A review of Rechargable Li-Ion Battery packs, Battery Management Systems, Thermal Analysis of a Battery Pack, Fundammental Methods to Determine Important Battery Properties.

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Introduction

Electric vehicles are becoming popular, and several companies started to produce their electric vehicles (EV). There are various reasons for companies to get into the EV industry. Pollution and environmental concerns are the biggest motivation for EVs. According to the Department of Environmental Conservation, the vehicles that use internal combustion engines are sources of air pollution. When fuel burns in an internal combustion engine, carbon monoxide, nitrogen oxides, and hydrocarbons are released to the environment. This pollution is threatening the future of Earth. Furthermore, Hugh (2018) claims that EVs are more efficient than gas-powered vehicles from the perspective of energy usage. For these reasons, zero-emission vehicles (ZEV) are becoming popular, and battery-electric vehicles are one type of ZEV. Hu (2011) claimed that an Electric Vehicle contains the following essential components: electric motor, motor driver, battery, battery management system, plug-in charger, wiring system, vehicle body, and frame. In this paper the battery pack, which includes a battery, battery management system and cooling system is analyzed.

Literature Review

Reducing pollution and greenhouse gas emissions is one of the most critical issues in the automotive industry. Electric vehicles are produced to get over with these issues. The battery is a major component of an EV. It stores electrical energy and releases it when needed. However, Li-ion batteries need a well-designed management system to operate effectively for a long time. Li-ion battery management systems have been studied in detail over the years. Clarence M. Shepred (1965) proposed his battery model, called Shepred Model. By calculating the potentials of each cell, he derived an equation for the discharging process of different cells in the battery pack. In this way, Shepred formulated the cell capacities, cell charges and the power evolution of the cells. Thus, the unbalanced cells in a battery pack are determined and necessary procedures are applied. Tremblay (2009) proposed a new battery model. He only used the State of Charge (SOC) as the variable to avoid algebraic loops that create complexity. According to Mu, Tremblay's model accurately represented the battery chemistries. However, Mu claimed that these battery models do not perfectly fit in real-life applications because the following effects are ignored: self-discharge effect, temperature effect, and effect of the fading capacity. The perfect modeling of the battery is still under development.

1. Battery Pack

The battery pack is one of the indispensable components of an EV. A battery pack consists of batteries, battery management system, and a battery cooling system.

1.1 Battery

Currently, there are several types of re-chargable battery chemistries available: lithium-ion (Li-ion), lithium-ion polymer, lead-acid, nickel-metal hydride (NiMH) and nickel-cadmium (NiCd). Li-ion batteries have numerous advantages over the others. One of the most important criteria for the selection of battery type is energy density. Hu (2011) indicates that Lithium has the greatest electrochemical potential and the largest energy density per weight among all the metals found in nature. Thus, lithium-based batteries can provide high voltage, great capacity, and a high energy density. For these reasons, li-ion batteries are preferred in this EV project.

The battery pack consists of Li-ion batteries. There are three different shapes of li-ion batteries on the market: cylindrical, pouch and prismatic. These cells have advantages and disadvantages according to their usage areas.

Prismatic cells are easy to cool and they are cheap due to the simple manufacturing process. These cells are also durable against physical impacts. Furthermore, their pack efficiency is higher due to their rectangular geometric shapes. However, their energy density is poor when compared to a cylindrical cell. Plus, the charge-discharge cycle life of a prismatic cell is shorter than a cylindrical cell.

Pouch cells are also used in the EV industry. Their capacity flexibility is higher compared to cylindrical and prismatic cells. Because they have a well designed rectangular shape, the packaging efficiency of pouch cells is even better than prismatic cells. However, mechanical containment is very poor. The pack has to have a good compression control so that the cells are kept safe. Most importantly, they start swelling after a certain time and become unusable. Andrea (2010) states that the pouch cells require retaining plates at the ends of the battery. Moreover, there are no standardized pouch cells in the market. They are all produced for a specific use.

Cylindrical cells have good mechanical stability. Andrea claims that these cells can stand under high internal and external pressures due to the cylindrical geometry. They keep their shape as it is, and they do not swell under high internal pressures. Also, Its electrodes are wound evenly and tightly and encased in a metal casing. This minimizes the electrode material from breaking up due to the mechanical vibrations. Cylindrical cells are produced more quickly which makes them cheaper than the other types of Li-ion batteries. Furthermore, Andrea claims that cylindrical cells provide the lowest cost per Watt-hour. Moreover, these cells are widely used for a variety of engineering applications. Thus, there is a significant number of companies in the world that produce cylindrical cells. Therefore, they are easy to find in the market. Most importantly, the cycle life of a cylindrical cell is higher than the prismatic and pouch cells. On the other hand, there are some disadvantages of using cylindrical cells. Firstly, cylindrical cells are relatively harder to cool. Secondly, the cylindrical geometry causes a packaging inefficiency. When they are put together in a pack, there will be some empty places and this will cause the battery pack to be bigger. However, the empty places could be used for natural convection for thermal management

After this comparison, it is concluded that cylindrical cells will be more efficient for this EV design. Their price, reliability, durability, and sustainability are the main reasons why they are preferred for this project. Currently, there are several cylindrical cell producers in the market. Samsung, Sony, Efest and Panasonic are well-known battery producers. However, Panasonic is one of the most preferred brands for EVs among all the others. Kodata (2009) announced that Panasonic has been in this industry since 2009. Moreover, this brand (Panasonic NCR18650) is also used in Tesla Model S due to its advantages over the other brands. Hence, Panasonic NCR18650B is preferred for this EV project. The official specifications of PanasonicNCR18650B is illustrated in Table 1.1.

Capacity (Ah)	3400 mAh (3.4Ah)
Nominal Voltage (V)	3.6 V- 3.7V
Charging Voltage (V)	4.2 V
Max. Discharge Rate (C)	2C (Max recommended current is 6.8A)
Energy (Wh)	12.2 Wh
Energy Density (Wh/L)	730 Wh/L
Weight (g)	46g
Diameter (mm)	~ 18mm
Height (mm)	~ 65mm
Model	NCR18650B

Made in Japan by Panasonic

Table 1.1: Official specifications of Panasonic NCR18650B

Note: The cells will not be charged over 4V to enable the regenerative braking. Also, they will not be discharged under 2.8 V for sustainable use.

1.2 Battery Pack Cell Connection Configuration

Cells are connected in series and parallel to form battery packs. In this design, the output voltage is required to be at least 96V for electric motor. Besides, the pack should have enough capacity to provide up to 20-25A current for the necessary acceleration. Moreover, the series connected cell limit for the designed BMS is 16, and there is not a limit for parallel connected cells. To obtain the required voltage level, 32 cells are connected in series. Furthermore, 6 series combination is connected in parallel so that the required capacity is achieved. The cell connection configuration is illustrated in Figure 1.2.1.

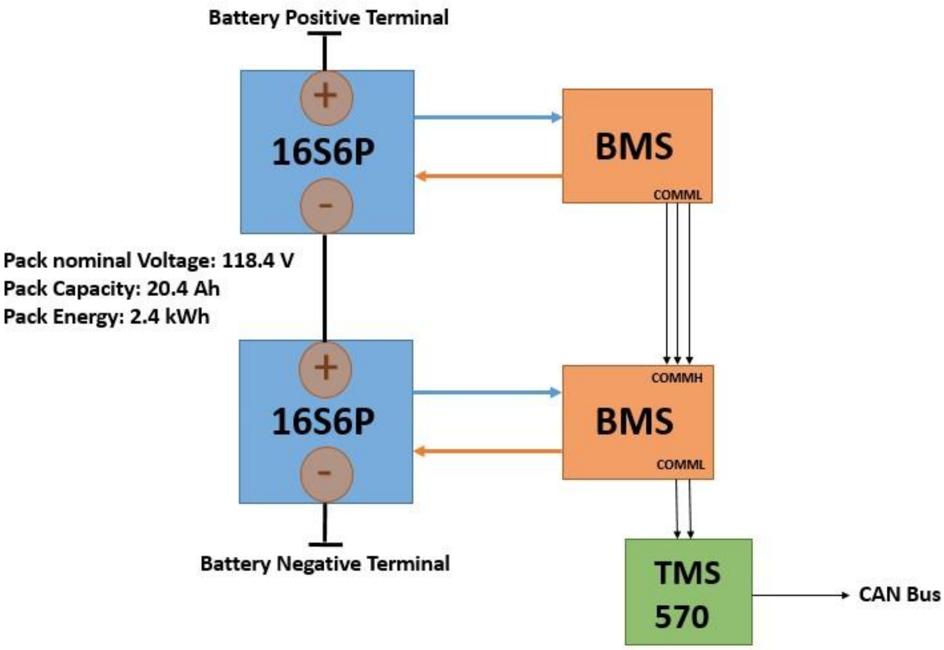


Figure 1.2.1: Cell connection configuration

1.3 Battery Management System

Li-ion batteries have certain drawbacks over their tremendous advantages. Large battery packs, such as in EV, consists of several series and parallel connected li-ion cells. According to Andrea, cells in series are more prone to be unevenly charged or discharged. In addition, these cells should not be overcharged or overdischarged depending on the upper and lower voltage limits. Furthermore, Hu reports that in order to arrange the Safe Operation Area (SOA) for li-ion batteries, a protective device is required. This device is Battery Management System (BMS), and it should provide the following features: monitoring, protecting, eastimation of the battery charge level, maximization of the battery's performance. The BMS also controls the maximum charging or discharging current, and monitors the temperature. It ensures that the risk of damaging the battery is minimal. Moreover, the BMS must interact with the motor controller, communication bus, safety system and cooling system. Overall, the main aim of a BMS is to create the SOA for each and every cell in the battery pack. BMS has six main functions: discharging control, charging control, state-of-charge determination, stat-of-health determination, cell balancing and communication.

1.3.1 Charging Control

There are several reasons for batteries to be damaged, and overcharging is the most frequent cause of damage. Therefore, charging control is a must. Mu states that a two-stage charging method, which is constant current (CC) constant voltage (CV), is used. Batteries are charged with the constant current, and it increases their voltage levels. When the battery is nearly fully-charged, it enters to the constant voltage stage. In this stage, the charging current decreases and ends. According to Sanyo Electronics, Panasonic NCR18650 should not be charged over 4.2V. If the regenerative braking is used, the batteries should not be charged over 80% state of charge level. Otherwise, the battery may heat up and explode or its life-span decreases.

1.3.2 Discharging Control

Batteries are discharged as they are used. Panasonic NCR18650B should not be discharged after its voltage level is below 2.5V. The BMS must communicate with the other systems in the EV and stop the discharging for the sake of battery lifespan.

1.3.3 State-of-Charge (SOC) Determination

SOC, which is determined by the Fuel Gauge, indicates the charge level of the battery, and SOC determination is one of the most important features of a BMS. BMS should monitor the SOC on the user panel. Also, SOC must be calculated for cell balancing. According to Mu, currently, there are three ways of determining the SOC: through direct measurement, through coulomb counting, and the combination of these two. In the direct measurement method, simply a voltmeter can be used to measure the voltage levels of the cells. According to Murnane (2017), this method is not efficient since measuring the voltages of each cell by a voltmeter will take a huge amount of time. On the other hand, the Coulomb Counting Method is the most common technique for measuring SOC. In this method, the current that enters and leaves are counted and the remaining capacity is calculated. However, this method is not 100% percent accurate due to the losses during the charge and discharge stages. Furthermore, self-discharging and fading capacity effects are other causes of this inaccuracy. Murnane (2017) defines the SOC as the ratio of the releasable capacity ($C_{releasable}$) and the battery rated capacity (C_{rated}). $C_{releasable}$ is the released capacity when the battery is totally discharged at the time when it is being measured, and C_{rated} is the capacity of the battery given by the manufacturer.

$$SOC = \frac{C_{releasable}}{C_{rated}}$$

Coulomb counting is the most used method to estimate SOC of a li-ion pack. Following section explains this method in detail.

1.3.3.1 Coulomb Counting Method to estimate the SOC of a Li-ion battery

This section is a review of previous studies from Ines Baccouche and her team.

This method counts the incoming and outgoing current of a battery to determine the current SOC. It is one of the most reliable methods to estimate SOC. However, there is a couple of problems performing such a method. The following formula shall be known to have an idea of what the Coulomb Counting Method is.

$$SOC = SOC_0 + \frac{\int_{t_0}^{t_0+\tau} I_{bat} \Delta\tau}{Q_{rated}} * 100$$

As seen, to estimate the SOC, the initial SOC, rated capacity of the cell, and the change in charge must be known. The problems arise due to these needs.

1- The initial SOC of the battery might not be accurately known

2- The current sensors, which are used to count the charge and discharge currents, might not be accurate.

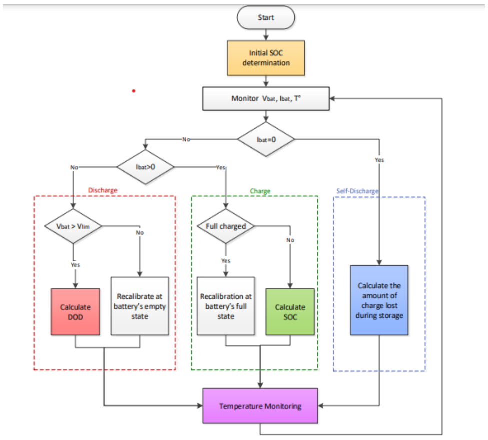
3- Variable ambient temperature causes the charge and discharge cycle to be irregular. (Not a major problem)

4- Battery might not be used for a long time and face self-discharge. When this occurs, the battery loses capacity without discharging which is detected by the sensors.

To overcome such issues, the following precautions shall be executed.

- When the battery is connected to a load, when, the voltage, current, and temperature variables must be monitored accurately.
- When the battery is in open circuit condition, the self-discharge must be accurately monitored.

Figure 1.3.3.1.1 depicts the aforementioned procedure.

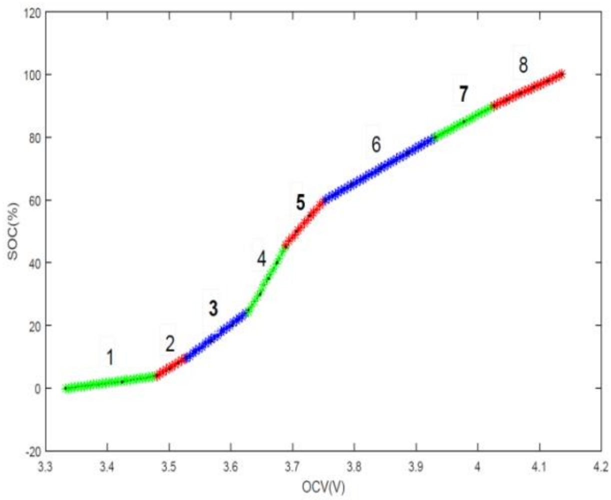


1.3.3.1.1: Block diagram

Proposed Enhanced Coulomb Counting Method that solves the aforementioned issues.

1- Initial SOC Determination

Li-ion batteries have the following OCV-SOC curve.



1.3.3.1.2: SOC/OCV curve of a li-ion battery

The cells are neither linearly charged nor discharged. The accuracy problems arise due to this non-linearity. The referred paper formulates the curve using coefficients as follows.

$$SOC = f(OCV) = a * OCV - b$$

Segment	1	2	3	4	5	6	7	8
Voltage Range (V)	[3.3; 3.452]	[3.452; 3.508]	[3.508; 3.595]	[3.595; 3.676]	[3.676; 3.739]	[3.739; 3.967]	[3.967; 4.039]	[4.039; 4.132]
A	26.55	125	149	344	229.5	111.9	104.8	90.61
B	88.6	431.1	516.1	1225	800.9	359.9	332	274.7

2- Charge Mode

In this mode, the incoming charge is counted and added to the initial SOC of the battery.

3- Discharge Mode

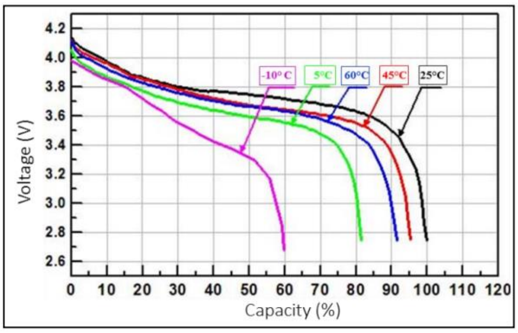
In this mode, the outgoing charge is counted and subtracted from the initial SOC of the battery.

4- Self-Discharge Mode

If the self-discharge rates of the cells are tested, org given by the manufacturer, the self-discharge per hour is calculated. After this calculation, the accumulated self-discharge is added to the discharge count.

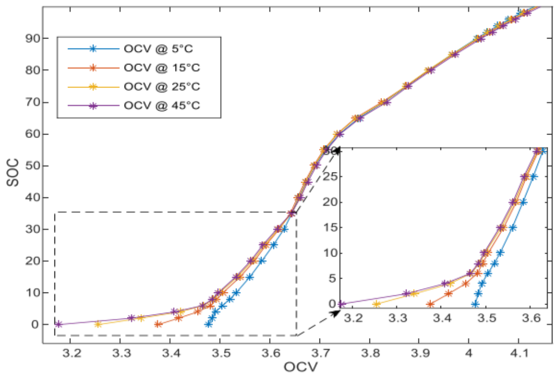
5- Temperature Monitoring

The behavior of the battery is significantly affected by the ambient temperature. This effect can be seen as follows.



1.3.3.1.3: Temperature verus capacity of a li-ion cell

The capacity drops to 60% degrees at low temperatures. That is the reason why your battery might die even though its SOC is shown as 50%. The following graph supports this argument.



1.3.3.1.4: Simulation results

To overcome this issue, the authors proposed the remaining capacity percentage depending on the temperature and added it to the SOC estimation algorithm. The coefficient is multiplied by the calculated SOC, and the ultimate SOC is found.

$$\alpha = \begin{cases} 0.5 & T^{\circ} < -10 \\ 0.6 & -10 \le T^{\circ} < 5 \\ 0.8 & 5 \le T^{\circ} < 25 \\ 1 & 25 \le T^{\circ} < 45 \\ 0.9 & 45 \le T^{\circ} < 60 \end{cases}$$

For example, if the charge-discharge counting shows the battery to have 60% SOC at -10C degree, the actual SOC needs to be halved.

To measure the voltage and the current of the pack, a sense resistor is employed. The voltage across this resistor is measured via the processor and the current is also found. This resistance value shouldn't be high to avoid energy loss.

1.3.4 State-of-Health (SOH) Determination

SOH measures the general condition of the battery. Simply, SOH is the current condition of the battery compared to its initial conditions. Ideally, the SOH of a battery is 100% just after the manufacturing and tends to decrease by time. This is indeed caused by the fading capacity effect. Murnane defines the SOH as the ratio of maximum releasable capacity (C_{max}) and the rated capacity (C_{rated}). C_{max} is the releasable capacity when the battery is totally charged.

$$SOH = \frac{C_{max}}{C_{rated}}$$

Note: The battery is totally charged when SOC is equal to SOH.

1.3.5 Cell Balancing

The battery packs consist of series and parallel connected cells. Over time, the SOC of each cell varies due to the unequal fabrication of the cells. During the charging state, unbalanced cells create an overcharging issue, and during discharging state, they create an over-discharging issue. These issues damage the cells. For these reasons, cells should be equally charged and discharged. Equalizing the SOC of each cell is another function of a BMS. Currently, there are two cell balancing methods: passive balancing, active balancing. According to Plett (2015), in the passive balancing method, the charge is drained from the cells that have more charge and dissipated as heat. In the active balancing method, the charge is drained from the high cells and moved to the low cells. From the perspective of efficiency, active balancing is preferred in large li-ion packs.

1.3.6 Communication

The BMS used in the battery must communicate with the vehicle controller. The SOC, SOH, and temperature should be known by the user. The most known communication method is the controller area network (CAN). It is more commonly used in the EV industry.

1.4 Thermal Management of the Battery Pack

Li-ion batteries are widely used for many industrial purposes due to their long life cycle time. These batteries are very useful when they are managed from both thermal and electrical perspectives. Otherwise, the life cycle of the batteries decreases and they lose their useful features. Thus, the operation conditions should be satisfied with the efficient use of li-ion cells. Heating management of lithium-based batteries is crucial for these reasons. The medium that the batteries are staying should not be so cold or so hot.

1.4.1 Heat Generation of Li-ion Batteries (LIB)

During charge and discharge, li-ion batteries generate heat due to the movements of the ions located in anode and cathode. Indeed, it is the movement of these ions that create electrical energy. The charge and discharge rate is referred to as C-rate. More specifically, the ratio of charging or discharging current and capacity of the Li-ion battery is equal to the C-rate. Furthermore, the heat generation rate is directly proportional to the C-rate. According to Drake (2015), the flow of current causes heating in battery cells and it is proportional to the square of the current and the internal resistance of a single cell. Thus, as the C-rate increases, the heat generation rate increases. Drake demonstrated this correlation in their research, and the overall result is illustrated in Figure 1.4.1.1.

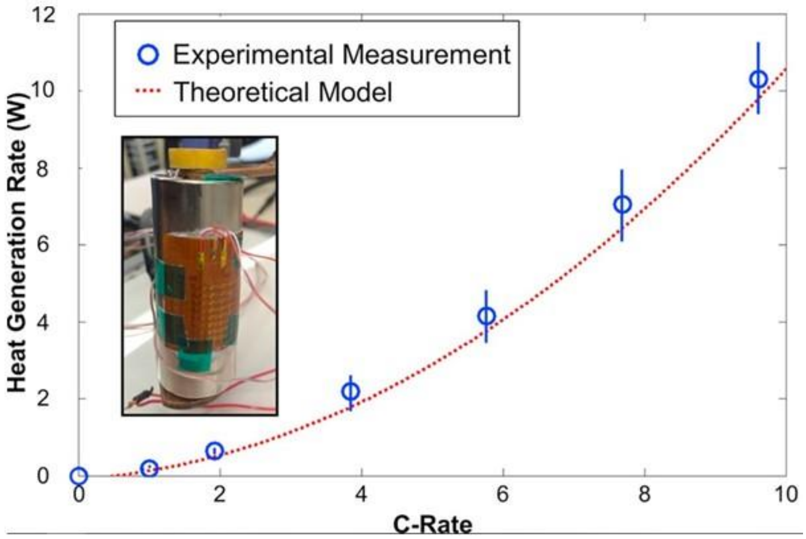


Figure 1.4.1.1: C-Rate and Heat Generation Rate Relation

When datasheet is checked, the maximum C-rate of the chosen cell (Panasonic NCR18650B) is 2C, which means that discharging current of the cells are not allowed to be larger than 6.8A. In addition, the internal resistance of the Panasonic NCR18650B is 0.11Ω. The heat generation rate for batteries is generally calculated by the ratio of power generation over volume (w/m^3). Moreover, the approximate power generation rate of cells is calculated by using $P(w) = I^2(amp).R(\Omega)$. As stated above, the heat generation is directly proportional to the C-rate, and the maximum C-rate of Panasonic NCR18650B is 2C. The nominal capacity of this cell is 3.4 Ah, which means that 3.4A can be drawn from the cell for 1 hour at 1C. To analyze the heating characteristics of the pack, the calculations are made for the worst case. Here, the definition of the worst case is important. It is known that the discharge rate of 2C will not be used more than 20-30 seconds. For the worst case scenario, 60 seconds of transient analysis is selected.

The discharge current is approximately 6.8A at 2C. This leads the power generation to be approximately 5.08 watts. Plus, the volume of a Panasonic NCR18650B is 16540mm^3. Finally, the heat generation rate of a cell when the charge/discharge rate is at 2C is around 307134 w/m^3. This value is taken into account when the heating management is simulated in ANSYS Fluent.

1.4.2 Importance of the heat management for the cells

The performance of Lithium-Ion batteries is dramatically affected by their temperature. The temperature affects the ionic conductivity of a li-ion cell, and ionic conductivity affects the performance. Hence, so low or so high temperatures negatively affect the performance of a cell. Nagasubramanian (2001) demonstrated that while the power density of a Panasonic NCR18650B cell is around 800W at 25°C, it dropped to 10W at -40°C. It can be understood that at very low temperatures, li-ion cells do not operate well. Furthermore, operating at a very high temperature is even more dangerous. The cell might explode and it can damage the other cells as well. The batteries age faster when the operation temperature is so high. Heat management of a li-ion cell is very important due to these reasons. According to Ma (2018), the acceptable operating temperature region for a li-ion battery is -20°C to 60°C. The temperatures out of this region may decrease the efficiency or cause the premature death of a cell.

1.4.3 Available Cooling Systems

There are several ways of cooling a battery pack such as fan cooling, air cooling, and liquid cooling. The most popular cooling system for electric vehicles in the market is liquid cooling due to its high cooling accuracy. It is the most appropriate cooling mechanism for huge battery packs. For instance, there are 7104 cells in the battery pack of Tesla Model S, and the preferred system for thermal management is liquid cooling. However, it is not preferred in this project due to its complexity and cost. Besides, the battery pack that will be used in the project contains around 300 cells. Hence, natural airflow and fans are used for cooling systems in this project. The location of the battery pack is the front side of the car for thermal management purposes. As the car moves, the air flows through the battery pack and it cools the cells down and flows out from the air channels. For the moments where the natural airflow is not enough, the fans start working and provide additional airflow to the cells.

1.4.4 Thermal Management Simulation using ANSYS Fluent

For this Electrical Vehicle (EV) project, the thermal management of the battery pack is simulated using ANSYS Fluent. This software contains wide physical modeling capabilities, and it is generally used for thermal analysis in industrial applications. It is currently one of the most confidential software in the market.

The initial step when simulating the heating characteristics of Panasonic NCR18650B was to create the geometry in the *Design Modeler* section. The information about the battery cells is directly taken from the original datasheet which was shared by Sanyo Electronics. The purpose of the first simulation is not the analysis of the cooling system, but it is the analysis of the heat generation and natural convection effect on a single cell. The pack is then simulated using a single cell simulation approach. The geometry of a single cell is a symmetric cylinder that has a diameter of 18 mm and a height of 65 mm. The entire geometry was drawn with a symmetric approach. In the very first step, the geometry was drawn, and the single-cell geometry is shown in Figure 1.3.4.1. All the images in this report are directly exported from ANSYS Fluent with the highest possible resolution rate.

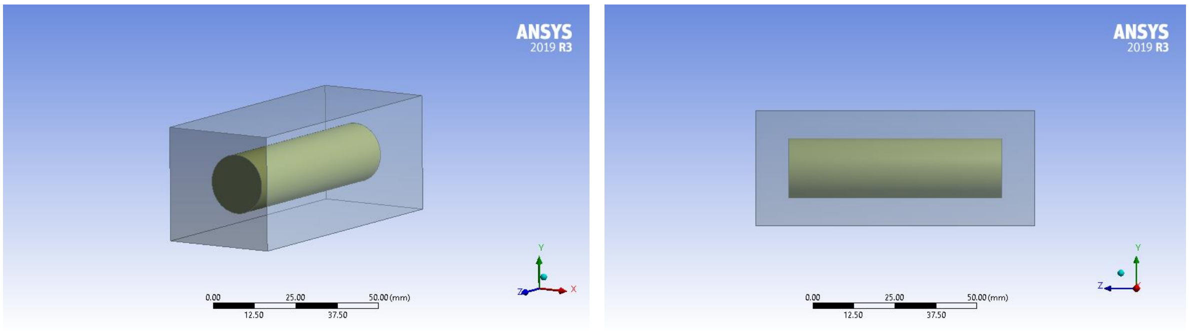


Figure 1.4.4.1: Geometry of a single cell in ANSYS Fluent Design Modeler

The rectangular prism-shaped geometry around the cylindrical cell represents the air domain in order to analyze the natural convection effect on the system. The rectangular prism and cylindrical shape are subtracted from each other using boolean operators, meaning that they do not coincide with one another. Next, the meshing was applied to the geometry. The patch confronting method is set to tetrahedrons for better accuracy. The meshing shape and quality are illustrated in Figure 1.4.4.2.

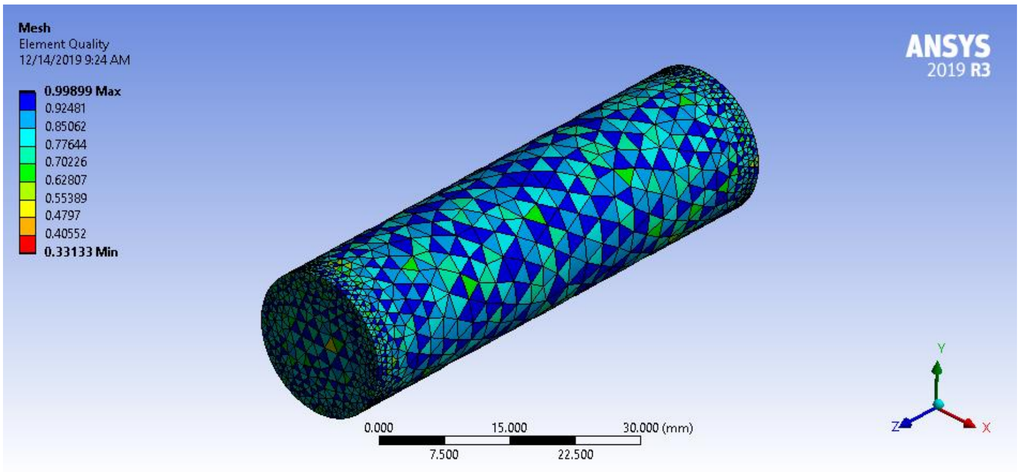


Figure 1.4.4.2: Mesh shape and quality

The minimum orthogonal quality of the machine is 0.18, and the minimum volume is 2.5e-11 These numbers demonstrate that the quality of meshing is sufficient enough to successfully finalize the calculation. A critical notice is that the minimum orthogonal quality should not be less than 0.1. Otherwise, *the Floating-Point Exception* error ends the solution of the simulation. Next, the problem is defined as the program. The material that covers the cylindrical li-ion cells is generally polyvinyl chloride(PVC). Thus, the thermal characteristics of the PVC are set to the cylindrical geometry. The material specifications are illustrated in Table 1.4.4.1. The material for the air domain is set to *air.* The material specifications for air are illustrated in Table 1.4.4.2. The values are set as constant values in order to decrease the complexity, which means that they do not vary in different conditions.

Density ($\frac{kg}{m^3}$)	1467
Specific Heat ($\frac{J}{kg-K}$)	880
Thermal Conductivity ($\frac{w}{m-K}$)	0.19

Table 1.4.4.1: The material specifications of PVC

Density ($\frac{kg}{m^3}$)	1.225
Specific Heat ($\frac{J}{kg-K}$)	1006.43
Thermal Conductivity ($\frac{w}{m-K}$)	0.0242
Viscosity ($\frac{kg}{m-s}$)	1.7 x 10^{-5}

Table 1.4.4.2: The material specifications of Air

The initial temperature of all the materials is set to 300Kelvin (27°C), and the heat generation rate of Panasonic NCR18650B at 2C is set to the cylindrical geometry (307134 w/m^3). The transient calculation is simulated for 60 seconds and the results are analyzed. The final moment of the calculation is displayed in Figure 1.4.4.3.

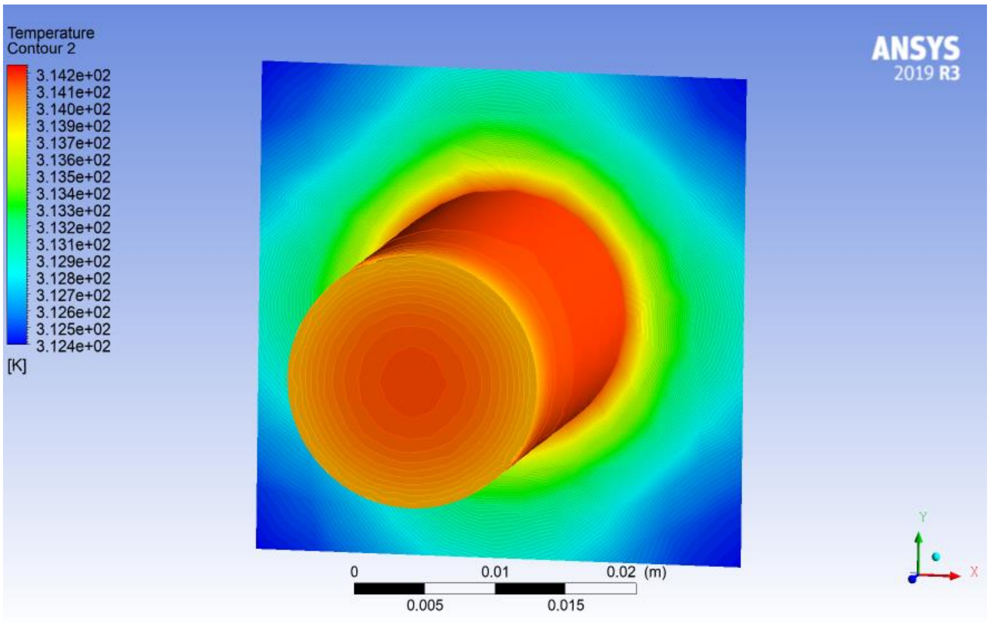


Figure 1.4.4.3: The calculation result

As can be seen in figure 1.4.4.3, a vertical virtual plane is created to analyze the natural convection behavior of the system. The heat is spread directly proportional to the distance to the air as expected because of the nature of natural convection. Moreover, the final temperature of the cell is 14 Kelvin more than the initial value. Here, the inference is that the temperature of a cell increases 14 Kelvin when 6.8 A is continuously drawn from the cell for 60 seconds without any sort of cooling application. It is important to know that a continuous current of 6.8A will not be drawn from the cell for a long time. The high discharge rate will only be necessary when the car starts accelerating. So, the reminder is that the simulation is calculated for the worst possible case.

Then, an air inlet and outlet (outflow) is created for the analysis of the air cooling system. Inlet was set to the wall that is parallel to the height of the cylinder. The velocity of the air is set to 20 m/s. The velocity of the air is dependent on the velocity of the car, which varies in time. 20 m/s is taken as the worst average velocity. Plus, the temperature of the air is again set to 300 Kelvin continuously. The same calculation was made again, and the results were analyzed. A slight temperature difference between the center and the surface of the cell is expected. The results of the calculation are shown in Figure 1.3.4.4.

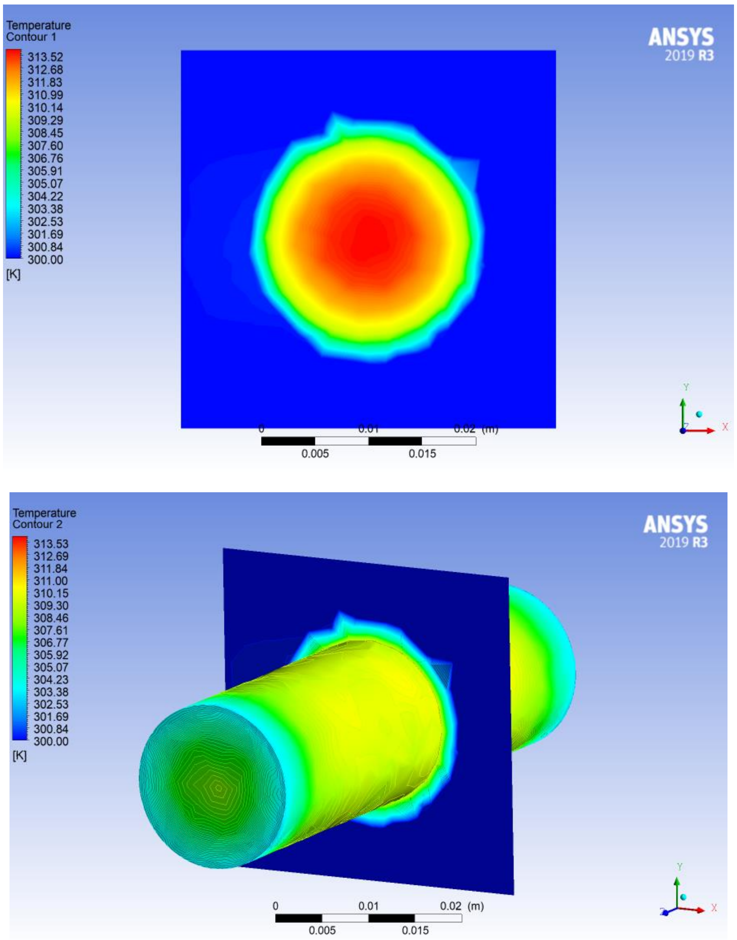


Figure 1.4.4.4: The heat dissipation contuor when forced convection cooling is applied

As can be seen in figure 1.4.4.4 the temperature varies depending on the distance from the center as expected. The inlet is the right side of the figure 1.4.4.4, and the air that is coming from this inlet is the air that flows inside of the battery pack as the car moves forward. Simply, it is the natural airflow that is caused by the movement of the car. Furthermore, the temperature of the air domain stayed at 300Kelvin because the airflow continuously renews this air. The temperature difference between the surface and the center is around 8 Kelvin after a 60 seconds transient analysis. The anode and cathode (sidewalls of the cylindrical shape) cooled down more compared to the inside of the cell surface due to the geometric shape of the whole system. Hence, the effect of the forced convection cooling in ANSYS Fluent proved the expectations correct. This is the reason why the forced convection cooling is preferred as the cooling system of the battery pack in EV.

A further step was to create a little part of the real battery pack and simulating it. A little part of the whole battery is analyzed to decrease the simulation time. By the results of this simulation, the estimation for the whole pack can be made. Since the cooling is provided by both the natural airflow and cooler fans, the necessary geometry was drawn and the necessary parameter inputs are set accordingly. Additionally, the inlets are partial and there are 5 air inlets (2 for a fan, 3 for natural airflow). The geometry is shown in Figure 1.4.4.5.

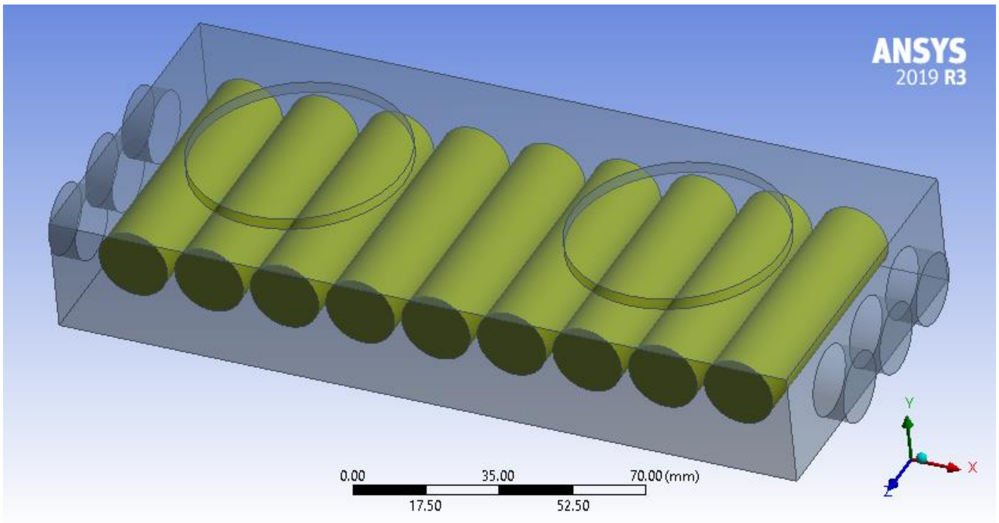


Figure 1.4.4.5: A part of the whole battery pack having 9 cells, 5 inlets, 3 outlets

9 identical Panasonic NCR18650B cells are generating 307000 of heat (at 2C), initially having 300 Kelvin temperature. Plus, the air that comes from both fans and the front side of the car has 300 Kelvin continuous temperature. The diameter of the fan inlets is 55mm, whereas the diameter of natural air inlets is 10mm. Similar to the previous simulation, the same mesh is applied in the tetrahedron

method. This simulation is calculated for a steady-state case to analyze the steady-state situation of the system and decrease the simulation time. Here, an important notice is that the cells are discharging at 2C and generating the highest possible heat so that the worst case is simulated. The temperature diagram of the system is shown in Figure 1.4.4.6 and Figure 1.4.4.7. The air inlet & outlet locations and the behavior of the air is illustrated in Figure 1.3.4.6 and Figure 1.4.4.7.

Note: The arrow colors do not stand for temperature. They represent the velocity of the air.

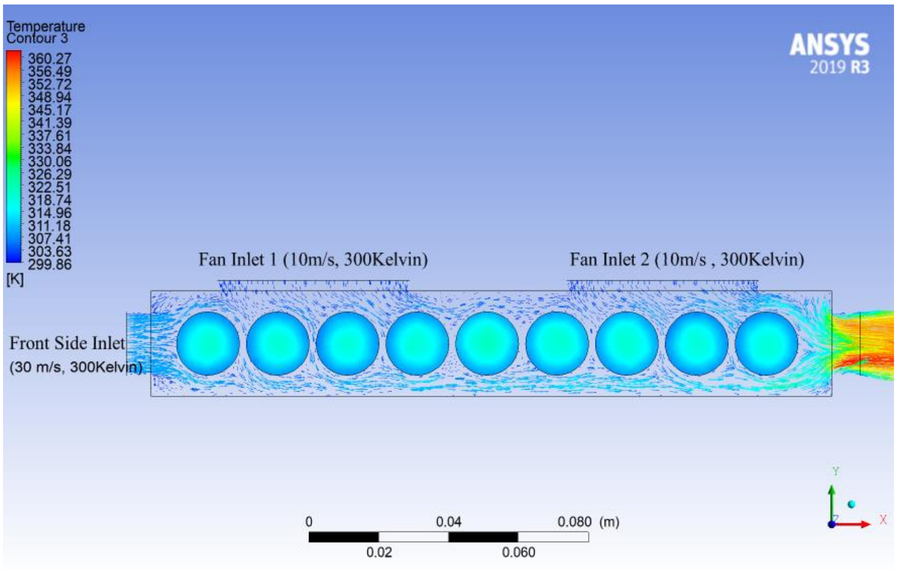


Figure 1.4.4.6: Inlets, outlets and the behaviour of the air-flow (From the side)

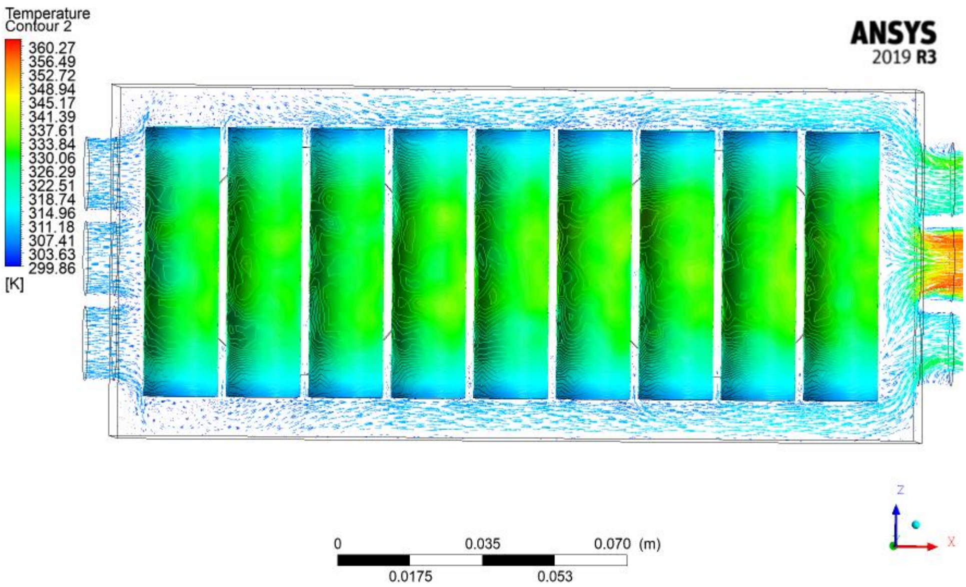


Figure 1.4.4.7: Inlets, outlets and the behaviour of the air-flow (From the top)

Finally, the simulation results demonstrated that the steady-state temperature of the pack stacked up to 9 cells is between 300K (27°C) and 360K (87°C). The maximum temperature at the surface is approximately 330K, yet the center of the cells is at 360K according to the simulation. 360K is above the best operation temperature of Panasonic NCR18650B cell. Here, note that the temperature of a single cell when used in 2C increases 13K in one minute as demonstrated in Figure 1.3.4.4. However, when the simulation is conducted for a steady-state, the temperature increased by 60K. By mathematical estimation, the system comes to a steady state in 5 minutes. This implies that when 6.8 Ampere current is drawn from the cells for 5 minutes, their temperatures increase to a level where the operating conditions are not safe. However, the discharge rate of 2C will only be used at the beginning of the competition to accelerate the car. The acceleration stage is not expected to be longer than 30 seconds. Besides, the cooling system kept the temperature at 313K when it is simulated for 60 seconds. Thus, the applied cooling system will be efficient enough to create good operating conditions for the entire pack.

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