Numerical Analysis on Cooling Techniques for Lithium ion Batteries

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Abstract

Electric vehicles have grown exponentially in recent years as a result of their low emissions and high tank to wheel efficiency. However some factors such as battery performance, cost, lifespan, and safety are limiting the production of electric vehicles. As a result battery management is required in order to achieve optimum efficiency while operating under different conditions. The battery thermal management system is critical for controlling the thermal behavior of the battery. The technologies used in battery thermal management systems include air cooling, liquid cooling, direct refrigerant cooling and phase change material cooling. To dissipate the heat produced by the battery pack and ensure the safety of electric vehicles, a battery thermal management system is essential. In this paper, various cooling system techniques are investigated and numerical analysis is carried out on two new proposed designs of air plus PCM and liquid plus PCM cooling system.

Keywords Cooling system, Battery, Thermal Management.

Paper type Research Paper.

1. Introduction

When two or more electrical cells are connected by electricity and each cell is containing two electrodes and an electrolyte, then redox (reducing oxidation) reaction occurs in these electrodes and they convert it into electrical energy. In everyday use, the 'battery' is used to refer to a single cell. A solid state batteries are used where the electrolyte is in a solid, facing position the formation of ions from one electrode to another electrode. In 1800, Alessandro Volta invented the first modern battery. Lithium is the lightest metal and can float in water. The electrochemical features of lithium are very good and also very effective. These devices allow Lithium to gain maximum power and power in a much smaller battery application such as car power and standby. Lithium ion batteries are basic batteries where the lithium metal (or) lithium compound acts as an Anode. The lithium cell can generate power from 1.5 V to 3 V depending on the type of material used.

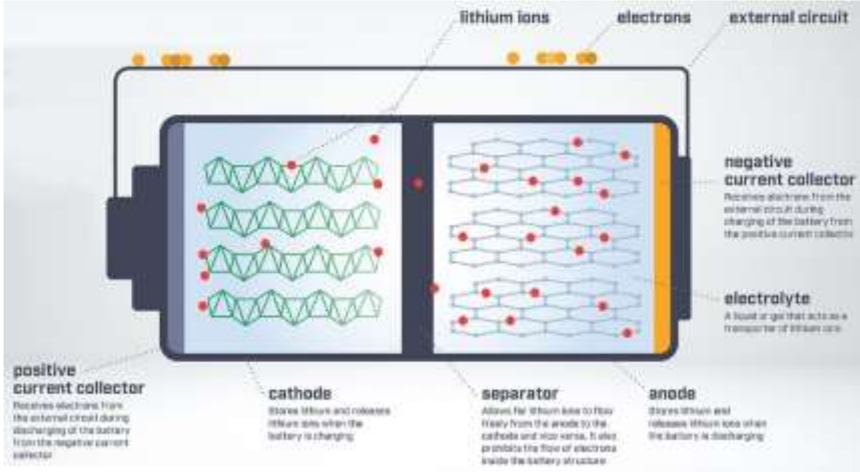

Figure 1 Lithium ion battery pack

Working Principle

Traditional batteries are based on galvanic action but the second Lithium ion battery relies on a "blending" machine. This involves inserting lithium ions into the crystalline lattice of the host electrode without altering its crystal structure. These electrodes have two important characteristics. One is an open crystal structure, which allows the insertion or removal of lithium ions and the second is the ability to receive charged electrons simultaneously. Such electrodes are called intercalation hosts. The chemical reactions that take place inside the battery are as follows, during charging and discharge operations.

Lithium ion is inserted and inserted into the anode and cathode structure during charging and discharging. During the current discharge flows through the outer region with bright light. During charging, no electrons flow to the other side.

Many kinds of climatic changes have already emerged in the twenty first century such as global warming. According the studies and analysis, vehicle emissions contribute to approximately half of this. Automobile exhaust produces green house gases, which trap the sun’s heat, leading to the rise in the earth’s temperature. The combustion of the fossil fuels causes significant emissions of toxic gases, which results in climatic changes such as green house gas effect, ozone layer depletion and plenty of other negative health effects in mankind.

Both of these considerations are emphasizing the importance of employing certain alternative approaches in the automobile industry. As a result one may find it necessary to turn into towards electric vehicles, which emit zero emissions and are truly eco friendly.

Though switching to electric vehicles appears to be the right choice. There are some major challenges that must be tackled while using batteries in electric vehicles. The key challenge is to

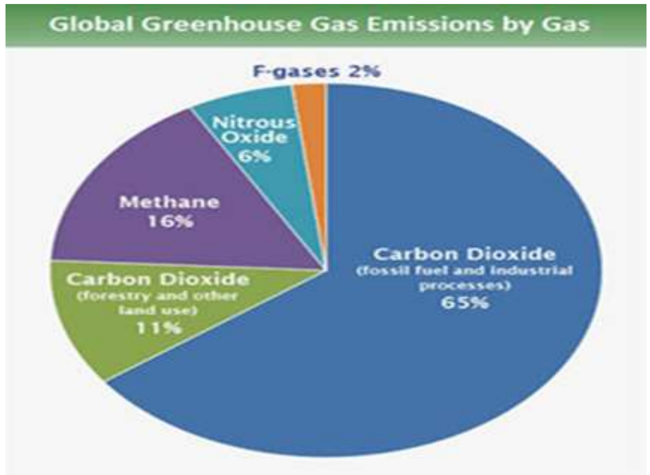

Figure 2 Global Greenhouse Emissions

identify the appropriate cooling system for a lithium ion battery in order to maintain the temperature within the optimal range of 15 to 35 degree Celsius. Battery thermal management system is also critical to dissipate the heat generated by the battery pack and guarantee the protection of the electric vehicles. A battery pack can be cooled in a number of different ways that includes air cooling system, liquid cooling system, direct refrigerant cooling system and phase change material cooling system[1]. A battery cooling system usually has following components:-

- battery pack
- a fan/ pump
- a heat exchanger
- coolant pipes

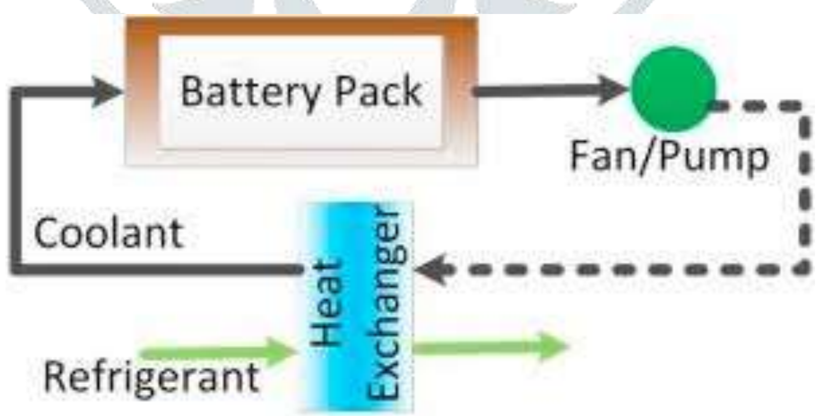

Figure 3 Schematic view of battery pack loop

1.2 Phase change material cooling system:-

By changing from solid to liquid, phase change materials absorb heat energy. The material can absorb a lot of heat during changing phases with little temperature change. The material can absorb a lot of heat during changing phases with little temperature change. The cooling requirements of the battery pack can be achieved with phase change material cooling systems, but the volume change that occurs during a phase change limits their application. Furthermore, phase change materials can only absorb heat rather than transfer it, so they won't be able to decrease overall temperature as effectively as other systems. Although phase change materials are not suitable for use in electric vehicles, they can improve overall thermal performance by reducing internal temperature fluctuations and peak cooling loads.

1.2.1 Air cooling system

The method of convection is used to transfer heat away from the battery pack with air cooling. The heat emitted by the pack will be taken away by the air as it passes over the surface. Air cooling is quick and straightforward but it is ineffective when compared to liquid cooling. Earlier versions of electric vehicles, such as the Nissan leaf, used air cooling. As electric cars become more prevalent, safety concerns about purely air cooled battery packs have arisen, especially in hot climates.

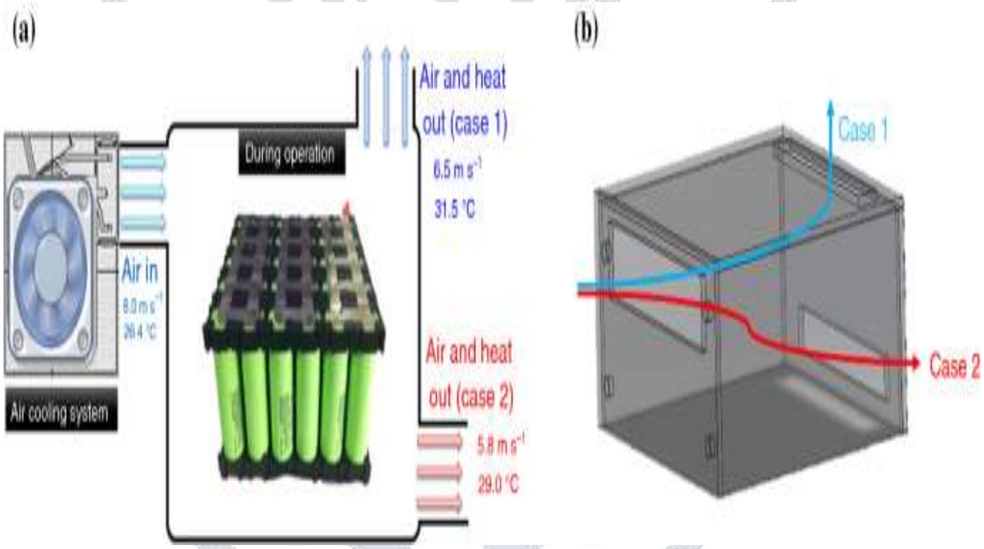

Figure 4 Air cooling system

1.2.2 Fin cooling system

Cooling fins increase surface area and thereby increases the heat transfer rate. Conduction transfers heat from the battery pack to the fin and convection transfers the heat from the fin to the air. Fins possess high thermal conductivity and can contribute to cooling also but they add a significant amount of weight to the pack. Fins have witnessed a lot of success in electronics and they have historically been used as an extra cooling system in I.C engine cars. Fins are no longer being used to cool the electric vehicle car batteries because the added weight of the fin outweighs the cooling benefits.

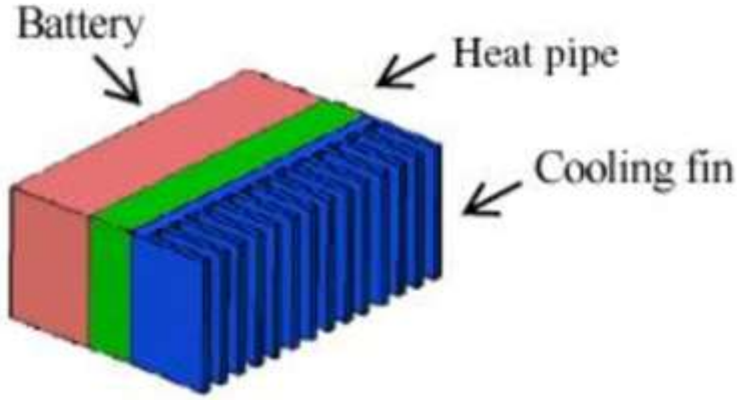

Figure 5 Fin cooling system

1.2.3 Liquid cooling system

Other automakers, such as Tesla believe that liquid cooling is the most secure option because of the fact that liquid coolants have higher heat conductivity and heat capacity than air. Liquid coolants perform very well and has certain advantages such as compact structure and ease of installation. Liquid coolants, out of all those mentioned above, can provide the best performance in terms of maintaining a battery pack's temperature within the optimal range and uniformity. Liquid cooling systems have their own set of safety concerns regarding leakage and disposal. Glycol can be hazardous to the environment if handled incorrectly. Tesla, Jaguar and BMW are the ones who are currently employing these systems.

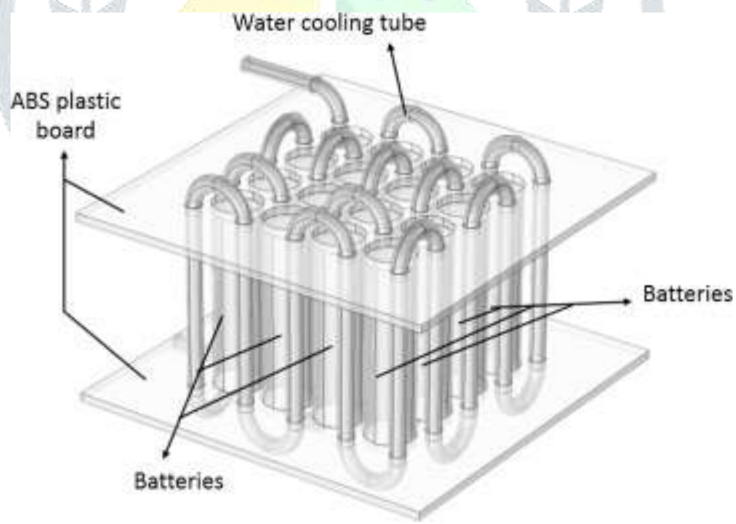

Figure 6 Liquid cooling system

In this paper, study is made on PCM type of cooling technique. In addition to that, two new designs have also been proposed during this study. The two designs employ air plus PCM and Liquid Plus PCM technique in order to optimize the battery pack temperature.

2 Literature Review

This chapter is related to review of previous work, done by various researchers in the past, related to the cooling techniques in lithium ion batteries. In past many scholars presents their knowledge including substantive findings as well as the theoretical and methodological contribution to the topic cooling of lithium ion battery pack. The literature review are discussed as follows.

S.Al Hallaj et al.[1999]

In this paper, the author uses a thermal mathematical model to recognize the temperature profile inside a lithium ion battery. The heat generation parameters were observed in a Sony US18650 cell. At the end, the result showed that scaled-up cells of 10–100 A h are expected to work safely at very low to moderate discharge rate of current from cell under normal conditions. And during high discharge rate there is a risking of thermal explosion.[2]

Mao-Sung Wu et.[2002]

In this paper, the author experimental showed that the natural convection is not efficient for removing of heat from the pack of lithium ion battery. While doing this experiment it is found that forced convection cooling can alleviate temperature rise in the battery. However, the temperature which is non uniform in nature is not easy to escape from the surface and this makes difficulty in thermal management. Inserting the heat pipe in an aluminum fin seems to be suitable for reducing the increase in temperature and maintaining a uniform temperature distribution on the surface of the battery.[3]

Paul Nelson et al.[2002]

In this paper, author with the help of computer aid program studied the need of thermal control system as being instructed by PNGV i.e. Partnership for a New Generation of Vehicles. The worst-case cooling requirement during prolonged aggressive driving was estimated to be 250 W per cell for 48 cells battery. And rapid heating of battery in harsh weather is much difficult than to cool down while the battery is in dynamic mode. The temperature generated during the working of batteries is not always difficult to the performance of the battery pack. In extreme weather conditions, the battery is significantly used, the battery may give many years of useful service. On the other hand the more insulation to battery case will be efficient in slowing the heating process in warm weather when the vehicle is parked and slowing the cooling process in very cold weather.[4]

Y. Inui et al.[2006]

In this paper, the author experimentally developed the two dimensional and numerically three dimensional simulation codes of the transient response of the temperature distribution in the lithium ion secondary battery during a discharge cycle. Firstly the two dimensional for a cylindrical battery was developed and simulation result were compared experimentally and then three dimensional was compared numerically. As a result it has been made clear that battery with the laminated cross section shows an efficient suppression in rising the temperature with having a square cross section.[5]

Chris Mi et al.[2007]

In this paper, the author numerically showed that in order to get an efficient cooling to the battery pack, a minimum 25mm of cooling fins is to be required. The thermal management system in lithium ion battery pack which is designed for hybrid electric vehicle is estimating the thermal loss of lithium ion battery of a vehicle. It is not yet ready for the hybrid electric vehicle due to its limitations in heat disputation. As in case of hybrid electric vehicle, the number of battery packs are more and the disputation of heat is required to cool down the battery packs.[6]

Ralph E et al.[2008]

In this paper, the author experimentally measured the change in entropy of various cathode and anode materials using an electrochemical thermodynamic measurement system (ETMS). The comparison between theoretical results and experimental results were made. It has been found that the shape of entropy curve depends upon the manufacturing materials. Also no significant temperature gradient was observed at the center of the stack (inside of the battery). As a result the lithium cobalt oxide is having larger entropy change than other elements like Li Ni Co Mn O2.[7]

R. Kizilel et al.[2009]

In this paper, the author numerically showed that the passive thermal management system is evaluated for high power lithium ion battery packs under the stressful conditions and compared with purely atmospheric air cooling mode under normal conditions. Compact thermal management system utilizing with phase change material, provides efficient and faster cooling than active cooling method. During the numerically observation, it has been investigated that how passive cooling with PCM contributes to preventing the propagation of thermal runaway in a single cell or adjacent cells due to a cell catastrophic failure.[8]

YUAN Hao et al[2012]

In this paper, author has designed a optimum geometric design to keep the average battery temperature from the range of 20° to 40° C and the temperature gradient of 3° C Based on a typical cooling/heating plate's geometric model, this paper investigated cooling effects of similar structures with different pipe diameters and vertical distances, and found the relationships among these factors. In this paper it has been recorded as the experimental and numerical studies performed to obtain plate's heating characteristics.[9]

WANG Lifang et al.[2012]

In this paper, different structure flow distribution has been studied through numerical simulation. And the author has found that the structure with inlet and outlet on the same side had an even flow distribution. Based on a typical cooling/heating plate's geometric model, it is also investigated that cooling effects of similar structures with different pipe diameters and vertical distances. The combined simulation and optimization was performed to find the best combination of inlet velocity and temperature to minimize the temperature gradient of the plate's surface.[9]

Yixiang Shib et al[2014]

In this paper, a two dimensional electrochemical thermal mod-ling was developed on the cross-plane of a laminated stack plate pouch lithium ion battery. The thermal efficiency of large lithium ion batteries were numerically investigated. The thermal contact resistance among laminated structures would reduce the cross-plane effective thermal conductivity and significantly increase the temperature difference between the center and the surface of the battery. The resulting high temperature gradient would induce non-uniformity of charging-discharging current and state of health among the multiple unit cells within the battery. The poor cross-plane thermal conductivity makes it difficult to reduce the maximum temperature and narrow down the temperature difference by simply intensifying the external cooling. Pulse charging protocol, which is a solution of thermal loss during fast charging, is found incapable to reduce the thermal increments, because of higher time-average heat generation rate than constant current charging on the bias of same total charging time.

Tao Wang et al.[2015]

In this paper, A thermal modelling method for varies types of batteries, empirical heat source model, is introduced based on CFD calculation and the measurement of thermal and physical properties of battery. It notably simplifies the mathematical behavior in battery thermal analysis and provides instinctive layout of battery thermal behavior. The perfection of the model is obtained as the input data is obtained from thermal insulation experiment directly. A divergent thermal model for the three-dimensional 5 _ 5 battery module is developed based on the empirical heat source model in order to specify the thermal behavior of cylindrical lithium-ion batteries.[11]

Yimin Li et al.[2017]

In this paper, a liquid cooling technique for thermal management system of a cylindrical lithium-ion battery module is designed. And is found that the thermal efficiency of the system is obtained. A battery module with six cells along flow channel is chosen to study the effects of aluminum block and velocity on the thermal performance in a analyize. The maximum temperature and temperature difference are monitored. The maximum temperature of the battery module is well controlled under 40 _C when inlet velocity is 0.05 m/s. moreover to improve the temperature distribution in the battery module, variable contact surface (aluminum blocks with linear changeable l) is used and its performance is compared with constant contact surface.

CongWang et al.[2017]

In this paper, a new type of liquid cooling system based on thermal silica plate was designed in this study to manage the large amount of heat generated within a Li-ion battery during fast charging discharging process and in aggressive operating conditions. The effects of different channel density, inlet flow rates, and flow directions on the cooling performance were analyzed through the combination of simulations and experimental measurements. The following conclusions could be drawn:

1. With the increase in the number of thermal silica plates and liquid channels, the maximum temperature of the battery is reduced.
2. Increasing the inlet flow rate improves cooling
3. The flow direction played an insignificant role on the cooling performance. Efficiency, but also the energy consumption.

Abdul Haq Mohammed et al.[2019]

In this paper, a design of cooling plate was proposed for thermal management of LIB packs to supply excessive cooling to combat the heat generation during normal operation and thermal runaway of the battery a computer model was developed in COMSOL Metaphysics to simulate the performance of the designed cooling plate. Two different designs of the cooling plate were examined for a commercial prismatic LIB with the nominal capacity of 20 Ah and the nominal voltage of 3.3 V. The simulation results showed that both cooling plates are suitable to control the battery temperature during normal and thermal runaway operation modes.

Hamidreza Behi et al.[2020]

In this paper, author has suggested an SHCS for high current discharging of the LTO battery cell. In the first analyzes, the temperature of the cell is set to be as in natural convection. In the second to fourth simulations, the effect of SHCS is calculated in a natural and forced convection to improve the efficiency of cooling. As a result it was resulted that that the maximum cell temperature embedded with SCHS for natural convection, forced convection for SHCS, and forced convection for cell and SHCS reduce the cell temperature by 13.7%, 31.6%, and 33.4% respectively.

2.2 RESEARCH GAP

According to our research and perception made from many resources and papers, we have learnt that many people had contributed their knowledge and skills in maintaining the temperature inside the battery pack. In this study, it deals with mechanism of cooling of battery that has been observed from the pack while it is in charge or discharge process. Here, the main motto for targeting this study deeply about the heat that is been released from the battery. During our research the performance of different types of cooling methods were compared. With the help of computer fluid dynamics (CFD), a new improved cooling system for lithium ion battery were developed. The main proverb for targeting this study enormously about the cooling techniques for cooling system used for lithium battery. These techniques will help in preventing the toxic chemicals released into the air which negatively affect breathing in livings and will contribute to global warming.

2.3 OBJECTIVES

- To study different types of cooling techniques for cooling system used for lithium ion battery.
- To develop a CFD model of Air cooling integrated with PCM and liquid cooling integrated with PCM cooling system.
- Numerical analysis to simulate the performance of selected cooling system.

- To study the variation of temperature distribution and heat transfer behavior on selecting cooling system.
- To compare the performance of Air cooling integrated with PCM and Liquid cooling integrated with PCM cooling system.

2.4 RESEARCH METHODOLOGY

Following steps have being followed while doing analysis for selected techniques

2.4.1 BATTERY DESIGN

This study considers a Lithium ion battery packs having high delivering power which is suitable for plug in hybrid electric vehicle (PHEV) application. This Lithium ion battery is specially designed to replace the NiMH battery pack. The lithium ion battery consists of 67 modules, each containing 20 (1.5 Ah) high power cells. Each module consists of five lines of four cells in series with the five strings connected in parallel.

The PCM (phase change material) is packed into the graphite matrix via capillary forces between liquid PCM and the graphite. We can use Paraffin wax which will help in increasing the thermal conductivity and capacity to store the heat.

2.4.2 MATERIAL SELECTION

The following materials were used in the simulation in Lithium ion Battery pack

- **Liquid Cooling integrated with PCM design**
    1. Water.(used as the coolant)
    2. Aluminum.(heat spreading plate)
    3. Bakelite layer.(electrical insulation)
    4. Battery.
- **Air Cooling integrated with PCM design**
    1. Graphite Composite.
    2. Battery Pack.

2.4.3 THERMO PHYSICAL PROPERTIES OF MATERIALS.

Table 1 Liquid cooling investigated with PCM properties

Materials	**Density(kg/m^3)**	**Specific heat (J/kg.K)**	**Thermal Conductivity (W/m.K)**	**Dynamic Viscosity (Pa.S)**
Water	998.2	4182	0.60	1.003 x 10^{-3}
Aluminum	2719	871	155	-
Bakelite layer	1000	1200	0.19	-
Battery	2510	1028	K_x, k_y=1.63 k_z=36.92	-
PCM	880	2000	0.13	0.00091

- *Liquid Plus PCM* *k_x, K_y : radial thermal conductivity of battery k_z axial.*

Table 2 PCM properties (Graphite)

Material	**Density(kg/m^3)**	**Specific heat (J/Kg.K)**	**Thermal conductivity (W/m.K)**	**Melting Point in Degrees**
Graphite	641	709.6	1950	3600

3 CAD MODEL PREPARATION (CHAPTER-3)

3.1 AIR COOLING INTEGRATED WITH PCM.

A high power li-ion battery pack suitable for plug in hybrid vehicle application is considered. The battery pack consists of 67 modules each containing twenty commercially available 1.5 Ah type 18,650 high power cells. Each module consists of five strings of four cells in series with the five strings connected on parallel. The nominal voltage and capacity of each module is 14.4v and 7.5 Ah

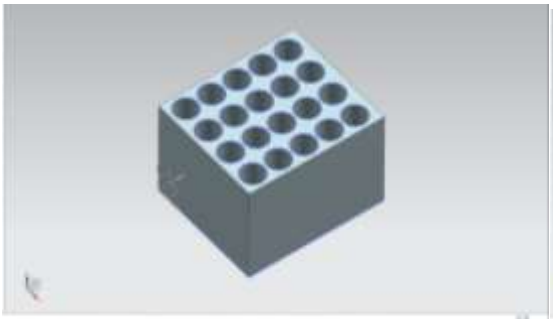

Figure 7 PCM filled box

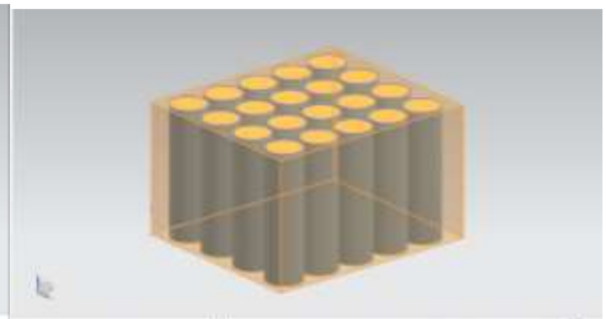

Figure 8 Lithium ion cells

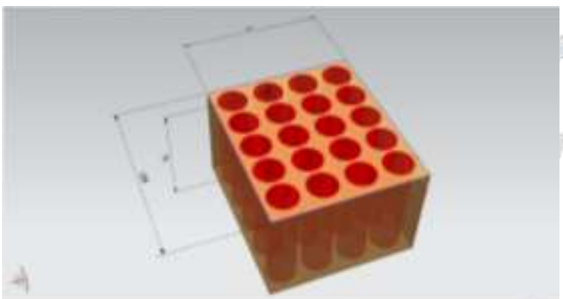

Figure 9 Battery module

3.2 Liquid Cooling Integrated with PCM.

A rectangular battery module in 6×5 array is taken. The cold plate made up of aluminum is located at the bottom of the batteries, along with a layer of 1 mm thick Bakelite layer between the batteries and the cold plate as electrical insulation. A heat spreading plate made up of aluminum is installed at the upper part of the batteries with a 0.9 mm thick for better contact and heat exchange with the batteries. The heat spreading plate is attached to the cold plate through thermal columns made of aluminum arranged in between the batteries. Paraffin is filled in the gap among the batteries which is used as a phase change material (PCM). Straight flow channels are made at the bottom of the battery module. Each flow channel has a cross-sectional area of 2 mm ×8 mm and the fin width between adjacent channels is 2 mm. Deionized water is used as the coolant. Considering the light-weight design, the materials of the heat spreading plate, thermal columns and cold plate are aluminum.

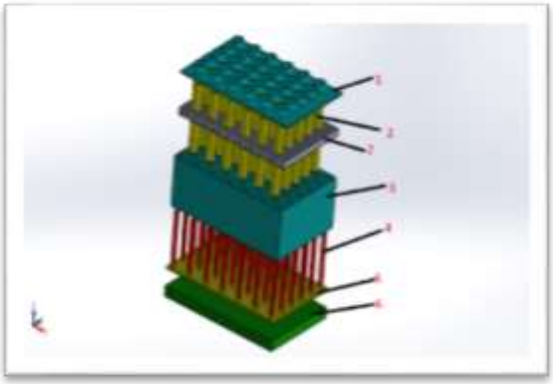

Figure 10 Battery pack design

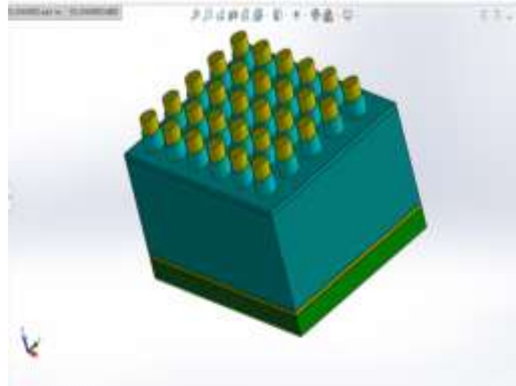

Figure 11 Battery Module Assembly

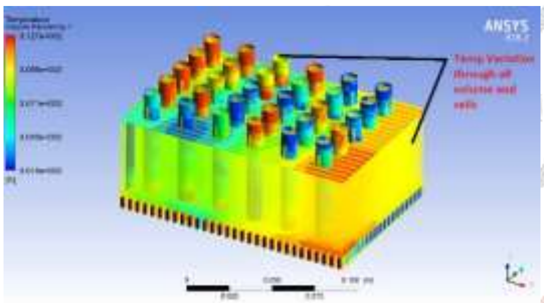

Figure 12 Temperature variation across the whole battery module

4 RESULTS AND DISCUSSION (CHAPTER-4)

For the numerical analysis of cooling system for the lithium ion battery, the two cases has been investigated numerically. The first one is Air cooling integrated with Phase Change Materials and second one is Liquid cooling integrated with Phase Change Materials.

For numerical analysis of these two above mentioned cooling techniques, the temperature variation of heat transfer rate are studied.

The following cases are discussed under the result and discussion part:

4.1 AIR COOLING INTEGRATED WITH PCM.

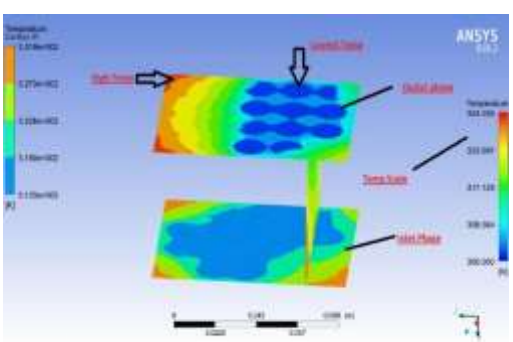

Figure 13 Heat transfer through the walls

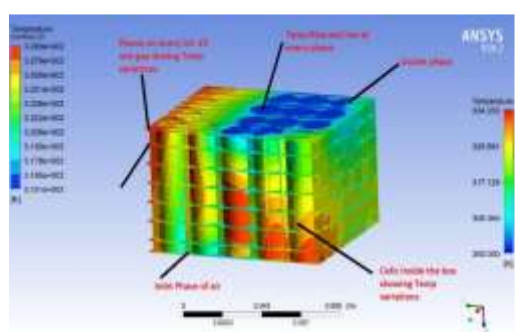

Figure 14 Temperature variation of air

in all Cell zones and walls.

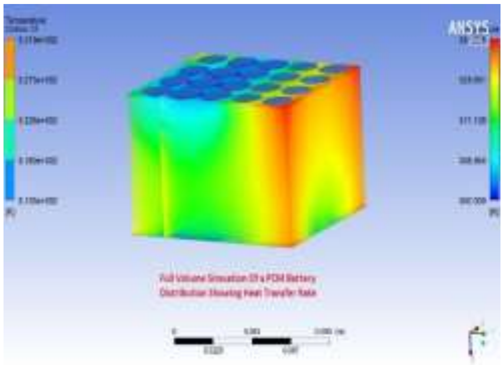

Figure 15 Distribution of Heat transfer rate through PCM

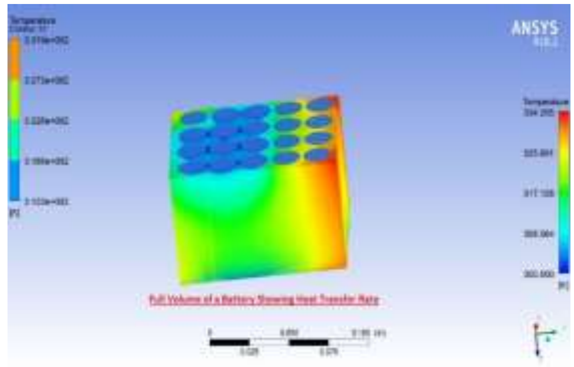

Figure 16 Distribution of Heat transfer rate through air

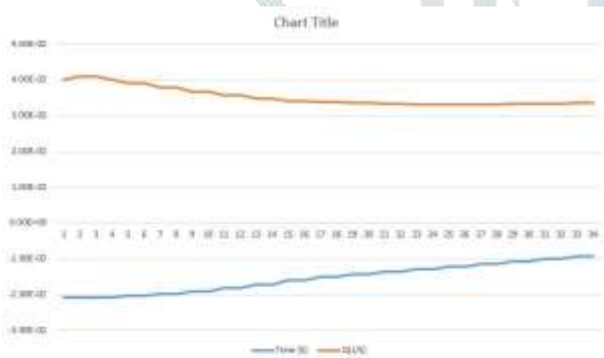

Figure 17 Graphical representation of heat transfer rate

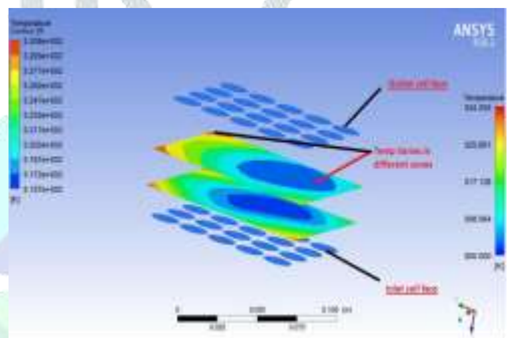

Figure 18 Heat transfer through inside battery module

Initial temperature= 40°C.
Air inlet velocity = 5m/s.
Discharge rate= 2C.

4.1.1
CASE 1 MAXIMUM AND MINIMUM TEMPERATURE ACROSS THE BATTERY.

In an Air Cooling integrated with Phase Change Materials, the maximum and minimum temperature across the lithium ion battery pack was calculated. It has been seen that the maximum temperature obtained throughout the simulation of a battery pack was obtained as 334.255K, which is equal to the 61 degree Celsius.

It has been seen that the minimum temperature obtained throughout the simulation of a battery pack was noted as 300K, which is equal to the 26.85 degree Celsius.

And the melting point of PCM is 334.225K which is equal to the 61.075°C.

CASE 2 THE RATE OF HEAT TRANSFER ACROSS THE BATTERY PACK.

During the simulation of a battery pack numerically, it has been noted that the rate of heat transfer inside a lithium ion battery pack is 308K, which is equal to the 35 degree Celsius.

The use of Air cooling integrated with PCM (graphite composite) can control the maximum temperature rise and temperature difference of battery module 61°C and 35°C at the end of discharge where the discharge rate is taken at 2C. The advantage of using the PCM thermal management systems over conventional active cooling systems indicates that a PCM-graphite matrix absorbs and spreads the heat very quickly due to its high thermal conductivity.

4.2 LIQUID COOLING INTEGRATED WITH PCM

4.2.1

CASE 1: MAXIMUM AND MINIMUM TEMPERATURE OF THE BATTERY MODULE:

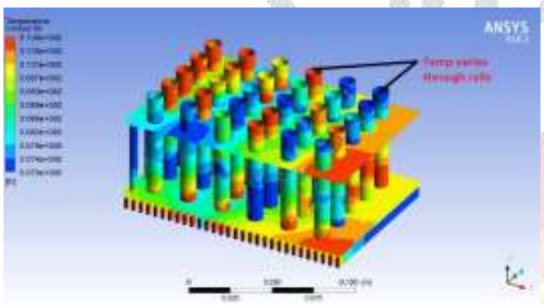

Figure 19 Temperature varies through Cell

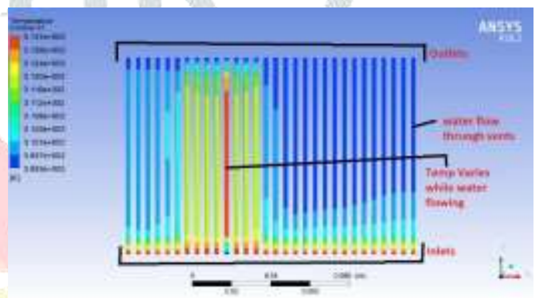

Figure 20 Variation in Temperature while water is flowing.

The use of Liquid cooling system integrated with phase change material can control the maximum temperature rise of battery module to 47.6°C and the minimum temperature dropped in the battery module is 40°C. When the discharge rate was 2C and the initial temperature of the battery was taken 40°C and the inlet water velocity is taken at 1m/s.

The melting point of PCM is 313.304K which is equal to the 40.154°C.

CASE 2: TEMPERATURE VARIATION IN THE BATTERY MODULE:

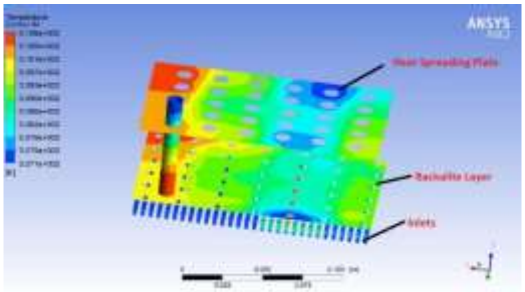

Figure 21 Heat transfer through the plates and layers.

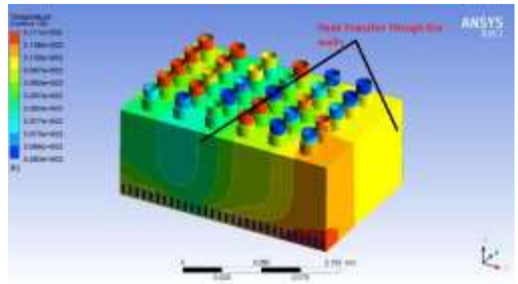

Figure 22 heat through walls.

The temperature variation witnessed in the battery module by the use of liquid cooling system integrated with phase change material is the difference between the maximum temperature and the minimum temperature which is

(47.6°C – 40°C) = 7.6°C.

CASE 3 COMPARISON BETWEEN AIR COOLING SYSTEMS INTEGRATED WITH PHASE CHANGE MATERIAL WITH LIQUID COOLING SYSTEM INTEGRATED WITH PHASE CHANGE MATERIAL:

Table 3 Comparison between Air and Liquid cooling integrated with PCM.

SERIAL NO.	PARAMETERS	AIR COOLING INTEGRATED WITH PCM	LIQUID COOLING INTEGRATED WITH PCM
1	Maximum temperature rise	61°C	47.6°C
2	Minimum temperature drop	26.85°C	40°C
3	Temperature variation	34.15°C	7.6°C
4	Melting temperature	61.075°C or above	40.154°C or above

In both cases the discharge rate of the battery was taken at 2C and the initial temperature of both the battery module was taken at 40°C. Comparing both the cooling system we found that the maximum and minimum temperature was more in air cooling system integrated with phase change material. The minimum temperature variation in battery module was 7.6°C for liquid cooling system integrated with phase change material which will help in maintaining good battery condition.

5 CONCLUSION (CHAPTER-5)

In this study, simulation on ANSYS software is done on two different methods of battery module i.e. air cooling integrated with phase changing material and liquid cooling integrated with phase changing material. Phase changing material is the best ever and most efficient cooling technique where the materials change their phase from liquid to solid or solid to liquid. Two different methods of cooling are used in this study to find the maximum efficient cooling of the battery at the discharge rate of 2C.

1. In air cooling integrated with phase changing material the material of battery module is graphite composite and is a simple and modified design, the ANSYS software has done 1000 iterations during this simulation.

2. In air cooling integrated with phase changing material the air flow rate is 5P and the minimum temperature obtained after the simulation is 300.00K i.e. 26.85ºC and the maximum temperature throughout the simulation was obtained as 334.255K i.e. 61ºC.

3. The initial temperature was 40ºC and the heat transfer rate is T2 – T1 = 61-26 =35ºC .• In liquid cooling integrated with phase changing material a different design is used in which the materials of assembly are hard plastic for casing , lithiumion for batteries, liquid is water and the separating plating is of Bakelite .The ANSYS software has done 3000 iterations during this liquid cooling integrated with phase changing material.

4. In liquid cooling integrated with phase changing material the liquid is water and the velocity of water is kept as 5m/s.

5. the minimum temperature obtained in simulation Is 313K i.e. 39.85ºC and the highest temperature obtained in simulation is 320K i.e. 46.85ºC.

6. The initial temperature was 40ºC and the heat transfer rate is T2 – T1 =46.85-39.85 =7ºC By comparing the above results this study concludes that the minimum temperature observed in air

cooling integrated with air is 26.85ºC and the heat transfer rate is 35ºc which is greater than the heat transfer rate of liquid cooling integrated with phase changing material i.e. 7ºC.

Hence Air cooling integrated with phase changing material has many advantages over Liquid cooling integrated with phase changing material which are as follows :-

1. Air cooling integrated with phase changing material has more heat transfer rate
2. Air cooling integrated with phase changing material has higher level of efficiency
3. Air cooling integrated with phase changing material has Less complicated design.
4. Air cooling integrated with phase changing material sustains cool temperatures over time.

6 NOMENCLATURE (CHAPTER-6)

C_p heat capacity (J kg^{-1} K^{-1})

Q(t) heat generation term during discharge (W m−3)

k thermal conductivity (W m−1 K−1)

h heat transfer coefficient (W m−2 K−1)

T temperature (K) of a cell.

c cell

PCM phase change material

A ambient

0 initial

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