimally.

Similarly, in northern areas of Pakistan during winters, the temperature can drop below freezing point, and without proper insulation, the battery pack can cool down significantly. This can cause the battery cells to lose their capacity, which reduces the range of the electric vehicle and can also cause premature battery failure.

Therefore, the thermal insulation of the battery pack is crucial in Pakistan's extreme weather conditions, ensuring that the battery pack operates at a temperature range that maximizes its performance and lifespan. Insulation acts as a thermal barrier and reduces heat loss or heat gain, depending on the outside temperature, providing the battery with a stable and optimal operating temperature.

## 4.4 Monitoring and control:

The BTMS should be designed with sensors and control systems to monitor the temperature of the battery and adjust the cooling or heating system accordingly. This will ensure that the battery operates within the optimal temperature range.

Monitoring and controlling the temperature of cells is a crucial feature of Battery Thermal Management Systems (BTMS) because batteries are highly sensitive to temperature changes. Batteries are designed to operate within a specific temperature range, and any deviation from this range can result in reduced performance, shortened lifespan, and even safety hazards such as thermal runaway.

To maintain the ideal temperature range for the battery, a BTMS uses temperature sensors that monitor the temperature of the battery cells in real-time. These sensors are placed strategically throughout the battery pack to provide accurate temperature readings.

The data collected from the temperature sensors is analyzed by the BTMS controller, which then adjusts the heating or cooling mechanisms as needed to maintain the optimal temperature range. For example, if the temperature of the battery cells exceeds the desired range, the BTMS may activate a cooling system to bring the temperature back down to the optimal range. Conversely, if the temperature is too low, the BTMS may activate a heating system to warm up the cells.

## 4.5 Safety features:

The BTMS should be designed with safety features such as over-temperature protection, pressure relief valves, and thermal cutoff switches to prevent thermal runaway and other safety hazards.

Battery thermal management systems (BTMS) are essential components of modern battery technology, especially for high-energy-density batteries that can generate significant amounts of heat during operation. The BTMS plays a crucial role in maintaining the optimal temperature range of the battery and ensuring its safe and efficient operation. Safety is a top priority when it comes to BTMS design, and several features have been implemented to enhance the safety of the system.

One of the critical safety features of a BTMS is the use of temperature sensors to monitor the temperature of the battery cells in real-time. The sensors provide the necessary data to the BTMS controller, which can then adjust the heating or cooling mechanisms as needed to maintain the optimal temperature range for the battery. This feature helps prevent thermal runaway, a dangerous condition that can occur when the battery's temperature exceeds a critical level and can cause the battery to explode or catch fire.

Another safety feature of a BTMS is the use of cooling systems to prevent the battery from overheating. This feature is especially crucial for high-energy-density batteries that generate significant amounts of heat during operation. The cooling system can range from air-cooled to liquid-cooled, depending on the specific requirements of the battery. By dissipating the heat generated by the battery, the cooling system helps prevent thermal runaway and ensures the battery operates safely and efficiently.

In addition to temperature sensors and cooling systems, BTMS may also incorporate safety features such as overcurrent protection, overvoltage protection, and short circuit protection. These safety features help protect the battery from damage due to excessive current, voltage, or short circuits that could lead to thermal runaway. Overcurrent protection can detect and limit the current flow through the battery, while overvoltage protection can detect and limit the voltage applied to the battery. Short circuit protection can detect and interrupt any short circuits that may occur within the battery.

Finally, the BTMS may also have fail-safe mechanisms, such as emergency shutdown systems, to prevent catastrophic failure in the event of a malfunction. These mechanisms can shut down the entire system or specific components of the system, such as the cooling system, to prevent damage to the battery or other critical components.

## 4.7 Energy efficiency:

The BTMS should be designed to minimize energy consumption and maximize the efficiency of the battery system. This can be achieved through the use of efficient cooling and heating systems, as well as intelligent control systems that optimize energy use.

Energy efficiency is a crucial aspect of battery thermal management systems (BTMS) because it directly impacts the perfor5ance, reliability, and safety of the battery. The main objective of BTMS is to maintain the optimal temperature range of the battery cells to prevent overheating or overcooling, which can cause battery degradation, reduced performance, and safety risks. The BTMS helps to maintain the ideal temperature range of the battery, which is usually between 20°C and 35°C, to ensure efficient operation and prolonged lifespan.

The choice of cooling system for the BTMS is also critical as it affects the overall efficiency and effectiveness of the system. Liquid-based cooling systems are becoming increasingly popular for BTMS due to their higher efficiency compared to air-cooled systems. Research suggests that liquid cooling systems require 60% less power to perform the same cooling job as an air-cooled system.

The main reason for this increased efficiency is that liquid cooling systems have a higher heat capacity and thermal conductivity than air, which allows them to transfer heat more efficiently. In addition, liquid cooling systems can provide more uniform cooling throughout the battery cells, which reduces thermal gradients and prevents localized hotspots that can cause cell degradation.

## 4.7 Thermal Gradients:

Thermal gradients refer to the differences in temperature across the battery pack, with the highest temperature being at the center of the pack and decreasing towards the edges. Thermal gradients can have a significant impact on the performance, reliability, and safety of the battery.

In an air-cooled battery pack, thermal gradients can reach 15 to 20 degrees Celsius, which can cause localized hotspots and thermal stress on the battery cells. These hotspots can result in cell degradation, reduced performance, and safety risks such as thermal runaway. Thermal runaway is a condition in which a battery undergoes a self-accelerating exothermic reaction that can lead to fire or explosion.

In contrast, liquid-based battery thermal management systems (BTMS) can significantly reduce thermal gradients and prevent localized hotspots. Liquid cooling can provide more uniform cooling throughout the battery cells, which reduces thermal gradients and prevents localized hotspots. This is because liquid cooling can transfer heat more efficiently than air cooling, which means that it can remove heat from the battery cells more effectively.

Studies have shown that thermal gradients in a liquid-cooled battery pack can be reduced to as low as 3 to 4 degrees Celsius. This is because liquid cooling systems can maintain a more consistent and controlled temperature throughout the battery pack, which reduces the risk of thermal stress and degradation of the battery cells.

Liquid-based BTMS can also provide more precise control over the temperature of the battery cells, which allows for more efficient operation and longer battery life. Liquid cooling systems can also operate at a lower temperature difference between the coolant and the battery cells, which reduces the energy required for cooling and increases the efficiency of the system.

# Chapter 5

# Design inspirations

Choices for Battery heat exchangers: The two most common choices in liquid battery thermal management systems for cooling electric vehicle battery packs are Tesla's cooling ribbons and cooling base plates.

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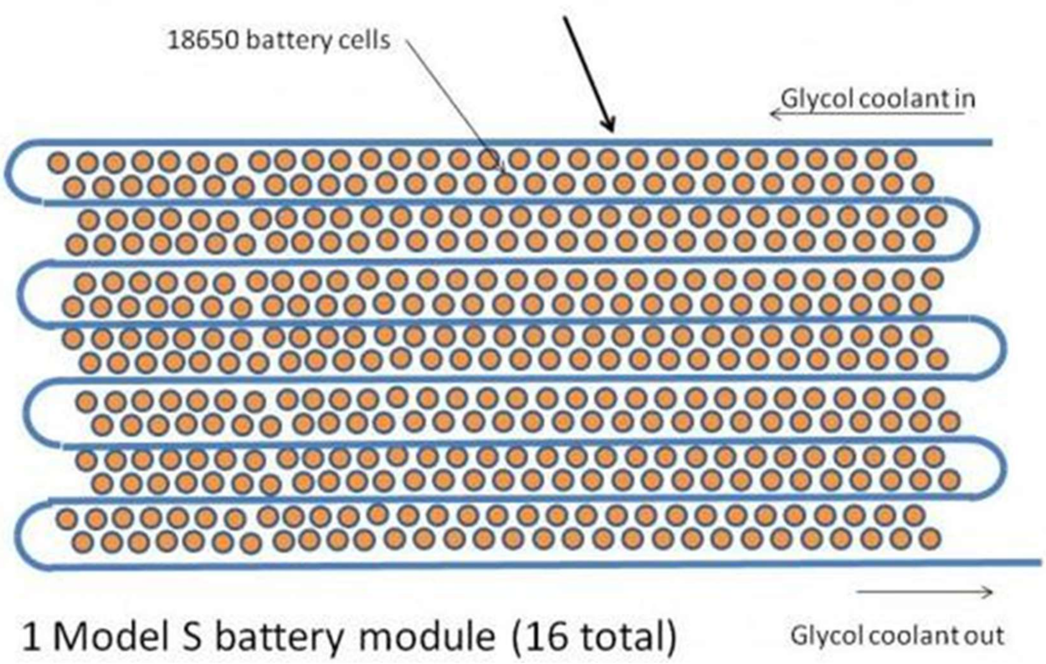

**Figure 5.1**: Tesla cooling ribbons-[5]

## 5.1 Tesla Cooling Ribbons:

Tesla's cooling ribbons are a type of thermal management solution used in their electric vehicle battery packs. They are designed to help manage the heat generated by the battery cells during operation, ensuring that the cells remain at a safe and optimal temperature range.

Tesla cooling ribbons are made up of a thin layer of metal with a complex network of tiny channels running through it. These channels are typically only a few microns wide, and they are arranged in a tightly packed, serpentine pattern. The metal layer is usually made of copper, which has excellent thermal conductivity properties, allowing heat to be rapidly transported away from the battery cells.

The cooling ribbons are also coated with a thin layer of insulating material, typically made of a polymer or a ceramic material, to prevent electrical shorts between the ribbon and the battery cells.

Tesla's cooling ribbons work by circulating a coolant, typically a mixture of water and ethylene glycol, through the tiny channels in the metal layer. As the coolant flows through the channels, it absorbs heat from the battery cells, which is then carried away from the cells and dissipated into the surrounding air or to a heat exchanger.

The tight spacing and serpentine pattern of the channels in the cooling ribbons provide a large surface area for the coolant to come into contact with the metal layer, allowing for efficient heat transfer. Additionally, the insulating layer on the ribbons helps to prevent any electrical shorts between the ribbons and the battery cells.

One advantage of using cooling ribbons is that they can be easily integrated into the battery pack design. Tesla typically weaves the ribbons in between the battery cells and secures them using adhesive, ensuring that the ribbons make direct contact with the cells. This allows for efficient heat transfer and helps to maintain a consistent temperature across all of the cells.

## 5.2 Base plate heat exchanger:

A base plate heat exchanger is a thermal management solution that is commonly used to cool electric vehicle battery packs. It consists of a flat plate that is attached directly to the bottom of the battery pack and has coolant channels running through it. The coolant is typically a mixture of water and ethylene glycol.

The base plate heat exchanger is usually made of aluminum or copper, both of which have high thermal conductivity properties. The plate is machined to have a series of channels that run through it, forming a serpentine pattern that allows coolant to flow through the plate. The channels are typically less than a millimeter in diameter, and they are tightly packed together to maximize the surface area available for heat transfer.

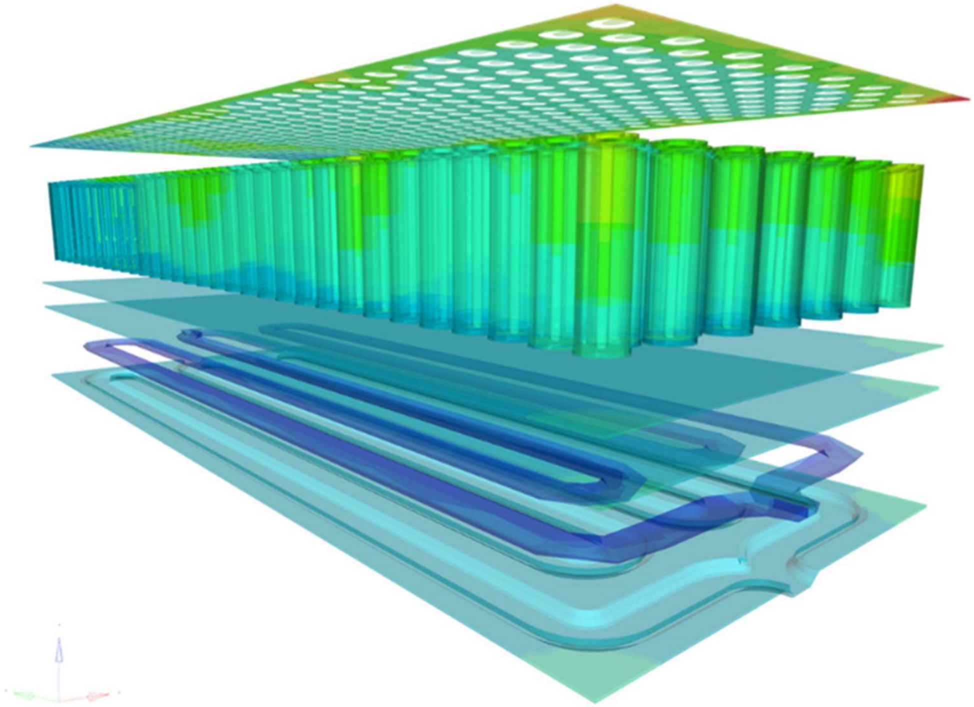

**Figure 5.2**: Cooling mechanism of base Plate-[5]

The base plate heat exchanger works by circulating coolant through the channels in the plate, which absorbs heat from the battery cells. As the coolant flows through the channels, it carries the heat away from the battery pack and dissipates it into the surrounding air or to another heat exchanger.

The base plate provides a large surface area for heat transfer, which allows for efficient cooling of the battery pack. By attaching the heat exchanger directly to the bottom of the battery pack, the base plate also ensures that the temperature across all of the cells remains consistent.

One of the advantages of using a base plate heat exchanger is that it is a relatively simple and cost-effective solution for cooling electric vehicle battery packs. It can also be easily integrated into the design of the battery pack, and it does not take up much additional space.

Overall, a base plate heat exchanger is an effective solution for managing the heat generated by electric vehicle battery packs. It helps to ensure that the battery cells remain at a safe and optimal temperature range, which is crucial for maintaining the performance and longevity of the battery pack.

## 5.3 Why we chose base plate cooling?

Base plate cooling can work well for battery packs that have a flat or planar surface, as the base plate can be in direct contact with the battery cells to provide efficient cooling. This method can help to dissipate heat from the battery cells more evenly and effectively than other cooling methods, such as air or liquid cooling, which may not be as efficient in cooling the cells closest to the center of the battery pack.

Another advantage of base plate cooling for battery packs is that it can be relatively simple and cost-effective to implement, particularly if the battery pack is already designed with a flat base or if the base plate can be integrated into the battery pack design. This can make it an attractive option for manufacturers who want to improve the cooling of their battery packs without significantly increasing the cost or complexity of the overall design.

Overall, base plate cooling may be a practical and effective solution for cooling battery packs, particularly those with a flat or planar surface. However, it is important to consider the specific design requirements of the battery pack and to evaluate different cooling options to determine the most effective and efficient solution.

## 5.4 Tesla Octovalve:

The Tesla Octovalve is a critical component of Tesla's electric vehicle (EV) thermal management system. It is responsible for managing the flow of coolant and refrigerant to regulate the temperature of the battery pack, electric motors, and cabin heating and cooling. The Octovalve is made up of several interconnected valves and pumps that work together to optimize the efficiency of the cooling and heating system.

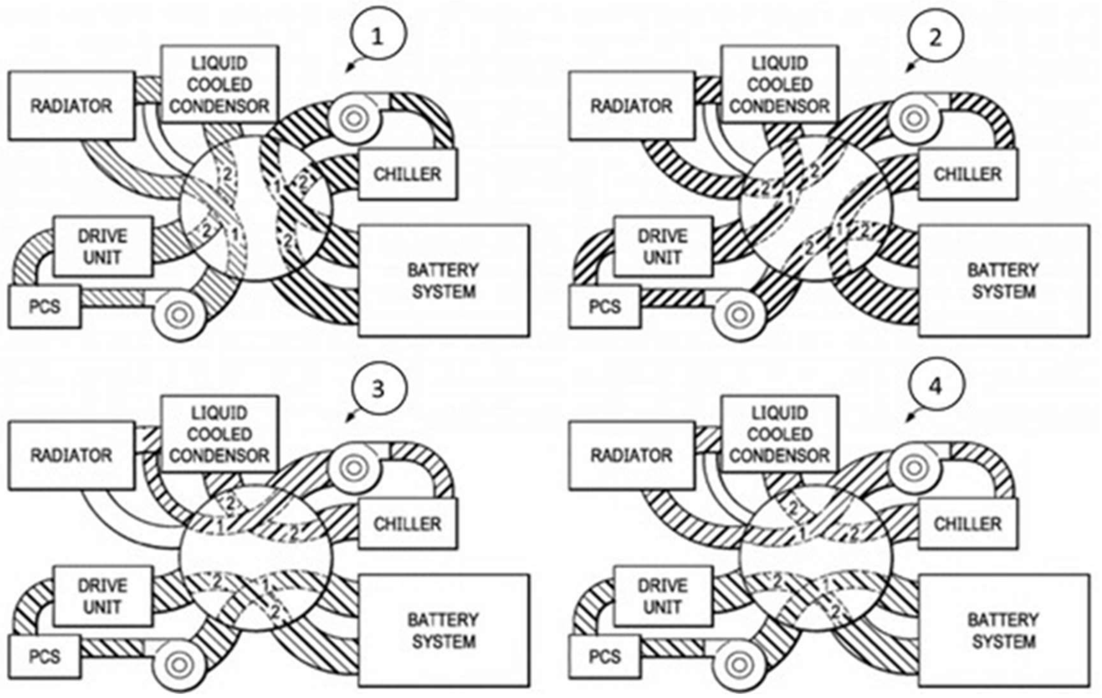

**Figure 5.3:** Tesla Octa Valve-[5]

The Tesla Octovalve is a compact assembly made up of several key components. These include:

a) **Pump module:**
The Octovalve has two pump modules that circulate coolant through the battery pack, electric motors, and cabin heating and cooling system. Each pump module consists of a pump and a motor, and they are controlled by the Octovalve's electronic control unit (ECU).

b) **Valve block:**
The valve block contains several valves that regulate the flow of coolant and refrigerant throughout the thermal management system. These include a four-way valve, two three-way valves, and a two-way valve.

c) **Heat exchanger:**
The Octovalve has a heat exchanger that transfers heat between the coolant and refrigerant circuits. This helps to optimize the efficiency of the thermal management system and reduce energy consumption.

d) **Sensors:**

The Octovalve has several sensors that monitor the temperature and pressure of the coolant and refrigerant circuits. These sensors provide data to the ECU, which can adjust the operation of the system in real-time to optimize efficiency.

The Tesla Octovalve works by managing the flow of coolant and refrigerant to regulate the temperature of the battery pack, electric motors, and cabin heating and cooling system. The Octovalve uses a four-way valve to switch between heating and cooling modes. When in heating mode, the Octovalve circulates coolant through the heat exchanger, which absorbs heat from the coolant and transfers it to the cabin. When in cooling mode, the Octovalve circulates refrigerant through the heat exchanger, which absorbs heat from the cabin and transfers it to the outside.

The Octovalve also has two three-way valves that regulate the flow of coolant through the battery pack and electric motors. These valves can route coolant to either the battery pack or the motors, depending on the cooling needs of the system. The Octovalve also has a two-way valve that regulates the flow of refrigerant to the cabin.

The Octovalve's electronic control unit (ECU) monitors the temperature and pressure of the coolant and refrigerant circuits and adjusts the operation of the system in real-time to optimize efficiency. For example, if the battery pack is overheating, the ECU can increase the flow of coolant through the battery pack to cool it down.

## 5.5 Different Battery Thermal Management Systems:

### 5.5.1 Simple Cooling system:

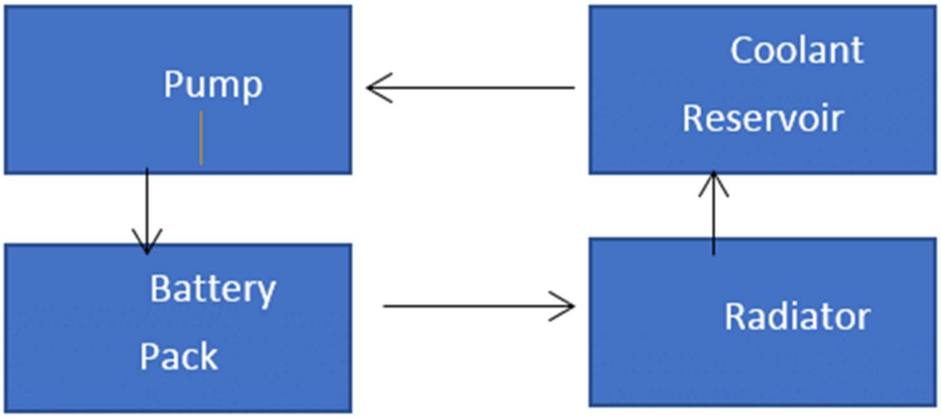

**Figure 5.4:** Simple Cooling system

A simple battery thermal management system works by using a coolant to transfer heat away from the battery cells. The coolant is circulated through the battery base plate, a radiator, and a coolant reservoir, before being pumped back to the battery.

The battery base plate is in direct contact with the battery cells and acts as a heat sink, absorbing heat from the cells. The coolant flows through the base plate, absorbing the heat and carrying it away from the battery. The heated coolant then flows through the radiator, where it is cooled by the ambient air. The cooled coolant is then stored in a coolant reservoir before being pumped back to the battery to repeat the cycle.

However, this system may not be very helpful during hot summers as the ambient air temperature can be higher than the battery temperature. In such cases, the system cannot cool the battery temperature below the ambient air temperature.

This is because heat flows from hot objects to cold objects, and the rate of heat transfer is determined by the temperature difference between the objects. In this case, the battery cells are hotter than the ambient air, and therefore, heat will flow from the battery to the air. The coolant can only remove heat from the battery up to the temperature of the ambient air, and cannot cool it below that temperature.

In hot summer conditions, the coolant may not be able to remove enough heat from the battery to keep it within a safe operating range, leading to reduced battery life and performance. To mitigate this issue, active cooling systems may be required, which can actively remove heat from the battery using external energy inputs such as fans or pumps, and can therefore cool the battery temperature below the ambient air temperature.

## 5.5.2 Proposed BTMS:

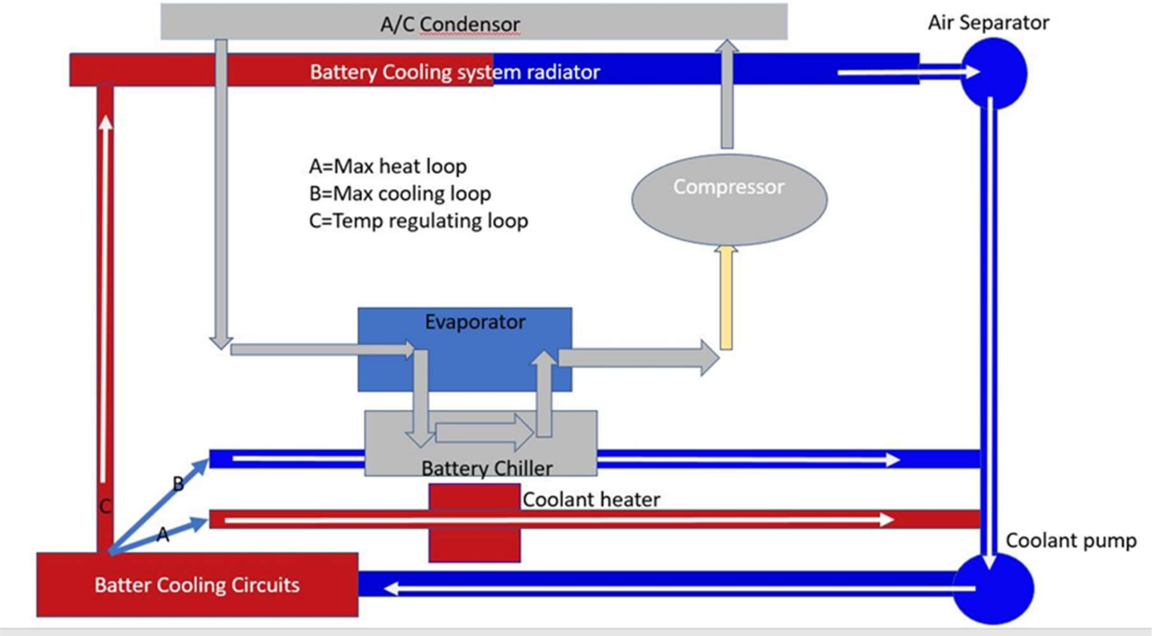

**Figure 5.5:** Proposed hybrid Cooling system

# Chapter 6

# Methodology

## 6.1 Theoretical Overall Heat Transfer Coefficient

The transfer of heat can generally be expressed using the overall heat transfer coefficient, which is determined by the following equation to measure the efficiency of heat exchange.

$$Q = UA\Delta Tm$$

Where:

Q - Rate of heat transfer (W)

U - Overall heat transfer coefficient [(W/m2K)]

A - Heat transfer surface area (m2)

ΔTm - Approximate mean temperature difference (K)

This equation incorporates both convective and conductive components of heat transfer between the hot and cold fluids in the heat exchanger, while disregarding the radiation component and heat transfer between the heat exchanger and air.

The total heat transfer coefficient for the un-finned, tubular cross-flow heat exchanger can be calculated as:

$$1/UA = 1/hiAi + Rfi/Ai + Rw + Rfo/Ao + 1/hA$$

Where:

UA=Product of U and A (W/K), A could be either Ao or Ai

ho, hi= Convective heat transfer coefficients of outer and inner tube surface (W/m2K)

Ao, Ai = Contact area of outer and inner tube surface (m2)

Rfi, Rfo= Fouling factors (m2K/W)

Rw=Conductive resistance (K/W)

In this case, Rw represents the tube's conductive resistance, which is calculated using the formula ln(Do/Di)/(2πkL), where Do is the tube's outer diameter, Di is the tube's inner diameter, k is the tube's thermal conductivity, and L is the tube's length. If the convection on the outer surface is particularly strong (i.e., ho = ∞) and the fouling effect is negligible, the terms 1/(ho * Ao), Rfi/Ai, and Rfo/Ao in the equation become irrelevant, leading to a simplified form.

$$1/UA = 1/hiAi + l\,n(Do/Di)\,/2kL$$

When the calculation is based on the inner tube surface (A = Ai) and considering that Ai = πLDi, is equivalent to:

$$1/U = 1/hi + \llbracket Di\ ln \rrbracket\ (Do/Di)/2k$$

Where Di and Do refer to the tube's inner and outer diameter. Above will be used to characterize the heat transfer between battery cells and the heat transfer fluid in the subsequent "Battery Pack" model unit. One parameter, 'h' convective heat transfer coefficient, is still undefined in Equations 3.3a to 3.3c. The following equations can be used to calculate it:

$$NuD = hfl * Dh/Kfl$$

Where Dh is the hydraulic diameter, which equals Di in the case of a filled circular tube, kfl is the thermal conductivity of the fluid, and NuD is determined based on various flow conditions (laminar or turbulent). Since the value of Re (Reynolds number) is < 2300, NuD is given by the following equation:

$$NuD = 3.66 + \left[\left(\left(0.668 * (D/L * RePr)/1 + (0.04) * \left((D/L) * Re * Pr\right)\right)\right)^{0.}\ 67\right]$$

In above, Re is the Reynolds number determined by the following equation:

$$Re = pvD/u$$

The Prandtl number Pr, defined by the equation, interprets the ratio of momentum and thermal diffusivities.

$$P_r = \frac{\mu C_p}{k}$$

## 6.2 Battery Unit:

The assumption was made that the battery cells have uniform areas and a high internal thermal conductivity, enabling rapid heat transfer between cells and ensuring that all points within the battery cells maintain the same temperature, referred to as the battery temperature Tba. The following equation describes the change in battery temperature over time:

$$\frac{dT_{ba}}{dt} = \frac{(Q_{gen} - Q_{dis})}{(m_{ba}C_{p,ba})}$$

Qgen and Qdis represent the rates of heat generation and heat dissipation, respectively. The former is determined using either an internal signal generator or a heat generation rate profile obtained from the FTP-75 driving cycle. This heat generation is a result of the electro-thermal effects within the battery. The latter is controlled by the subsystem of the battery unit, which is expressed in the equation

$$Q_{dis} = UA(\overline{Tfl} - T_{ba})$$

This quantity (s) represents the heat dissipated during the thermal cycle. When the thermal cycle is in the cooling phase, the value is positive, and when it is in the heating phase, the value is negative. The mass of the battery is denoted by mba, and its specific heat capacity is denoted by Cp,ba.

In order to facilitate heat transfer to and from the battery, three separate copper tubes are connected in close proximity to the battery cells within the battery pack. the overall heat transfer coefficient U will be determined. The contact area, which refers to the combined inner space of the three tubes, is represented by the symbol A. The estimated mean temperature difference is denoted by Tfl - Tba, where Tfl represents the average temperature of the liquid at the inlet and outlet.

## 6.3 Active cooling

The temperature difference of the fluid is represented by the following equation when the heat transfer fluid passes through an air conditioner:

$$\frac{dT_o}{dt} = \left[ \left( mdot_{fl} * C_p * (T_i - T_0) \right) - \frac{Q_{Ac}}{(m_{fl,Ac} C_{p,fl})} \right]$$

As the air conditioning system removes heat from the liquid, the variable q always carries a negative sign. In its place, q is replaced by QAc, which denotes the cooling load and is consistently positive. The following equation can be employed to quantify QAc.

$$Q_{Ac} = P_{el,Ac} * COP$$

The electrical energy consumed by the Air conditioner is denoted as Pel,Ac, and the coefficient of performance (COP) depends on the operating state of the air Conditioner.

The heat transferred by the warmer, denoted as Q, can be calculated using the coolant's inlet and outlet temperatures (Tin and Tout), the mass flow rate of the coolant (ṁ), and the mass of the coolant in the tubes (m).

$$P = P_{\max} = \text{constant}$$

## 6.4 Pump

The electrical energy consumption of the pump can be determined using the following equation:

$$P = \frac{\gamma H mdot}{\eta}$$

The specific gravity, represented by $\Upsilon$, is obtained by multiplying the density of the coolant by gravity. It can be calculated as follows:

y=p*g

Where ṁ is the mass flow rate, η is the pump's efficiency, and H is the total head, which is related to the mass flow rate ṁ:

$$H=f(m)$$

The performance of the water pump is displayed, while the performance of other viscous coolants is determined using a correction factor.

$$mdot_{cl} = C_p mdot_w$$

$$H_{Cl} = C_h H_w$$

$$\eta_{cl} = C_\eta \eta_w$$

The correction factors, namely Cp, Ch, and Cη, account for the force adjustment, head rectification, and productivity remedy factors, respectively. These factors are specifically selected considering the low viscosity and comparability to water of the coolant.

$$C_p, C_h, C_\eta = 1$$

## 6.5 Performance Parameters:

The following are the conditions for the output limits, briefly described below. These conditions involve the electrical energy consumption of each device, the temperature of the battery, and the operating time of the component.

The total electrical energy consumption is calculated as the sum of all individual energy consumptions. Each component consumes a specific amount of energy as follows:

$$E_T = \sum E_{HT} + E_{BP} + E_{AC}$$

When the heater is activated, the heater consumption is determined using the following equation:

$$E_{HT} = \int P_{Ptc} + P_{pump} dt$$

When the coolant passes through the bypass, the bypass consumption is obtained by integrating the pump power:

$$T_{b,\max} = \int P_{AC} + P_{pump} dt$$

The average temperature of the battery (Tb, avec, c) represents the average battery temperature during detached and dynamic cooling. It can be expressed as: Tb, avec, c = ¯(Tb (t1)). Additionally, there are several other parameters to evaluate the model's performance. Tht, tbp, tpc, and tac refer to the operating periods of heating, bypass, latent cooling, and dynamic cooling, respectively. T10 indicates when the battery temperature exceeds 10°C for the first time after the start of the driving cycle in a cold state. tdes is defined as the time when the battery temperature falls below the desired temperature for the first time after the start of the driving cycle in a hot state.

# Chapter 7

# Mathematical Modelling Of Battery Electric vehicle

## 7.1 Matlab model for current profile:

An explanatory model was developed beforehand to establish a MATLAB/Simulink model that serves as a comprehensive framework for simulating the EV. It not only aided in the subsequent modeling steps but also facilitated potential modifications, additions, and enhancements.

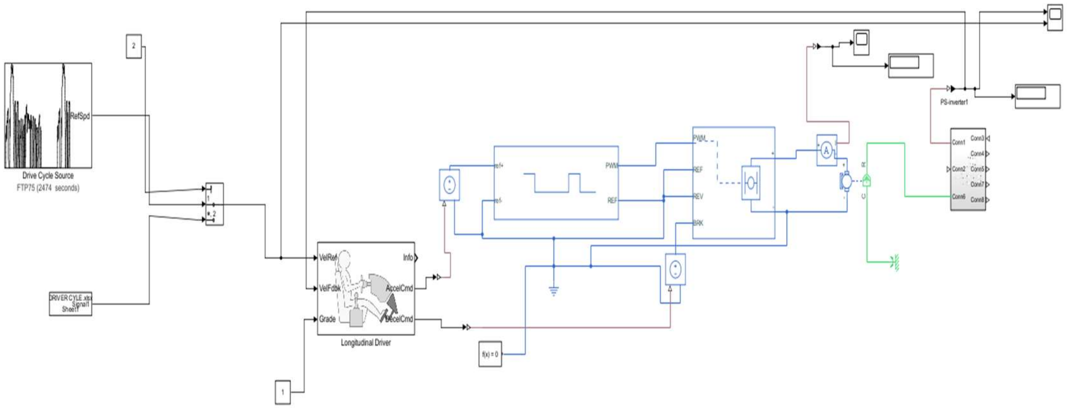

**Figure 7.1:** Simple EV model

Designed an Electric Vehicle (EV) model specifically for the Suzuki Ravi using MATLAB/Simulink. To initiate the simulation, we provided the initial inputs pertaining to the vehicle. This included parameters such as battery capacity, motor specifications, and vehicle weight, among others. The primary objective of this model was to determine the current draw of the vehicle under different operating conditions. We then integrated this current draw information into another model, which allowed us to analyze and calculate various cooling-related quantities associated with the EV system.

By incorporating the current draw into the cooling model, we were able to assess factors such as heat dissipation, temperature profiles, and cooling requirements for ensuring optimal performance and efficiency of the Suzuki Ravi EV.

## 7.2 Parameters for EV model are:

| Parameters | Value |
|---|---|
| Vehicle Weight | 1500 kg |
| Aerodynamic Drag | 0.3 |
| Motor Power | 15 kW |
| Battery Capacity | 13.2 kWh |
| Voltage | 72V |

**Figure 7.2:** EV parameters

To generate a current withdrawal graph specific to the Islamabad region, we employed the Islamabad drive cycle in our model. The Islamabad drive cycle is a representative pattern that simulates the driving behavior and conditions typically encountered in the city. By incorporating this drive cycle into our model, we were able to simulate the real-world driving scenarios experienced by vehicles in Islamabad. This allowed us to obtain an accurate depiction of the current withdrawal patterns exhibited by vehicles in the region. The resulting current withdrawal graph serves as a valuable tool for understanding and analyzing the power demands of electric vehicles in Islamabad, enabling us to optimize battery sizing, assess charging infrastructure requirements, and enhance overall energy efficiency in the context of Islamabad's unique driving conditions.

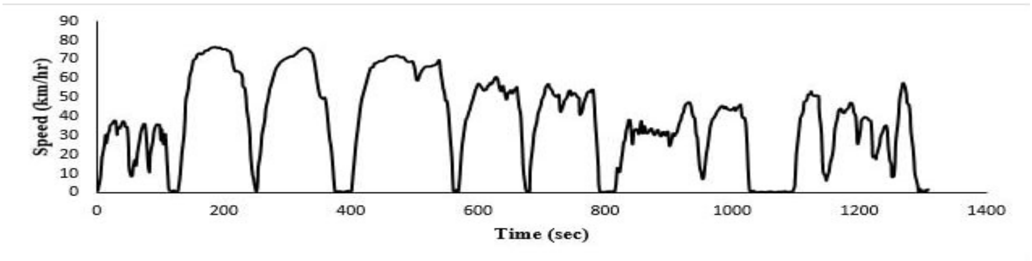

**Figure 7.3:** Islamabad Drive cycle

The current graph provides a visual representation of the electrical current drawn by a vehicle over a specific period of time. It showcases the fluctuations and patterns in the current consumption during different driving conditions and operational scenarios. The graph typically displays the current values on the y-axis and the corresponding time intervals on the x-axis. By analyzing the current graph, valuable insights can be gained regarding the power demands of the vehicle, such as peak current levels, duration of high current draw, and variations based on driving behavior or external factors.

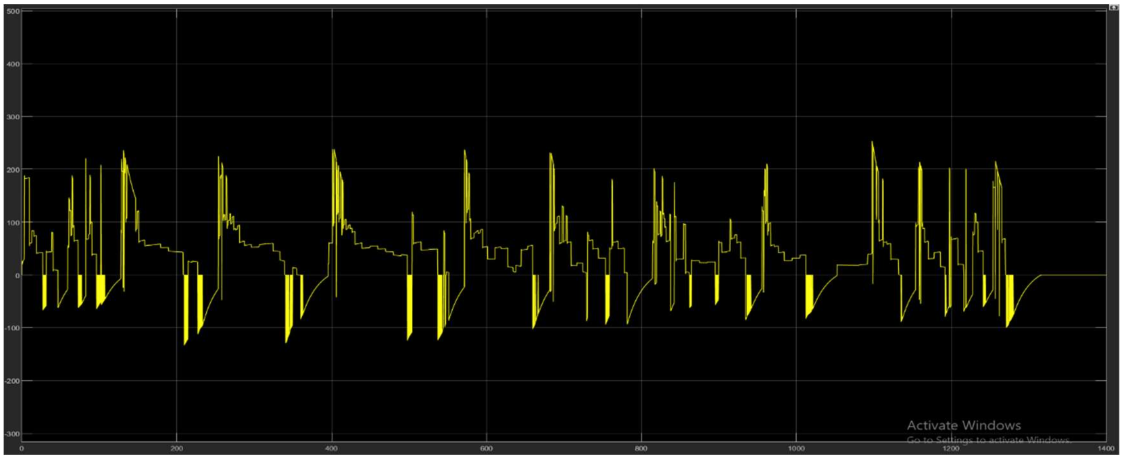

**Figure 7.4**: Current graph from simulink

In our simulation process, we utilized a pre-existing cooling model within MATLAB to complement our driving cycle simulation and current analysis. This cooling model was integrated with the existing MATLAB framework, enabling us to incorporate the current data obtained from the previous model. By coupling the current values with the cooling model, we were able to evaluate various cooling-related quantities and assess the thermal management of the vehicle. The integrated approach allowed us to analyze factors such as heat dissipation, temperature profiles, and cooling requirements in real-time, providing valuable insights into the vehicle's thermal behavior under different driving conditions. This comprehensive analysis of the cooling system, coupled with the driving cycle and current data, facilitated a more accurate evaluation of the overall performance and efficiency of the vehicle, aiding in the optimization of cooling strategies and enhancing the reliability of the simulated model.

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## 7.3 Initial inputs and settings for thermal cycles

The initial inputs and settings for the thermal cycles were determined as fixed boundaries, starting with the battery unit. When considering the battery pack's thermal issues, there were two significant heat transfer streams that influenced the battery temperature. The first was the internal heat generation, which was influenced by driving habits, battery characteristics, and vehicle parameters such as mass and aerodynamic performance. As this study focused on thermal rather than electro-thermal issues, the internal heat was generated using an external electro-thermal model. The second component was external heat dissipation, which was influenced by various thermal cycles that either removed or introduced heat to the battery. The amount of heat was determined by both the thermal cycle used and the surrounding thermal conditions. Consequently, several parameters from the battery unit and testing conditions were collected for estimation, leading to the development of the necessary battery thermal model.

## 7.4 Creating a control strategy

To create a control strategy, multiple thermal cycles were planned in most battery thermal models. Certain characteristic parameters, such as battery temperature and ambient temperature, were necessary to determine which cycle to execute. An operating state was selected based on these parameters. The state corresponding to the active thermal cycle, along with associated components such as the pump, would change their operational state. In some cases, a sub-state within the main operating state might be introduced to improve operational features.

## 7.5 Simplifying and decoupling

To simplify and decouple the simulation, an approximate or simplified calculation method was employed to solve infinite loops that could arise from complex calculation scenarios, thus speeding up the simulation process. Decoupling was an alternative solution in various cases. For example, the activated thermal cycle consumes power, resulting in increased load and subsequently increased heat.

The coupling of the thermal and electro-thermal models could lead to unexpected programming issues. Therefore, it was preferable to initially decouple these two models and connect them later when both were functioning appropriately.

The variable parameter of utmost importance was the ambient temperature, representing the climate conditions surrounding the vehicle during operation. The temperatures from 10°C to 20°C were categorized as mild. In contrast, temperature ranges from 20°C to 40°C were classified as hot environments.

Regarding the initial temperature of the battery, it is generally assumed to be equal to the ambient temperature. However, when pre-conditioning techniques are employed, these two temperatures may not match. Pre-heating the battery in a cold environment results in a higher initial battery temperature than the ambient temperature, whereas pre-cooling the battery in a hot environment leads to a lower initial battery temperature than the ambient temperature. Different levels of pre-conditioning can be utilized.

## 7.6 Desired temperature

The desired temperature represents the target temperature set by the Battery Thermal Management System (BTMS) control unit, typically the manufacturer's recommended operating temperature. The BTMS employs various thermal cycles to maintain the battery temperature as close to the desired temperature as possible. In this work, the generally targeted temperature is 25°C, although some special cases with a desired temperature of 20°C were also tested.

## 7.7 Driving cycle

In terms of the driving cycle used for testing, the focus of this model is on the BTMS during driving. The chosen driving cycle for the project is Islamabad driving cycle, which represents different driving behaviors. The vehicle speed profile for this cycle is depicted in Figure 8. The Islamabad driving cycle lasts 1400 seconds per single cycle and reflects a mild driving behavior with a maximum speed of almost 75  Kmph and an average speed of 34.12 Kmph. For testing purposes, the cycle was repeated multiple times as an input for the testing conditions, and the vehicle was driven according to the speed profile until the available battery capacity was depleted.

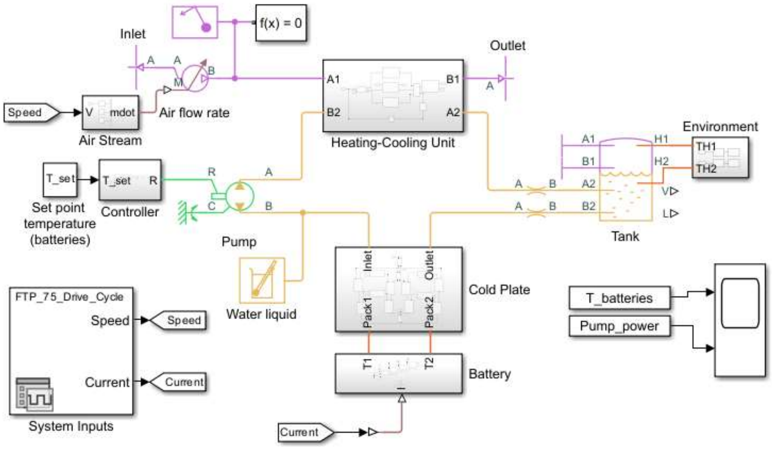

**Figure 7.5:** Cooling model from matlab-[12]

## 7.8 Graphs from model

The temperature behavior of the battery packs was analyzed and the results are presented in the accompanying figure. Initially, the temperature of the packs experienced a gradual rise, reaching approximately 30 degrees Celsius. However, with the implementation of the coolant in the form of water, an efficient cooling effect was observed. The temperature steadily decreased and eventually stabilized below the desired threshold of 25 degrees Celsius.

The figure provided a clear visualization of the cooling process, showcasing the effectiveness of the coolant in maintaining the temperature within the desired operating range. The initial rise in temperature was efficiently counteracted by the cooling system, ensuring that the packs remained within the optimal temperature limits. This temperature control is crucial for the overall performance, efficiency, and longevity of the battery packs.

The findings from the temperature analysis and the demonstrated effectiveness of water as a coolant underscored the successful implementation of the cooling system in managing and regulating the thermal conditions within the battery packs. This temperature control mechanism provides a reliable and safe operating environment for the batteries, contributing to their sustained performance and overall durability.

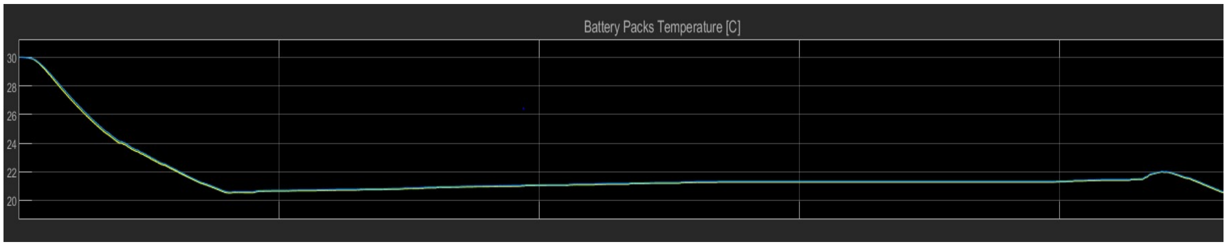

**Figure 7.6:** Battery Pack Temperature

The relationship between the temperature of the battery packs and the operation of the pump was investigated, and the results are illustrated in the provided figure. It was observed that as the temperature of the packs increased, the pump's activity also intensified.

This correlation was a direct response to the cooling system's functionality, as the pump was responsible for circulating the coolant and facilitating the heat transfer process.

When the temperature of the packs reached a high level, the pump operated at its maximum capacity to ensure an effective cooling effect. The increased pump work was necessary to enhance the flow rate of the coolant, promoting efficient heat dissipation and aiding in temperature reduction. This active cooling mechanism played a crucial role in preventing overheating and maintaining the desired temperature range.

As the cooling system successfully mitigated the heat buildup within the battery packs, the temperature gradually decreased. Consequently, the pump work reduced correspondingly, eventually reaching zero when the temperature normalized. This behavior demonstrated the intelligent operation of the cooling system, dynamically responding to temperature fluctuations and adjusting the pump's activity accordingly.

The observed relationship between temperature and pump work highlighted the system's adaptability and energy efficiency. By actively modulating the pump operation based on the thermal conditions, the cooling system optimized its energy consumption and minimized unnecessary pump work during periods of normal temperature range. This efficient pump control contributed to the overall performance and sustainability of the cooling system, ensuring the long-term reliability and safe operation of the battery packs.

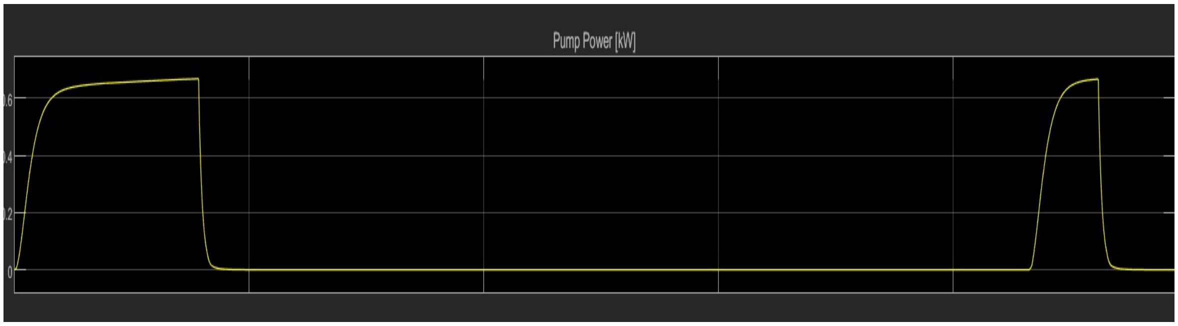

**Figure 7.7:** Pump work graph from matlab

# Chapter 8

# Analysis and Simulations

For the design of the cooling plate, we considered the battery capacity of and an arrangement of cells, resulting in a total of cells. The 64p20s configuration implies that there are 64 cells connected in parallel and 20 such groups connected in series. This arrangement allows for a higher overall voltage while maintaining a sufficient current capacity.

| Voltage | Cells in Series | Cells in Parallel | Total | Cells diameter | Cell Height | Cell name |
|---|---|---|---|---|---|---|
| 72V | 20 | 64 | 1280 | 18mm | 65mm | HG LG2 |

## 8.1 Construction

Due to the large number of cells in the battery pack, it was necessary to divide it into two separate parts, with each part containing 640 cells. This division was implemented to facilitate better management and handling of the battery pack. By splitting the pack into two smaller sections, the overall size and weight of each individual part became more manageable, making it easier to install, transport, and maintain the battery system. Additionally, dividing the pack into two parts allowed for more efficient cooling and thermal management, as the heat generated by each section could be more effectively dissipated. Furthermore, this partitioning strategy also offered enhanced flexibility in terms of battery maintenance and potential future upgrades, as individual sections could be serviced or replaced independently if required. Overall, dividing the battery pack into two parts provided practical advantages in terms of handling, cooling, maintenance, and potential scalability.

For the length of cooling plate each cell is off diameter of 18mm and additional 2mm gap is left between each cell so total length is:

$$\mathbf{18 * 32 + 2 * 32 + 20 = 660}\boldsymbol{mm}$$

For the width of cooling plate each cell is off diameter of 18mm and additional 2mm gap is left between each cell so total width is:

$$\mathbf{18 * 20 + 2 * 20 + 20 = 420}\boldsymbol{mm}$$

## 8.2 Cooling Plate Design

**Figure 8.1:** Cooling plate initial design

During the analysis conducted in ANSYS, it was observed that cooling plate design A exhibited a significant temperature gradient across the battery cells. This temperature variation was found to be undesirable as it could potentially lead to thermal imbalances, hotspots, and reduced overall performance of the battery pack. Consequently, after careful evaluation and consideration, design A was not chosen for implementation. The temperature gradient indicated that the cooling channels in design A were not effectively dissipating heat and maintaining uniform thermal conditions across the cells. In order to ensure optimal thermal management and prevent any adverse effects on battery performance, an alternative cooling plate design was selected.

The distribution of cell temperatures, as depicted in the figure, revealed a pattern that was deemed undesirable. The figure illustrated a non-uniform temperature distribution among the battery cells, indicating potential thermal imbalances within the system. This uneven distribution of temperatures across the cells could have negative implications for battery performance, efficiency, and longevity. It may lead to certain cells operating at higher temperatures, increasing the risk of degradation, reduced capacity, and even safety concerns. In order to ensure optimal functioning of the battery pack, it was imperative to address this undesirable cell temperature distribution.

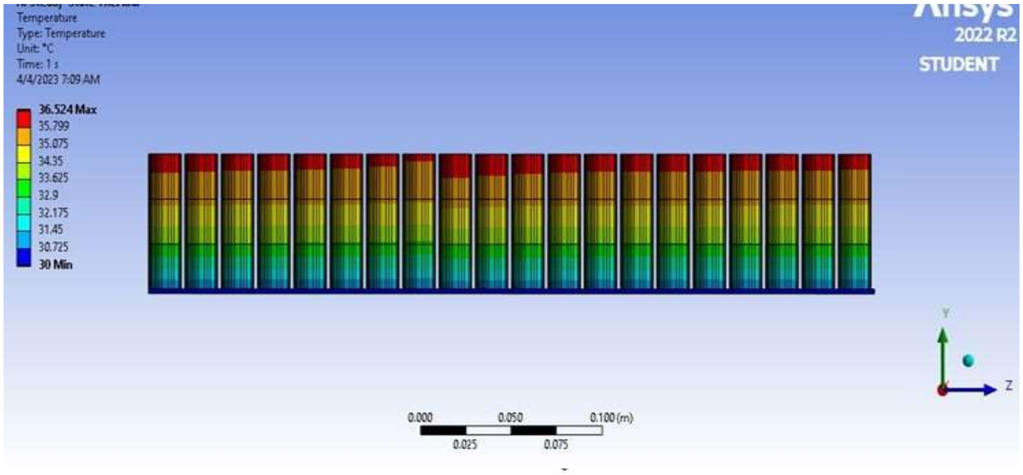

**Figure 8.2:** Cooling Plate Second design

The analysis of the aluminum plate alone, without the presence of the cooling plate and coolant, revealed a significant and even distribution of temperature over time. This analysis was crucial in assessing the thermal behavior and limitations of the aluminum plate. By subjecting the plate to the total heat generated by the system, it was possible to evaluate its effectiveness in dissipating heat and maintaining temperature within acceptable limits. The results demonstrated that the aluminum plate was capable of efficiently distributing and dissipating heat, ensuring that the temperature remained within the specified range. These findings provided valuable insights into the performance and suitability of the aluminum plate for use in the cooling system.

The trial served as a practical test to verify the effectiveness of the plate in managing the thermal load and showcased its ability to maintain a stable temperature profile, confirming its reliability and effectiveness in the overall cooling process.

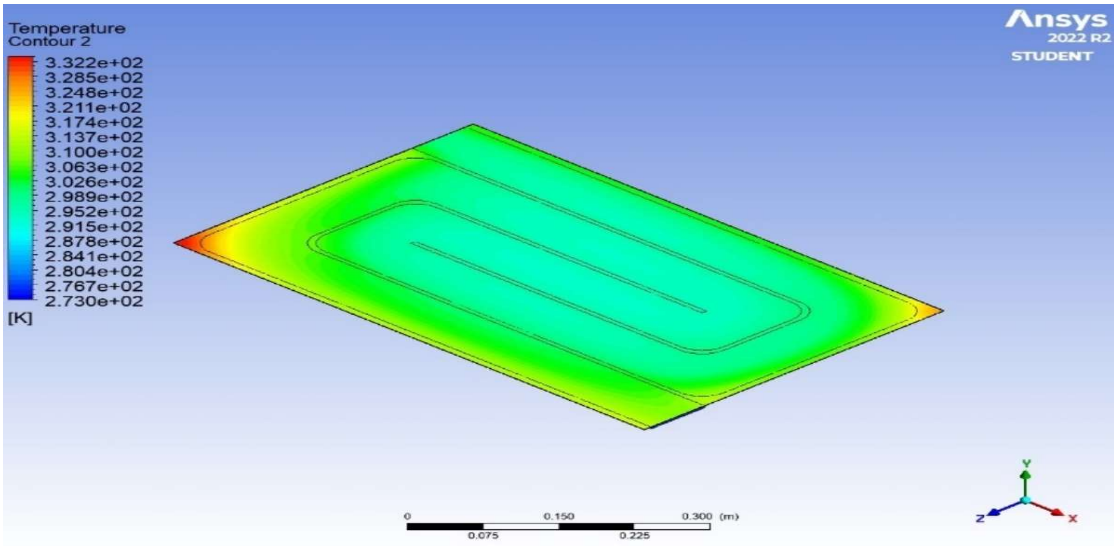

**Figure 8.3:** Cooling Plate Temperature distribution

## 8.3 Packs Simulations:

In the design process, careful considerations were made to ensure the structural integrity and protection of the battery cells. One approach involved placing the cells directly onto the cooling plate. To provide an added layer of cushioning and protection against potential impacts, a 2 cm layer of styrofoam was incorporated around the cells. This styrofoam layer acted as a shock absorber, safeguarding the cells from bumps and abrupt hammering effects that could occur during normal operation or in the event of an accident. The styrofoam served as a buffer, minimizing the risk of damage to the cells and preserving their functionality.

Additionally, to further enhance the structural strength and rigidity of the battery pack, an external layer of steel was introduced. This steel layer formed the main structure of the pack, providing robust support and stability to the entire assembly.

By encasing the cells and the styrofoam layer within the steel structure, the pack gained increased resistance to external forces, ensuring the protection and longevity of the battery cells in various operating conditions.

The combination of the cooling plate, styrofoam cushioning, and the steel external layer provided a comprehensive design solution that prioritized both thermal management and mechanical protection. This design approach accounted for the unique requirements of the battery pack, including the need for efficient heat dissipation, cushioning against potential impacts, and a robust structural framework. Through this thoughtful design, the battery pack was able to maintain optimal performance, withstand external forces, and provide a safe and reliable power source for the intended application.

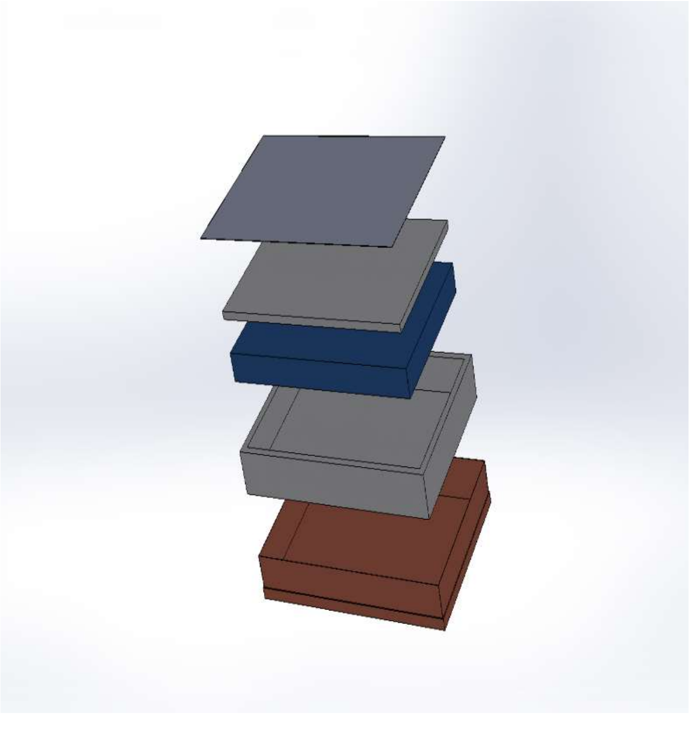

**Figure 8.4:** Pack design

To ensure the safety and structural integrity of the battery pack, extensive structural analysis was conducted on the outer steel cage. This analysis aimed to evaluate the pack's response to various loading conditions and potential impacts that could occur in accidental situations.

The results of the structural analysis indicated that the deflection experienced by the pack under these conditions was minimal, highlighting its robustness and ability to withstand external forces.

By subjecting the steel cage to simulations we were able to assess its strength, stiffness, and resistance to deformation. The analysis considered factors such as loads, as well as impact that could be encountered during transportation or in the event of an accident. The results demonstrated that the outer steel cage effectively absorbed and distributed these forces, minimizing deflection and ensuring the pack's structural integrity.

The findings of the structural analysis provided reassurance that the battery pack would maintain its shape and protect the internal components, including the cells and cooling system, in various scenarios. This reinforced the safety of the battery pack, as it exhibited a high level of resilience and the ability to withstand external impacts without compromising its structural stability. Ultimately, the structural analysis played a crucial role in verifying the design's effectiveness and instilling confidence in the pack's ability to remain intact and secure, even in unforeseen circumstances.

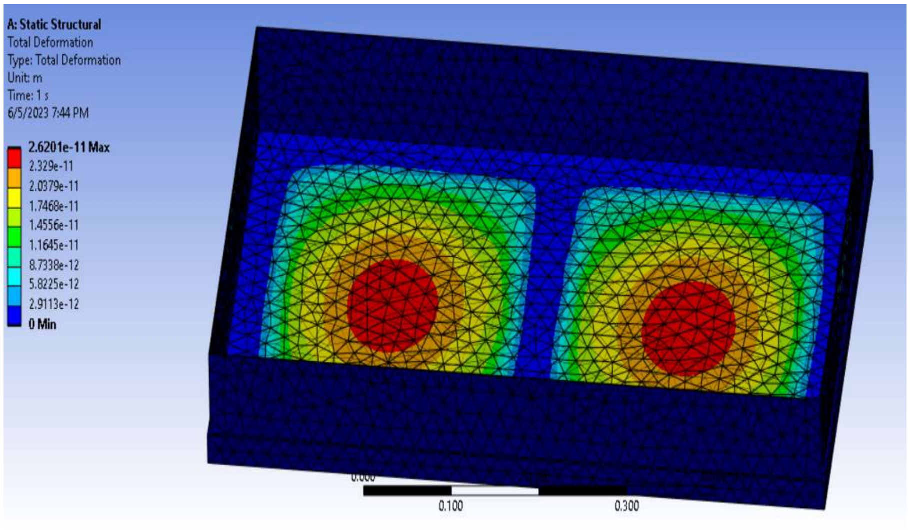

**Figure 8.5:** Deformation of Pack container

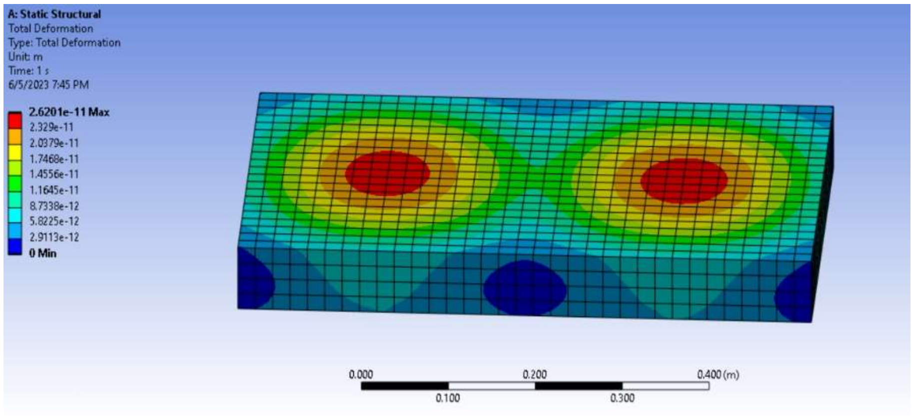

**Figure 8.6:** Cells pack deformation

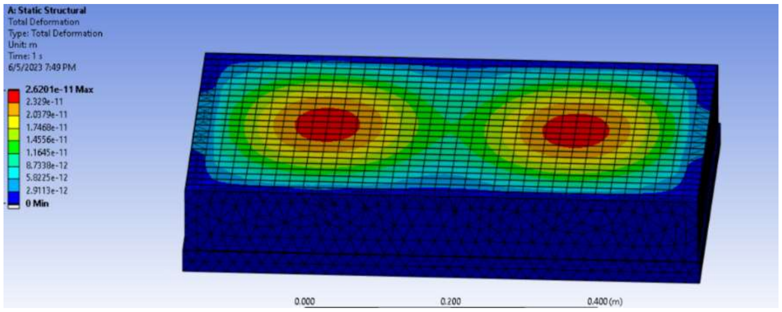

**Figure 8.7**: Complete pack deformation

## Chapter 9

# Conclusion

In this project on Battery Thermal Management System, our primary focus was on the design and analysis of the battery cooling plate and the structural analysis of the battery pack. The objective was to develop an efficient and reliable system for managing the thermal characteristics of the battery to enhance its performance and longevity. Throughout the project, we conducted extensive research, implemented design iterations, and performed detailed analyses to achieve optimal results. This comprehensive approach allowed us to draw meaningful conclusions and recommendations.

The first major aspect of our project involved the design and analysis of the battery cooling plate. We recognized the critical role of the cooling plate in regulating the temperature of the battery cells to prevent overheating and ensure optimal performance. Two CAD models were created and evaluated to assess their thermal performance. The initial model exhibited a higher than desired temperature gradient, indicating potential inefficiencies in heat dissipation. However, we iterated on the design and developed a second model with significantly reduced thermal gradients, demonstrating a more efficient cooling mechanism. The improved design showcased a substantial enhancement in maintaining uniform temperature distribution across the battery cells. This outcome validated the effectiveness of our design modifications and affirmed the importance of meticulous engineering considerations in achieving desired thermal management outcomes.

Furthermore, we focused on the structural analysis of the battery pack to ensure its integrity and durability. A robust and reliable structure is crucial for safeguarding the battery cells and maintaining their stability during various operating conditions. Through careful simulations and analysis using Ansys software, we evaluated the structural performance of the battery pack. Our chosen approach involved utilizing a gauge 20 steel sheet reinforced with angle irons, which provided the necessary strength and rigidity to withstand mechanical stress and external impacts. The structural analysis results indicated that the design effectively minimized deflection and stress concentrations, thereby ensuring a safe and resilient battery pack. This outcome affirmed the soundness of our structural design decisions and validated the reliability of our chosen materials and reinforcements.

In conclusion, our project on Battery Thermal Management System successfully addressed the challenges associated with maintaining optimal battery temperature and ensuring structural integrity. Through the design and analysis of the cooling plate, we developed an efficient cooling mechanism that significantly reduced temperature gradients within the battery pack.

The findings from this project provide valuable insights into the design considerations and engineering strategies necessary for effective battery thermal management. However, further research and experimentation are recommended to explore additional optimization possibilities, such as advanced cooling techniques or alternative materials. Additionally, conducting real-world testing and validation of the proposed designs would enhance the project's practical applicability and facilitate a more comprehensive assessment of their performance under diverse operating conditions.

Overall, our project demonstrates the significance of incorporating thermal management and structural analysis techniques in battery system design. As the demand for advanced energy storage solutions continues to rise, ensuring efficient thermal management and robust structural integrity will be pivotal in enhancing battery performance, reliability, and safety. By addressing these critical aspects, our project contributes to the advancement of battery technology and provides a foundation for future research and innovation in the field of battery thermal management systems.

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Author links open overlay panelAli Hussain Umar Bhatti, Syed Ali Abbas Kazmi, Asad Tariq, Ghulam Ali