Numerical and Thermal Analysis of Battery Pack

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Abstract
Research and development in batteries has resulted in a boom in the production of electric vehicles. Considered environmentally friendly, these electric vehicles are on a rise due to developments in battery chemistry. But a clear problem is associated with the batteries: temperature. These batteries tend to get hot as more current gets extracted from them. Ongoing research has made it possible to decrease the battery temperature using various methods. But with so many methods available and only one/two to select, it becomes difficult to choose one. Using a strong method can take more energy while a docile one will not do its job properly. Our project is based on selecting a battery for an electric vehicle, designing a battery pack, calculating the heat load and suitable method for cooling and validating it through a finite element analysis. This project will help to understand how the methods of cooling batteries for electric vehicles are selected.

Keywords - Electric Vehicle, Battery, Battery Pack, Finite Element Analysis, Battery Thermal Analysis

Introduction

Vehicle electrification is seen as a promising solution to looming energy and environmental problems. The success of electric vehicles, however, is dependent on battery development. Temperature has been shown to affect the battery's longevity, efficiency, and safety. When the temperature in the battery rises too high, it can cause thermal runaway, electrolyte fire, and, in some cases, explosions.

To achieve the required output specifications in a battery pack, a number of battery units must be assembled in parallel or series (or combination) to generate the large power density required for automotive applications. Due to the battery internal resistance and heat generation resulting from electrochemical reactions inside the individual cells in the absence of an effective battery thermal management system (BTMS), significant temperature gradients can develop inside the battery pack. The performance of an electric vehicle is heavily reliant on the performance of its battery pack.

Temperature variations inside the battery pack can cause differences in cell-to-cell internal resistance and voltage, lowering pack performance and shortening the battery's life cycle. The use of a BTMS is required to maintain temperature uniformity inside the pack and to prevent unfavorable voltage distribution in different cells. A BTMS must be able to regulate temperature and voltage distributions within the pack in order to keep battery performance within acceptable limits while also keeping cooling costs to a minimum.

Various methods for keeping the battery pack within the safe temperature range have been proposed. The active cooling method, which uses forced air convection or liquid cooling, and the passive cooling method, which uses phase change materials, are the two groups of thermal management techniques.

Battery packs are extensively used in electrical vehicles (EV). The safety, aging and life of the battery pack are significantly related to its thermal behavior. This work concerns analytical analysis followed by thermal analysis of an EV battery pack for real engineering applications. Based on the heat loss the cooling method is decided and will be validated using thermal analysis in Ansys.

Literature review

1] Study of Natural Convection of Lithium-Ion Battery Module Employing Phase Change Material. Horng-Wen Yu et al,Yi-Chen Ciou, Jun-Kuan Wu and De-An Huang - 2021

This study numerically examines three-dimensional transient natural convection of cylindrical lithium-ion batteries inside a rectangular pack with air between cylinders. The heat transfer technique in this study applies PCM (phase change material) between cylinders without or with fin array on top changing distance between cells. Authors study a Sony 18650 Li-Ion battery pack for cooling using natural convection. Designing and simulation is done in Ansys Workbench. Results conclude that natural convection along with PCM decreases temperature to more desired levels.

2] Modeling and thermal simulation of a PHEV battery module with cylindrical LFP cells Cicconi P.1, Germani M., Landi D - 2013

Authors studied the LFP battery pack for ECE R15 urban drive cycle with 2C Charge and 3C discharge rate. They modeled the temperature distribution of the battery pack during the entire cycle for 100 and 50 m^3/h volumetric flow of air. They concluded that heat dissipation around the middle of the pack occurred in much better fashion for large volumetric flows.

3] Transient Thermal Analysis of a Li-Ion Battery Module for Electric Cars Based on Various Cooling Fan ArrangementsVan-Thanh Ho, Kyoungsik Chang, Sang Wook Lee and Sung Han Kim - 10 May 2020

Authors have studied the same battery packs for different cooling speeds and positions of fans. They have modeled temperature distribution and vectors for different charge and discharge rates. They also compared temperature bar graphs of different motor speeds.

Battery Pack Configuration

To start with this project, we first need to finalize the vehicle for which we are going to design the batteries and do heat load calculations. For our analysis, we went with the electric scooter.

Fig. 1, Electric Scooter

Battery Capacity	2980	Wh
Voltage	60	V
Range	121	km/Charge

Table 1, Required specifications

After deciding the vehicle, we started the calculations for the battery pack and to choose the right batteries for our vehicle.

Energy consumption (Wh/Km)

Energy / Km = Battery Energy / Range Wh / km = 2980 / 121

Wh / km = 24.6 Battery Capacity in Ah.

Battery Capacity = Battery Energy / Battery Voltage Battery Capacity in Ah = 2980 /60 = 49.66 Ah

Imp: Considering the 20% DOD i.e. Depth of Discharge total battery capacity is given as Total Battery Capacity = Battery Capacity / 0.8 ….(20% DOD) = 49.66 / 0.8 = 62 Ah

Now if we consider 62 Ah battery capacity with 60 Voltage so we need a total battery pack of capacity of 3720 Wh. (3.27 kWh). To Obtain with this Battery Pack, the cylindrical cell (Samsung SDI) that we are using has nominal Voltage 3.6 V and 2.5 Ah, 18650 Cylindrical Cells. (Model : INR18650-25R) [1]

Table 2, Samsung SDI data

Specifications	Data
Manufacturer	Samsung SDI
Chemistry & Type	NCA & Cylindrical
Model	INR18650-25R
Length(m)	0.065
Diameter(m)	0.0184

Height	0
Width	0
Thickness	0
Mass(kg)	0.045
Capacity(Ah)	2.5
Overvoltage(V)	4.2
Undervoltage(V)	2.8
C-rate (C)	2
C-rate (peak) (C)	4
Nominal voltage (V)	3.6

Now, Number of cells required in parallel(Np) = Total Battery Capacity / Single cell capacity = (62 / 2.5) = 24.8 == 25
Number of cells required in Series (Nm) = Total Battery Voltage / Single cell Voltage = 60/3.6 = 16.6 == 17
Therefore, total number of cells required = 25*17 = 425

Table 3, Cell configuration

Form Factor	n cells	m cells	Total number of cells	Configuration
1865 Cylindrical cells	25	17	425	25p17s

Table 4, Battery Pack Sizing parameters

Battery Usable energy(Wh)	2980	
Battery Usable capacity(Ah)	49.66	
Battery voltage (V)	60	
	3720	

Total Battery Energy (Wh)		
Total Battery Capacity(Ah)	62	
No of cells in parallel (Np)	24.8	**25**
No of cells in series (Ns)	16.6	**17**
Total no of cells (Nt)	425	

Table 5, Final Battery Pack Calculation

Samsung SDI Parameters	**Battery Pack Parameters**
Volume(m^3)	0.007346562
Battery energy (Wh)	3720
Battery Volumetric energy density (Wh/m^3)	520651.7319
Battery Gravimetric energy density (Wh/kg)	200
Battery nominal voltage(v)	60
Battery over voltage(v) *(No of cells in series * single cell overvoltage)*	71.4

Battery under voltage(v) *(No of cells in series * single cell undervoltage)*	47.6
Battery capacity (Ah)	62.5
Battery current(A)	125
Battery current (peak) (A)	250
Battery power (W)	7500
Battery mass (kg)	19.125
Battery Pack Configuration	25p17s

Fig.2, Samsung SDI 25R battery

Fig. 3, Battery Design in Solidworks

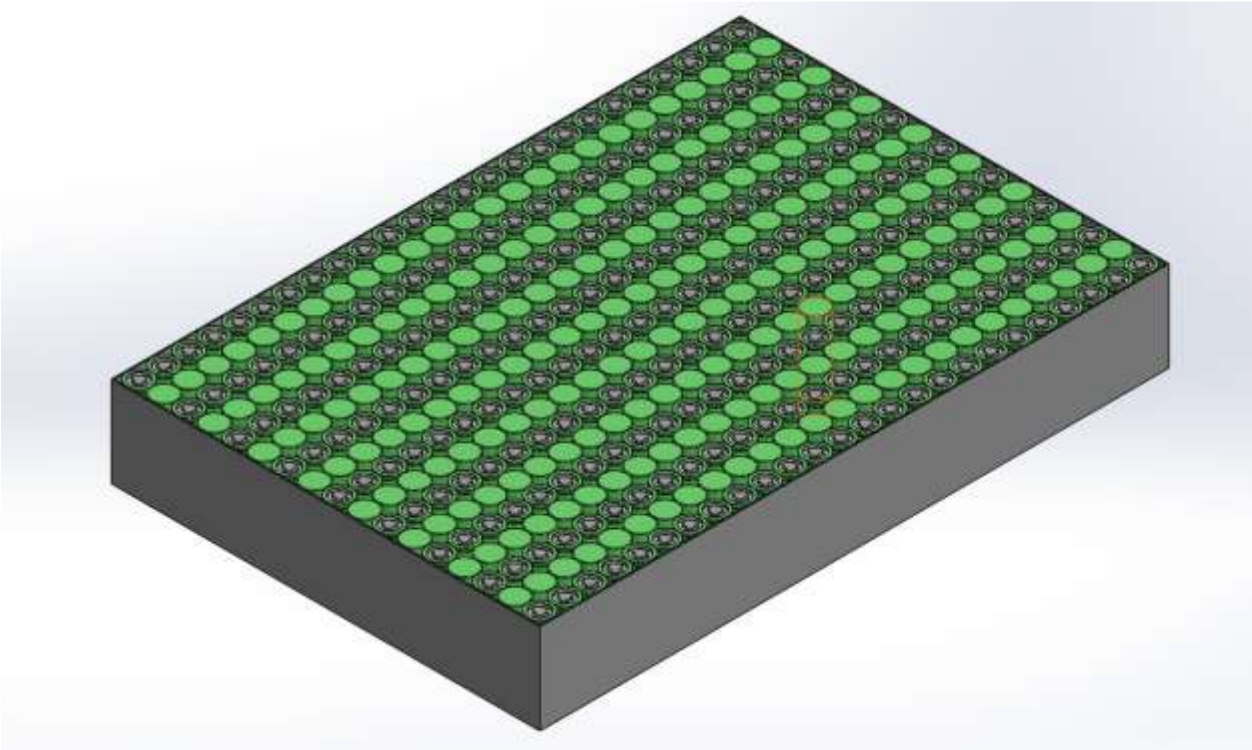


Fig.4, Proposed battery pack design

Heat load Calculations

Battery pack temperature is a very important parameter of consideration for designing a battery pack. It directly affects the electrochemical reactions, pack efficiency, life etc. Battery temperature needs to be in an optimal range of 10℃ to 50℃ at 1C/2C/3C charge rate. High temperature results in degradation of life and compromises safety while low temperature results in degradation of performance. It's important to check, monitor and control the battery pack temperature. There are several methods of regulating the battery pack temperature. The methods of regulation are broadly classified as follows.

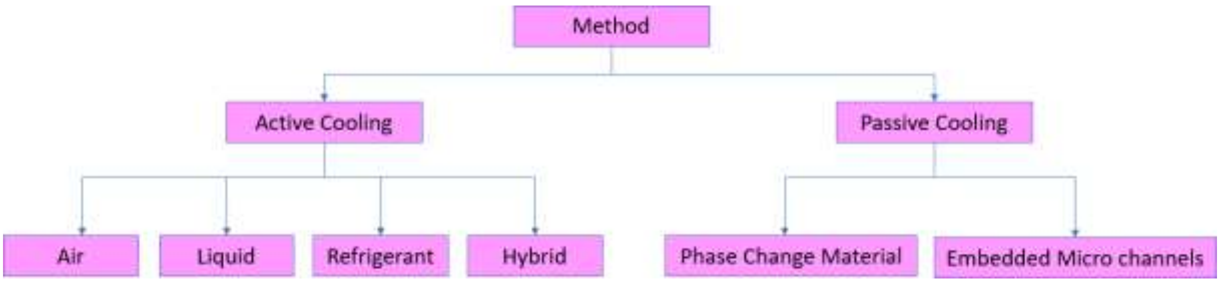


Fig.5, Methods of battery pack cooling

Passive cooling methods can be used when temperature rise is too large to be decreased by active methods. Our aim of the project is to check heat load determination, amount of energy lost in heat and the method of active cooling to be used. Since our battery pack configuration is already decided we can directly go towards heat load determination. One assumption is that we are considering a module to discharge from 100% to 20% SOC at 1C, 2C and 3C charge. Also, from samsung SDI datasheet, cell internal impedance is taken to be 18mΩ.

Table 6, Heat Generated in Cell (1C)

Cell current @ 1C	2.5 A
Cell internal impedance	18mΩ
Heat generated, $q = I^2R$	0.1125 W

Table 7, Heat Generated by pack (1C)

Total cells, n	425
Total heat generated, n*q	47.8125 W

Table 8, Energy lost by pack as heat (1C)

Time for 100% to 20% SoC @ 1C, t	2880 s (0.8*3600)
Heat energy lost by cell	0.1125*2880 = 0.324 kJ
Heat energy lost by pack	137.7 kJ

Table 9, Comparison with Total Pack Energy (1C)

Pack energy from 100% to 20% SoC, n*V*I*t	11016 kJ
% Energy lost as heat	(137.7/11016)*100 = 1.25%

Therefore, we can say that 1.25% of pack capacity is rejected as waste heat while the pack is discharged from 100% SoC to 20% SoC at 1C discharging rate.

Similar calculations for 2C and 3C charging will give following results

Table 10, Calculations for 2C and 3C discharge

Values	2C Discharge	3C discharge
Heat generated by cell	0.45 W	1.0125W
Total heat generated by pack	191.25 W	430.3125

Heat energy lost by cell	0.648 kJ	0.972 kJ
Heat energy lost by pack	275.4 kJ	413.1 kJ
% Energy lost as heat	2.5 %	3.75 %

Selection of Thermal Management Method (for 1C discharge rate because it is the most used charge discharge rate)

- As per Samsung SDI datasheet the operating temperature range during charging is 0-50 ºC (<45 ºC recommended) while during discharge its -20 to 75 ºC (<60 ºC recommended).
- Assuming temperature to be maintained at 45 ºC and ambient temperature of 27 ºC.

Calculations to calculate the Convective heat transfer coefficient "h"

1. To find convective area : Total cells in series = 17

Diameter of each cell = 0.0184 m
Length of battery pack = 17 * 0.0184 = 0.3128 Assuming some clearance between end plates, length = 0.33 m or 330 mm Height of each cell = 0.065 m
Convective area, A = 0.33 * 0.065 = 0.02145 m^2
Now,
Heat generated by battery by pack, Q = 47.8125 W Change in temperature, ΔT = 45 – 27 = 18 Thermal resistance, R = ΔT/ Q
R = 0.3765 K/W
Convective heat transfer coefficient, h = 1/(R*A) h = 123.825 W/m^2K or 0.0123825 W/cm^2K.

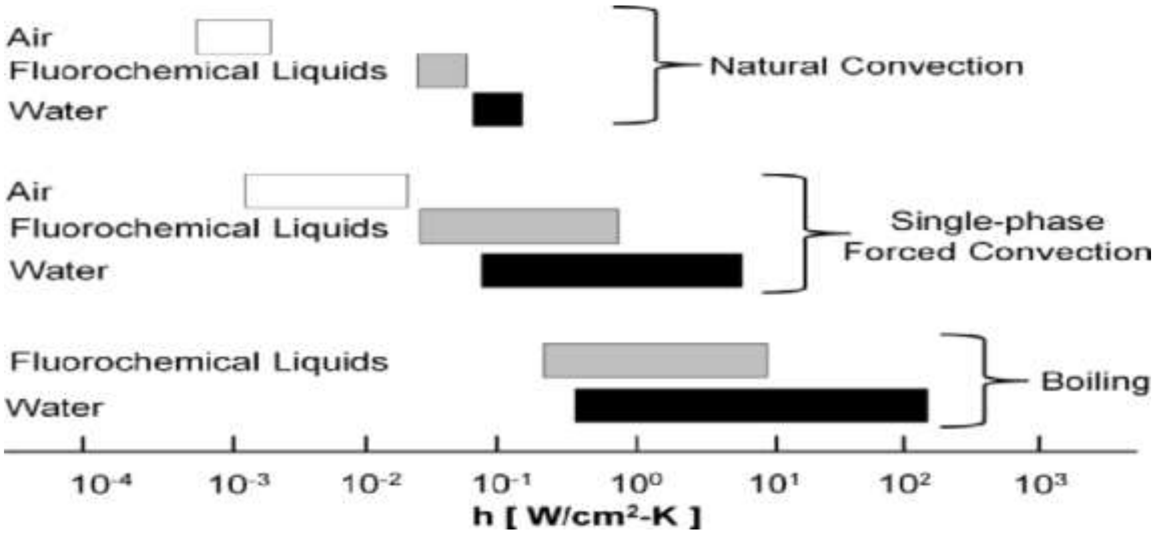


Chart.1 Shows the types of cooling method for batteries on the value of "h".

Therefore, (chart.1) Single phase forced convection using air is the best cooling method for our given battery pack with 1C charge/discharge rate.

Ansys Analysis

After the finalization of batteries, designing of the battery pack and determining the heat load calculations, we will move towards thermal analysis of the battery pack. We have used Ansys Steady

State Thermal for determining the single cell temperature on discharging at 1C, 2C and 3C rate from 100% to 20%SOC. The cell which was modeled in Solidworks 2018 was used for the analysis. The battery chemistry was chosen to be NMC 811, which was as per the Samsung datasheet. Some characteristics of the NMC 811 battery are as follows

Table 11, Characteristics of NMC 811 battery

Cathode	NMC ($LiNi_xMn_yCo_uO_2$)
Anode	Graphite
Specific. Energy density (Wh/kg)	160-325
Charge/discharge rates	1C/1C (2C with Silica in anode)
Life-cycles	2000 (8000 with Silica)
Safety	Cell < 55°C
Cell costs / kWh	$145

Thermal conductivity (W/m°C)	9.8
Density (kg/m³)	2200
Specific Heat capacity (J/kgK)	1040

The above characteristics make NMC batteries (along with NCA batteries) the most desirable batteries for Electric Vehicles. As per the experts, the Lithium ion batteries are there to stay due to slow development in other types of batteries like lithium air and lithium metal. So analyzing the lithium ion batteries is the best way to gauge electric vehicle performance.

For the sake of simple analysis, we have chosen the values on isotropic conditions due to the size of the battery. All the required parameters like thermal conductivity, convection coefficients have been taken assuming the isotropic conditions. The model is loaded in Ansys as a STEP AP203 file. Once it is loaded in the geometry section, it is assigned NMC 811 material with thermal conductivity of 9.8 W/m/K [2]. Once material assignment is done, meshing is provided on the model. Meshing characteristics and statistics can be seen in the image and the table below

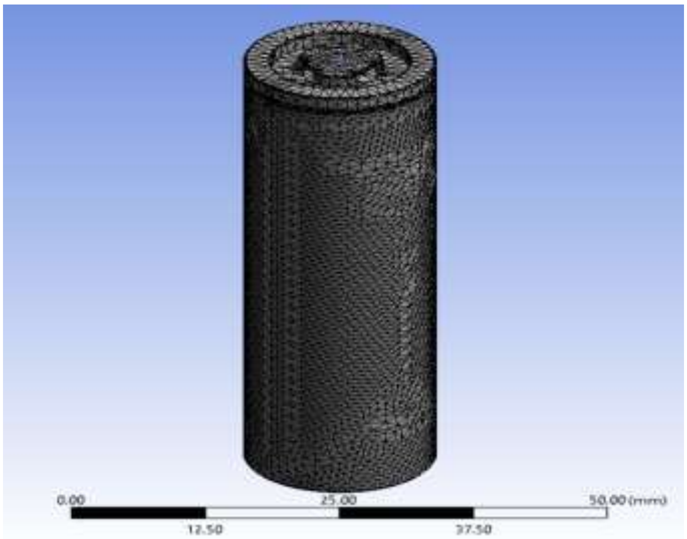


Fig. 6, Meshing of the cell

Table 12, Meshing characteristics

Element Size	1 mm
Nodes	60511
Elements	35322

Once a conformable mesh was created, we go towards the boundary conditions for the cell. Our main objective is to check the temperature of the cell between free convection and forced convection. The boundary conditions of heat generation were given to both the cells. Also, the values of convection coefficients were different for both of them as per the guidelines by the literature. The analysis for forced convection is done on the basis that a fan blows the air inside the battery pack compartment at a velocity of 1.25

m/s [6]. The value of convective heat transfer coefficient for forced convection is taken from our calculations while for free/natural convection we took it to be 8.4 W/m²°C [7,8] and ambient temperature is taken to be at 25 °C. Since, one face of the cell will be exposed to the air, convection was given only to that part of the cell.

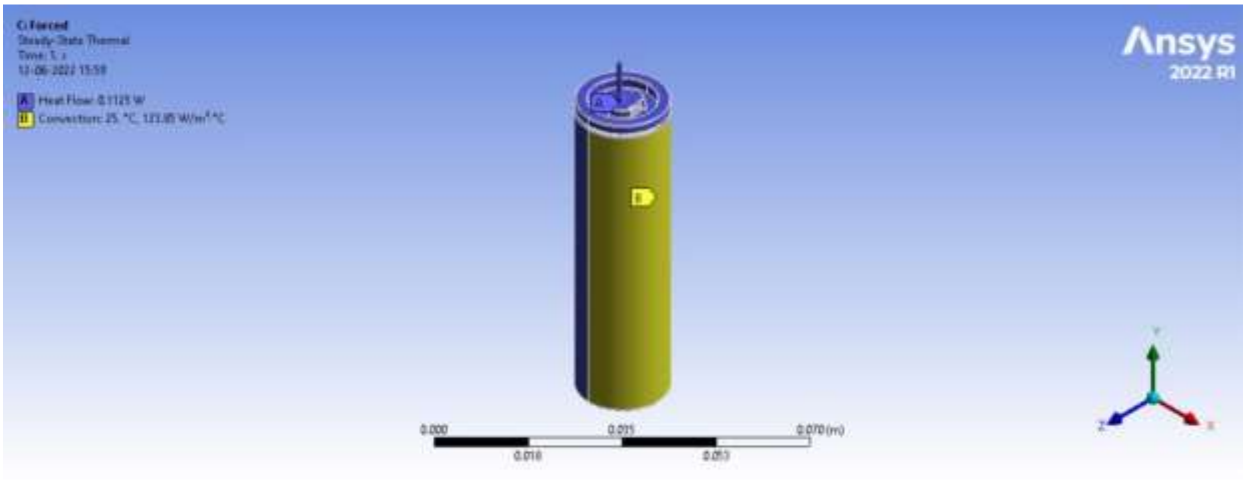


Fig. 7, Boundary Conditions for Forced Convection

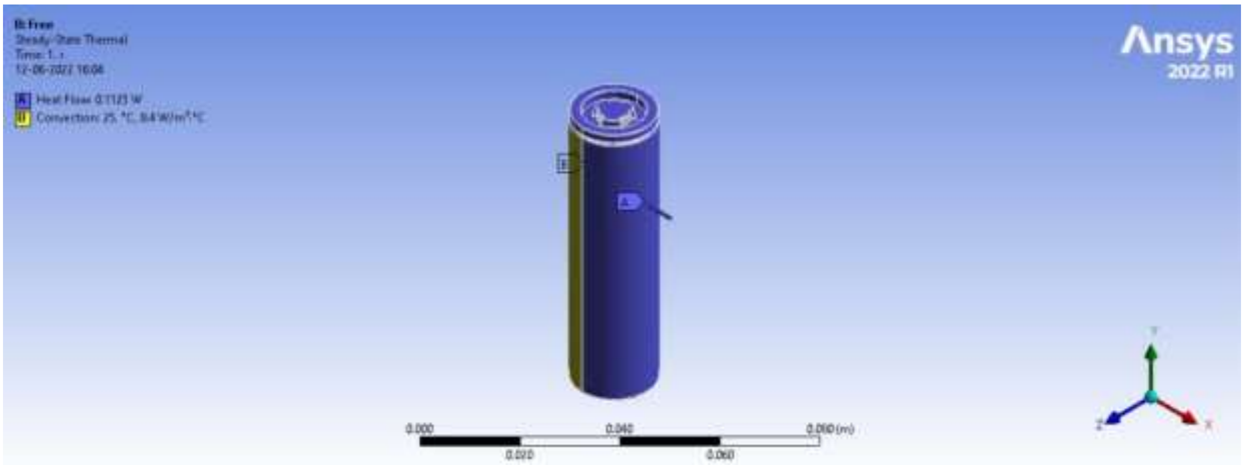


Fig. 8, Boundary Conditions for Free Convection

The conditions will be the same for 2C and 3C discharge with only change in heat flow rates. All we need to do now is to add a temperature tool in the solver to check for the temperature distribution along with the probe to check if the correct value of heat flow was taken or not.

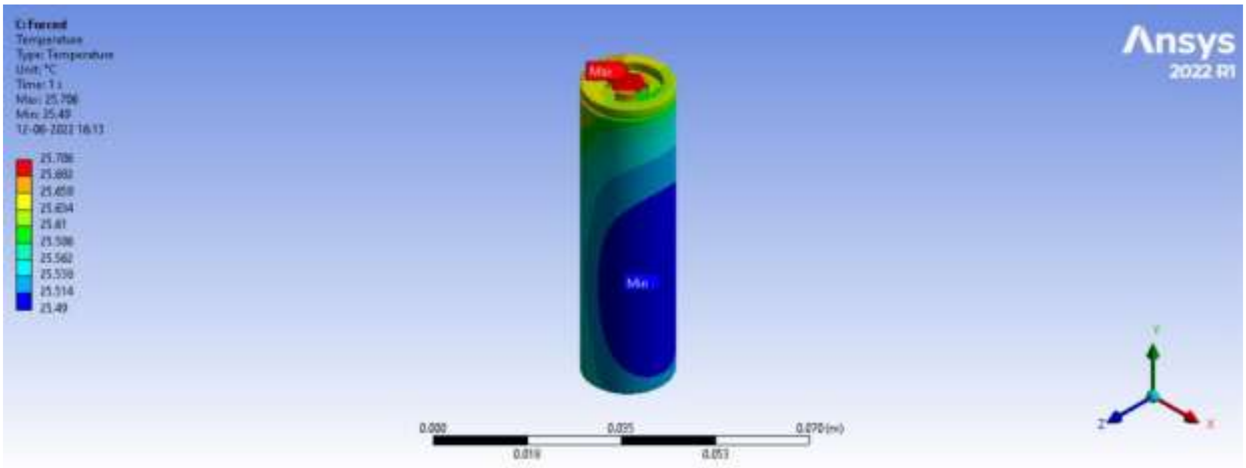


Fig. 9, Temperature profile for forced convection (1C)

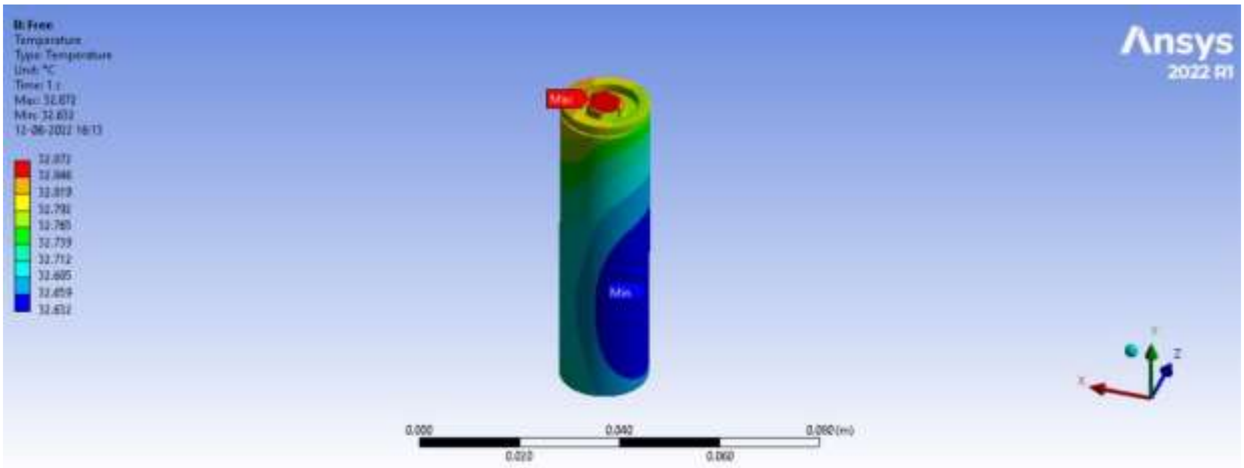


Fig. 10, Temperature profile for free convection (1C)

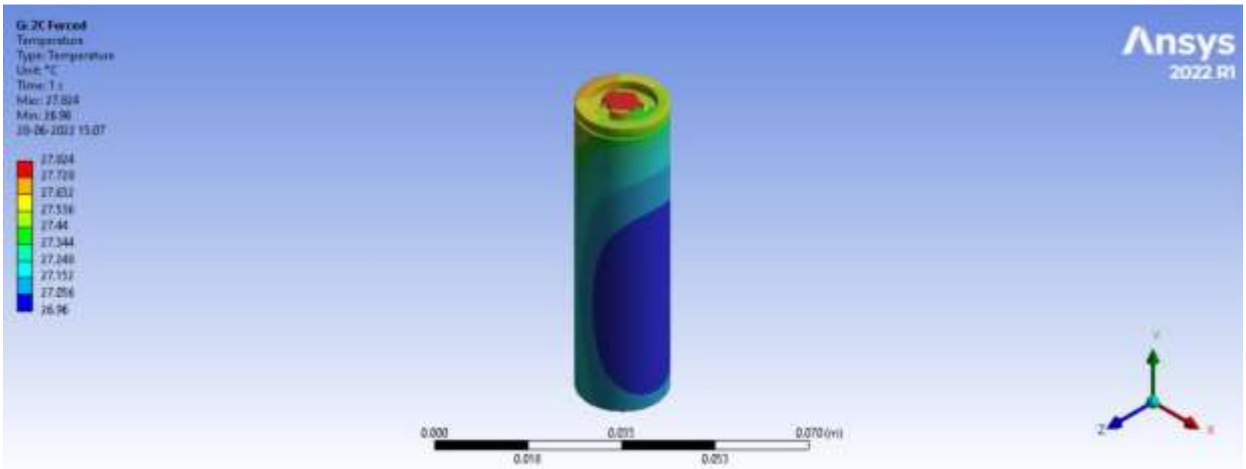


Fig. 11, Temperature profile for forced convection (2C)

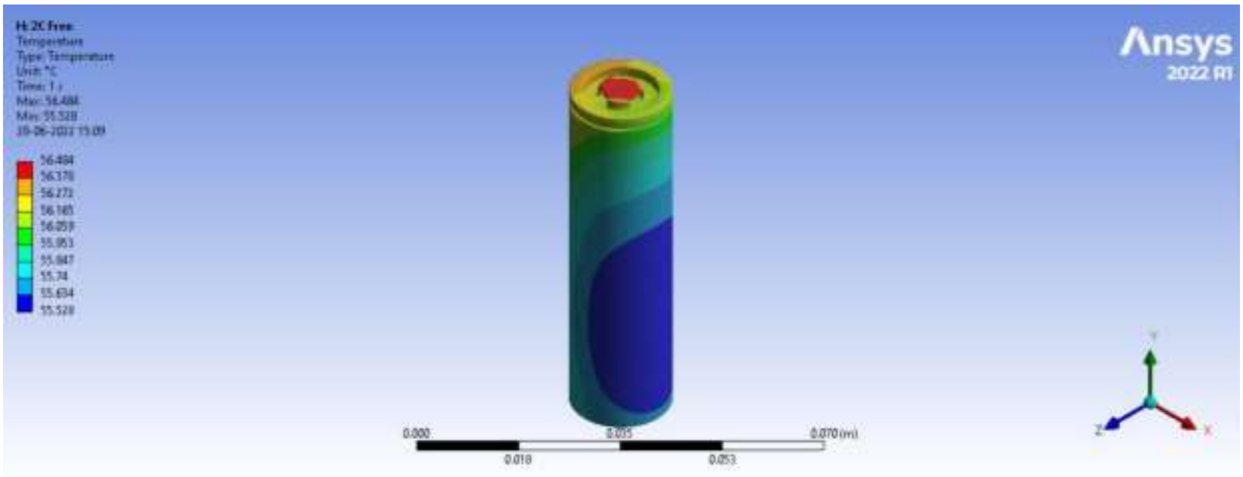


Fig. 12, Temperature profile for free convection (2C)

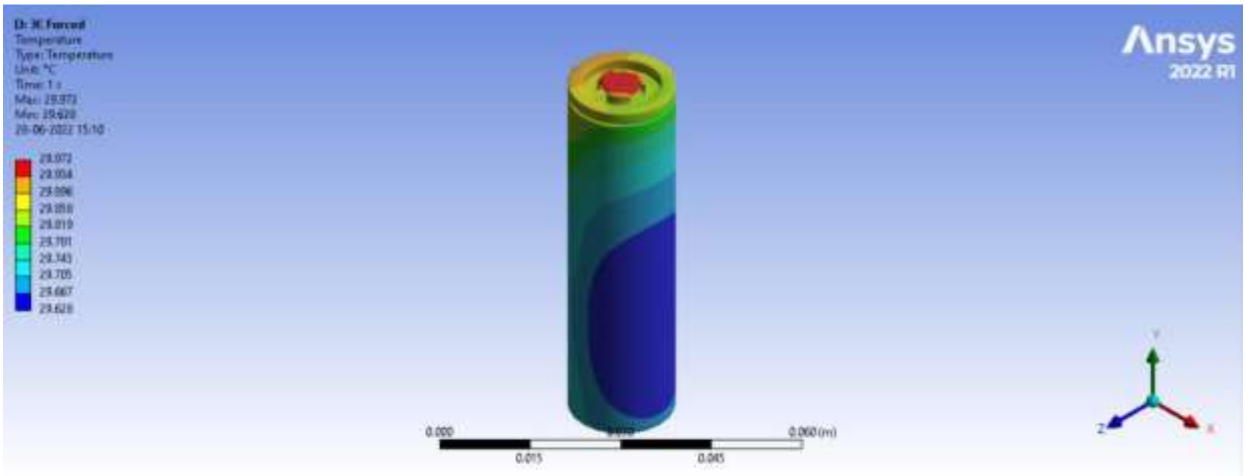


Fig. 13, Temperature profile for forced convection (3C)

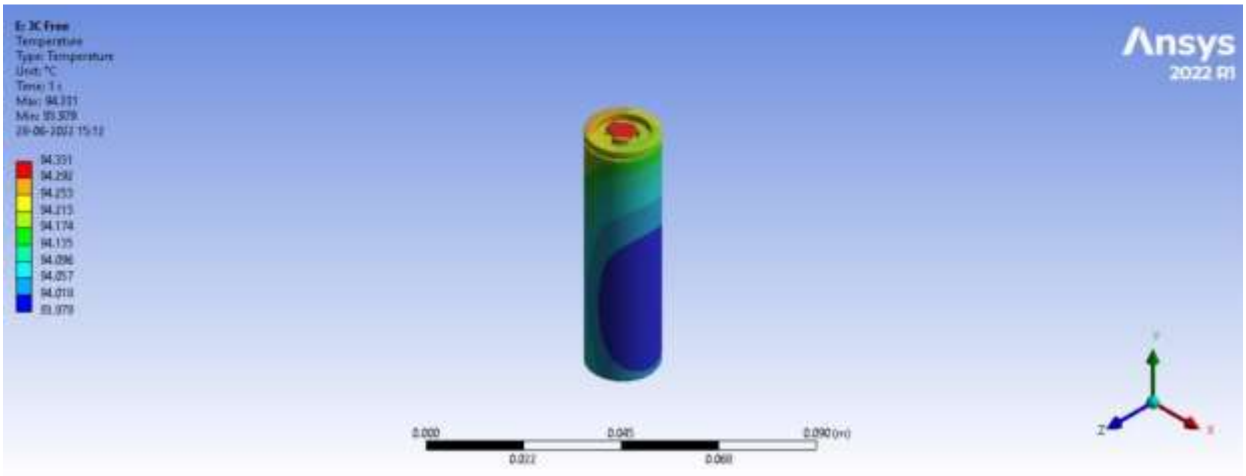


Fig. 14, Temperature profile for free convection (3C)

Results

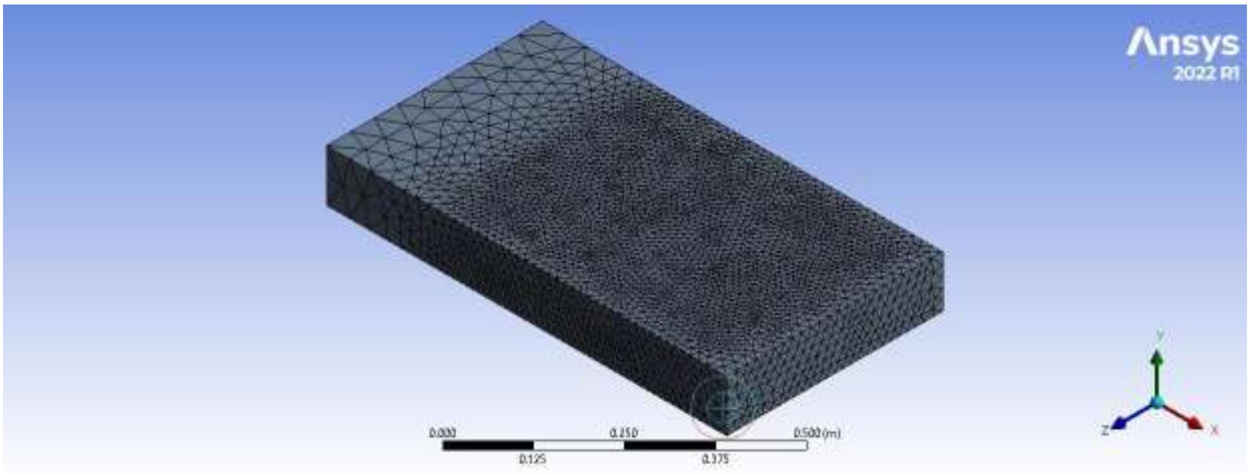
Table 13, Comparison

Properties	Free Convection	Forced Convection
Maximum Temperature (1C)	32.872°C	25.706°C
Maximum Temperature (2C)	56.484°C	27.824°C
Maximum Temperature (3C)	94.331°C	29.972°C

As we can see from the table, forced convection decreases the temperature much more significantly as compared to free convection even at 1C charge/discharge rate. In the absence of convection, the rise in temperature for our model would have been around 89°C (for 1C) but using single phase forced convection through air, we managed to decrease it to a maximum value of 25.706°C. The case for using forced convection becomes even stronger in case of 2C or 3C charge/discharge rate. Using a fluid like water instead of air would have resulted in a lesser temperature but the difference would have been insignificant and pumping water in the battery pack would have created different kinds of engineering problems.

But, multiple cells are going to be packed in series and each row of cells will block the airflow for the next row. So it becomes important to check the temperatures of the cells at the back and that can be done through CFD analysis. For CFD analysis we build a simple model similar to the one shown in fig. 4 and meshed the model as per default meshing only.

Fig. 15, Meshing of battery pack



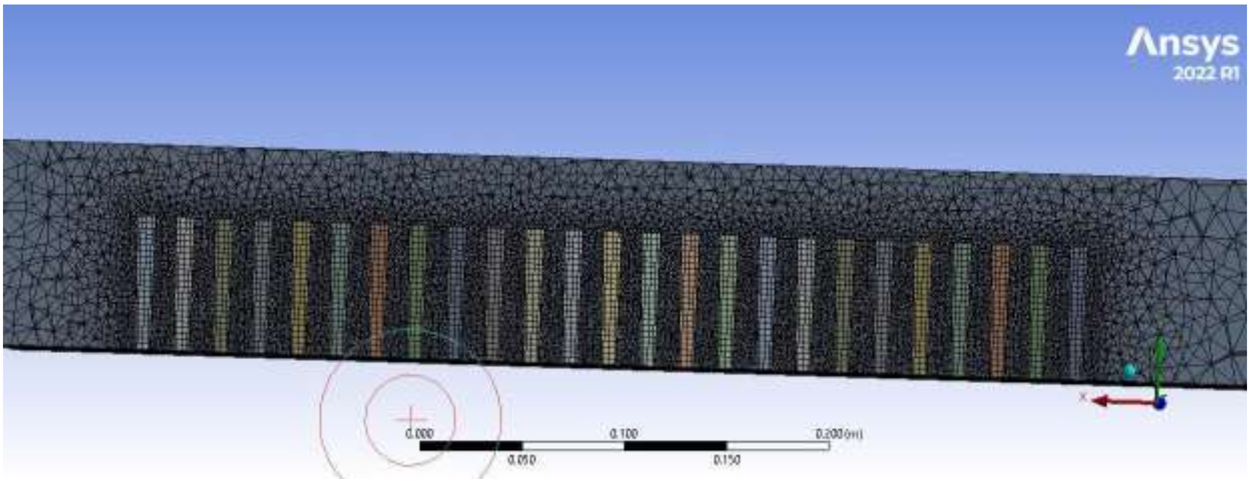
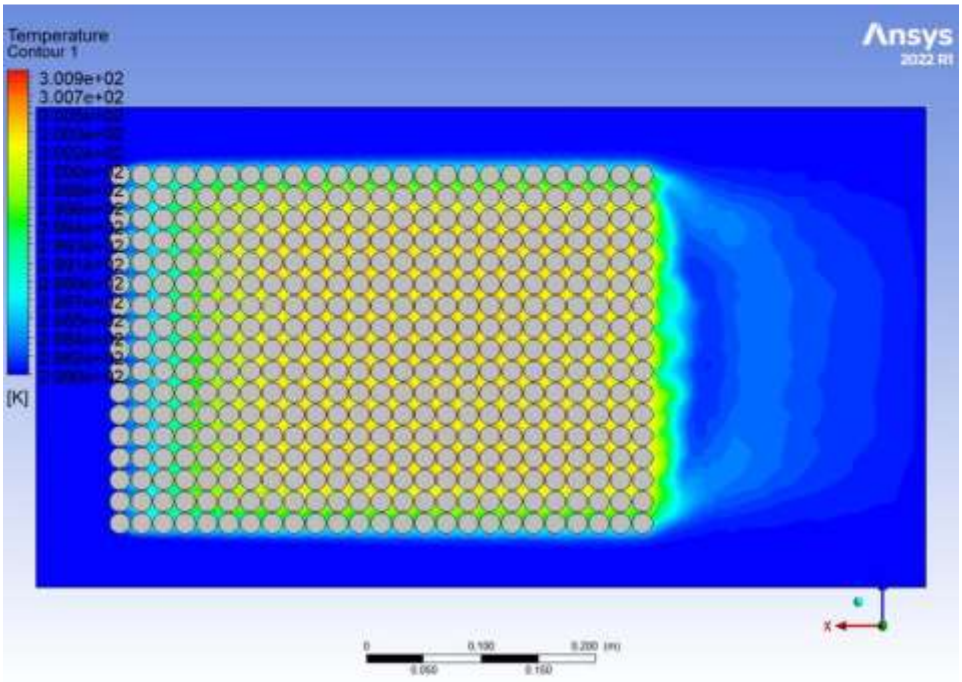


Fig. 16, Section plane representing meshing of batteries

After meshing, we simulated the assembly by assigning air properties to the fluid domain and NMC 811 properties to the batteries. Fluid flow speed was taken to be at 1.2 m/s [9] and internal heat generation of 6801.5 W/m³ was assigned. The results of the simulations are shown below.

Fig. 17, Fluid flow through batteries



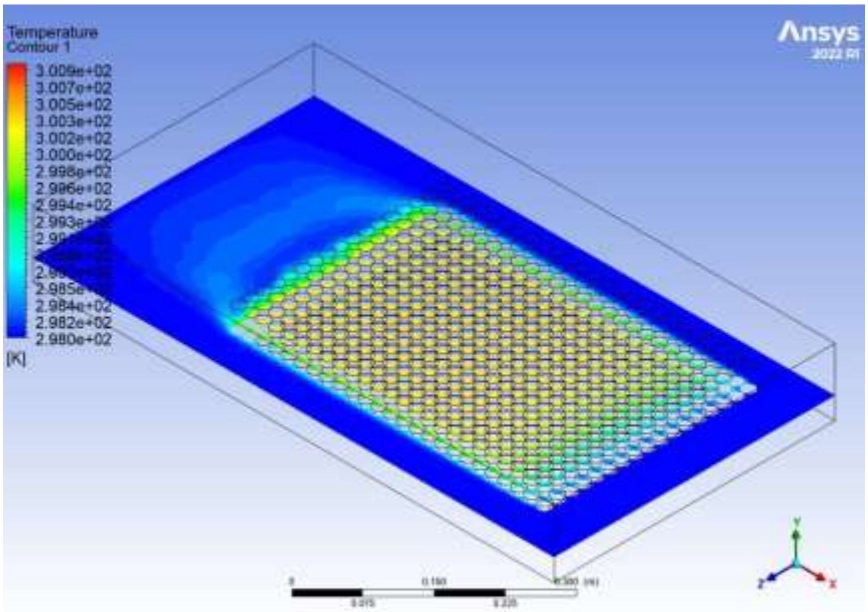


Fig. 18, Isometric view of fluid flow

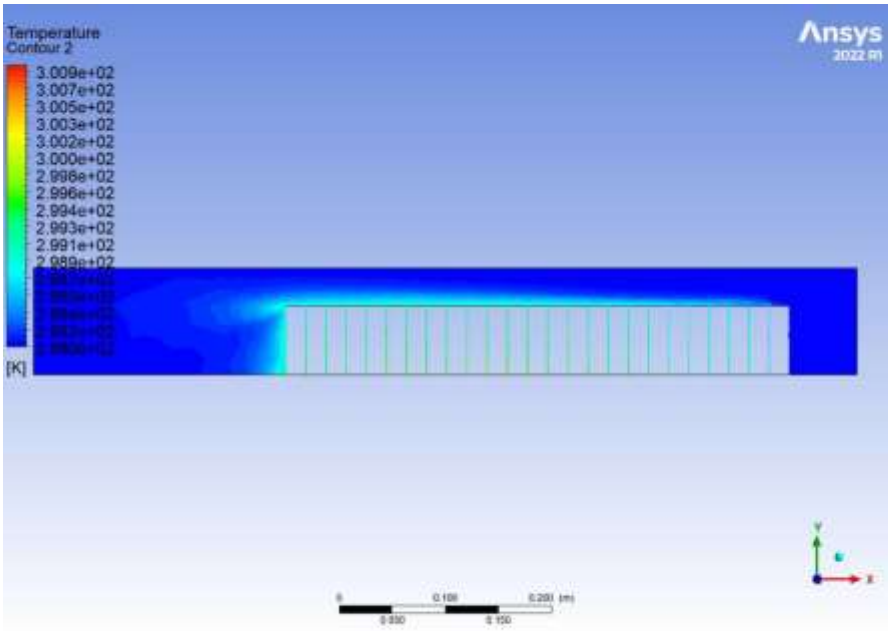


Fig. 19, Side View for fluid flow

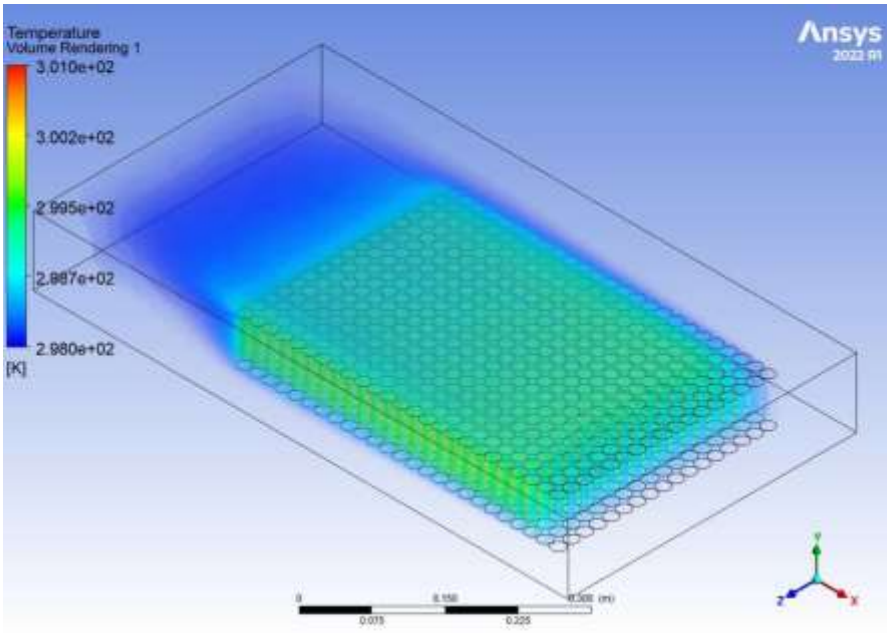


Fig. 20, Volume Rendering depicting the fluid flow

The above results show that the maximum temperature of the batteries goes upto 301 K or 28℃ which is almost what we got from the single cell analysis. This shows us that the method of cooling which we have used is correct and can be successfully applied for cooling of the battery pack.

Conclusion

The objective of this project was to model a battery pack for an electric vehicle on thermal considerations and check if the battery pack heat load can be negated by the use of the methods which we have chosen on the basis of our calculations. We first selected a vehicle, decided the batteries to be used, modeled a battery pack, calculated the heat load, selected the cooling method and validated our cooling method through FEA. As per our analysis, we find our model to be satisfactory and can be implemented in practice.

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