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Numerical Evaluation of Thermal Cooling in 32700 Lithium-Ion Cell-Based Electric Two-Wheeler Battery Pack

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Abstract
As the electric vehicle have become reality in today's world of technology advancement, lithium-ion cells are the main reason to achieve this paradigm shift. Lithium-ion cells properties have enhanced energy density, cycle life, and safety, making it suitable for electric vehicle utilization. The main disadvantage of these cells is that when run at high C-rate, the cell temperature increases. In order to maintain the cells healthy for a longer time frame and to prevent thermal runaway, the cells must be kept at their optimal operating temperature. Presently, no separate battery pack thermal management system is used in the two-wheeler electric vehicle. As a result, this study makes an earnest endeavor to provide a solution for battery pack temperature control employing phase change material (PCM). In this case, an entire battery pack of a two-wheeler electric vehicle is studied, and work is done on building a battery pack casing, 32700 lithium-ion cells, and PCM based thermal cooling system. A battery architecture of 20P16S (320 cells) with LFP 32700 cell is chosen for the pack, while paraffin wax with graphene nanoparticles mixture is selected as the cooling medium for cells. The designed top cover plate can withstand weight over 80kg with less than 0.1mm total deformation for steel and aluminum material. The passive cooling solution provides better cooling of battery pack in comparison to natural air cooling.
Keywords: Battery Pack, Paraffin Wax, Passive Cooling, Thermal Management, Lithium-ion

INTRODUCTION

Because IC engine-powered vehicles emit a large amount of pollution into the air, affecting both humans and the environment[1]. To regulate car emissions, governments around the world have attempted to enact rigorous policies that impose limits on tailpipe emissions[2]. However, as these standards become stricter, the number of vehicles on the street has increased, introducing additional pollutants into the environment[3]. This issue has heightened the need for alternative technology to handle the challenge of transportation with reduced or no polluting emissions into the atmosphere. As a result, one of the few solutions to the emission problem is to use alternative fuels or electricity. With the race of technological growth, battery-powered electric vehicles have become a sure solution at this point[4]. With significant investment in the development of the electric vehicle, it has become a reality for transportation, and people are accepting this technological transformation.

Lithium-ion cell is the backbone to make the electric vehicle a reality, considering its high energy density, fast charged/discharge, lower self-discharge and temperature tolerant. Lithium iron phosphate (LFP) and nickel manganese cobalt (NMC) are the two most often utilised chemistry-based lithium-ion cells on the market. Other lithium-ion cell chemistries, such as lithium sulphur, sodium ion, and solid-state batteries, have yet to be commercialized. Temperatures in the cell tend to rise with each charge or discharge cycle, and thermal management systems are utilized to keep them stable. In current automobiles, an air and liquid cooled based thermal management system of the battery module is used, researchers have worked on alternative hybrid systems to discover an ideal and superior solution. So, battery thermal management system (BTMS) has a significant impact to maintain the cell temperature and make the most effective usage of the battery pack[5].

Many researchers[6–9] have worked on PCM based cooling mechanism, PCM have a potential to be a solution for battery cooling because of its high latent heat capacity and researchers are working on developing a system suited for automotive applications. A study conducted in which PCM is used to cool the battery with additional fins surrounding the cell to accelerate the heat transfer rate, results revealed that the system is useful even at heat generation rate of 20W [10]. A study was conducted utilizing PCM and air cooling, in which the shape of the PCM enclosing the 18650 lithium-ion cell was hexagonal and circular, and the outcome revealed that both shapes gave the same results[11]. An investigation was conducted on PCM with mini channels of water to improve the thermal performance and the cycle life of the battery pack, the outcomes demonstrated that PCM maximum temperature will be decreased with the usage of mini channels[12].

In this study, a numerical analysis of the electric two-wheeler's battery pack with cooling system is performed. Here a LFP 32700 cell is considered for the battery pack and PCM is selected for cooling of cells. A detailed battery pack casing assembly is designed with battery pack vent, cable gland, handle, rocker switch, top cover and with internal structure to hold the cells. The top cover of the battery is designed and analysed to withstand a load of 80kg and maximum deformation should be less than 1mm. Initial the temperature analysis is carried out without PCM and natural air convection is considered for 1C rate of discharge of the cells. Thermal analyses are then performed using PCM around the cell, and the findings are compared.

CONCEPT DEVELOPMENT

Concept Description

As the two wheeler electric vehicle battery pack do not have any dedicated thermal management system, it is important to have a cooling mechanism to preserve the optimum cell temperature. The purpose of this study is to determine a solution that does not disrupt the current battery pack package and provide a thermal cooling solution for the cells. It is not advised for the two-wheeler battery pack to provide any more energy for the auxiliary equipment needed for forced air and liquid based cooling system, since these equipment require additional auxiliary equipment and absorb energy from the battery pack. Hence, PCM is a desirable solution for the two wheeler battery pack and with PCM addition of graphene nanoparticles will enhance the overall thermal conductivity. In this research a high density lithium-ion is selected with specifications as mentioned in table 1 and battery pack is designed. A total of 320 cells have been considered for this study and organised as 20P16S, with a pack voltage of 51.2 V and capacity of 120 Ah. It is also critical to preserve the cells intact in the battery pack casing; a detailed battery pack casing is designed to bear the weight of the cells and is also regarded a condition to withstand a load over the top cover of the battery pack casing.

Table 1: Specifications of 32700 Cell.

Parameters	Details
Nominal capacity	6 Ah
AC Impedance	≤ 8 mΩ (At AC 1000 Hz)
Nominal voltage	3.2 V
Cell Size	D: 32.2±0.3 mm H: 0.5+0.4/-0.3 mm
Weight	140± 5 g
Voltage (nominal)	3.60 V
Discharge Current (Max)	18A
Cycle Life	≥2000
Operating Temperature Range	Charging Temp: 0~60 °C Discharging Temp: -20~ 60°C

Mathematical Model

Mathematical representations of lithium-ion batteries have the ability to predict how the battery will function under specific conditions. Such models usually consider factors such as cell temperature, charging and discharging speeds, and the battery's inherent resistance. These prediction tools can

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provide estimates for elements like the battery's voltage, current, capacity, energy, and more. Additionally, they offer a means to examine the effect of different operational situations on the functioning of the cell.The heat generated in a battery is primarily caused by the chemical reaction that occurs within the cell. Chemical energy is converted into electric energy during the charge and discharge of a battery, and vice versa. This process of converting energy raises the temperature, consequently in heat generation. Internal resistance, which is caused by the flow of electrons through the cell, also generates heat. By using high-quality materials and designing efficient cooling systems, the heat generated by the battery can be reduced.

Entropic heat (Hs) and Ohmic heat (Ho) both contributed to the heat generated in a cell (Hp)[9].

Hp =Ho+ Hs (1)

Ohmic heat (Ho) can be written as : Ho = (I^2)R (2)

Entropic heat (Hs) can be written as: Hs = ΔS * T * I (3)

Equating equation (2) and (3) in equation (1):

Hp = (I^2)R + ΔS * T * I (4)

Where,

H : total heat energy generated in watt-hours (Wh), I : current in amperes (A), R : resistance in ohms (Ω), ΔS : entropy change in joules/kelvin (J/K) and T : temperature in kelvin (K).

When allocating cell zone conditions, the user-defined function (UDF) Eqs. (1)–(4) was created and called. Internal resistance (R) of the cell is dependent on temperature, in this research It is assumed that internal resistance remains constant and considered to be 0.025 **Ω**. Equation Number (2) is employed to determine the internal heat generation in the cell, here the charge and discharge current(I) is known based on C-Rate parameter.

The continuity and momentum equations for the current numerical simulation are provided below:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial x}(\rho v)=0 \quad (5)$$

$$\frac{\partial}{\partial t}(\rho u) + \frac{\partial}{\partial x}(\rho u^2) + \frac{\partial}{\partial x}(\rho u v)= -\frac{\partial P}{\partial x} + \frac{\partial}{\partial x}\left(\mu \frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right) - Su \quad (6)$$

$$\frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial x}(\rho v^2) + \frac{\partial}{\partial x}(\rho u v)= -\frac{\partial P}{\partial y} + \frac{\partial}{\partial x}\left(\mu \frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial v}{\partial y}\right) + \rho g \beta (T - T_m) - Sv \quad (7)$$

Where,

Where **ρ** represents the density of the phase change material (PCM), **μ** is its dynamic viscosity, **P** denotes pressure, **g** is the gravitational acceleration, **β** refers to the thermal expansion coefficient, and **S** is the momentum source term accounting for reduced porosity within the mushy zone.

Few assumptions have been made before analysis i.e. initial temperature cell is same as ambient temperature, Molten state of PCM is not considered, internal heat is considered to be constant throughout cell volume.

CAD Modelling

The 3D models of the battery pack will help to understand the position of the battery pack components and review the design. In this research, a battery pack for 2-wheeler is designed with consideration of lithium-ion cells, battery pack vent, outer casing, aluminium cross section bar, handle, cable gland, CAN connector, SPDT on/off switch, M6 bolt and M6 nut as highlighted in table 2. In this modelling wiring of the cell and battery management system is not shown, but overall weight is considered for study purpose. The dimensions of the parts of the battery pack are shown in figure 1.

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Table 2: Battery pack parts detailed specifications and quantity

Item No	Description	Qty
1	Outer Casing	1
2	19 MM * 19 MM cross section bar- aluminium	16
3	Handle	2
4	PG 11 – Cable Gland	2
5	Battery Pack Vent – M32	1
6	Connector - CAN	1
7	Rocker Switch – SPDT on/off switch	1
8	M6 Nut	8

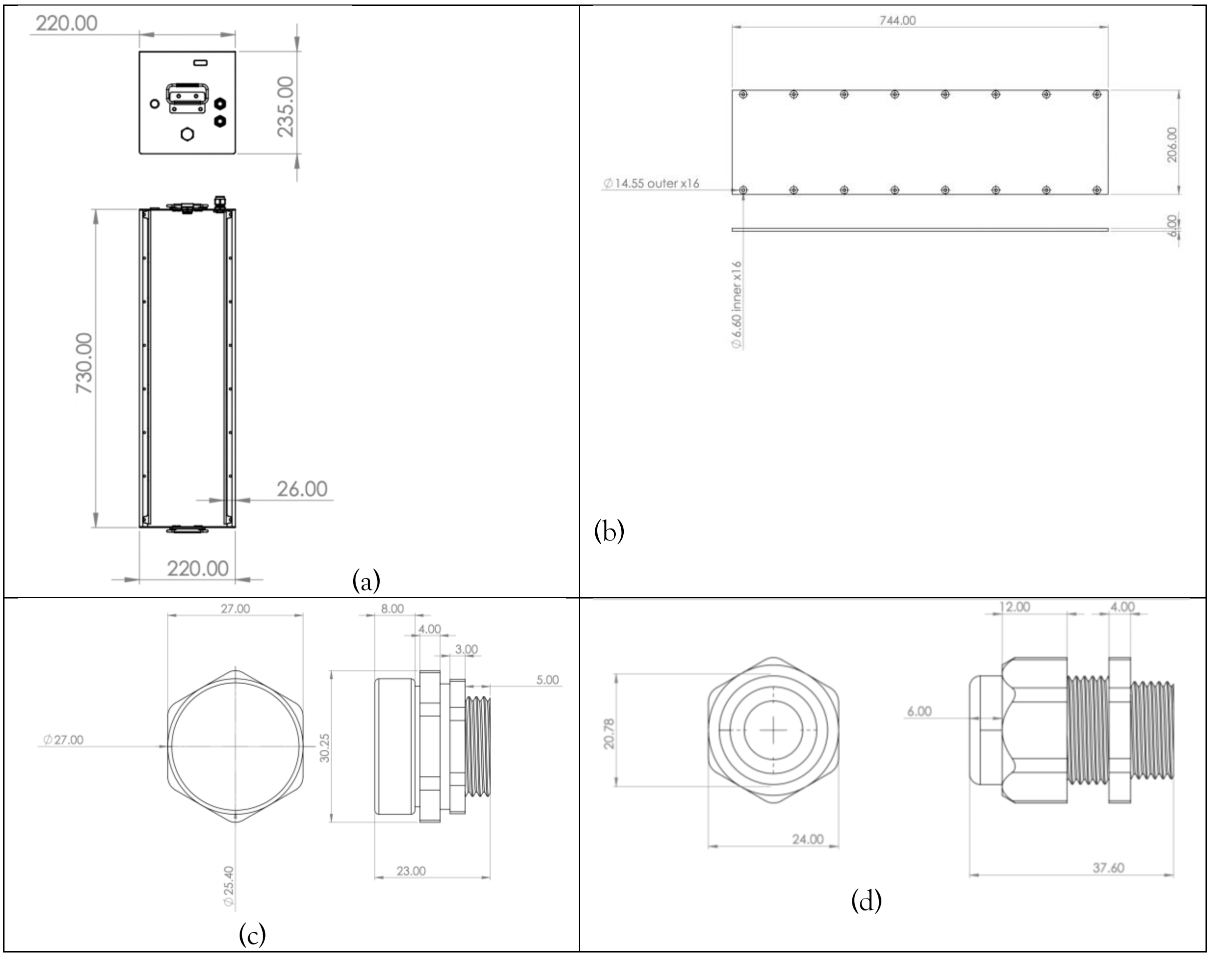


Figure 1: Dimensions of the battery pack (in mm) - a) Battery pack outer casing with handle, b) Battery pack top plate, c) Battery pack vent, d) PG 11 – Cable Gland

To ensure that the cells are safe in the pack, the battery pack top plate must sustain a load of 80kg and deformation of the plate must be less than 1 mm. Because the battery pack is deemed to be located beneath the vehicle's seat and there is a possibility of a load operating on the battery pack plate. Figure 2 illustrates the cad model of the top plate, which has hole of 16 x ø 6.60, ⌴ ø 14.55 ↧ 4.00, which helps to keep the plate intact.

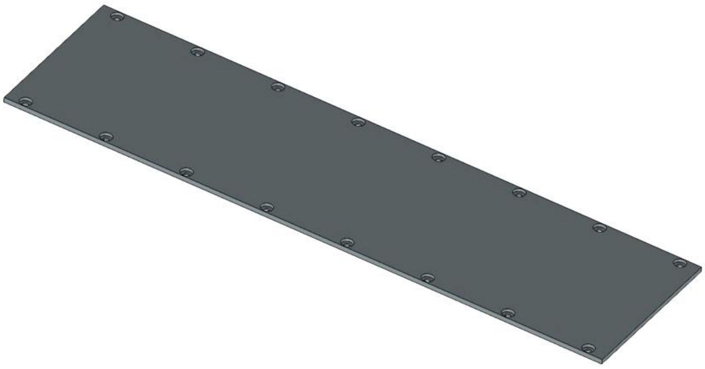


Figure 2: Top cover of the battery pack.

Figure 3 depicts the final battery pack enclosure, with the parts labelled as in table 2. This battery pack case will keep the battery pack intact and provide load bearing support from the top cover. The aluminium cross section bar (part 2) is used to reinforce the casing to support the top cover and is lightweight, corrosion resistant, has high heat conductivity, and is inexpensive. The battery pack handle (part 3) is a designed feature aimed at enhancing the portability and ease of handling of battery packs. Crafted to ensure a secure grip, it allows users to transport and position battery packs safely, reducing the risk of drops and potential damage. Beyond mere functionality, the handle often factors in ergonomic design, providing comfort to the user during transportation. Incorporating a handle is a testament to the evolving need for making battery technology user-friendly and accessible in various applications. The PG 11 cable gland (part 4) serves as a pivotal component in ensuring secure cable connections. Originating from the German term "Panzer-Gewinde," PG 11 indicates a specific size and threading pattern. Designed to offer strain relief, these glands preserve cable integrity by preventing environmental contaminants such as water and dust from infiltrating. Moreover, they play a key role in fortifying connections against physical stress, enhancing both safety and durability in diverse applications. The battery pack vent – M32 (part 5) is a crucial component in battery management, specifically designed to maintain the internal pressure balance within battery packs. With its M32 specification, it offers a standardized size ensuring compatibility with various applications. This vent not only ensures the safety of the battery pack by allowing the controlled release of gases but also protects against external contaminants, enhancing battery longevity and performance. Its integration is pivotal for maintaining battery health, especially in high-demand scenarios. The connector – CAN (part 6) is a specialized interface designed for the controller area network (CAN) communication within battery systems. This connector ensures reliable data transmission between the battery pack and other electronic components, facilitating real-time monitoring and control. By using the CAN protocol, this connector plays a pivotal role in ensuring efficient communication, diagnostics, and safety functions in modern battery management systems. Its presence underscores the integration of advanced electronics in optimizing battery performance and health. The Rocker Switch – SPDT on/off switch (part 7) is a versatile electrical component distinguished by its toggle action. The acronym "SPDT" stands for Single Pole Double Throw, indicating its capability to switch between two separate circuits. Characterized by its simple, rocking mechanism, this type of switch allows users to seamlessly transition between on and off states. Its straightforward design and tactile feedback make it a popular choice for various applications, from household appliances to industrial equipment, offering both functionality and user-friendly operation.

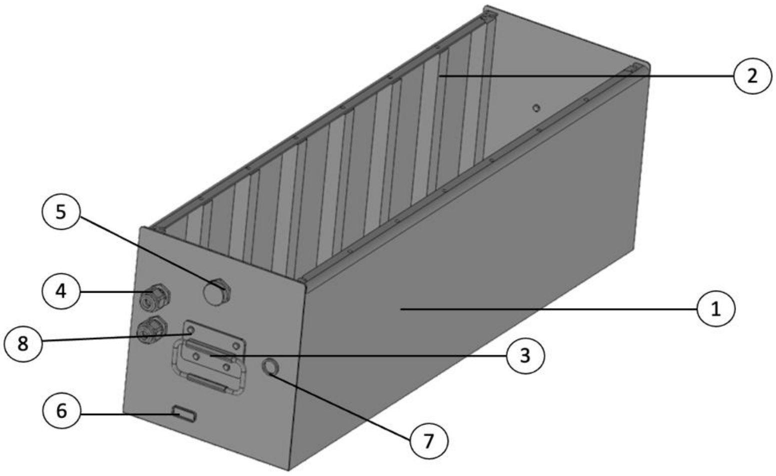
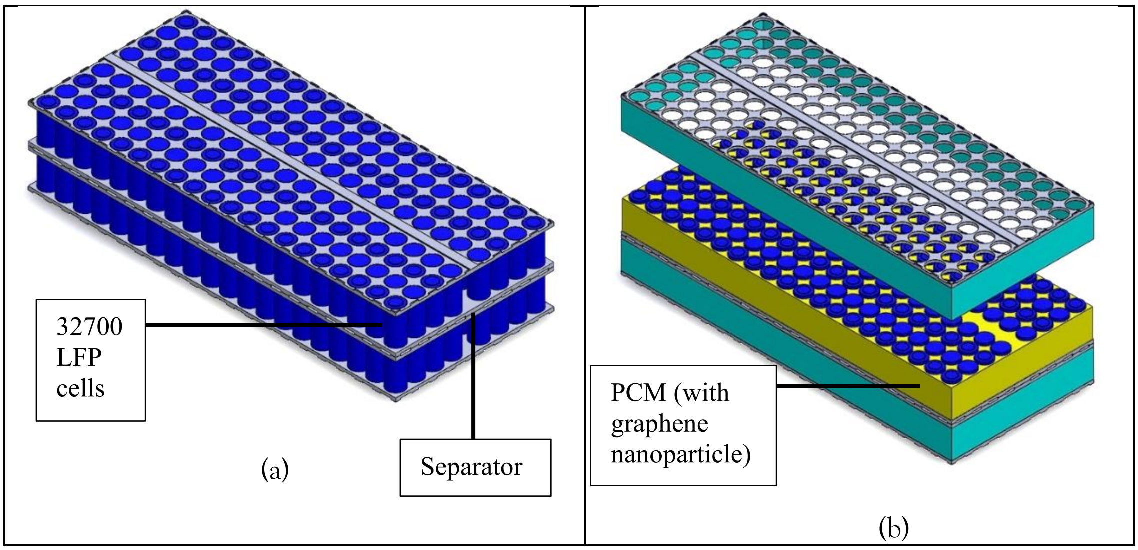


Figure 3: Final assembly of the battery pack casing.

As mentioned earlier, 32700 LFP cells are selected for this study and designed them using CAD software. Here, 320 cells are arranged in two layers, with one module consisting of 160 cells and the remaining 160 cells stacked on top of each other as shown in figure 4. The cell pack is 704 mm x 303 mm x 144 mm in L x W x B dimensions. In the research undertaken, the integration of PCM and graphene nanoparticles emerged as a pivotal strategy to regulate and stabilize cell temperatures. These materials are renowned for their thermal management capabilities. The PCM undergoes a phase transition, absorbing or releasing latent heat, ensuring the cells remain within their ideal operating temperature range. When combined with the high thermal conductivity of graphene nanoparticles, this approach offers enhanced heat dissipation and distribution. Surrounding the cells with this composite mixture ensures they benefit from consistent temperature regulation. The final encapsulation within an aluminum case not only adds an additional layer of protection but also boosts the thermal performance. Special attention was given to the design to ensure it is leak-proof, preventing any potential escape or seepage of the composite PCM, thus ensuring the system's safety and longevity.



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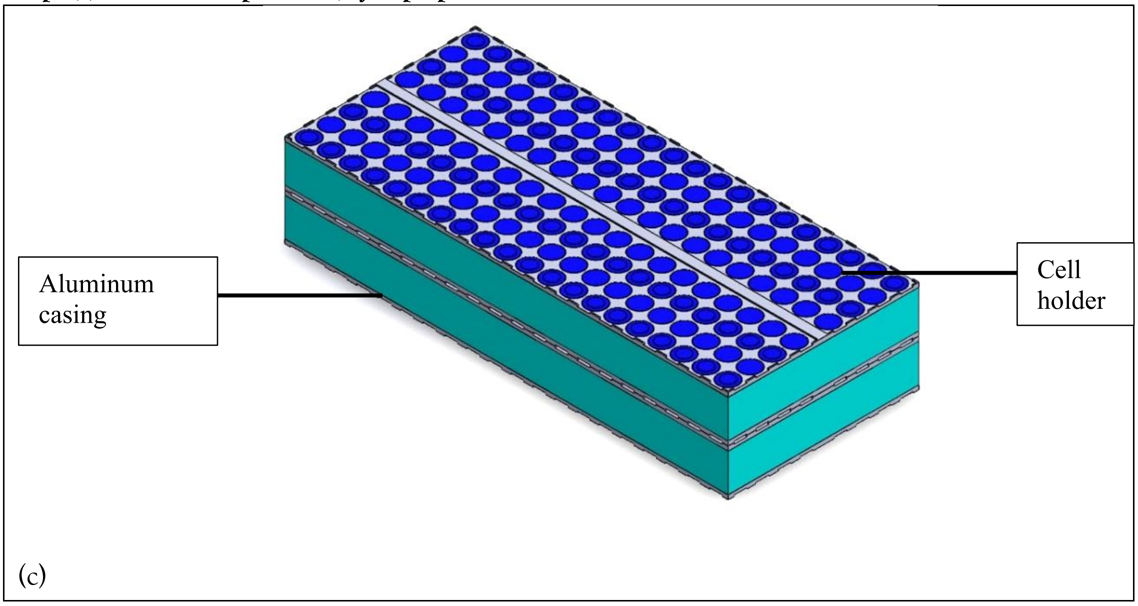

(c)

Figure 4: 32700 LFP cell (a) Battery pack with no cooling mechanism, (b) Battery pack with PCM material, (c) Final assembly of battery pack with PCM cooling.

Model Analysis

Simulation can be extremely useful in implementing a battery model and achieving the best design solutions for cooling system. Thermal analysis results can be used to optimise cooling system design by providing insight into the system's temperature distribution. This can be used to decide which regions need to be cooled more and which can be lowered. As a result, designers can create more efficient and dependable cooling systems. Thermal analysis can also be used to assess the thermal performance of a system and advise on system components that need to be modified or upgraded. Finally, thermal analysis results can be used to predict potential problems, allowing designers to take proactive measures to ensure system reliability.

Meshing a battery pack is a important step in computational modelling and simulation that entails breaking down the battery pack structure into smaller, more manageable pieces, or "cells." A tetrahedrons mesh is chosen because of its flexibility and ability to accommodate irregular complex shapes more effectively. The mesh is built with a total of 1469304 elements and 2635856 nodes for battery packs with PCM and 1442424 elements and 2543968 nodes for battery packs without PCM as shown in figure 5.

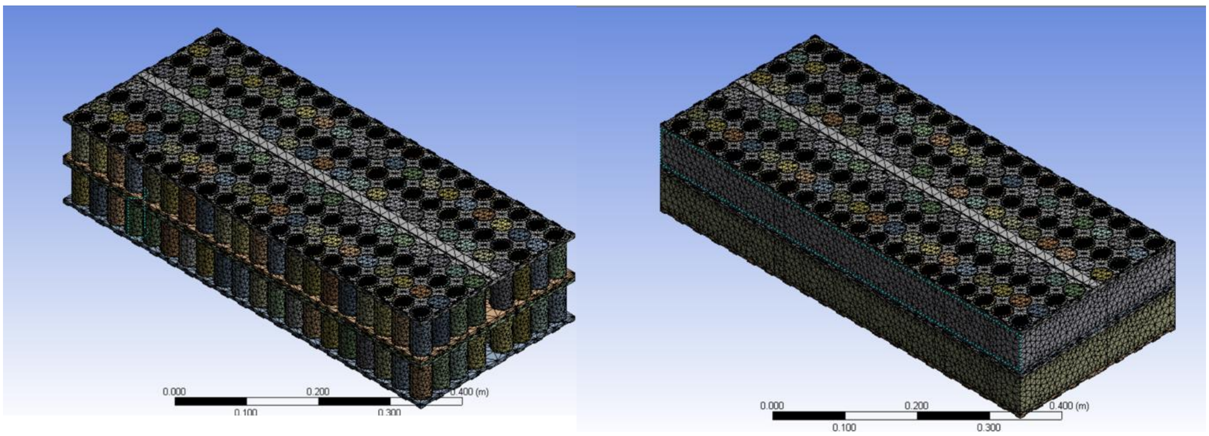

Figure 5: Mesh of battery pack a) without PCM, b) With PCM

RESULTS AND DISCUSSION
CAE Results of battery pack top plate.
The top cover, as shown in figure 6, is examined in this study using two distinct materials: steel and aluminium. The properties of steel and aluminium material is shown in table 3. It's imperative to assess the top plate of the battery pack, considering the weight it has to endure. A comprehensive evaluation ensures a substantial safety margin, especially when accounting for potential distortions due to vibrations. Taking these factors into account is crucial for the longevity and stability of the battery system.

Table 3: Properties of steel and aluminium

Properties	Steel	Aluminium
Young's Modulus (Gpa)	186	70
Poisson's ration	0.32	0.35
Yield stress (MPa)	350	160
Elongation (%)	15	7
Ultimate stress (MPa)	420	215

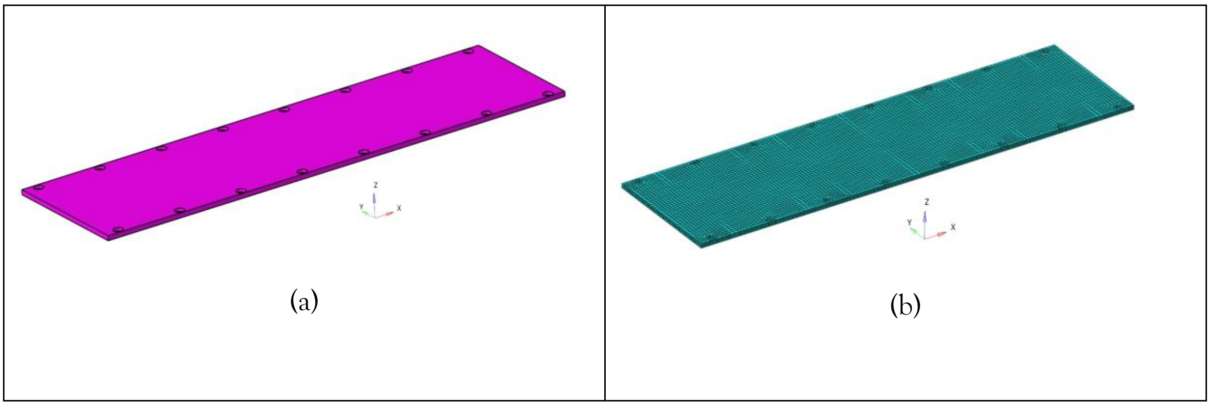
(a) (b)

Figure 6: a) Top cover of the battery pack, b) Mesh on top cover

Further the boundary conditions need to be applied to the plate to get the results on load bearing capacity and deflection. All the holes for the screw are constrained and load of 80 kg is applied on one face of the plate and the load is uniformly distributed over the plate and other boundary conditions are as mentioned in table 4. Figure 7 shows the boundary conditions applied over the top cover for steel and aluminium top cover and Z-displacement (mm) at applied pressure of 0.0054 MPa (80Kg). Figure 8 shows the Von-Mises (MPa) stress for steel and aluminum and figure 9 shows the maximum stress acting on steel and aluminum.

Table 4: FEM with loads and boundary conditions

L (mm)	B (mm)	Area (mm^2)	Mass (kg)	G (m/s^2)	F (N)	Pressure (MPa)
744	194	144336	80	9.81	784.8	0.005437313

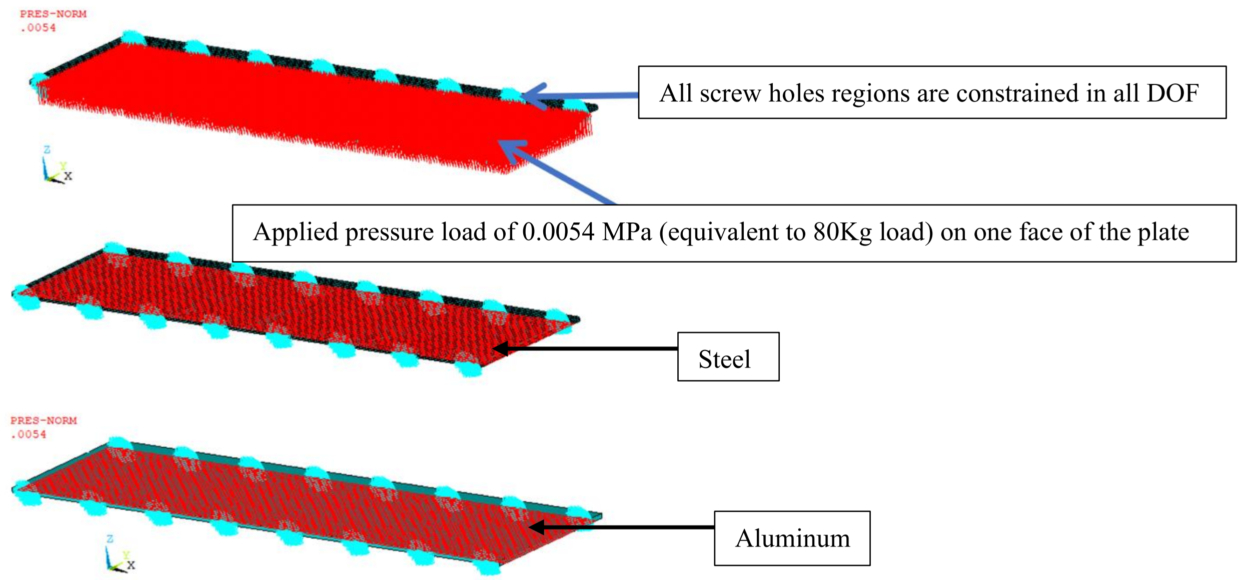

Figure 7: Boundary conditions applied on top plate for steel and aluminium.

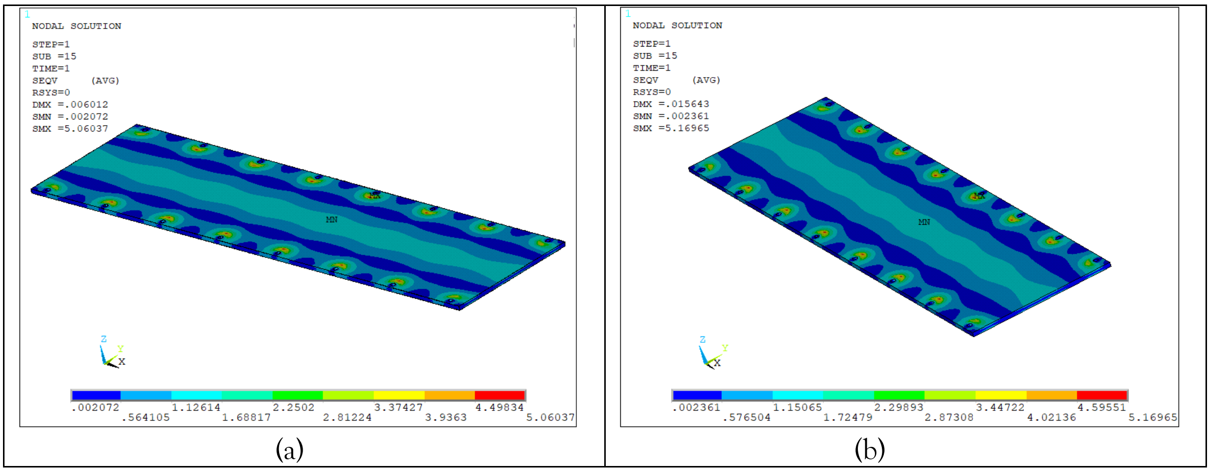

Figure 8: Von-Mises (MPa) stress distribution on top cover a) steel, b) aluminum

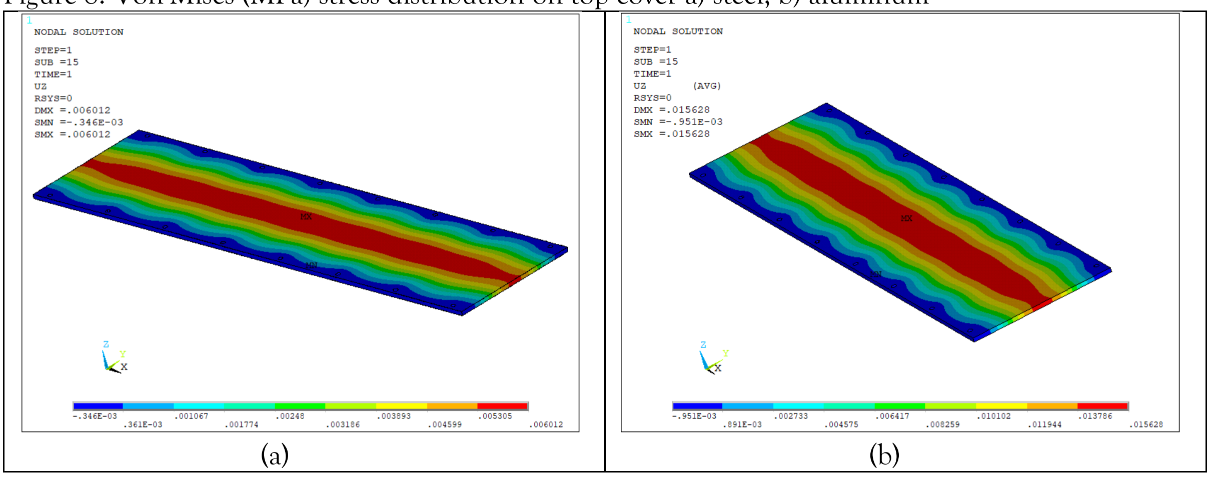

Figure 9: Maximum stress acting on top cover a) steel, b) aluminum

Observation on structural analysis results:

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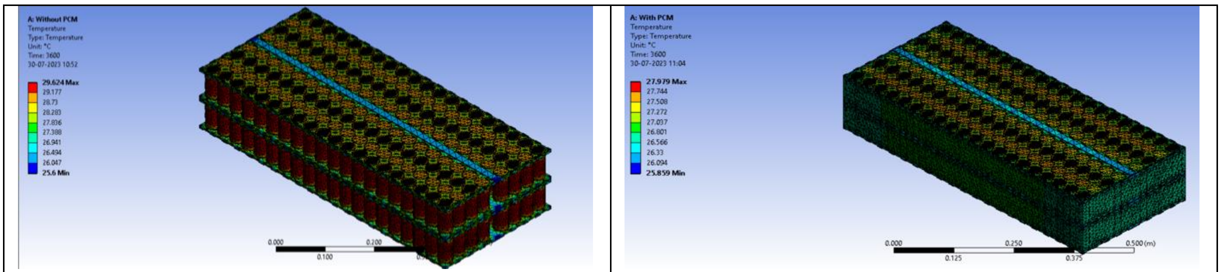
- The maximum displacement is 0.006mm for steel material and 0.015mm for aluminium material (Z-direction displacement).
- There is maximum stress developed 5.06Mpa (steel) and 5.17 MPa (Aluminium). This stress value is <<160 MPa (yield limit of the material). Therefore the assembly is safe under applied pressure load case.
- At present condition the factor of safety is 160/5 ~32

3.2 CAE Results of battery pack with PCM.

The cells are analysed for 1C discharge rate for with PCM and without PCM (air)on battery pack. Internal heat generation is calculated for this rate of discharge, by taking into consider the initial internal impedance specified by manufacturer. The internal heat generation for this 32700 LFP cell at 1C discharge rate is 0.324 W. The properties of PCM (paraffin wax) and graphene nanoparticle mixture are density is 1150 kg/m^3, thermal conductivity 0.376 W/m °C, and specific heat constant is 2100 J/kg °C and the transient thermal analysis output is as shown in figure 10.



(a) (b)

Figure 10: Transient thermal analysis of the battery pack a) without PCM, b)with PCM

For this analysis the natural convection of air around the cell has property i.e density is 1.1614 kg/m^3, thermal conductivity is 0.026 W/m °C and specific heat constant is 1007 J/kg °C.

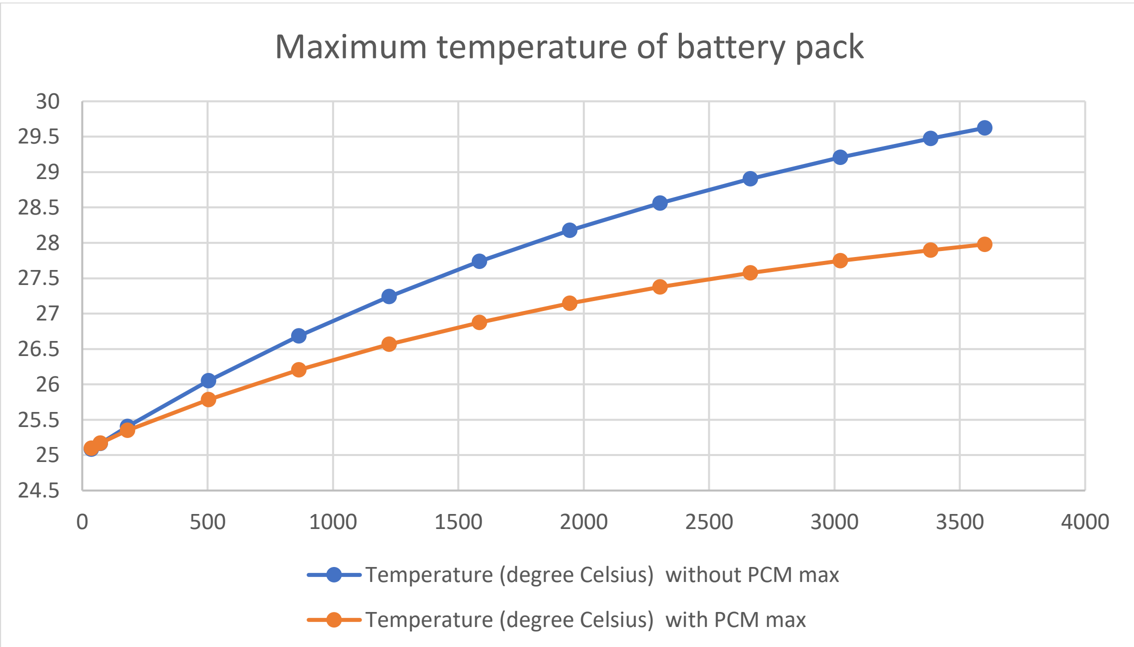


Figure 11: Maximum battery pack temperature with and without PCM

According to figure 11, the maximum temperature of the battery pack without the PCM is 27.5 °C and 29.5 °C with the PCM. This demonstrates that the temperature is lower with PCM than it would be without it.

3.3 Validation of transient thermal analysis results with experimental results

The results are validated with the data published in our previous paper by Govind Kadam and Punit Kongi [13].

CONCLUSION

In this study a full scale battery pack of two wheeler is designed and analysed and following are the conclusion.

- This study will help the design engineers of the battery pack to precisely map the wiring, position of cells, connection of cells, weight optimization, cooling system layout and finally test the pack at different condition.
- The selected top cover plate for the battery pack has load bearing capacity of above 80kg.
- The selected passive cooling of phase change material and graphene nanoparticles has produced better results in comparison to natural air cooling.
- An approximately 11kg of the PCM and graphene nanoparticles is required for full scale battery pack cooling of two wheeler electric vehicle.
- The study's methodology can be replicated and adapted for designing battery packs for other vehicular applications, potentially revolutionizing the broader electric vehicle market.

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