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Enhancing Lithium-Ion Battery Cooling with Composite Phase Change Materials: A Numerical Approach

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Abstract

Battery Thermal Management Systems (BTMS) are essential for ensuring the optimal performance, safety, and longevity of lithium-ion batteries, especially during high-rate discharges. Phase Change Materials (PCMs), known for their high latent heat capacity, are commonly employed in BTMS to stabilise battery temperatures. However, the low thermal conductivity of PCMs restricts their effectiveness under intense thermal loads. To overcome this drawback, Carbon Quantum Dots (CQDs) are incorporated into PCMS to form Composite Phase Change Materials (CPCMs), which enhance thermal conductivity and improve heat dissipation. This study presents a numerical analysis of a 13S4P Panasonic 18650 battery pack under three cooling strategies: no cooling, PCM-based cooling, and CPCM-based cooling, evaluated at discharge rates of 1C, 2C, and 3c using ANSYS Fluent. The main performance indicators include peak battery temperature and thermal uniformity across the battery pack. Simulation results reveal that CPCMs significantly outperform traditional PCMs by lowering the maximum temperatures and enhancing temperature uniformity. At a 3C discharge rate, CPCMs reduce the peak temperature from 35°C (no cooling) to 22°C, compared to 25°C with only PCM. Moreover, CPCMs minimise the temperature gradient within the battery pack by 3°C relative to PCM and by 13°C compared to no cooling. These results confirm that CPCMs offer improved thermal control, mitigate the formation of hotspots, and promote consistent battery operation under demanding conditions. As a result, CPCMs emerge as a highly effective passive cooling solution for electric vehicles and stationary energy storage systems.

Major Findings: *The study reveals that Composite Phase Change Materials (CPCM) infused with carbon quantum dots provide significantly improved thermal management for lithium-ion battery packs compared to traditional PCM and no cooling scenarios. At a high discharge rate of 3C, CPCM reduced the peak temperature by 33.6°C relative to the uncooled system and by 3.6°C compared to PCM, showcasing its superior heat dissipation capabilities. Moreover, CPCM enhanced temperature uniformity across the battery pack, effectively minimising thermal gradients, which is crucial for improving operational safety, performance stability, and extending battery life under high-stress conditions.*

Keywords: *Ansys Fluent, Battery Thermal Management System, Composite Phase Change Material, Lithium-Ion Battery, Phase Change Material*

1.0 Introduction

A new composite phase change material and air-cooling system were also designed combined as thermal management systems in hybrid power trains to improve the performance of Lithium-Ion Batteries (LIBs).

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Comparisons made using the experimental and numerical assessments highlighted that the integrated system was superior to air cooling only by achieving battery temperatures below 49.2°C at optimal airflow through the cooling tunnel. Successfully tested thermal regulation in discharge cycles with the help of the presented system and did not require any additional power during six cycles[1]. A new thermal control system based on paraffin Composite Phase Change Material (CPCM) with liquid cooling was designed to control the temperature of the LIB at a 3c discharge rate. A computational fluid dynamics assessment revealed the highest cooling effectiveness at flow rates higher than 0.08 m/s, with a channel configuration. The battery temperature increased by 2.1°C with the help of 6 wt % in CPCM and gained steady charge-discharge cycle performance at low flow velocities[2]. Thermal management module made from a battery, phase PCM, and a heat pipe, providing a sandwich structure for improved lithium-ion battery performance. Simulations in the author's previous papers and laboratory experiments also demonstrated that integration of heat pipes through PCM contributes to the recovery of the inherent heat and preservation of the battery temperatures in the charge-discharge phases. An optimum melting point of PCM 3 K above the ambient temperature, a condenser heat transfer coefficient of 30-60 W/m^2K, and a thickness ratio of 0.17 is found to be safe and effective for long-term cycling[3]. A newly designed lithium-ion battery pack cooled with a paraffin composite PCM was used to improve thermal management. The outcomes of experiments show composite PCM condensed temperature fluctuation in the battery pack to below 5° and improved performance compared to only normal air cooling, too pure paraffin. Experimental results supported through computational analysis showed the enhanced cooling capabilities of greater pore density, thermal convection coefficient, and cell arrangement, providing substantial feedback regarding battery cooling designs[4]. A LIB thermal management using PCM for a 25-parallel 18650 battery module. It remained presented that thermal conductivity and latent heat enhance temperature regulation, though the values are less significant at very high levels. Best porosity of 94% to reduce the maximum temperature of paraffin/metal foam PCM and improve thermal characteristics of this composite[5]. The micro-scale cooling using PCM cooling with fin structures were analysed numerically to improve the thermal regulation of battery modules. Changing fin numbers and shapes and outer shell convection showed that the optimised PCM module gave an enhancement in heat transfer. It also indicated that the optimised design was intended to improve battery temperature by 2.38% at 2C and 9.28% at 3C discharge rates in standard PCM modules[6]. The silicone-coupled PCM system is proposed to optimise thermal regulation in LIB modules. It was found that a 14 mm thick PCM layer coupled with 3 mm of silicone increased cooling efficiency; the battery temperatures sank by 24°C at 4°C discharge rate with no additional power losses. The complement PCM by providing the best method to enhance the deficiency in high-efficiency battery thermal management[7]. This work designed a thermal organisation system for Li-ion cells by employing a PCM-metal foam composite and modelled mathematically using MATLAB-COMSOL model. Temperature data confirmed that aluminium foam enhanced heat transfer, and increasing the volume of PCM had an effect on the temperature on the surface. The thickness of the PCM is also important to avoid temperatures going to extremes to achieve effective thermal control[8]. Examine thermal directive of lithium-ion battery packs employing Paraffin Wax (PW) built on phase change material, also incorporating graphite powder in hexagonal and trapezoidal PW and CPCM configurations. CPCM cooling was better than PCM cooling, peak temperatures lowered by 9.1% at 2C discharge, and the increase in temperature was reduced by 14.2% in trapezoidal packs. The hexagonal CPCM pack kept battery temperatures below 50°C for all discharge rates because of improved performance[9]. LIBs drive electric vehicles due to their high energy density and extensive cycle time as the world shifts to a green energy system, but thermal regulation is sought to enhance the batteries' efficiency and safety. The aims are to discuss PCM for battery thermal management and the methods, such as metal fins, foams, carbon fibres, graphene, etc., to progress the thermal conductivity of PCM. Problems and research directions for PCM-based thermal management systems are then identified based on recent developments, such as machine learning for multi-scale modeling[10]. The 3d simulation model was built to study the hybrid cooling system of phase change material too heat pipes aimed at the cylindrical lithium-ion battery modules. The outcomes obtained indicated

that the PCM prepared with 12 wt % is superior to pure PCM in terms of heat dissipation characteristics and has a lower temperature gradient; it is most effective at higher discharge C-rates. The study also showed that lower C-rates and more period to charging period reduce the risk of thermal failure and give improved command over thermal issues in charge-discharge cycles[11]. Its analysis on CPCM-based Battery Thermal Management Systems (BTMS) through a special effort on passive as well as hybrid systems. This concerns issues such as low thermal conductivity, stability, then flammability in PCM, promising to rectify them by including porous media and thermally conductive nanomaterials. It is proposed that further studies should be devoted to a thorough understanding of the method of assembling components using CPCM, mechanical characteristics of BTMS, and manufacturing readiness levels[12]. Physical performance of LIB pack with integrated hybrid thermal management system employing copper foam/paraffin composite phase change material and liquid cooling. The implications of the enhancement were presented as follows: Get full content: Increasing Reynolds numbers led to a rise in temperature non-uniformity, but this gradually increased with being enhancement. PCM use in combination with the hybrid cooling system costs less than PCM cooling in general, but proved to be much more efficient with the former weekdays dropping temperature by 8K in hot weather, while the weekend reduces temperatures by 13K in a cold climate[13]. The cooling of LIBs with aluminium plates serving as fins to facilitate convection and air flow from a blower. When air velocity was usual at 8.5 m/s, the cooling results with dummy cells were satisfactory at around 10°C to 20°C. The numerical and experimental results were shown to generalise the effects of convection methods on temperature decrease[14]. A BTMS with both the CPCM and Heat Pipes (HP). The thermal performance was also clearly proved and compared, and the hybrid system clearly outperforms the air-cooled solution and it was seen that under 2C discharge, the maximum temperature was decreased by 22°C by using the hybrid system. Based on the identified heat transfer mechanisms, a thermal model was created and optimised, including parameters such as the absorbency of copper foam as well as convective heat transfer coefficients, to make recommendations for the optimum design for cooling and operational efficiency[15]. The three technologies that were discussed include CPCM cooling or HP removal, liquid cooling or removal, and a composite phase change material-liquid cooling or hybrid system. Hence, Case 3, which represents the hybrid system, obtains the lowest extreme temperature and good control of thermal risk with the maximum temperature of 48.97°C at a discharge rate of 2C. Critical parameters like CPCM thickness, coolant velocity and temperature were fine-tuned for improved battery performance and safety[16]. This affects which phase change temperature that has on thermal regulation of batteries using a CPCM of expanded graphite and paraffin wax. The outcomes suggest that PW with a transition temperature of 48°C is more effective for thermal applications. An optimisation model was formulated for battery layout, convection heat transfer coefficient and expanded graphite mass fraction and a similar pattern of results indicated that there was a decrease in PCM volume by 18.4% with thermal safety constraints[17]. The application of PCMs in controlling the temperature of a 5 x 5 arrangement of 18 650-cell battery packs. The above comparison indicates that PCM cooling is realistic only well below the lowest Tm of the PCM, while the results suggest that the spiral fins have a better thermal performance than the circular fins at high ambient temperature. The PCM with spiral fins system is found to have higher thermal efficiency compared to the baseline system, especially in high temperature conditions[18]. An 18,650 lithium-ion battery pack formed in a hexagonal configuration to counter thermal issues is incorporated with PW as well as CPCM. The use of nanomaterials such as the Graphene Platelet Nano Powder (GPN) and Graphite-Synthetic Powder (GSP) enhances cooling performance. CPCM cooling satisfies temperature requirements with discharge rates ranging between 0 and 25C/W and provides even temperature distribution[19]. The effects of PCMs on the thermal performance of BTMS are investigated under different gravitational acceleration changes and by altering the inclination angles of the battery packs. The effect of gravity is different in various conditions; in general, the increased gravity affects decreasing the melting time of PCM while thermal conductivity and heat exchange coefficients remain determined by the fin designs. An improved BTMS structure at various positions is presented here, including an annular fin along with a straight fin, which would give the optimum efficiency at θ

= 45° for aerospace applications[20]. The use of PCM within lithium-ion battery modules for electric vehicles. Four PCMS with different melting points were used in the study, and based on their efficiency, OM35 and PW were used to control the temperature of the batteries. The analysed data indicated that OM35 helps to maintain the battery temperature optimum for the thermal regulator of Li-ion based batteries[21]. In Saudi Arabia, where temperatures can rise so high during the day, a battery thermal management system is very important to avoid heat-related damage. This work investigated the ability of nano-enhanced PCMs using RT44 and SWCNT for controlling pouch battery temperatures. As noted earlier, the CPCM thickness affects the temperature; however, the best design for the chamber's CPCM thickness is 10mm and 15mm at the top of the chamber, while the operating condition is dominated by the surrounding environment[22]. Paraffin-composite battery modules of thermal control, incorporating Al2O3, carbon black and Expanded Graphite (EG) for conductivity boost. Computational studies revealed that the incorporation of EG led to a decrease of the maximum temperature by 4°C and thereby made sure that the battery temperature came somewhat above 39°C under 3c discharge. The simulation results were further supported by experimental tests that showed the EG/PCM module sustained an ideal maximum temperature of 45 °C after 20 min of the 3c discharging rate[23]. A trapezoidal battery pack for electric vehicles employs three kinds of thermal management material: A CPCM composed of PW and a phase change material of graphite powder. Graphite powder enhances the thermal conductivity and thus increases the heat transfer rate of the system. The battery pack with a small liquid cooling system in it was verified at 1c, 2c, and 3c discharge rates and maintained a great stability at temperatures varying up to 45°C[24]. A single Li-ion cell model with PCM and fins was created to analyse BTMS for electric vehicle batteries. The analysis highlighted that complex honeycomb fin configurations yielded superior performance to simple honeycomb fins as the fin arrangements in question maxed at a temperature decrease of 5C, Discharge and 2.77 %. The integration of 1-Tetradecanol as PCM along with copper fins provided the highest thermal dissipation by lowering the determined cell temperature by 13.36 K during 5C discharge[25]. The problems existing with the traditional vehicles in India, like emission of smoke and a sustainable increment in the oil prices, are being countered by the rise of EVs backed by LIBs. The present work examines the computational evaluation of the inactive heating systems with fins and PCM integration for low-temperature thermal management of 18650 Li-ion batteries. By ANSYS FLUENT, numerical analysis of the battery aimed at determining the effect of PCM thickness on heat transfer and battery performance[26]. For investigating thermal escape spread in battery packs, an original cooling system using both CPCM and liquid cooling was developed. In practice, research confirmed that higher coolant flow rate and space between the batteries also reduced the occurrence of thermal runaway, whereas lower thermal conductivity of CPCM slowed down the heat spread and lodged it at the edges of the battery. The amount of cooling plate channels also had less influence on the propagation time and other important findings in the development of a safer thermal control system for LIBs[27]. A Hybrid Thermal Management System, incorporating PCM, is proposed to enhance the cooling effectiveness of BTMS. This work also presents an overview of approaches to improving PCM thermal conductivity, which include the incorporation of conductive particles, the use of cellular foams and encapsulation. Parameters such as per cell width, PCM mass, thickness, specific heat capacity and thermal conductivity are investigated. Further, the conclusions provide results of experimental studies where PCM cooling has been applied[28]. Several computational studies have explored the integration of Phase Change Materials (PCM) for effective thermal management in smartphone circuits and IC chips. These studies emphasise the role of PCM in maintaining device reliability by enhancing heat dissipation. CFD-based approaches have been widely applied to analyse and optimise PCM cooling performance in electronic components[29-34].

2.0 Problem Specification

The battery cell used is the Panasonic 18650, which has a diameter of 18mm and a height of 65mm. The battery pack consists of 52 cylindrical lithium-ion batteries (52 LIBs) arranged in a 13x4 configuration as shown in

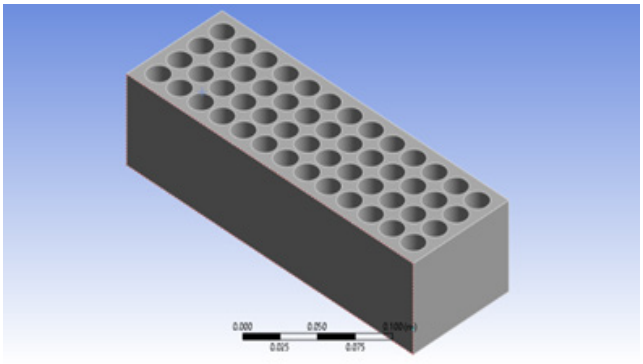


Figure 1. Schematic diagram of a 13*4 configuration lithium-ion battery pack.

Figure 1. Each battery cell has a nominal voltage of 3.7 V and a nominal capacity of 2.5 Ah. In this configuration, using spot welding, the cells were connected using pure nickel strips in a 13 series and 4 parallel (13s4p) arrangement. Previous studies indicated that there is a 3 mm spacing between adjacent cells.13 cells remain connected in series, resulting in a total voltage of 48v.

Meanwhile, the 4 cells connected in parallel contribute to a total capacity of 10Ah for the entire pack. Therefore, the total voltage and capacity of the battery pack are 48 V and 10 Ah, respectively. Commercially available PCMs such as PW and CPCM are used, with aluminium serving as the container material.

In this numerical analysis study in a BTMS that uses two materials. They are:

- Paraffin wax.
- Carbon Quantum Dots (CQDs) powder.

PW is a low-cost PCM that is widely used in battery thermal management due to its high latent heat of fusion, which allows for the dissipation of excessive heat, preventing thermal runaway. Further, it combines chemical stability with variable melting points to provide for safety as well as efficiency in battery systems. But it has a very low coefficient of thermal conductivity, as a result, its capacity to spread heat can be well impeded, which by incorporating graphite or metal foam is well solved. Moreover, the volume changes which occur during phase transitions must be precisely sealed to retain dependability.

Carbon Quantum Dots (CQDs) are small, spherical nanoparticles with unique optical, electrical, and chemical properties, offering fluorescence, high biocompatibility, and photo stability. Due to their small size and large surface area, CQDs are ideal for applications in bioimaging, sensing, and energy storage systems. In BTMS, CQDs improve heat dissipation and enhance the performance of Thermal Interface Materials (TIMs) or PCMs, ensuring efficient temperature control. Their high surface area and electrical conductivity help maintain optimal battery performance while improving stability and extending battery life.

Table 1. Thermal physical Properties of materials

	Battery	**Aluminium**	**PCM**	**Ne-PCM**
Density (kg/m^3)	2775	2700	818	840
Specific heat (kJ/kg K)	880	870	1.81	1.52
Thermal conductivity (W/m K)	3	223	0.188	0.302
Melting temperature (°C)	-	-	56.02	62.36
Latent heat (kJ/kg)	-	-	129.2	143.2
Thermal expansion coefficient ($*10^{-4}°C^{-1}$)	-		7.5	7.5
Dynamic viscosity ($kg\ m^{-1}s^{-1}$)	-	-	0.035	0.042

Through this work, the synthesis of PW and CQDs promotes thermal regulation within batteries by increasing heat transfer. The Thermal physical Properties of materials are indicated in Table 1. PW acts as an efficient PCMs that stores heat in its phase transition, while CQDs enhance its thermal conductivity. The stability and highly developed surface area of CQDs enhance the performance and efficiency of the thermal system even more. This integration assists in regulating the temperature of the batteries to mitigate short battery lifetimes and fire incidents. Furthermore, CQDs are useful in enhancing the environmental profiles and biocompatibility of the thermal management system.

3.0 Numerical Modelling

3.1 Governing Equations

For transient 3d melting and solidification processes, the system is governed by three fundamental equations: continuity, momentum, and energy. These equations are expressed as follows:[35].

3.1.1 Continuity Equation

A mass conservation law for the cooling fluid is applied in BTMS that matches the proportionality of change of density of the choke fluid and the flow measure. It ensures the integrity of the system by not allowing for build up or a decrease of fluid in the system.

$$\frac{\partial u}{\partial t}+\frac{\partial\left(\rho u\right)}{\partial x}+\frac{\partial\left(\rho v\right)}{\partial y}+\frac{\partial\left(\rho z\right)}{\partial z}=0$$

3.1.2 Momentum Equation

The continuity equation, which acts as a momentum equation in a BTMS, provides the framework for the fluid flow carrying capability changes due to pressures and viscous forces and the external force. They create conditions that guarantee forces within the cooling fluid are equal, so that proper flow dynamics are supported. This balance is important because one has to aim at making the heat transfer in the best way and avoiding something like the heat from cooling unevenly. The effective mathematical representation of such characteristics is crucial for the implementation of appropriate thermal management systems.

$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial\left(\rho uu\right)}{\partial x}+\frac{\partial\left(\rho vu\right)}{\partial y}+\frac{\partial\left(\rho wu\right)}{\partial z}=$$
$$-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu\frac{\partial u}{\partial z}\right)+S_x$$

$$\frac{\partial(\rho v)}{\partial t}+\frac{\partial\left(\rho uv\right)}{\partial x}+\frac{\partial\left(\rho vv\right)}{\partial y}+\frac{\partial\left(\rho wv\right)}{\partial z}$$
$$=-\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left(\mu\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu\frac{\partial v}{\partial z}\right)$$
$$+S_y+\rho g\beta\left(T-T_m\right)$$

$$\frac{\partial(\rho w)}{\partial t}+\frac{\partial\left(\rho uw\right)}{\partial x}+\frac{\partial\left(\rho vw\right)}{\partial y}+\frac{\partial\left(\rho ww\right)}{\partial z}=$$
$$-\frac{\partial p}{\partial z}+\frac{\partial}{\partial x}\left(\mu\frac{\partial w}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial w}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu\frac{\partial w}{\partial z}\right)+S_z$$

3.1.3 Energy Equation

The energy equation in a BTMS describes how heat is transferred within the cooling fluid through conduction, convection, with heat generation. It ensures proper thermal distribution and management to maintain optimal temperatures.

$$\frac{\partial(\rho h)}{\partial t}+\frac{\partial\left(\rho uh\right)}{\partial x}+\frac{\partial\left(\rho vh\right)}{\partial y}+\frac{\partial\left(\rho wh\right)}{\partial z}=$$
$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)$$

$$h=h_{ref}+\int_{T_{ref}}^{T}C_p\,dT+\lambda L$$

The mathematical model consists of several equations that use ρ, μ, β, k, h and Tm to symbolise the density, dynamic viscosity, thermal expansion coefficient and thermal conductivity and total enthalpy and melting temperature of the PCM. The gravitational acceleration appears as g among the equation terms, together with momentum sink source terms named Sx and Sy. The total enthalpy of PCM comes from its sensible and latent enthalpy values.

The first two items on enthalpy are sensible Enthalpy, and the third item depicts the latent enthalpy of the food. The symbols used about the present model are Cp for specific heat, λ for liquid fraction, and L for the latent

heat of the PCM. The volume of the liquid fraction at any point in time can be measured from the temperature of the PCMs.

3.2 Initial and Boundary Conditions

3.2.1 Initial Condition

The initial conditions are defined as follows:

At time t = 0,

T (x, y, z) = T0.

3.2.2 Heat Generation Rate

Based on the battery cells' charging and discharging rates, a constant volumetric heat generation is applied as a heat source. The heat generation rates are 45,379 W/m^3, 90,758 W/m^3, and 1, 36,137 W/m^3 for charging rates of 1C, 2C, and 3C, correspondingly.

3.2.3 Boundary Conditions

At the interface between the battery and the PCM, the boundary condition is governed by the principle of energy conservation[2]:

$$-k_{battery}\frac{\partial T_{battery}}{\partial \eta} = -\,k_{PCM}\frac{\partial T_{PCM}}{\partial \eta}$$

Energy conservation serves as the basis for the boundary condition that exists between the PCM material and its container:

$$-k_{PCM}\frac{\partial T_{PCM}}{\partial \eta} = -k_{container}\frac{\partial T_{container}}{\partial \eta}$$

Meanwhile, the boundary condition at the interface between the container and the ambient environment is determined by Newton's law of cooling:

$$-k_{container}\frac{\partial T_{container}}{\partial \eta} = h_1(T_{container} - T_0)$$

Similarly, the boundary conditions at the interface between the top of the battery and the surrounding atmosphere, as well as between the PCM and the surrounding atmosphere, are:

$$-k_{battery}\frac{\partial T_{battery}}{\partial \eta} = h_2(T_{battery} - T_0)$$

$$-k_{PCM}\frac{\partial T_{battery}}{\partial \eta} = h_3(T_{PCM} - T_0)$$

Under the conditions outlined above, $k_{battery}$, k_{pcm} and $k_{container}$ refer to the thermal conductivities of the battery, PCM and container material, respectively. The three heat transfer coefficients h1, h2 and h3 represent, respectively, the convective heat transfer between the container and atmosphere and between the battery and atmosphere and between the PCM and atmosphere. The reference temperature T0 serves as the central point for control function achievement.

3.3 Computational Approach

The thermal management strategy of the battery used PCM and CPCM, and its simulation was done using Ansys 2024 R1. In Ansys Design Modeller, a detailed 3D Cartesian model was created for the analysis, and the model was then meshed with tetrahedral cells in Ansys Mesh to attain greater geometric accuracy of all parts included in the analysis. After getting the model and mesh, Ansys Fluent 2024 R1 was used to simulate thermal presentation of the battery module well below the load. To emulate discharging of the battery, various numbers of resistors were introduced for controlling the electric load through a voltage tolerance of 0.1 V. All the tests were carried out indoors in a test chamber with controlled temperature maintained at around 30 °C. A data logger capable of registering changes in temperature to 0.1 °C was used. Further, temperature measurement of the cell pack was recorded using a K-type thermocouple connected to a data acquisition system and recorded on a computer in real time. This approach made the following control enhancements throughout the simulation method.

The battery segment was charging at a 1C rate, a charging current equivalent to the battery's capacity. Full charge was attained, and the module was allowed to rest before its first discharge for 12 hours, which enabled it to come to thermal equilibrium with the surrounding environment. Subsequently, the battery pack was discharged at the rates 1C, 2C and 3C to compare performance at the various loads. For safety considerations, this experiment was conducted only for one charge and discharge cycle. A basic shutdown algorithm was used, and the test stopped automatically at the battery module temperature of 60 °C to avoid thermal runaway or damage. This configuration allowed the process to be kept as controlled as possible, to learn how the module functioned at various discharge rates without exceeding safety boundaries.

3.4 Grid Size and Time Step Independence

To ensure the accuracy and efficiency of the computational model used in simulating the thermal behaviour of the 13S4P lithium-ion battery pack, a comprehensive mesh and grid independence study was conducted shown in Figure 2. This was vital to achieve a balance between solution accuracy and computational effort.

3.4.1 Mesh Generation

The geometry of the battery module, including individual cylindrical cells and the encompassing PCM/CPCM domains, was developed using ANSYS DesignModeler. A 3D Cartesian model with tetrahedral mesh elements was selected due to the complex cylindrical features of the battery cells and irregular geometry of the cooling medium. To preserve geometric fidelity and accurately simulate heat transfer, especially near cell boundaries and PCM interfaces, mesh refinement was employed locally around critical regions.

- Element Type: Tetrahedral
- Total Nodes: 456,586
- Total Elements: 393,162
- Face Zones: 1,289,410 across 160 zones

Grouping of cells for Laplace smoothing and mesh quality improvement was employed to prevent numerical errors and enhance convergence stability.

3.4.2 Time Step Selection

A fixed time step of 1 second was used throughout the transient simulation to capture detailed thermal variations during the discharge cycle. This time step was determined through iterative testing, balancing the need for thermal resolution with feasible computation times.

3.4.3 Grid Size Independence Test

To validate mesh independence, simulations were conducted using three progressively finer mesh densities:

The maximum temperature difference between the medium and fine meshes was found to be only 0.1°C, indicating minimal variation. Hence, the fine mesh configuration was deemed sufficient to yield accurate results with acceptable computational load. The results demonstrate that the selected mesh (element size: 0.002 mm) and time step (1s) provide a stable and accurate simulation environment. Further mesh refinement beyond this point does not significantly enhance accuracy, confirming the mesh independence of the model. This validated setup was used for all subsequent simulations in this study.

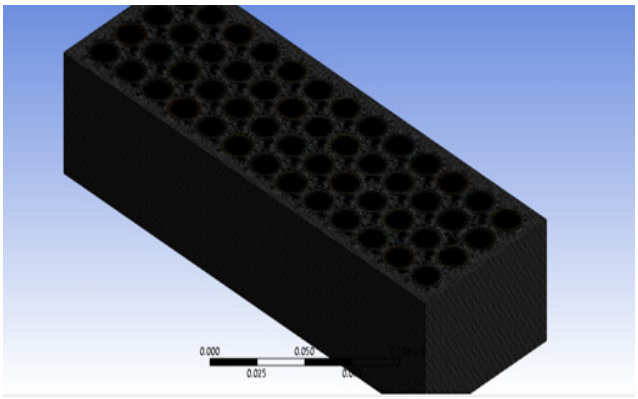


Figure 2. Meshing of a 52 LIB battery pack.

4.0 Results and Discussion

In the present Ansys analysis, three different thermal management options were applied to a LIB module. The first test was conducted with no cooling medium, and the temperature was maintained at 30 % °C across different discharge rates. Because of the inherent cooling capability that the 18650 cylindrical cells possess, a temperature gradient across the pack was found to exist, with the temperatures being higher in the middle of the pack than at the corners. In the second situation, PCM was employed passively to help in controlling the excess heat

Mesh Level	Element Size (mm)	Elements Count	Max Temperature at 3C (°C)
Coarse	0.004	~240,000	29.6
Medium	0.003	~330,000	29.5
Fine	0.002	~393,000	29.4

produced through the charge and discharge process. The PCM effectively dissipated the heat that accumulated in the battery pack; as a result, the temperature distribution across the battery pack was enhanced, thus improving the overall thermal performance of the battery pack in the case without cooling.

To expand the thermal conductivity of PCM, CPCM was developed as an advanced form of PCM. The particle size enhancement also enhanced the heat transfer current then identity within the battery pack, thus enhancing the temperature control efficiency. This reduced the fluctuation rates with temperature, which made this approach offer the steady and even temperature distribution of all the other cases and scenarios in thermal management with CPCM. Such results will then be simulated and analysed in Ansys to improve the efficiency of thermal management for the battery pack.

4.1 Performance of a Lithium-Ion Battery Pack without Cooling at Various Discharge Rates

Lithium-ion battery packs generate heat during discharge due to inside resistance and electrochemical reactions. Without a cooling system, this heat accumulates, leading to temperature rise, voltage drop, and potential performance degradation. The severity of these effects depends on the discharge rate, which determines how quickly energy is drawn from the battery.

4.1.1 1C Discharge Rate Without Cooling

An increase of 21°C takes place within the battery pack when subjected to a 1C discharge rate, which raises the temperature from 27 °C to 48 °C as indicated in Figure 3. Throughout the discharge process, the voltage decreases in a regulated manner, thereby enabling the battery to provide almost its entire capacity. The battery maintains stable operation while heat generation remains under control without anticipated thermal collapse. Prolonged 1C operation without cooling leads to battery degradation, although it does not immediately create thermal issues.

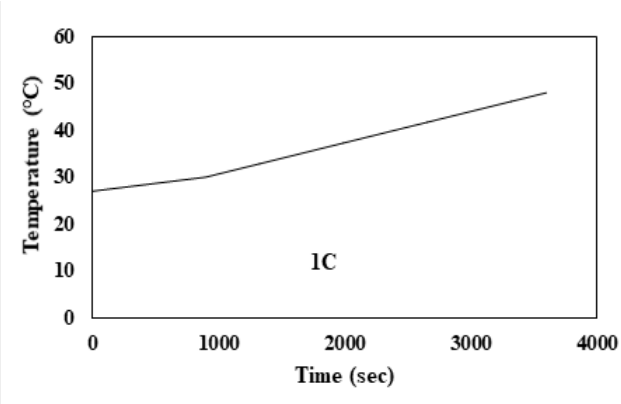


Figure 3. The temperature of the battery pack without cooling at a 1C discharge rate.

4.1.2. 2C Discharge Rate Without Cooling

The discharge rate at 2C results in profound heat generation, which raises the temperature from 27 °C to 51 °C in Figure 4. High internal resistance causes the voltage drop to become more prominent. The battery fails to reach its maximum capacity because of elevated losses, which creates temperature imbalances throughout the pack. The battery will develop hotspots, which both age and degrade the overall operational effectiveness, unless the heat dissipation occurs effectively.

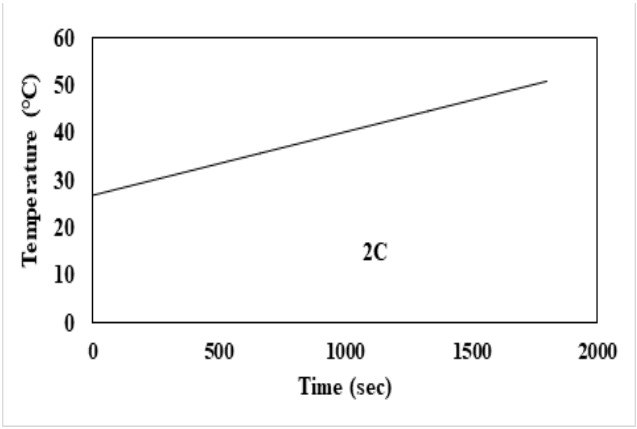


Figure 4. The temperature of the battery pack without cooling at a C discharge rate.

4.1.3. 3C Discharge Rate Without Cooling

Under 3C discharge conditions, the battery sustains heavy thermal stress because its temperature rises from 27 °C to 63 °C Figure 5. The rapid voltage decline occurs while the ability to store energy drops because of resistance. Batteries need to provide a capacity which is 5-10 % lower than their nominal rating during performance. Uncooled conditions would result in serious thermal runaway

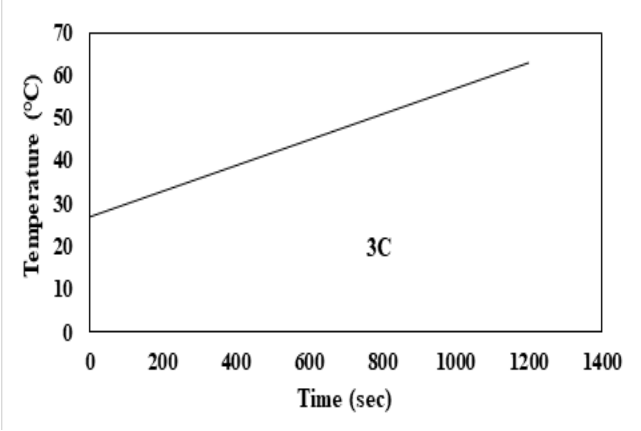


Figure 5. The temperature of the battery pack without cooling at a 3C discharge rate.

risks that cause additional degradation and electrolyte decomposition as well as safety dangers.

At the beginning of battery discharge, without cooling, the cells show a similar temperature distribution because they start at ambient temperature. The temperature rise during the discharge period results from increasing heat generation, which stems from internal resistance. Significant temperature rises become evident in parts where current densities reach their highest levels according to the final temperature. Presenting the initial and final temperature contours becomes unessential because each discharge rate follows the same uniform-to-hot transformation pattern. Displaying the temperature evolution for a single representational case provides adequate insight into thermal behaviour while omitting repetitive information as presented in Figure 6.

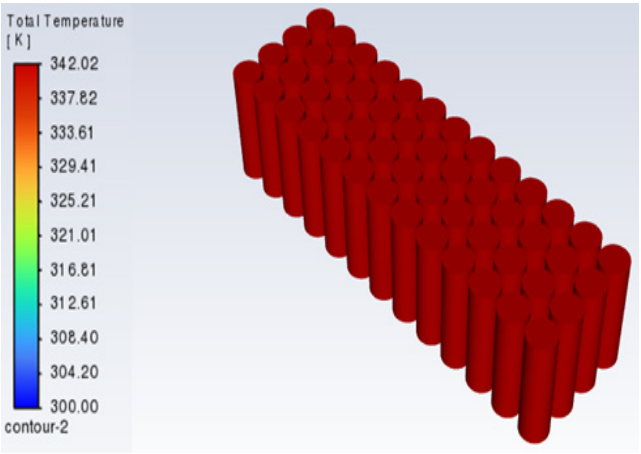


Figure 6. Temperature contour of the battery pack without cooling.

4.2 Performance of a Lithium-Ion Battery Pack with PCM Cooling at Various Discharge Rates

PCM are used in lithium-ion battery packs to absorb and regulate heat through discharge. PCM absorbs heat by melting, preventing excessive temperature rise and reducing thermal stress on the battery. The effectiveness of PCM cooling varies depending on the discharge rate, as higher rates generate more heat.

4.2.1 1C Discharge Rate with PCM

The battery temperature increases by just 6°C when operated at a 1C discharge rate starting from 27°C and rising to 33°C, as shown in Figure 7. The use of PCM creates an effective heat absorption method that helps delay temperature increase for operational stability. The controlled voltage decrease happens progressively while the battery supplies almost its complete power output. Due to low heat production at 1C there is insufficient melting of the PCM, which preserves its cooling efficiency across multiple cycles.

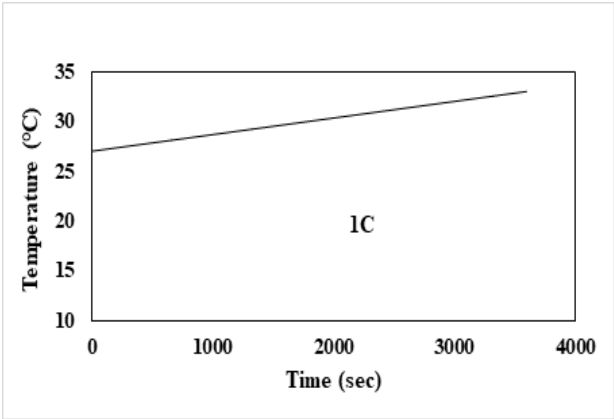


Figure 7. Temperature of the battery pack with PCM at a 1C discharge rate.

4.2.2 2C Discharge Rate with PCM

The temperature elevation with a discharge rate of 2°C amounts to 6.5°C, leading to an operating temperature

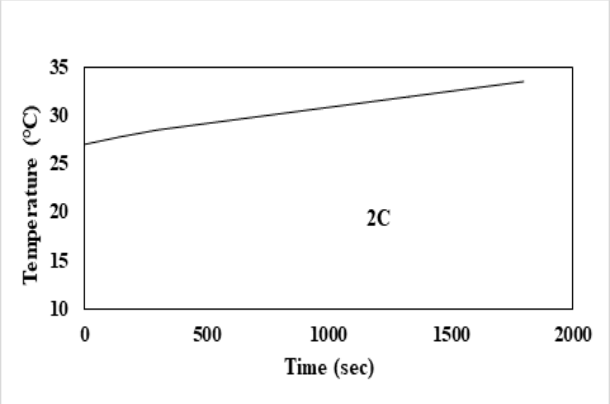


Figure 8. Temperature of the battery pack with PCM at a 2C discharge rate.

range between 27°C and 33.5°C Figure 8. During the phase change process, the PCM becomes more apparent because it absorbs heat, which makes hotspots less likely to form. Some PCM partially melts during rapid discharge procedures, so their cooling power decreases toward the end of the cycle. Vehicles operating with this temperature control maintain better efficiency, together with capacity retention, because voltage drop remains noticeable but minor.

4.2.3 3C Discharge Rate with PCM

The battery experiences high heating at a 3C discharge rate, yet PCM-based cooling technology allows the temperature to rise only up to 33°C from 27°C Figure 9. At such a high discharge rate, PCM melts quickly, which decreases its cooling effectiveness during the discharge

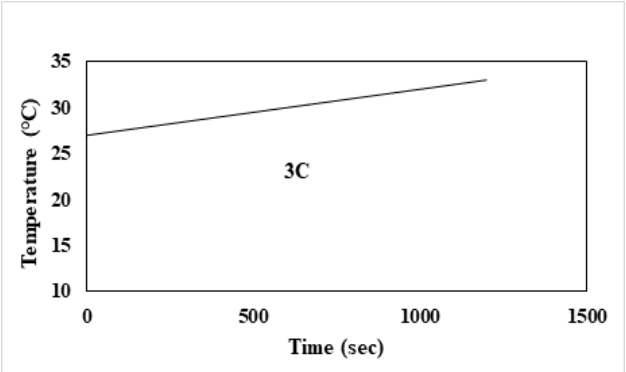


Figure 9. Temperature of the battery pack with PCM at a 3C discharge rate.

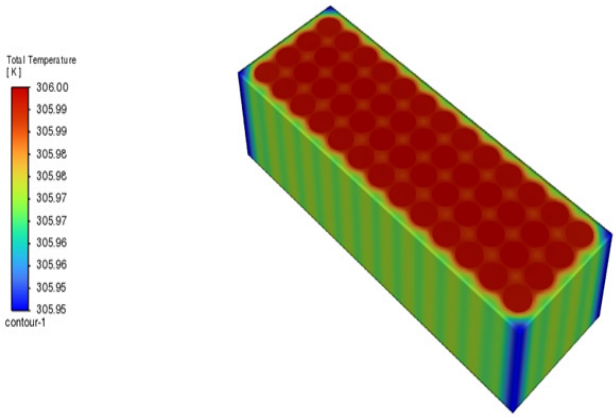


Figure 10. Temperature contour of the battery pack with PCM.

process. A poorly designed PCM layer or a layer with insufficient mass could result in overheating within some parts of the battery pack. PCM contributes to better battery temperature control at 3C yet it does not provide complete protection for extended usage unless further cooling solutions are applied.

Figure 10 illustrates the battery pack temperature distribution after PCM cooling applications, which shows effective heat dispersion alongside uniform thermal distribution. The core cell area reaches temperatures of about 33°C, but the outer regions experience temperatures within the 33°C range due to PCM acting as a heat absorption agent that controls hotspots. The even temperature distribution through PCM improves battery safety parameters and decreases thermal strain, which results in minimised degradation, allowing it to function optimally as an effective cooling method for lithium-ion battery packs.

4.3 Performance of a Lithium-Ion Battery Pack with CPCM Cooling at Various Discharge Rates

CPCM are an advanced thermal management solution for lithium-ion battery packs. By combining nanoparticles such as carbon quantum dots, graphene, or metal oxides into traditional PCM, CPCM improves thermal conductivity, allowing faster heat absorption and dissipation. This results in better temperature regulation and improved performance at higher discharge rates compared to conventional PCM.

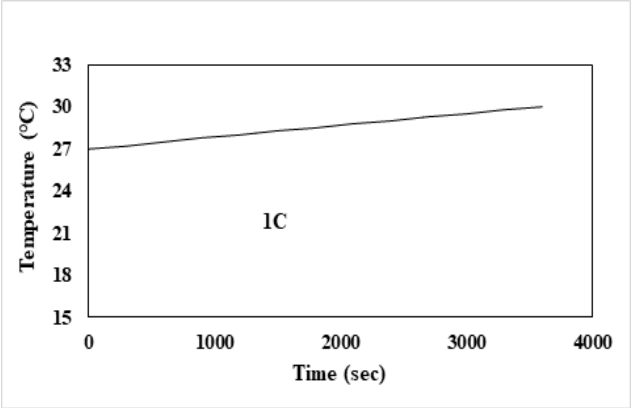


Figure 11. Temperature of the battery pack with CPCM at a 1C discharge rate.

4.3.1 1C Discharge Rate with CPCM

When discharged at 1C recharge the battery produces a 3°C temperature increase that elevates from 27°C to 30°C according to Figure 11. CPCM improve thermal conductivity in the battery, which enables heat to be uniformly distributed across the entire device. The battery sustains a low voltage reduction while providing almost its complete capacity load under minimal thermal stress. Repeated operation of the CPCM remains effective due to its partially solid state.

4.3.2 2C Discharge Rate with CPCM

The temperature increases by 3.3°C to reach 30.3°C when the discharge rate stands at 2C as shown in Figure 12. CPCM achieves efficient melting, which allows fast heat transfer from battery cells, leading to hotspot prevention. Thermal efficiency improvements create better voltage stability and higher battery efficiency results. Thermal properties in CPCM function better than PCM, resulting in improved cooling performance, while the melting properties of PCM decrease towards the cycle end.

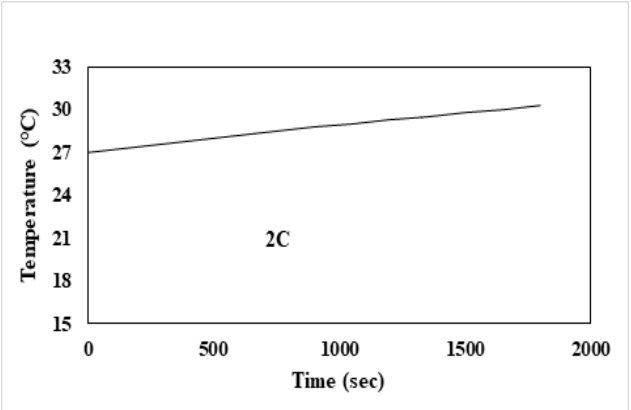


Figure 12. Temperature of the battery pack with CPCM at a 2C discharge rate.

4.3.3 3C Discharge Rate with CPCM

The maximum heat generation rate of 3C discharge leads CPCM to control temperature increase to 2.4°C, resulting in a cell range from 27°C to 29.4°C based on Figure 13. Thermal conductivity increases within CPCM, whereby heat dissipates quickly, thereby prolonging temperature stability until complete melting takes place. Extended operation at high-rate discharge rates needs supplementary cooling techniques, including heat sinks, together with forced air circulation to protect against possible thermal runaway even when using CPCM.

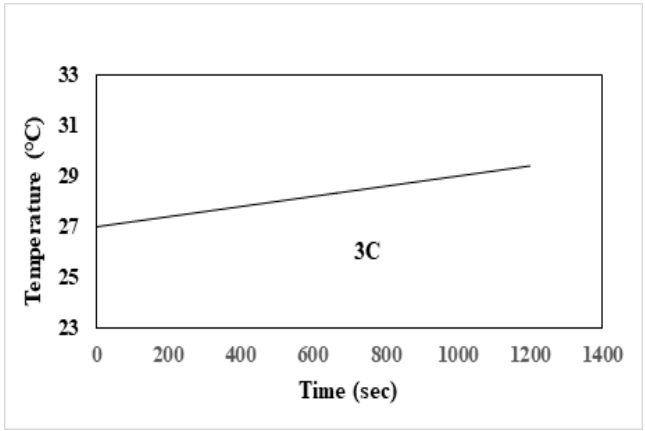


Figure 13. Temperature of the battery pack with CPCM at a 3C discharge rate.

An improved thermal regulation emerges from the battery pack cooling system with CPCM as shown in Figure 14. The maximum temperature reaches 30°C, but cooler outer regions appear because CPCM improves thermal conductivity, which enhances heat dissipation. The uniform temperature regulation provided by CPCM systems decreases thermal stress for batteries to achieve better performance. The advanced thermal management capability of CPCM leads to decreased peak temperatures, which produces enhanced safety together with longer

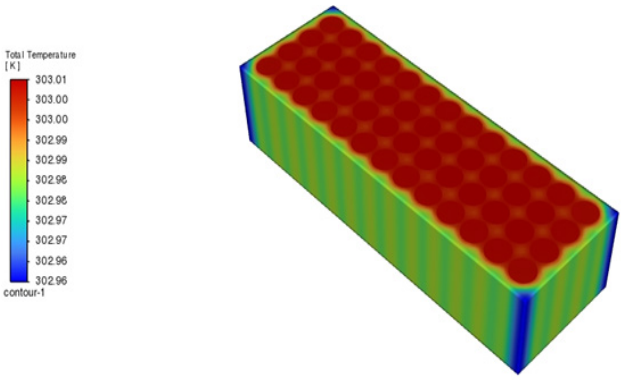


Figure 14. Temperature contour of the battery pack with CPCM.

life duration for battery packs under rapid discharge operations.

4.4 Maximum Temperature Difference of the Lithium-Ion Battery Pack at Three Different Discharge Rates

The battery experiences a temperature increase of 21°C when charged at 1C without cooling, which reaches 48°C, but only reaches 33°C when PCM is used and achieves a 30°C temperature rise with CPCM. A 15°C temperature difference exists between the PCSM and the uncooled control system, which proves how PCM absorbs thermal energy. CPCM enhances thermal regulation capabilities, which leads to an overall temperature rise reduction of 3°C beyond PCM performance. The heat dissipation capability achieved by CPCM exceeds PCM performance, resulting in less temperature elevation. The temperature rises to 24°C at a 2°C discharge rate when monitoring the battery from 27°C to 51°C under no cooling, whereas PCM achieves a temperature rise of 6.5°C to 33.5°C and CPCM maintains a 3.3°C temperature increase up to 30.3°C. The uncooled system creates a 17.5 °C temperature differential with PCM, but the CPCM reduces the temperature further by 3.2°C beyond PCM performance. The phase transition capabilities of PCM succeed in absorbing heat quantities, but CPCM equipped with nanoparticles maintains better heat conductive abilities, which limit temperature escalation at elevated discharge speeds. The thermal stress reaches its peak at 3°C discharge rate because the temperature increases by 36°C without cooling (63°C), 6°C with PCM implementation (33°C) and CPCM provides the lowest temperature rise of 2.4°C (29.4°C). Passive thermal management with PCM establishes 30°C as the difference between uncooled condition temperatures and PCM separation temperatures. CPCM shows an additional 3°C reduction in temperature rise compared to PCM, thus preventing quick thermal breakdown. CPCM outperforms PCM in thermal management systems because it spreads heat evenly and controls the melting process, which maintains the cooling duration longer during discharge periods, as shown in Figure 15.

Passive thermal management through these temperature measurements shows that it effectively decreases temperature changes across discharge rates that prevent damage to lithium-ion battery packs. CPCM demonstrates superior performance as an effective solution because it achieves lower temperature variations alongside better stability than both PCM and the uncooled system. This demonstrates the capability of CPCM to prolong and keep safe battery packs that operate in high-power applications.

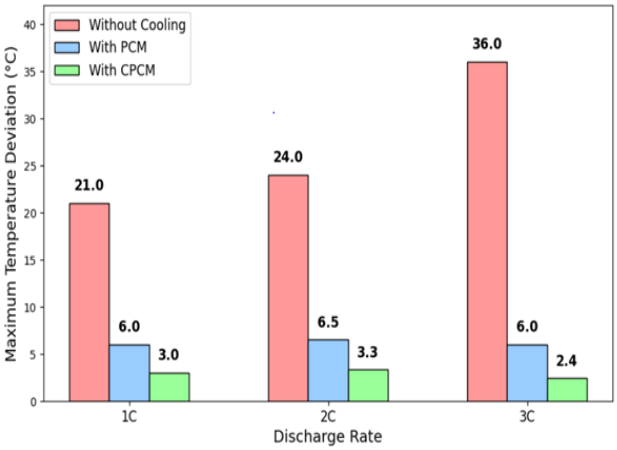


Figure 15. In all conditions, the maximum temperature deviation between cells in a battery module.

4.5. Error Analysis

To ensure the accuracy and reliability of the numerical simulations performed in this study, a detailed error analysis was conducted. The sources of error were categorised into numerical, modelling, and experimental comparison errors. Table 3 below summarises the key contributors to uncertainty along with their estimated magnitudes.

Table 3. Error analysis

Error Type	Source	Estimated Error/Uncertainty
Numerical Error	Mesh discretisation (element size variation)	±0.1°C
	Time step sensitivity (1s vs. smaller intervals)	±0.2°C
Modeling Error	Material property variability (e.g., PCM/CPCM conductivity)	±5 %
	Phase change modelling accuracy (enthalpy–porosity method)	±1.0°C
	Boundary conditions (convection assumptions, ambient temp)	±1.5°C
Experimental Comparison Error	Deviation from the literature and validation experiments	±5%
Overall Uncertainty	Cumulative impact of all errors	±6%

4.6. Quantitative Results

The thermal performance of the lithium-ion battery pack was evaluated under three different cooling scenarios—No Cooling, PCM, and CPCM—at 1C, 2C, and 3C discharge rates. The quantitative results in terms of maximum temperature, temperature rise, and temperature difference reduction are summarised in the following Table 4 :

4.6.1 Key Findings

- CPCM consistently achieved the lowest peak temperatures under all discharge rates, demonstrating superior thermal performance.
- At the 3C discharge rate, CPCM cooling reduced the temperature by 33.6°C compared to no cooling, and by 3.6°C over PCM cooling.

Table 4. Thermal performance summary at different discharge rates

Discharge Rate	Cooling Type	Max Temp (°C)	Temp Rise (°C)	Temp Reduction vs No Cooling (°C)	Temp Reduction vs PCM (°C)
1C	No Cooling	48.0	21.0	–	–
	PCM	33.0	6.0	15.0	–
	CPCM	30.0	3.0	18.0	3.0
2C	No Cooling	51.0	24.0	–	–
	PCM	33.5	6.5	17.5	–
	CPCM	30.3	3.3	20.7	3.2
3C	No Cooling	63.0	36.0	–	–
	PCM	33.0	6.0	30.0	–
	CPCM	29.4	2.4	33.6	3.6

- The temperature rise was reduced by up to 93.3% when comparing CPCM to no cooling at 3C.
- CPCM outperformed PCM by 3–3.6°C across all discharge conditions, confirming the enhanced heat dissipation due to carbon quantum dots.

These results confirm the effectiveness of CPCM in maintaining thermal stability, reducing thermal gradients, and enhancing safety in high-rate battery discharges.

5.0 Conclusion

An investigation was conducted on a 52-cell lithium-ion battery pack enhanced with CPCM to evaluate the role of PCM in thermal management. The study examined how CPCM improves heat dissipation and regulates temperature during operation. Results showed that CPCM significantly reduced maximum temperatures and enhanced temperature uniformity. This improvement helps prevent thermal runaway and extends battery lifespan.

- The battery component's safe temperature limits, but operating at 1C, 2C and 3C discharge rates because non-uniform heat distribution caused thermal risks. The findings demonstrate the necessity for a reliable cooling system during battery usage since it improves reliability across all discharge rates.
- The implementation of PCM achieved a significant temperature decrease, which maintained battery operational safety during every discharge rate. Improved thermal stability through this method extends battery life while making the device safer to use in operation.
- During 3C discharging, CPCM displayed better cooling performance by keeping temperatures stable at a maximum 2.56% variation compared to the 1.16% variation from PCM cooling. The discharge performance-and-thermal-safety trade-off became evident when the system lacked cooling, since its variation reached 8.18%.
- CPCM outperformed PCM regarding temperature control since its maximum differential remained at 1.3 °C, but PCM only achieved 1.6 °C. CPCM displays better heat transfer properties and thermal distribution capabilities.
- Under high-pressure situations, along with hot ambient conditions, CPCM establishes itself as the optimal cooling technology, whereas standard PCM performs better within average operating parameters.

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Abbreviations

BTMS	Battery Thermal Management Systems
EV	Electric Vehicles
LIBS	Lithium-Ion Batteries
PCM	Phase Change Material
Ne-PCM	Nano-Enhanced Phase Change Material
CQDS	Carbon Quantum Dots
PW	Paraffin Wax
CPCM	Composite Phase Change Material
HP	Heat Pipe
GPN	Grapheme Platelet Nano Powder
GSP	Graphite Synthetic Powder
EG	Expanded Graphite
TIMS	Thermal Interface Materials