IJIREEICE ISSN (O) 2321-2004, ISSN (P) 2321-5526

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering

Impact Factor 7.047 ⋇ Vol. 10, Issue 5, May 2022

DOI: 10.17148/IJIREEICE.2022.10504

Modelling and Comparison of Different Cooling Methods for a Lithium-Ion Battery Pack

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Abstract: This paper describes and focuses on the major comparison between different cooling methods used for thermal management in a lithium-ion battery. It is the most suitable battery power alternative for electric vehicles. High power density, long-lasting life cycle, no memory effect, and minimal auto discharge features are the responsible factors behind its suitability. However, thermal issues related to Li-ion batteries can degrade the battery's performance and function. Therefore, selecting an appropriate cooling technique becomes essential for the commercialization of electric drive vehicles (EDVs). Fostering an ideal cooling control procedure to keep the temperature at an ideal scope of 20°C to 40°C is crucial for extending wellbeing, expanding the pack the board life, and decreasing costs. In this paper, we have considered three distinct types of cell cooling methods i.e. air, water, and PCM. Results have revealed that the temperature distributions inside the battery pack can be significantly affected by the type of coolant used. As compared to air, liquid coolant affects cooling 10-15 times faster.

Keywords: EVs - Electric Vehicles; HEVs - Hybrid Electric Vehicles; HP - Heat Pipes; PCM - Phase Change Material; BTMS - Battery Thermal Management System.

1. INTRODUCTION

1.1 Introduction to Electric Vehicles

An electric car is an automobile that is propelled with the help of energy stored in batteries that runs the electric motor.[1] Being a substitute for fossil-fuelled vehicles, (EVs) have tremendous advantages such as low pollution and high efficiency.[2] Many countries have provided incentives to users through lower tax or tax exemption, free parking, and free charging facilities. On the other hand, the hybrid electric vehicle (HEV) is an alternative. It has been used extensively in the last few years. Nearly all car manufacturers have at least one model in hybrid electric vehicles.[3] The HEV is broadly divided into series hybrid and series hybrid. The engine power of the series hybrid is connected totally to the battery. All the motor power is derived from the battery. For the parallel hybrid, both the engine and motor contribute the propulsion power. The torque is the sum of both motor and engine. The motor is also used as a generator to absorb the power from the engine through the transmission. Both the series and hybrid can absorb power through regeneration during braking or deceleration.[4] Electric car or vehicle components and functions depend on the car type. There are various kinds of components assembled in the vehicle which are overall responsible for the smooth and efficient propulsion of the vehicle.

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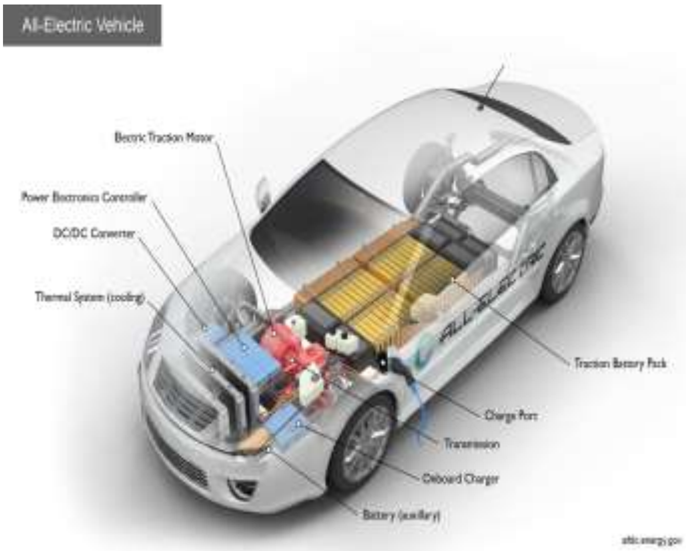

Figure 1.1: Block diagram of an electric vehicle.
Image courtesy: afdc.energy.gov

1.2 Introduction to Li-Ion Battery

Lithium-ion (Li-ion) batteries are reversible batteries employed in electrical vehicles yet as several moveable electronic devices. The energy density of such batteries is beyond that of typical lead-acid or nickel-cadmium rechargeable batteries.[5] Li-ion batteries have a very high power-to-weight ratio, which makes them an excellent choice for electric vehicles. Furthermore, their performance at high temperatures is exceptional. This battery has a greater energy ratio per weight, which is a factor of great importance when it comes to electric car batteries. On a single charge, the car can travel farther if the battery weight is smaller (same kWh capacity). Also, this battery's "self-discharge" level is lower than most other batteries, so the battery usually maintains its charge longer. Last but not the least, most parts of Li-on batteries are recyclable, making them a smart choice for those looking for environmentally-friendly electric cars.[6] The general Li-ion batteries that are available in the commercial markets are the Lithium-Ion Phosphate ($LiFePO_4$), Lithium Nickel Cobalt Aluminium Oxide ($LiNiCoAlO_2$), Lithium Manganese Oxide ($LiMn_2O_4$), Lithium Cobalt Oxide ($LiCoO_2$). All of these characteristics of Li-ion batteries make them a perfect choice for electric vehicles.

A lithium-ion battery consists of a positively charged cathode, negatively charged anode, separator, electrolyte, and positive and negative current collectors.[7] During discharge, the anode is the electrode that is oxidized to remove electrons. Correspondingly, the cathode is the oxidizing electrode that receives electrons from the external circuit. The electrolyte is the medium to transfer ions between electrodes inside the cell and the separator is used to isolate electrodes.[8] Thus, during discharging the lithium ions travel from anode to cathode through the electrolyte thus generating an electric current, and while charging, lithium ions are released from the cathode and go back to the anode.[7] The charging and discharging processes occurring in the Li-ion battery are depicted in the picture presented.

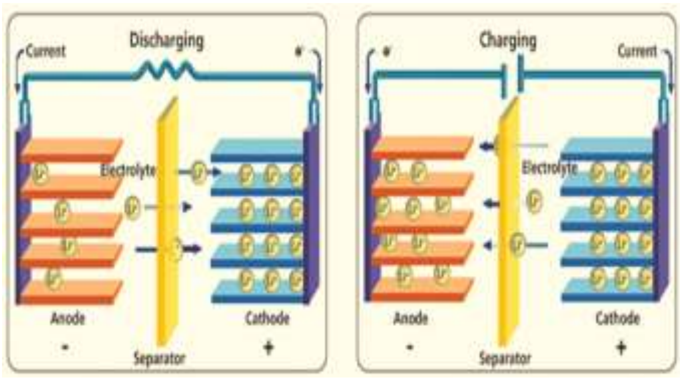

Figure 1.2.1: The Physical Structure and the charging-discharging operations.[3]

DOI: 10.17148/IJIREEICE.2022.10504

The electrochemical reactions for Li-cobalt in the positive electrode and negative electrode are expressed as follows:

The positive electrode reaction is

$$LiC_0O_2 \Leftrightarrow Li_{1-x}C_oO_{2} + xLi^{+} + xe^{-} \quad \text{[Equation 1.2.1]}$$

The negative electrode reaction:

$$xLi^{+} + xe^{-} + xC_6 \Leftrightarrow LiC_6 \quad \text{[Equation 1.2.2]}$$

The electrochemical reactions in the positive electrode and negative electrode for other lithium batteries are similar.[8]

1.3 Thermal Issues of Li-Ion Battery:

Overall performance of the lithium-ion battery, in particular, is based upon factors: Temperature and Voltage. Whenever this battery operates below restricted voltage and current, they work in an efficient manner and its life span additionally increases. Therefore, it becomes really important to manipulate the battery temperature very correctly. Both extra heat and its absence can lead to issues with the battery module.[8] As the performance of these batteries is solely dependent on the temperature within the battery pack, it is important to understand how heat is generated and dissipated inside batteries.[9] It is very obvious that chemical reaction rates have a direct relationship to temperature. The reaction rate and the current carrying capacity of a battery will decrease as the operating temperature decreases during charging and discharging. In other words, the battery power capacity is decreased. High temperature, on the other hand, not only enhances the reaction rate with higher power output but also increases heat dissipation, resulting in even higher temperatures.[8] However, comprehending the entire heat-generating process inside batteries is a difficult task that necessitates knowledge of how electrochemical reaction rates fluctuate with time and temperature, as well as how current is dispersed throughout bigger batteries.[9]

1.4 Thermal Management in Li-ion Batteries

Li-ion batteries perform best and last the longest at temperatures between 25-40°C. Thermal management will affect the battery pack's charging and discharging power, cycle life, cell balance, capacity, and ability to charge fast. Hence, a thermal management system is needed in order to enhance the performance and extend the life cycle of the battery pack.[10] Thermal management allows an electric vehicle to both improve battery power and endurance, as well as reduce the size of the electric engine. So controlling the temperature in a battery is a key parameter, as well as using appropriate electrical and thermal insulation materials.[11] The fundamental types of BTMS(Battery Thermal Management System) use air, liquid, heat pipe (HP), and phase change material (PCM) as heat conduction fluids or structures to deliver the waste heat from the battery to outer space.[12]

1.5 Importance of Thermal Management in Li-ion Batteries

Temperature affects batteries in five major ways: operation of the electrochemical system, efficiency and charge acceptance, power and energy efficiency, safety and reliability, and life-cycle costs. Li-ion batteries are extremely sensitive to low and high temperatures. For best performance and life, battery packs must be regulated to stay within the required temperature range, as well as to avoid the uneven distribution of temperature throughout the pack, which would result in diminished performance.[13]

According to Joule's law, an electric current flowing in an electrical conductor produces heat through the Joule effect. Consequently, the more powerful a battery cell is, the more heat it will produce. When designing a battery, the key factor that restricts power increase is temperature. Sensors are installed during the design phase of batteries to detect hotspots and control the interior temperature. When designers record abnormally high temperatures, they have two options: reduce the burden on the battery by lowering its power or improve heat outflow.[11-13]

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When there is a significant internal temperature differential, different charge and discharge rates for each cell can occur, resulting in poor battery pack performance. If the battery overheats or if the temperature distribution in the battery pack is not uniform, potential thermal stability issues such as capacity deterioration, thermal runaway, and fire explosion may occur. In the face of life-threatening safety challenges, the electric car industry is always innovating to improve the battery cooling system.[14]

1.6 Different Cooling Methods

1.6.1 Air Cooling

There are two types of air-based cooling methods: natural convection and air-forced convection. Natural air is practically impossible to utilize to cool the batteries independently due to the thermophysical features of air (low heat capacity and limited thermal conductivity). For the forced air, a higher flow rate is needed to obtain similar cooling performance to the liquid-based cooling system. The temperature distribution of the forced-air cooling system is not stable due to poor heat capacity, which is a problem that must be addressed.[15] Air cooling generally uses the principle of convection for transferring heat away from the battery pack. Convection is a process in which bulk movement of molecules within gases takes place.[16]

1. Natural convection: When the convection takes place due to the buoyant force because of the difference in densities caused by the difference in temperature is called natural convection. An example of this may be natural air.

2. Forced Air-cooling: When the convection takes place due to a special type of heat transfer in which fluids are forced to move, in order to increase the heat transfer is called forced air cooling.

Advantages: The air cooling system is less complicated and has a low cost.

Disadvantages: Due to the power density required and the broad range of ambient temperatures it must endure, the air cooling technique cannot be employed for most new high-performance applications.. It is not possible to extract sufficient heat from the battery with the help of just the cooling system. Some cooling may take place within the battery because of the passing air but that is not sufficient to meet the full cooling that the battery needs. The forced air extraction fan is enormous, and it requires power from the battery to operate, which might result in a significant pressure reduction.

1.6.2 Liquid Cooling

In current instances increasingly battery thermal control structures are primarily based totally on liquid cooling ideas because of the blessings which include better warmness switch capability in comparison to air cooling, ingesting relatively much less power, and turning in cooling requirements; higher green temperature maintenance. Although it could be compact and suits effortlessly into the battery pack, for those reasons, it's far a developing area of study with inside the vicinity of thermal control of EVs and HEVs.[18] Tesla, BMW i-3 and i-8, Chevy Volt, Ford Focus, Jaguar i-Pace, and LG Chem's lithium-ion batteries all use some form of the liquid cooling system. In liquid cooling systems, there is another division between direct and indirect cooling that is based on whether the cells are submerged in the liquid or if the liquid is pumped through pipes.[14]

Direct cooling systems place the battery cells in direct contact with the coolant liquid.[14] Convection always occurs on the surface of batteries, or most of them.[18] At the present, this thermal management scheme is still in the research and development stage, with no cars with this system on the market. Direct cooling is more difficult to achieve because of the reason that a new type of coolant is required. Because the battery is in contact with the liquid, the coolant needs to have low to no conductivity. [14] Generally, ethylene glycol, propylene glycol, or deionized water are advised as the coolant and the reason for this is solely the low conductivity for this method of liquid cooling of battery packs of electric vehicles.

DOI: 10.17148/IJIREEICE.2022.10504

Compared with direct contact mode, indirect contact mode is more convenient and commonly used in commercial electric vehicles on the grounds of its safety and stability. The core concept is conducting heat to outer space by setting a plate exchanger or tube exchanger onto the battery cells' surface [18] In contrast to direct cooling, the indirect cooling method facilitates temperature control by running the liquid around or between the battery components through either piping or chamber structures.

1.6.3 PCM (Phase Changing Materials)

Because of the stable temperature of the phase transition, PCM-based cooling strategies appear to be more suited than the two standard techniques of cooling systems outlined. PCMs have many advantages such as high energy efficiency, high compactness, and low maintenance cost, and have drawn great attention in passive thermal management. [19] Organic materials (paraffin wax, alkane, and organic acid), inorganic materials [aqueous solution, salt hydrate, and molten salt], and eutectic are among the materials that may be employed in
PCM-based cooling.

Due to its limited heat conductivity, pure PCM is insufficient to transmit heat from the batteries to outer space. To tackle this challenge, a variety of composite phase change materials (CPCM) are devised to improve heat transmission. Graphite, metal foam and carbon fiber are the most common thermal conductive enhancement materials used in pure PCM.[21-22] Using PCM has many significant improvements for the overall performance of BTMS. One of the improvements is to improve thermal uniformity due to its fluidity, which is similar to the direct liquid cooling mode.

PCM is thought to provide a viable alternative to forced-air cooling and simplify the BTMS framework. However, due to the low latent heat of phase transition for many types of PCM, heat saturation always occurs while working for lengthy periods of time under extreme BTMS conditions.[23-24]

2. DESIGN AND SIMULATIONS

2.1 Design and Simulation of Lithium-Ion Battery with 5 Cells

The models are prepared in Ansys Fluent software for the lithium-ion battery pack ($LiFePO_4$) consisting of 5 lithium-ion pouch cells with the dimensions and specification parameters as described in **Table 1**. The cells are connected in series connections by using solid blocks.

The geometry structure for the A 20 Ah $LiFePO_4$ used for simulation is shown in the Figure (2.1.1) and the meshing structure in the Figure (2.1.2).

The battery module defined in this model has a density equal to 3000 kg.m-3 and a specific heat capacity equal to 1224 J kg/K and a thermal conductivity equal to 0.2 W/m K. The mesh for the 3D model of the battery pack is made up of in total of 1,58,574 elements and 2,17,336 nodes with the mesh metric as skewness.

The size of each element is 0.7 mm. The battery model used for simulation purposes in Ansys fluent is CHT Coupling with joules heating to passive zones being enabled. The cells are assigned as the active zones and the tabs passive zones. The boundary conditions assigned to the outer wall have a free steam temperature of 300K and a heat transfer coefficient of 10 W/m^2K. The battery is initialized under hybrid initialization.

IJIREEICE ISSN (O) 2321-2004, ISSN (P) 2321-5526

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Table 1. $LiFePO_4$ 20Ah Lithium-Ion pouch cell specifications.

Specifications	Value	Units
Material of electrolyte	Carbonated base	-
Material of anode	Graphite	-
Material of cathode	$LiFePO_4$	-
Nominal voltage	3.3	V
Dimensions	50[b]×100[l]×2[t]	mm
Volume	10000	mm^3
Capacity of the cell	20	Ah
Energy Source	5	W
Density	3000	kg/m^3
Specific power	2400	W/kg
Specific heat	1224	J/kg K
Heat Transfer Coefficient	10	W/m^2K

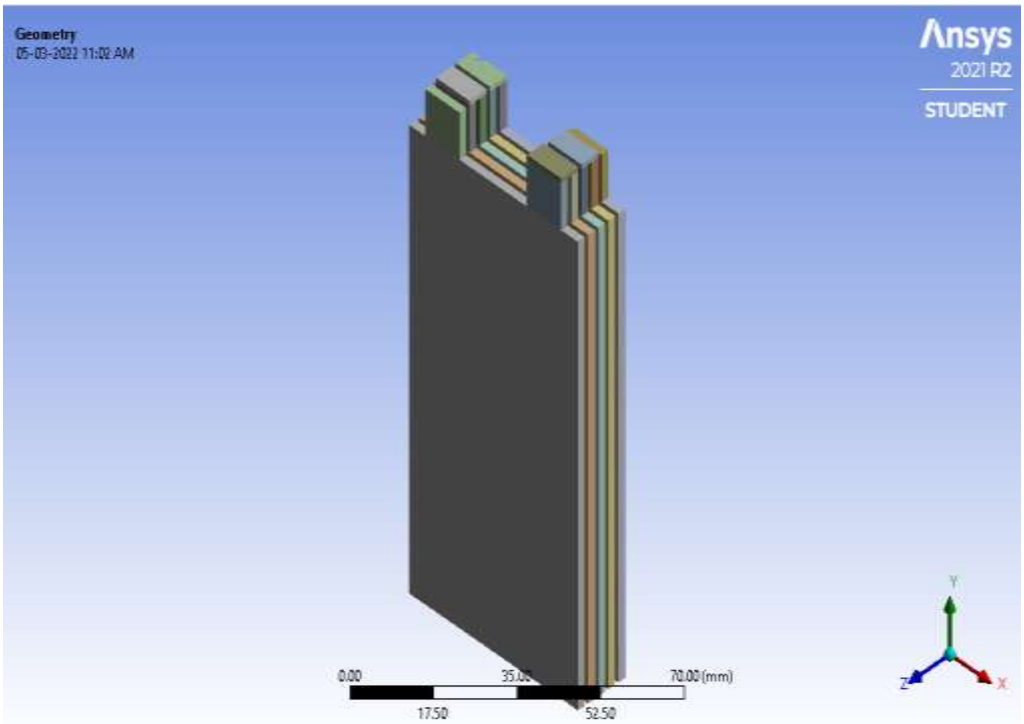

Figure 2.1.1: Geometry Structure of Lithium-Ion Battery with 5 Cells

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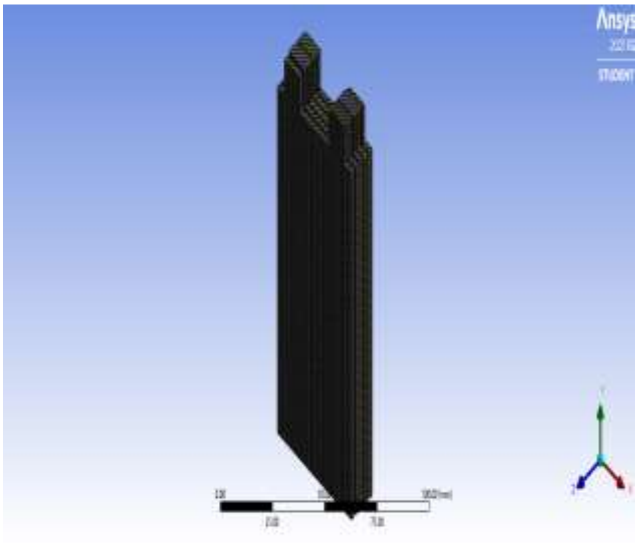

Figure 2.1.2: Meshing Structure of Lithium-Ion Battery with 5 Cells

2.2 Design and Simulation of Lithium-Ion Battery with 5 Cells with Air Cooling and Liquid Cooling.

The model of the lithium-ion battery having air or liquid cooling as a temperature control mechanism has been created in the Ansys Fluent software. The dimensions and the specification of the battery module remain similar to what it was before. To employ air or liquid cooling methodology and for the flow of coolant through the cells surfaces of the battery pack, chambers have been created on each of the vertical surfaces of the cell. The thickness of these chambers is assigned at 1mm and the flow rate of coolant is kept at 0.5m/s.
Air is the coolant in case of air cooling whereas, for liquid cooling, water is used as the coolant. The geometry structure for the 20 Ah $LiFePO_4$ using the cooling technique used for simulation is shown in the Figure (2.2.1) and the meshing structure in the Figure (2.2.2). The mesh for the 3D model of the battery pack is made up of in total of 2,19,492 elements and 3,41,752 nodes with the mesh metric as skewness. The size of each element is 0.7 mm.
The battery model used for simulation purposes in Ansys fluent is CHT Coupling with joules heating to passive zones being enabled. The cells are assigned as the active zones and the tabs passive zones. The boundary conditions assigned to the outer wall have a free steam temperature of 300K and a heat transfer coefficient of 10 W/m2K. The battery is initialized under hybrid initialization

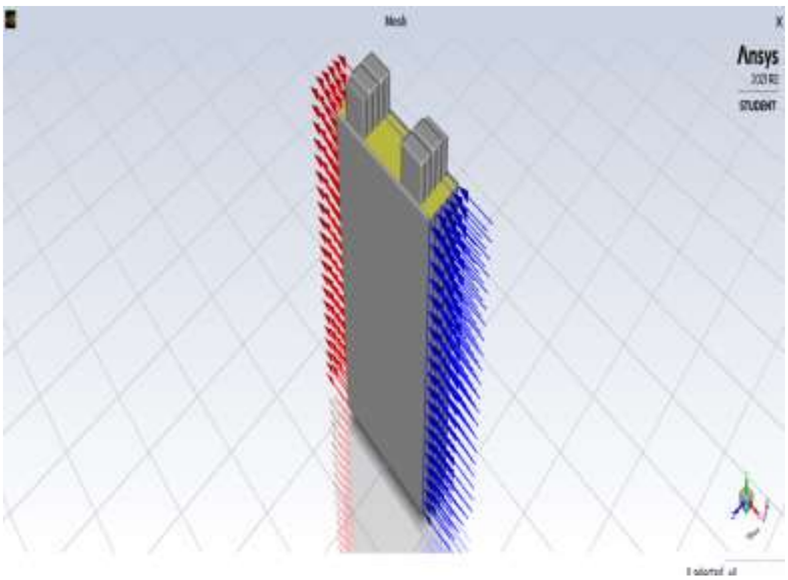

Figure 2.2.1: Geometry Structure of Lithium-Ion Battery with 5 Cells with air and liquid cooling.

IJIREEICE
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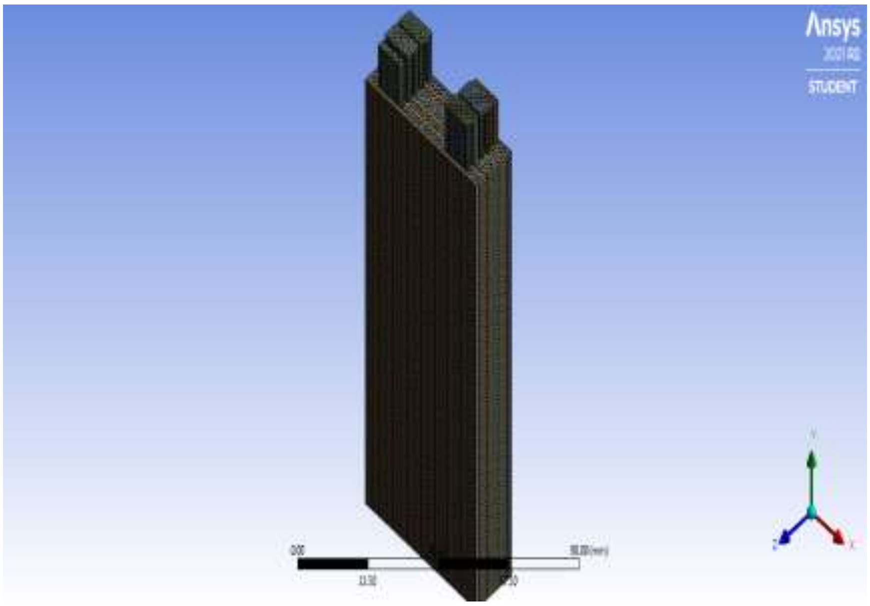

Figure 2.2.2: Meshing Structure of Lithium-Ion Battery with 5 Cells with air and liquid cooling.

2.3 Design and Simulation of Lithium-Ion Battery with 5 Cells with PCM (Phase Change Material) Cooling.

The model of a lithium-ion battery having PCM cooling as a temperature control mechanism has been created in the Ansys Fluent software. The dimensions and the specification of the battery module remain similar to what it was before. To employ the PCM cooling in the first step of the simulation, a row of one of the battery elements is modelled. In this simulation, a single layer is assumed whose thickness is equal to the sum of the thickness of its constituent layers, and its thermophysical properties are equivalent to a combination of the thermophysical properties of each layer independently. In the second stage of the simulation, a layer of phase change material is designed as a coating on both sides of the battery body. The phase change material defined in this model is paraffin which has a density equal to 810 kg.m-3 and a specific heat capacity equal to 2000 J kg/K and a thermal conductivity equal to 0.2 W/m K Viscosity are equal to 0.0269 kg/ms. The geometry structure for the 20 Ah $LiFePO_4$ using a cooling technique used for simulation is shown in the Figure (2.3.1) and the meshing structure in the Figure (2.3.2). The mesh for the 3D model of the battery pack is made up of in total of 2,90,563 elements and 3,31,384 nodes with the mesh metric as skewness. The size of each element is 0.7 mm. In the third step, the models from the Ansys library including, viscous, solidification and melting and, energy are used. The boundary conditions assigned to the outer wall have a free steam temperature of 300K and a heat transfer coefficient of 10 W/m^{2}K. The battery is initialized under standard initialization

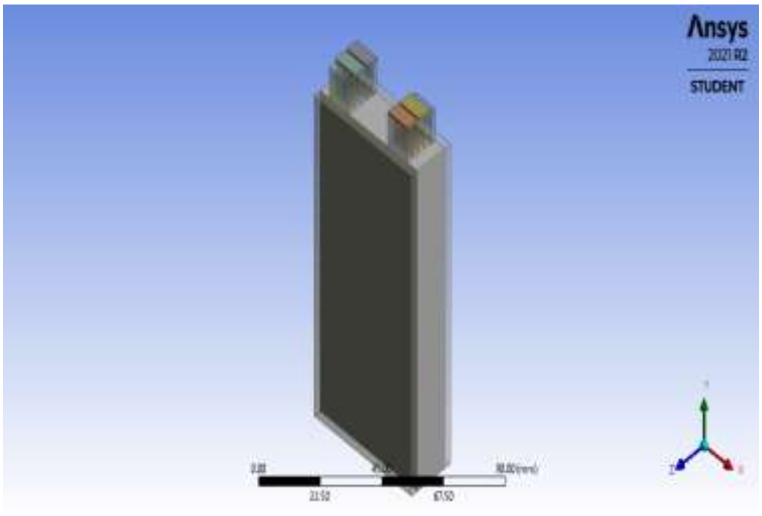

Figure 2.3.1: Geometry Structure of Lithium-Ion Battery with 5 Cells with PCM cooling.

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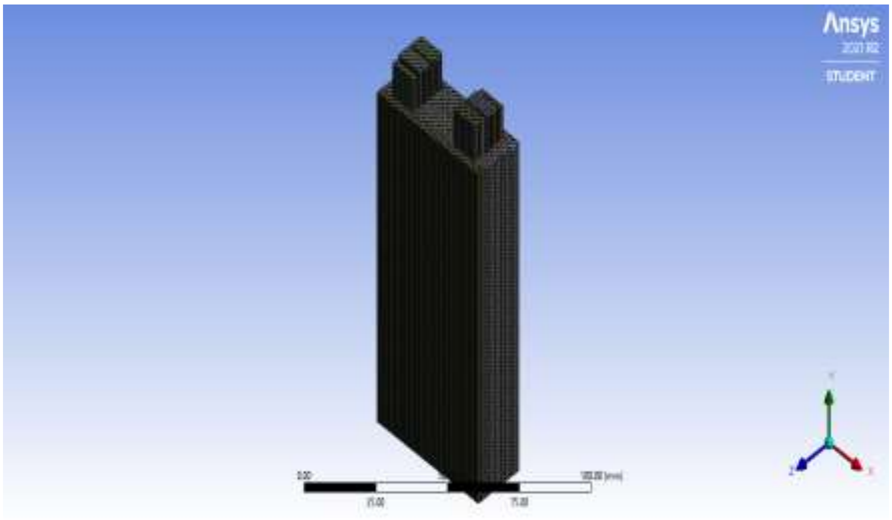

Figure 2.3.2: Meshing Structure of Lithium-Ion Battery with 5 Cells with PCM cooling.

3. RESULTS

At the end of the solution process, a two-dimensional graph and three-dimensional temperature contours have been obtained. Also, the average temperature changes of the battery in terms of time have been obtained without any cooling mechanism. The chart is presented in ten minutes timeline. The Figure (3.1.1) and Figure (3.1.2) show the volume average temperature of the battery without using any cooling method and the highest temperature recorded at the end of the simulation is noted to be around 340K. Similarly, Figure (3.1.3) and Figure (3.1.4) elicit the volume average temperature of the battery using the air cooling method, and the highest temperature recorded at the end of the simulation is noted to be around 315K. In the case of liquid cooling, the Figure (3.1.5) and Figure (3.1.6) represent the volume average temperature of the battery, and the highest temperature recorded at the end of the simulation is noted to be around 289K. Finally, the Figure (3.1.7) and Figure (3.1.8) depict the volume average temperature of the battery using the PCM cooling method, and the highest temperature recorded at the end of the simulation is noted to be around 300K.

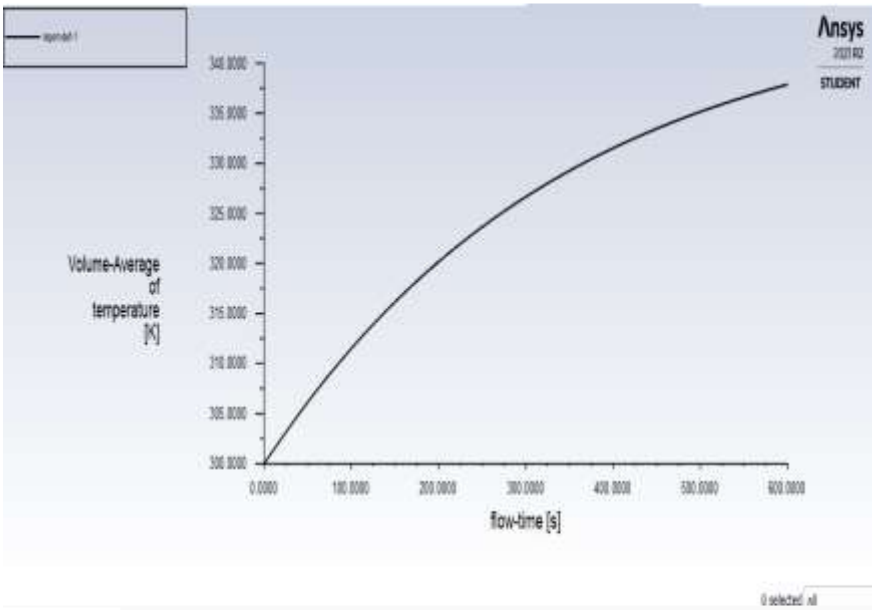

Figure 3.1.1: The volume average temperature of the battery without using any cooling method.

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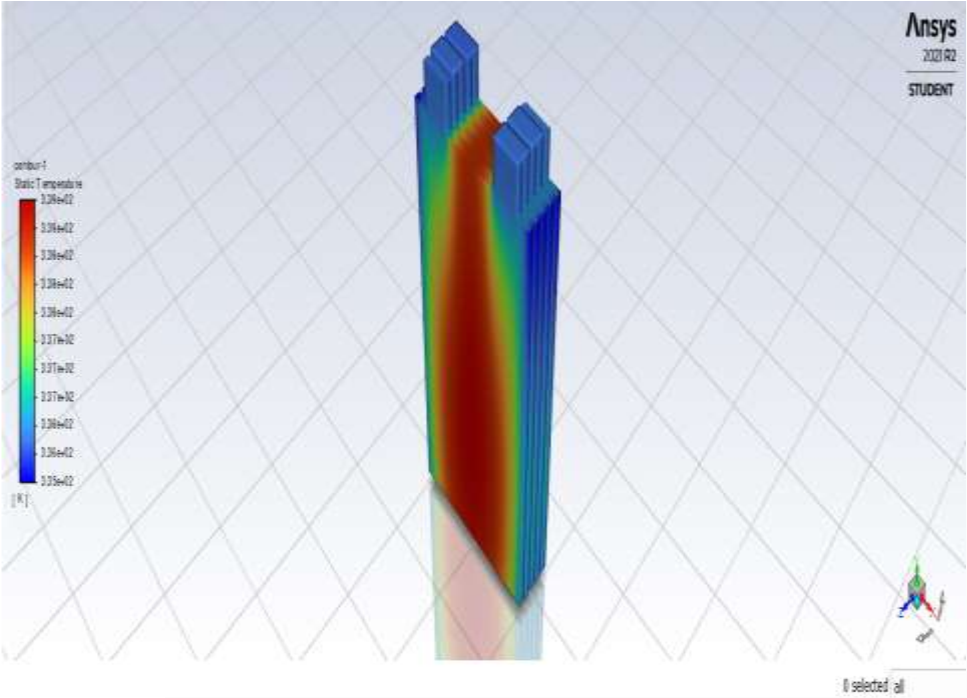

Figure 3.1.2: The volume average temperature of the battery without using any cooling method.

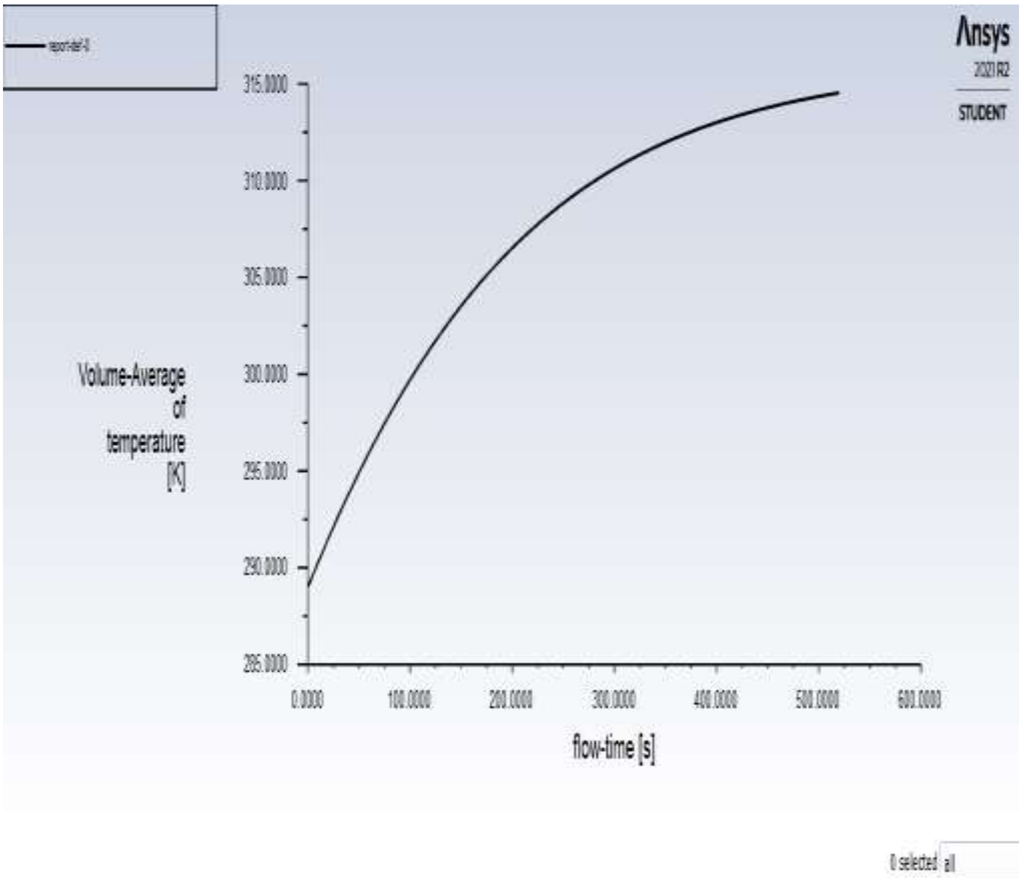

Figure 3.1.3: The volume average temperature of the battery using the air cooling method.

IJIREEICE ISSN (O) 2321-2004, ISSN (P) 2321-5526

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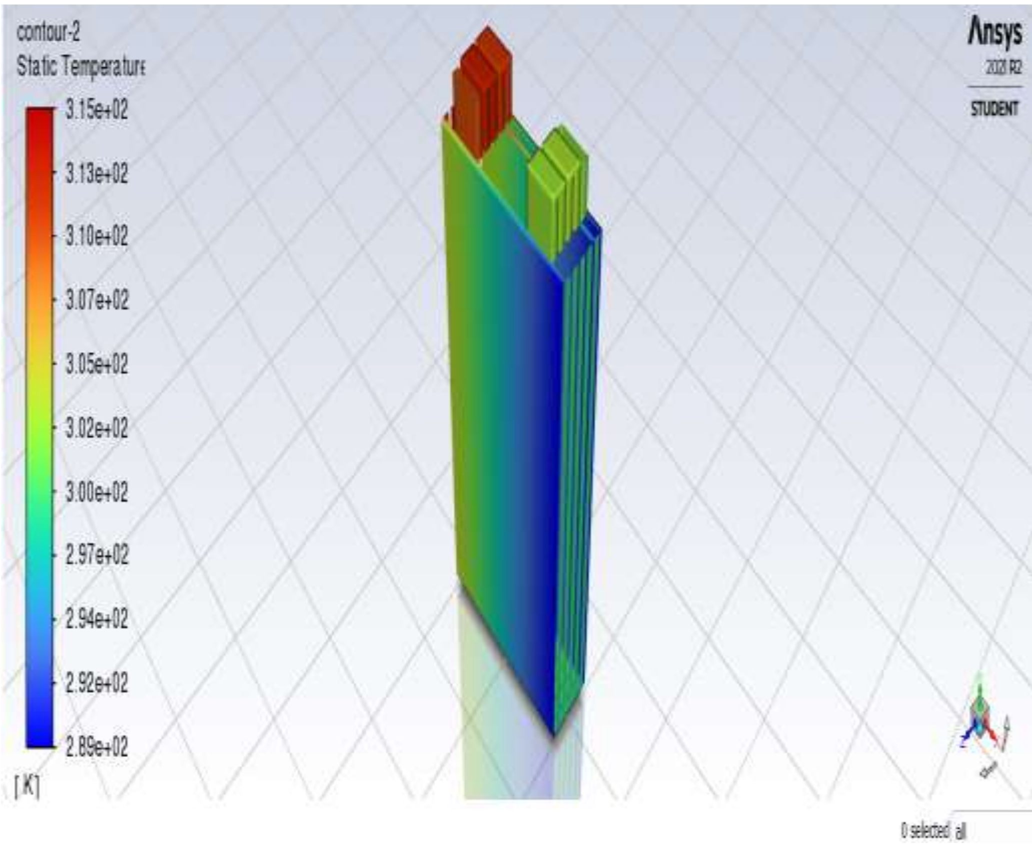

Figure 3.1.4: The volume average temperature of the battery using the air cooling method.

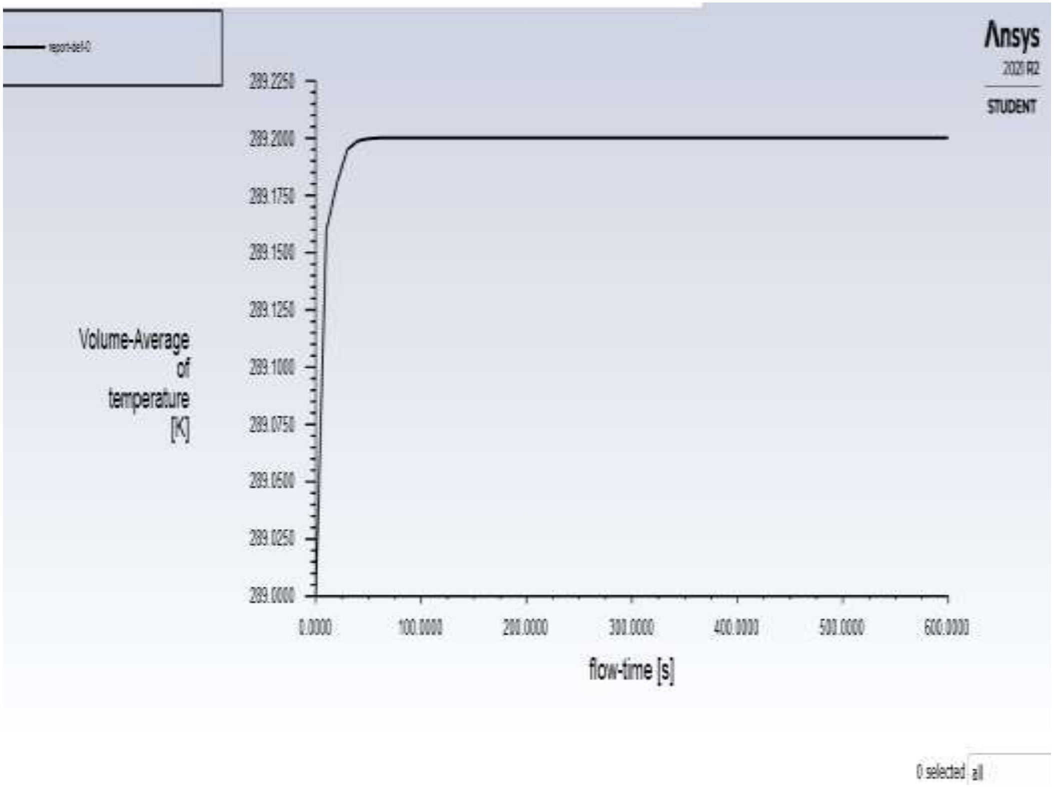

Figure 3.1.5: The volume average temperature of the battery using the water cooling method.

DOI: 10.17148/IJIREEICE.2022.10504

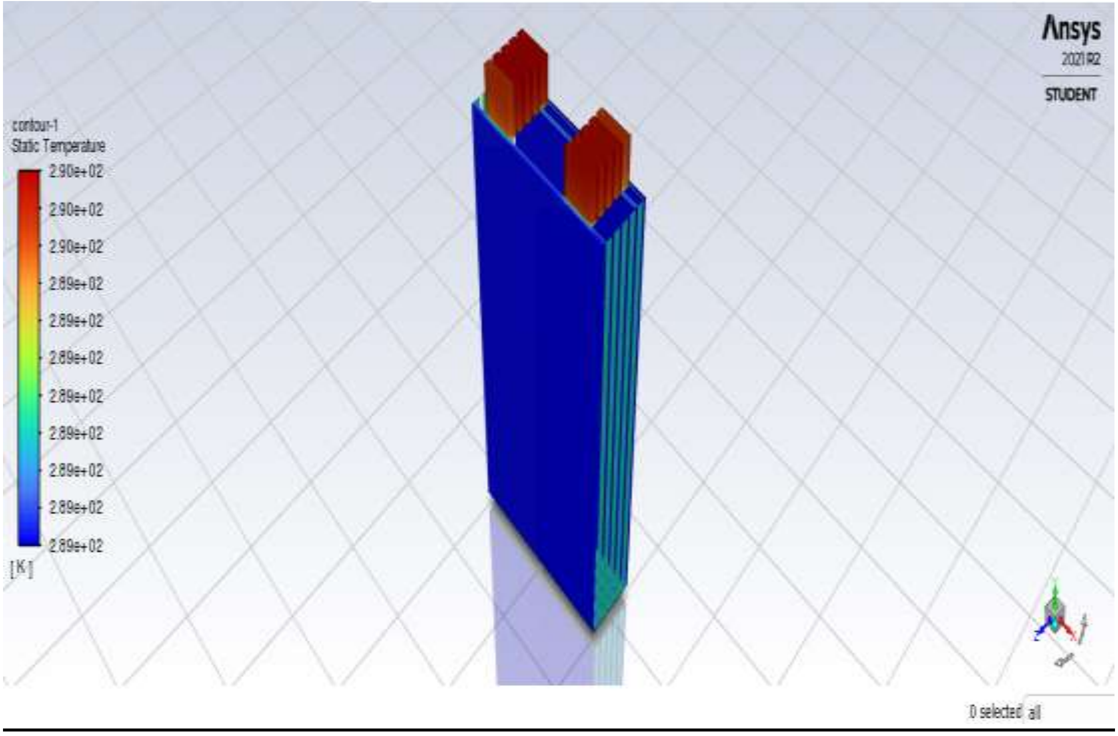

Figure 3.1.6: The volume average temperature of the battery using the water cooling method.

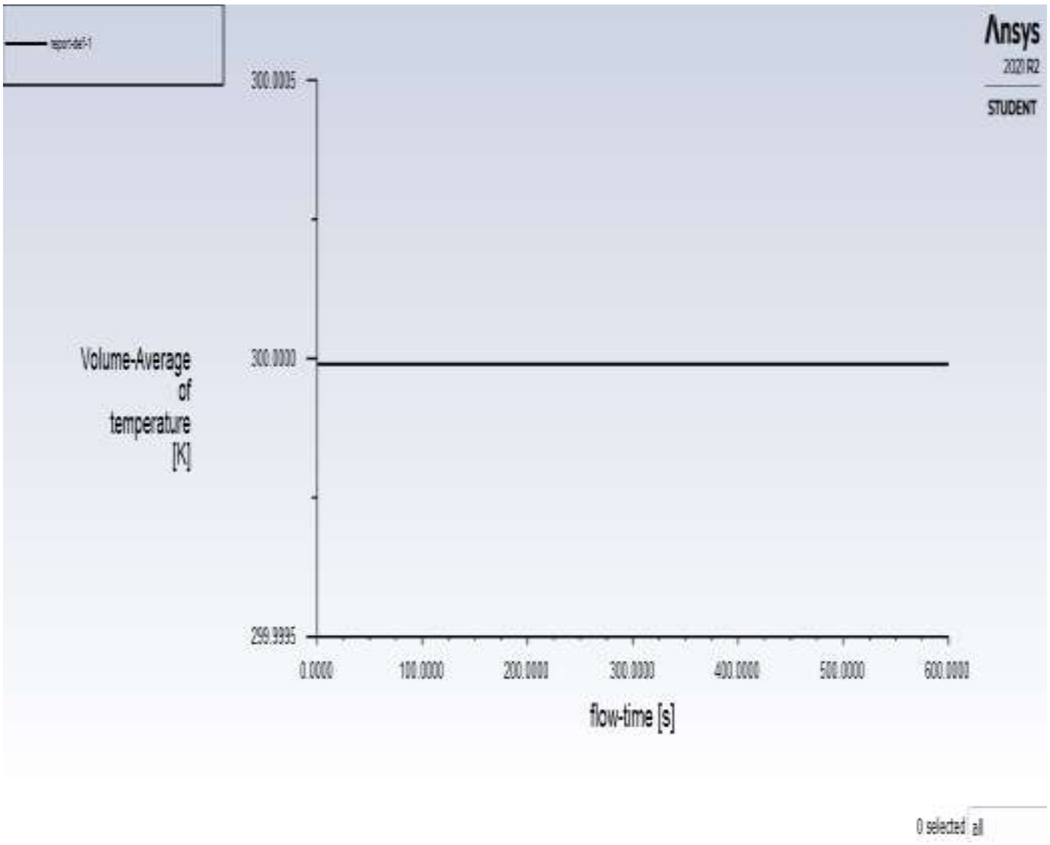

Figure 3.1.7: The volume average temperature of the battery using the PCM cooling method.

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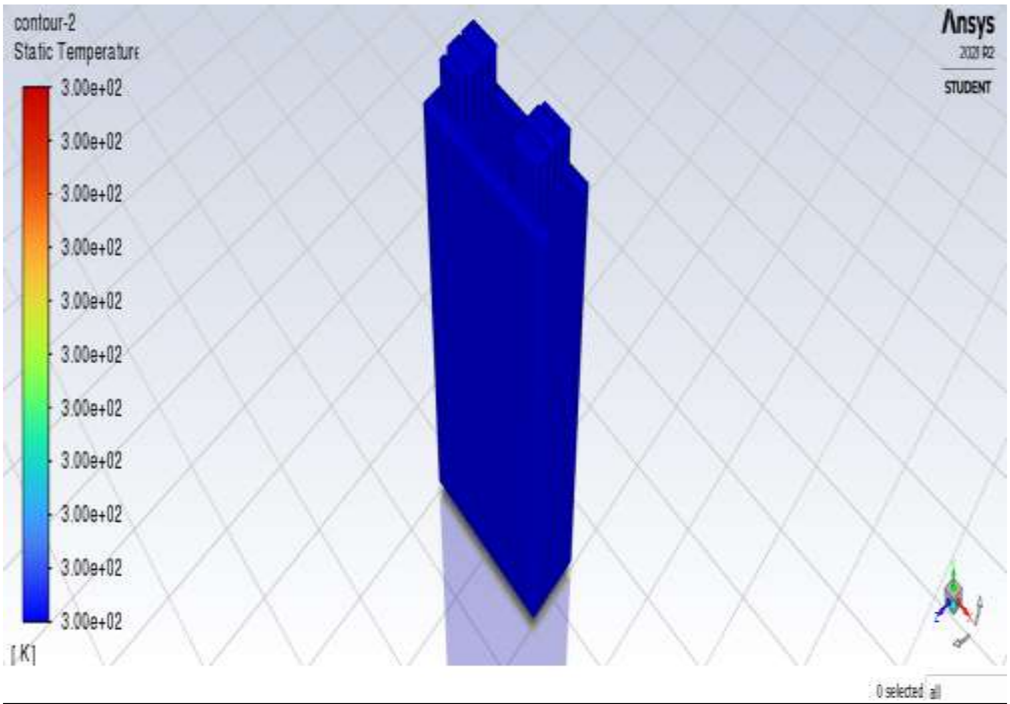

Figure 3.1.8: The volume average temperature of the battery using the PCM cooling method.

4. CONCLUSION

The overall temperature of the lithium-ion battery was recorded to be more than the optimal temperature, which is considered to be fatal for the battery pack and also degrades the efficiency of the vehicle. Hence three different methods of cooling were carried out to bring down the temperature within the optimal range, which was air, liquid, and PCM-based cooling. Therefore after clearly examining the results from the simulations carried out in (Ansys Fluent), it is been observed that out of all the applied cooling methods, the liquid cooling method is found to be the most effective method as maximum degradation in the temperature of the battery pack is seen in this type of battery cooling system. This is also the main reason behind its usage in the current electric vehicle industry.

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