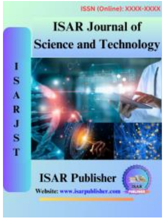

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Thermal Management of Domestic Battery Packs in Renewable Energy Systems: The Role of Phase Change Materials

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Abstract: This research investigates the use of n-octadecane as a phase change material (PCM) for the thermal management of lithium-ion batteries. During simulation runs in ANSYS CFD the research team evaluates heat distribution together with the n-octadecane phase change processes during its entire solidification and melting period. N-octadecane serves as a heat conduction agent during battery charging and behaves similarly as a heating source during discharging to achieve proper battery temperature control. The temperature interval from 28 °C to 30 °C serves as the total melting point range for n-octadecane and possesses a latent heat of fusion value equal to 200 kJ/kg. The localization of battery-PCM interface after melting happens primarily due to the thermal conductivities of solid-phase n-octadecane at 0.222 W/mK and liquid-phase n-octadecane at 0.198 W/mK. Multiple research investigations confirm the temperature regulating characteristics of n-octadecane to safeguard batteries from thermal failure together with preserved operational functioning. Research findings indicate that PCM phase change efficiency improves when cylindrical holes in the PCM casing receive optimized placement for better heat distribution. To achieve long-term battery safety and stability of battery performance active cooling systems need to integrate with PCM technology. Data shows that n-octadecane thermal systems possess potential as electric vehicle battery storage management solutions because they ensure stable performance and safety levels.

Keywords: Phase Change Material (PCM), n-Octadecane, Battery Thermal Management, Lithium-Ion Batteries, Energy Storage Systems.

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1. Introduction

Lithium-ion energy storage systems that people use in homes show decreased performance when subjected to changes in temperature. Heat increases rapidness of deterioration and raises the odds of thermal runaway while temperate conditions decrease operational performance and efficiency. The phase change materials function as heat storage particles that transfer big quantities of heat energy when moving between solid material to liquid throughout their temperature transition. For PCM selection one must consider the melting point alongside thermal conductivity together with latent heat capacity as well as compatibility with battery materials. Organic PCMs show chemical stability and non-corrosiveness at the same time but their thermal conductivity remains low [1]. The thermal conductivity along with latent heat capacity of inorganic PCMs including salt hydrates is high however the materials demonstrate corrosiveness and phase segregation behavior. The composite PCMs advancement these days includes expanded graphite and metal foams to improving thermal conductivity and structural strength [2]. Scientists have designed composite systems to improve the low thermal conductivity defect which affects certain PCMs. The combination of PCMs with expanded graphite or metal foams results in an improvement of their overall thermal performance. Rapid thermal absorption together with heat dissipation occurs efficiently through these composite structures. Experimental evidence shows composite PCM technologies succeed at reducing peak temperatures and achieving consistent temperature distribution across battery cells according to [3]. Various benefits accompany the usage of PCMs but technical barriers exist for battery thermal management implementations. To achieve successful applications of PCMs additional attention needs to be directed toward solving problems which include leakage during phase transitions and material compatibility issues and long-term stability needs. The combination of encapsulation techniques with form-stable PCMs represents possible methods to stop leakage and increase lifetime stability [4]. The substantial power supply heat production increases the possibility of battery system temperature overheating. High temperatures lead to an extreme increase in the rate at which LIBs fade their capacity. Batteries will experience thermal runaway if heat is not properly dissipated from the system due to safety hazards. The ideal operating environment for batteries should be between 20–40 °C because this temperature range allows them to perform optimally and maintain a longer lifespan [5].

The paper by Khateeb et al [6] presents multiple techniques for dissipating heat within LIB modules. The research showed that PCM mixture with aluminum foam could decrease module temperatures significantly more than natural convection cooling alone. The low thermal conductivity of PCM acts as an obstacle to its effective cooling performance [7]. Researchers have introduced different methods to enhance the effective thermal conductivity of PCMs because of their inherent thermal conductivity barrier. The group of additives which includes Aluminum wire [8] and metal foam [9, 10] and carbon fiber [11, 12] as well as graphite [13] shows high thermal conductivity features when added to PCM.

Rao et al. conducted research on thermal control effectiveness in commercial LiFePO4 power batteries shaped like a rectangle that used PCM according to their study [14]. The researchers noted that PCMs which melt below 45 °C will perform better at heat dissipation because the optimal battery temperature function occurs below 50 °C. The surface temperature of the foam-paraffin composite decreases by 29% relative to air convective surfaces after complete discharge according to Li et al. [15]. The temperature decrease amounts to 12% compared to pure PCM surfaces. The ability for BTMS with PCM cooling to manage heat remains limited when the PCM cannot effectively release collected heat into the environment. Kizilel et al. developed a passive extreme-condition battery pack heat management system which utilizes PCM as reported in [16]. The capacity degradation of PCM-loaded battery packs decreases by 50% when discharging them properly at high current rates.

Ye et al. [17,18] created a heat pipe-based integrated battery thermal management system with multiple cooling methods which include air cooling. The authors noted that air-cooled heat dissipation at HP cooling end is insufficient for battery thermal management because air has low specific heat capacity.

The research of BTMS cooling effects was explored by Ling et al. [19]. The first BTMS used PCM as a passive system without additional assistance. The parallel BTMS employed PCM together with an air circulation system. The experimental results demonstrated that passive battery temperature control maintained less than 45 °C until the second discharge cycle yet failed to perform on the third cycle. The thermal management failure happens when PCM loses all its latent heat storage potential. The successful heat transport mechanism from PCM to surroundings determines the BTMS longevity throughout extended battery charge and discharge processes. Existing studies indicate that surface application of PCM to forced air convection enables successful heat removal from PCM. Air convection energy expenses become excessive due to poor heat dissipating capabilities between the battery/PCM composite. The group of cooling solutions proposed by Zhao et al. [20] included natural convection together with forced convection in horizontal and vertical directions along with water spray cooling and thermostat bath cooling and vertical forced convection.

The study presents PCM-based thermal management system upgrades through the combination of specific materials alongside innovative system construction and thermal enhancement designs. Research on PCM-based thermal management systems achieved an improvement through technical boundary removal leading to superior thermal efficiency than other modern upgrades. The study implements experimental and framework approaches which previous research had ignored during their investigations. PCM scientists use heated evaluation techniques to incorporate performance-improved PCM systems which permit behavioral tests in real operational situations.

The evaluation uses specific mathematical models to describe a new scientific methodology that differs from traditional analytical methods. Compact thermal conductor systems in PCM research require advanced materials with improved phase transition capabilities as their distinguishing element to increase operational effectiveness. The research analyzes PCM application development through three distinct fields that illustrate scalability in various systems including battery preservation technology and smart building management and industrial waste heat retrieval. The study addresses a knowledge deficit found between temperature management research and energy efficiency studies and material upkeep together with system administration practices to offer more value to existing scholarly work. This research leads to academic advancement and industrial growth to improve the development of energy storage technology integrated with thermal management systems.

2. Methodology

Computational Fluid Dynamics (CFD) is the method that has been used for this research project in order to investigate the impact that phase-changing materials have on the capacity of re-chargeable battery systems to carry heat for use in a variety of household applications. For the purpose of predicting the heat transfer and temperature drop characteristics of two PCM battery carrying systems, the professional computational fluid dynamics (CFD) tool ANSYS Fluent is utilized. The approach consists of several processes, the most important of which are the selection of the model geometry, the defining of borders and boundary conditions, the discretization of the domain, the resolution of the numerical simulations, and the analysis of the data generated. The legitimacy and dependability of the work will be ensured throughout each and every stage of the research project.

3. Model Geometry and Tube Arrangements

This study utilized the commercial CFD software ANSYS-Fluent 2021 R2 to simulate the thermal dynamics of PCM and to reproduce the temperature distribution within the battery pack. A battery pack comprising 8 cells was employed, utilizing air cooling, as illustrated in Figure 1. (A) and (B). The battery pack consists of eight cylindrical cells. The impact of distinct PCM materials on the cooling performance of battery cells and the surrounding temperature was evaluated in a parallel-series setup. The dimensions of the complete battery pack are 97 mm × 65 mm × 51 mm, and each individual battery cell measures 9 mm in diameter. This investigation encompassed phase changing material (PCM) n-octadecane. This research introduces a thermal management system that combines phase change materials (PCM) with air convection for a continuously charging and discharging lithium-ion battery pack. The principal specifications of the individual battery cell and its external shell are detailed in Tables 1 and 2.

Table 1. n-octadecane PCM properties.

Thermal-Related Parameters	**Value**	**Unit**
Melting Temperature	28-30	°C
Latent Heat of Fusion	200	kJ/kg
Density	777.0	kg/m^3
Specific Heat	1.91	kJ/kgK
Thermal Conductivity (solid)	0. 222	W/mK
Thermal Conductivity (Liquid)	0.198	W/mK
Viscosity	4×10^{-4}	P.S (Pascal Second)
Kinematic Viscosity	4.27×10^{-7}	m^2/s
Prandtl Number	3.81	-
Thermal Expansion Coefficient	7.6×10^{-4}	1/°C

Table 2. Battery cell thermo-physical properties.

Property	**Value**
Density	2700 (kg m^{-3})
Thermal conductivity	7.14 (W m^{-1} K^{-1})
Specific heat	0.9 (kJ kg^{-1} °C^{-1})

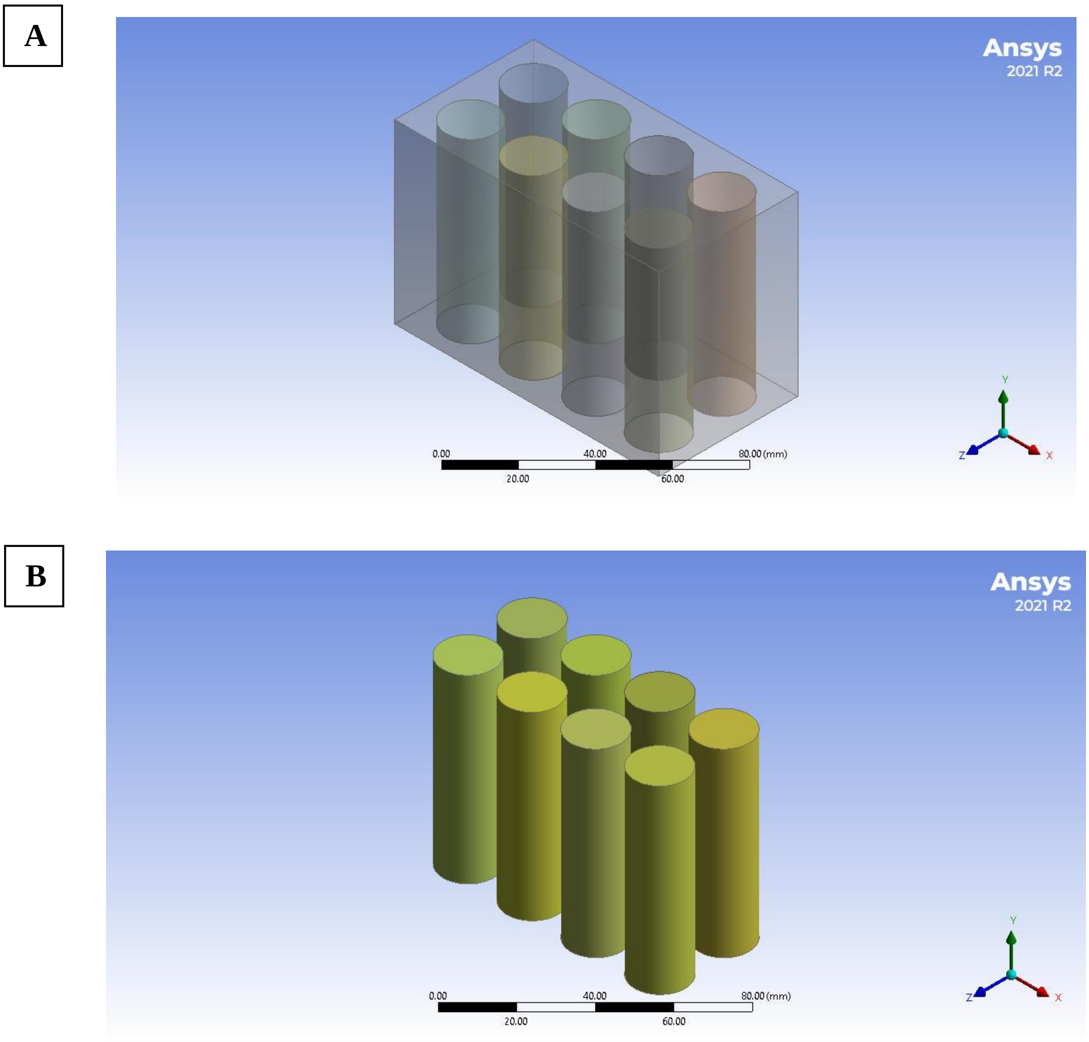


Figure 1. (A) PCM case with battery system, (B) battery pack.

4. CFD Modelling governor equations

The governing equations of fluid dynamics are the bedrock upon which CFD modeling is built. The conservation rules in physics can be mathematically expressed by these equations. Fluid flow processes are characterized by their essential features by use of the CFD model [21]. Proper numerical representation of physical boundary conditions relies on the mathematical formulation of the governing equations and the numerical approach used [22].

This study utilizes a lump-capacitance model that highlights battery thermal behaviors [23], selected for its lower computational expense. The lump-capacitance model presumes homogenous physical qualities throughout the battery cell and calculates the heat generation rate based on the observed current-voltage characteristics of the batteries. The equation that dictates energy conservation in a battery cell is expressed as:

$$P_b C_{p,b} \frac{\partial T}{\partial t} = K_b \nabla^2 T + q \qquad (1)$$

In Table 2, Pb, Cp,b, and kb represent the density, specific heat, and thermal conductivity of the battery, respectively. T and t represent the local temperature and time, respectively, whereas q indicates the volumetric rate of battery heat generation, determined as the aggregate of irreversible Joule heating and reversible entropic heating. The boundary condition at the interface between the battery and the phase-changing material is dictated by the principle of energy conservation, articulated as follows [24]:

$$-K_b \frac{\partial T}{\partial n} = K_{pcm} \frac{\partial T}{\partial n} \qquad (2)$$

$\frac{\partial T}{\partial n}$ represents temperature gradient. Continuity equation governing equations is expressed as:

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} = \frac{1}{\rho_{pcm}}\left(-\frac{\partial p}{\partial y} + u_{pcm}\Delta^2 u + (\rho\beta)_{pcm} g_y \left(T - T_{ref}\right)\right) \qquad (3)$$

The y-direction velocity component is v while $\frac{\partial v}{\partial t}$ stands for the time derivative calculation of y-direction velocity that measures y-direction acceleration because of temporal effects. The x-velocity component U can be found here but the spatial gradient of y-velocity when measured in x-direction is represented by ∂v/∂x. At the same time, these two terms demonstrate advection because the moving x-velocity supports transportation of y-velocity v through the x-direction. Additionally, ∂u stands for the spatial gradient of x-velocity v in y-direction as it shows x-velocity variations in the y-direction. Finally, ρcm stands for the pcm material density while cm stands for pcm material specific heat capacity. The specific heat capacity of pcm material appears as cm and the combination of $\frac{1}{\rho_{pcm}}$ describes how thermal properties and mass density factor into this term while $\frac{\partial p}{\partial y}$ shows the pressure changes that occur in the y-direction. u_{pcm} seems to indicate a velocity value which the phase change material applies as its basis. The expression $\Delta^2 u$ represents the Laplacian operator of the velocity field that defines the spatial distribution of momentum diffusion effects in the system.

The expression $(\rho\beta)_{pcm}$ shows the multiplication of density with thermal expansion coefficient from the phase change material and g_y indicates gravitational acceleration within the y-direction. The system contains a variable known as T which represents its temperature value. Tref stands for the reference temperature that potentially corresponds to the phase-change or base point temperatures. The buoyancy driving force in natural convection relies on the term $(\rho\beta)_{pcm} g_y \left(T - T_{ref}\right)$ that considers the density along with thermal expansion coefficient of the phase change material and basic gravitational acceleration. X-momentum equation expressed as:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{1}{\rho_{pcm}}\left(-\frac{\partial p}{\partial x} + u_{pcm}\Delta^2 u + (\rho\beta)_{pcm} g_x \left(T - T_{ref}\right)\right) \qquad (4)$$

Y-momentum equation expressed as:

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{\partial}{\partial x}\left[\frac{(K_{pcm}+Kd)}{(\rho C_p)_{pcm}} \frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial y}\left[\frac{(K_{pcm}+Kd)}{(\rho C_p)_{pcm}} \frac{\partial T}{\partial y}\right] \qquad (5)$$

Thermal diffusivity of the material is expressed through $\frac{(K_{pcm}+Kd)}{(\rho C_p)_{pcm}}$. The thermal conductivity of phase change material stands as K_{pcm}. The capacity of material to transmit heat appears in $\frac{(K_{pcm}+Kd)}{(\rho C_p)_{pcm}}$. The thermal conductivity of surrounding materials (Kd) determines the value next to the thermal conductivity of PCM (K_{pcm}) while density of PCM material (ρ_{pcm}) finishes the equation. The specific heat capacity of the PCM material is designated as C_p. Thermal diffusivity describes heat diffusion speed and can be computed by dividing $\frac{(K_{pcm}+Kd)}{(\rho C_p)_{pcm}}$. The present research utilizes the solidification and melting model with enthalpy porosity approach under these assumptions: [25]. The study makes the temperature-invariant assumption about thermo-physical conditions. The PCM material demonstrates homogenous and isotropic properties and contains laminar flow conditions. Thermal radiative transfer is considered negligible under these conditions.

5. Simulation model mesh independent test

Prior research unequivocally demonstrates that mesh quality is a pivotal element influencing the realism and reproducibility of simulations performed in ANSYS. The generation of a mesh divides the geometry into discrete parts, enabling the solver to estimate solutions to diverse physical issues. Precise meshes augment the accuracy of the model's behavioral representation, minimizing discretization errors and promoting enhanced convergence throughout the solution phase [26]. Substandard meshes defined by uneven geometries, elevated aspect ratios, or distorted characteristics may result in erroneous solutions, numerical oscillations, and possible solver malfunctions. The mesh sensitivity analysis is crucial for achieving precise and reproducible numerical outcomes; thus, it is vital for authors to guarantee their results are not influenced by mesh refinement. This procedure entails generating a fresh array of meshes distinguished by an increased number of components or superior quality, thereafter doing simulations on each mesh. The findings, including temperature and other pertinent output parameters, are then compared using the designated meshes [27]. Results that stabilize and attain enhanced precision are considered mesh-independent. This verifies that the mesh in this simulation is adequately refined to accurately depict the physical processes while minimizing computational resource consumption. The mesh approach for this study begins with the selection of the appropriate mesh size and method for the complete body, intended to improve mesh accuracy in alignment with the criteria outlined in figure (2) for model surfaces.

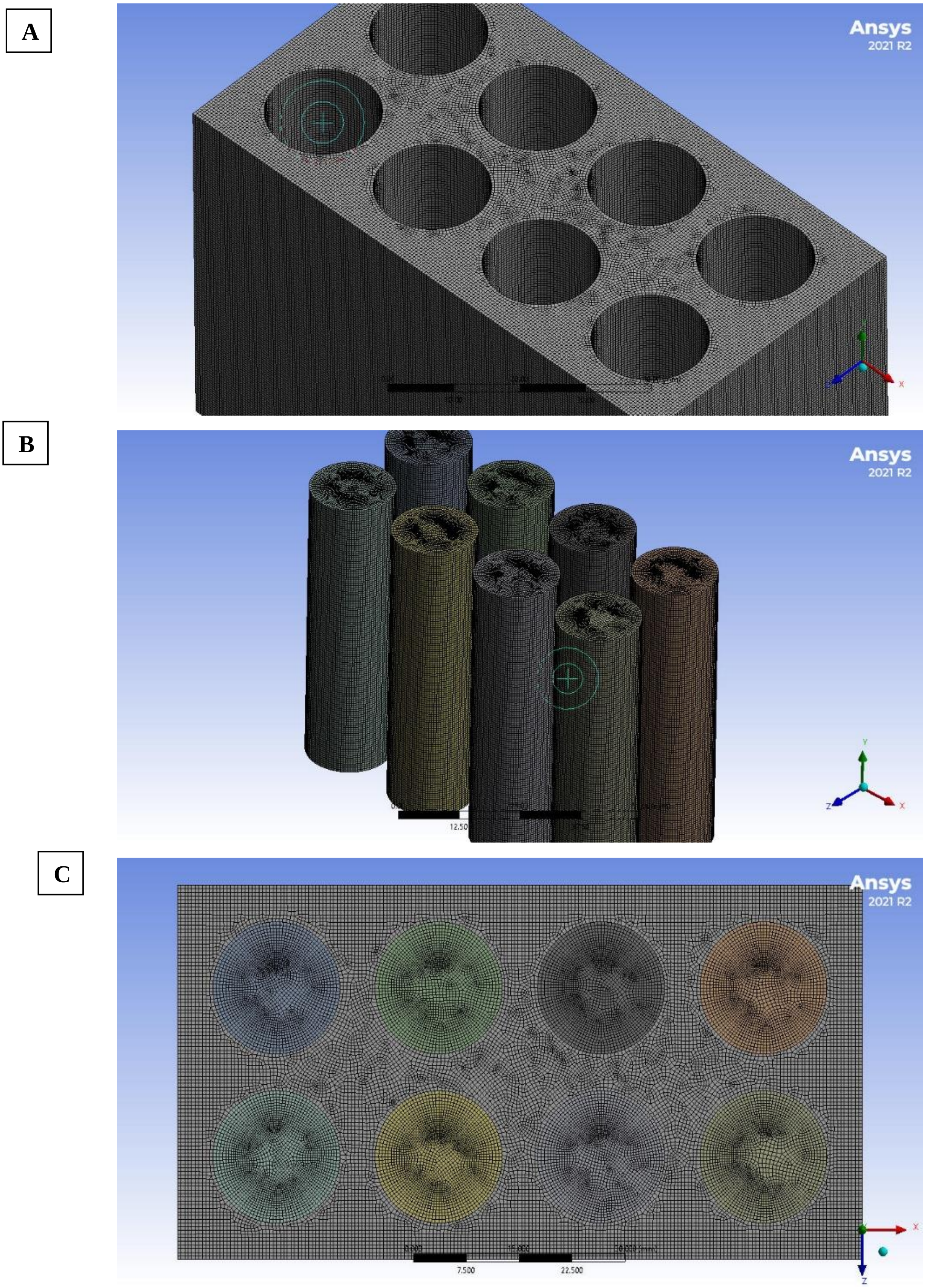


Figure 2. ANSYS software mesh (A) PCM case, (B) Battery cells arrangement, and (C) PCM and battery cells arrangement.

The mesh initially had a 0.7 mm element size, a notable discrepancy in liquid fraction outcomes was noticed when the mesh element size varied between 0.3 and 1.4 mm, exceeding these parameters. The authors chose 0.7 mm element size for this work, due to the very low variation between the results of 0.7 mm and 0.9 mesh size, a total of 3,695,125 elements and 3,8676,640 nodes over the simulation model. The results in figure 3 illustrated a liquid fraction distribution when the mesh element size between (0.3 to 1.4 mm), after these sizes a big divergent can noticed in temperature results.

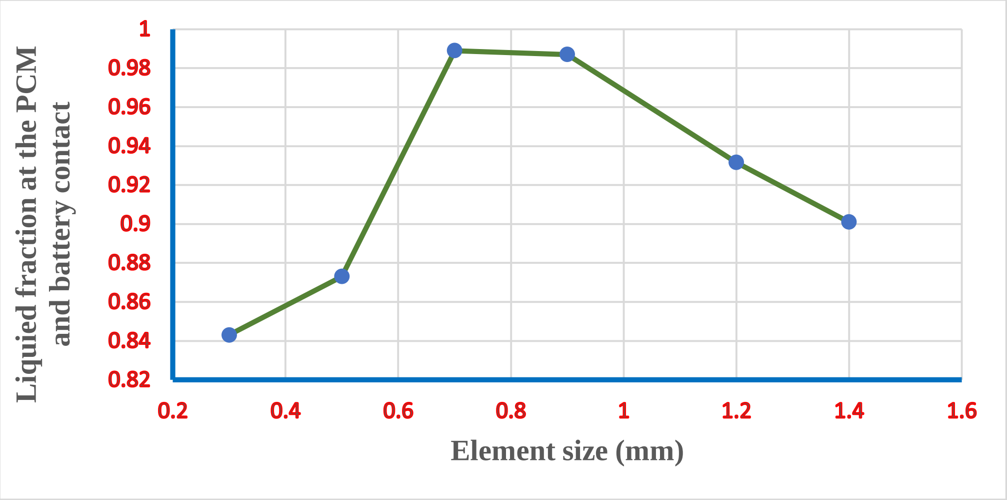
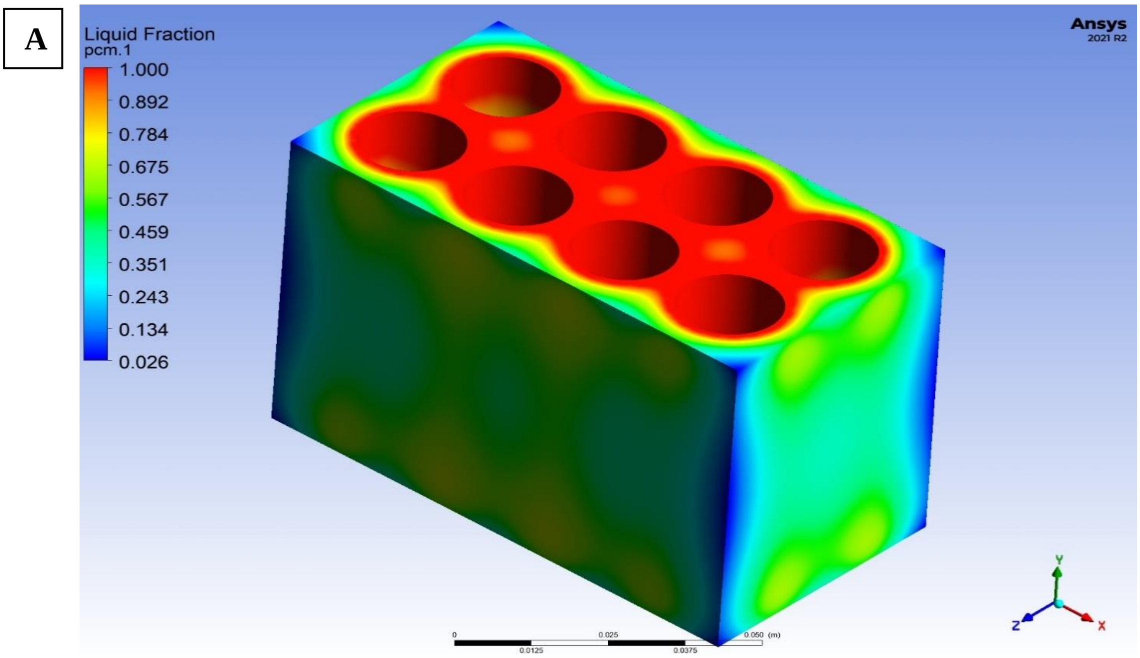


Figure 3. mesh independence test chart.

6. Results and dissections

a. N-octadecane PCM liquid fraction distribution

ANSYS simulation models in Figure 4 illustrates the distribution of the n-octadecane phase change material (PCM) liquid fraction within a battery thermal management system (BTMS) as depicted in figures (A) and (B). Figure 4 (A) depicts the PCM section of the battery case, whereas figure 4 (B) highlights the contact barriers between the lithium-ion cells and the PCM case. A comprehensive explanation of these photos necessitates an understanding of the thermodynamic behavior of n-octadecane, an examination of its heat transfer dynamics with battery cells, and a comparison of the liquid fraction outcomes with phase transition mechanisms. The simulation utilized boundary conditions that defined the battery cell boundary temperature at 30.85 °C and the initial PCM temperature at 26.85 °C, whereas n-octadecane melted within the range of 28-30 °C as indicated in Table (1). Figure 4 illustrates that n-octadecane serves as a phase-change material, melting within the temperature range of 28–30 °C. The battery boundary temperature (30.85 °C) somewhat exceeds the PCM melting range, prompting localized melting of the PCM adjacent to the cells prior to its uniform distribution throughout the material, due to heat conduction between the liquid and solid phases, together with natural convection currents.



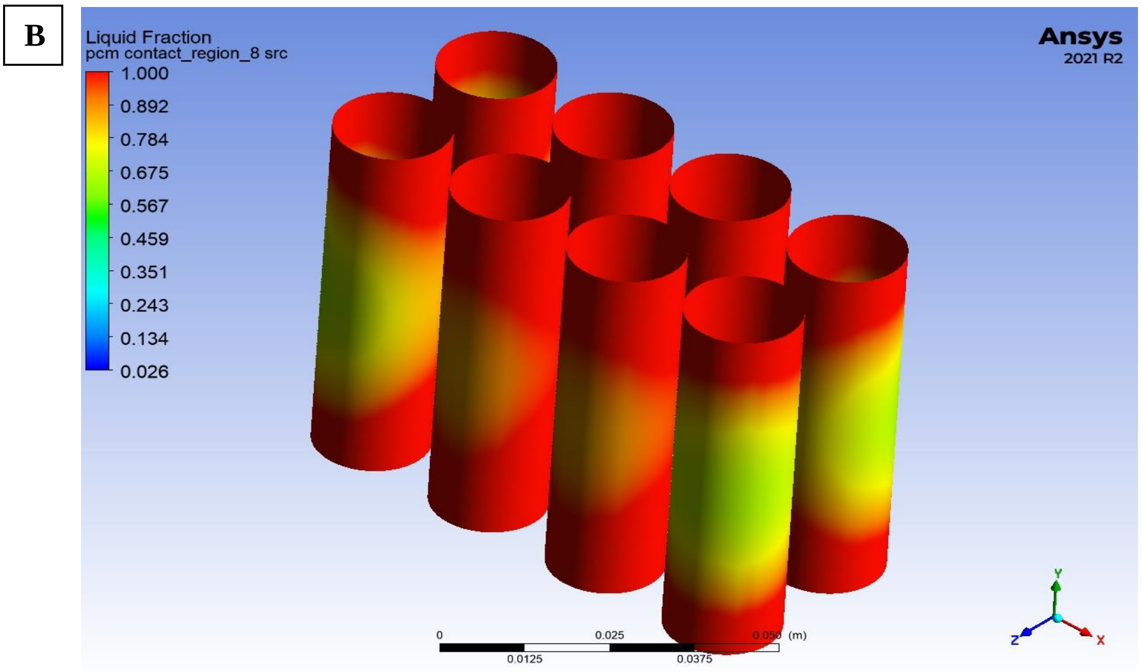


Figure 4. N-octadecane PCM liquid fraction (A) PCM case (B) PCM and battery cell contact regions.

The phase-change material n-Octadecane has a melting temperature range within 28 °C to 30 °C. The PCM exists only in its solid state at the starting temperature of 26.85 °C yet it begins to melt where the battery cell reaches 30.85 °C. The energy needed to melt the PCM depends on its latent heat of fusion which amounts to 200 kJ/kg. Regions displaying red colors indicate completely melted PCM in the red-colored (slightly solid material ≥ 1.0) zones found near battery cells since those zones experience the most heat transfer. The semi-solid to solid state existence of PCM occurs in the green and blue regions (liquid fraction < 0.5). The PCM near the contact regions of the top case surface melts completely but retains solid properties within the case bulk because heat penetration is reduced there. The battery cell heat transfers its energy to the phase-change material which converts from solid to liquid state. Throughout the simulation the liquid fraction indicates how much PCM has transformed into its liquid state.

The temperature of the battery cells attains 30.85 °C, causing localized interface melting between the battery and the surrounding PCM. The elevated thermal conductivity of the battery material facilitates heat dissipation, hence increasing the temperature levels of the phase change material (PCM). The thermal transfer from the battery to the bulk phase change material (PCM) occurs slowly due to the PCM's low thermal conductivity, which ranges from 0.198 to 0.222 W/mK, resulting in a protracted melting process. The phase transition process absorbs latent heat of 200 kJ/kg to stabilize temperatures without abrupt fluctuations. A liquid fraction gradient indicates that heat dissipation occurs more swiftly through conductive materials than through the phase change material (PCM).

The second image in figure 4 (B) analysis identifies the main content at the PCM to battery cell contact points as red liquid. Most of the contact walls display a red-colored liquid fraction while reaching approximately 1.0. These yellow-green areas reveal areas with partial melting which contains between 0.5 to 0.8 liquid fraction. Unstable melting appears between different parts of the study area because different heat flux levels prevail throughout. The battery cell surface temperature reaches 30.85 °C thus causing complete phase conversion of PCM located at the contact surface because it surpasses n-octadecane's melting point. The cell wall proximity contains a greater portion of liquid matter because this area transfers heat very rapidly leading to melting. The PCM structure contains thermal gradients because of irregular heat conduction and natural convection processes which produce lower liquid fraction readings. Heat transfer of n-octadecane depends primarily on conducting heat and convective processes rather than radiative heat transfer due to its low thermal conductivity [28]. Convection movements that occur inside liquid PCM seem to contribute to non-uniform melting by creating areas which do not fully reject their solid-state properties. Table 3 below comparison the results of the two simulation models in (A) and (B).

Table 3. PCM behavior in figure 4 (A) and (B) images comparison.

Aspect	Battery PCM Case (A)	PCM Contact Region (B)
Liquid Fraction	Gradual melting (0.0–1.0)	Mostly melted (~0.8–1.0)
Heat Transfer Mechanism	Conduction-dominated	High conduction + convection effects
Thermal Gradient	More pronounced	Less pronounced (localized melting)
PCM State	Mixed (solid & liquid zones)	Predominantly liquid

The key scientific insights observed from above simulation results in figure 4 can be summarized as: the battery-PCM interface creates a high degree of localized melting which results from its sharp temperature difference. The slow heat propagation in distant areas of n-octadecane happens because of its low thermal conductivity rate. The thermal buffering capacity of the PCM system works because PCM material outside battery cells stays solid.

Under thermal stress atom n-octadecane works as a Battery cool-down system by absorbing 200 kJ/kg latent heat to regulate temperature increases [29].

The diagram below in figure 5 displays n-octadecane phase change material (PCM) liquid fraction distribution across the lithium-ion battery cells to their PCM case. The analysis evaluates PCM liquid fraction changes between outermost battery cells and cells positioned in the center of the battery pack through blue curve and orange curve representation. The liquid fraction measurement indicates the amount of PCM which has experienced melting because of heat absorption by battery cells while operational. By studying these unique melting patterns scientists obtain better information about temperature accumulation and loss throughout the battery assembly. The detailed analysis serves vital purposes for thermal management systems because extreme heat causes both battery degradation and thermal runaway. The research shows how temperature regulations through edge effects, heat distribution and PCM properties affect battery temperature control and operational performance [30].

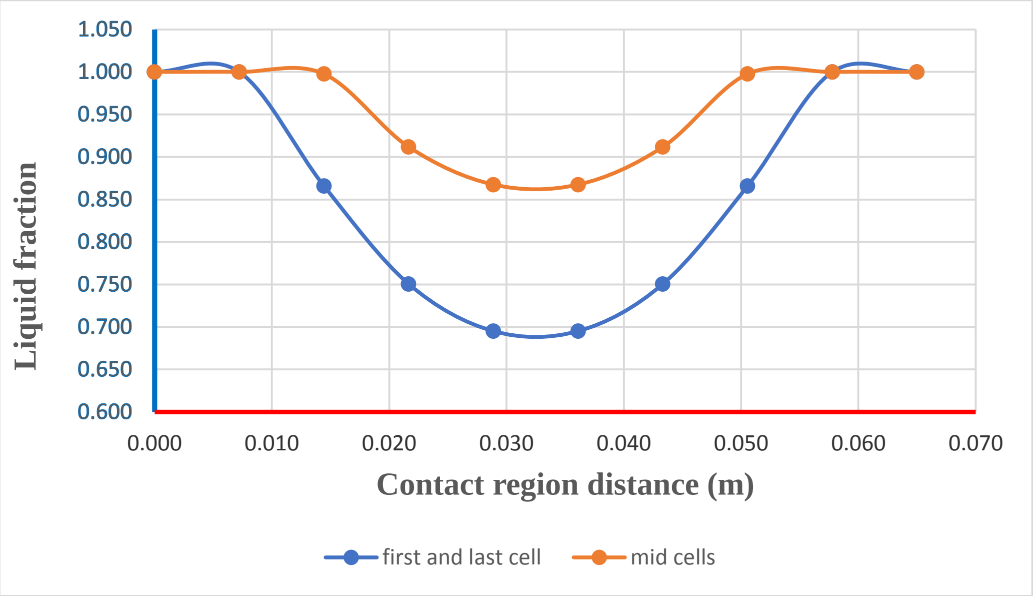


Figure 5. PCM and battery cells contact regions liquid fraction.

The liquid fraction measures the melted PCM portion which resulted from heat absorption by the battery cells. A review of the chart reveals the following patterns among the studied parameters. The blue curve demonstrates a dramatic decrease of liquid fraction within the contact area where the minimum reaches a value of approximately 0.70. The liquid fraction demonstrates nearly full melting ability in both the initial and final portions of the contact region while reaching its lowest point in the middle part. The localized edge-heating conditions of the first and last cells increase their PCM melting rate. The liquid fraction decreased steadily for the mid cells according to the orange curve yet failed to achieve similar minima compared to the blue curve. The PCM in middle cell areas maintains more than 85% solid phase due to its lower recorded liquid fraction levels. The mid cells receive PCM heating with more uniform coverage because of which they undergo high heat distribution along with slower melting times than the first and last cells. Near the first and last cells the liquid-vapor transition of n-octadecane occurs swiftly and deeply which correlates to intensified heat retention at those positions. The edges of the battery pack reach higher temperatures above 28-30°C relative to the central area because n-octadecane only starts to melt in this temperature range. The cells lack efficient heat dissipation mechanisms in the edge regions because they do not have neighboring cells to assist with heat transfer. An observation from the research reveals that the orange curve in the mid-cell area indicates a sustained higher percentage of liquid between connector points. Thermal buffering occurs due to edge effects as PCM situated on both sides creates a better heat absorption and distribution mechanism which leads to reduced melting at the center region. The slowing of melting occurs at locations with reduced heat input because the material demands greater energy to change from solid to liquid. The PCM maintains solid state in the mid-cell area because heat absorption distributes throughout the material. The thermal conductivity of solid n-octadecane stands at 0.222 W/mK while its thermal conductivity in liquid state equals 0.198 W/mK. Heat transfer delays after melting are possible in regions where efficient heat dissipation cannot occur because of lower thermal conductivity between liquid states. The low density value of 777 kg/m³ for n-octadecane indicates it has the capacity to increase in volume when it melts. A thermal expansion coefficient value of 7.6×10^{-4} 1/°C demonstrates that phase change will increase volume to some degree but may affect the heat exchange dynamics at the interface. Figure 6 below shows the curves measurements locations in battery outer cases indicated by yellow line.

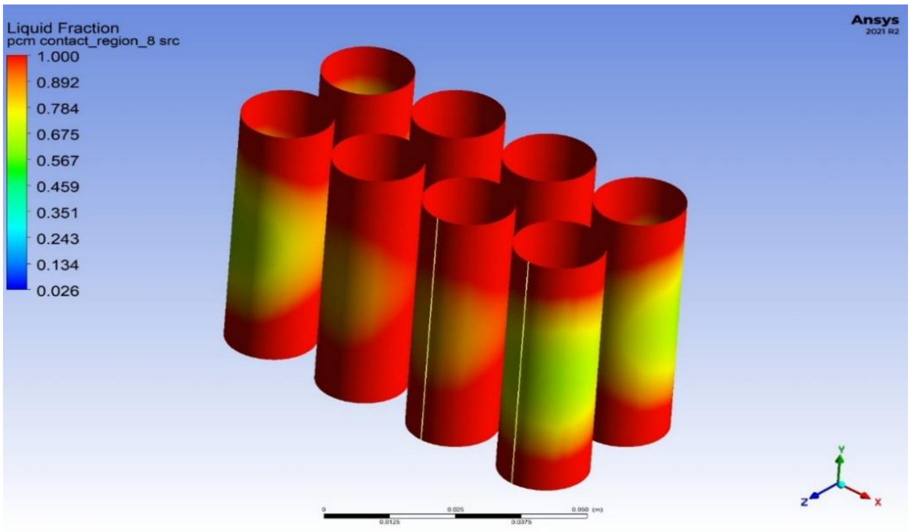


Figure 6. PCM liquid fraction measurement locations.

6.2 PCM state effects analysis in battery thermal management

Temperature regulation and thermal energy storage tasks heavily depend on Phase Change Materials (PCMs) which perform best in battery thermal management systems (BTMS). A PCM in different states between solid and liquid affects both heat absorption and heat dissipation processes as well as its performance as a battery. An analysis of the PCM state effects in different battery pack regions together with their role in thermal system functioning becomes possible by assessing your ANSYS simulation results. At the beginning of the simulation the PCM temperature remains at 26.85°C while n-octadecane melting range extends from 28 to 30°C. The solid PCM experiences heat transfer through conduction since the material cannot move its fluids during this state.

The low thermal conductivity value of 0.222 W/mK in solid n-octadecane causes slow heat diffusion resulting in temperature hotspots. The heat capacity of solid PCM during temperature increase decreases when compared to its phase transition state because it can store heat only through temperature elevation. When used as an insulator, the PCM reduces battery temperature rise at first but fails to adequately release accumulated heat. Temperature differences create separate hot and cold temperature areas which develop through slow conduction near the battery surface and further from the heat source. During solidification the PCM temporarily hinders temperature increase in the battery system yet it does not effectively remove heat from the system. The battery temperature may still increase during such conditions when heat production rates are high and the PCM transitions to the liquid state at a rate insufficient for heat dissipation. Solid-state PCM proves effective for brief heat situations though it might need conductive heat spreaders to achieve better performance.

The PCM starts its melting activities after simulation results indicate that battery boundaries reach 30.85 °C at contact areas. At this point the thermal management system using PCM achieves its most critical position. The phase change procedure allows the PCM to absorb considerable thermal energy of 200 kJ/kg in order to stop rapid temperature changes. Boundary sectors between 28-30 °C are sustained by the PCM after it directs absorbed energy toward bond-breaking processes. The mechanism uses both conduction in solid PCM as well as convection in liquid PCM material during its partial melting stage. The natural convection processes of heat transfer in liquid PCM work to achieve uniform distribution of heat. The thermal storage device shows its maximum liquid PCM concentration around battery surfaces based on figure 4 measurement data while the bulk PCM remains solid or partially melted. Heat penetration needs time in order for PCM to evenly melt in its deep sections. The application of battery temperature stability is more effective when the state engages with practical benefits during the melting phase. During the melting process different parts of the system reach their temperature targets at different times which creates overheating because heat exchange processes are inefficient. Heat distribution reaches its optimum level due to fins and both high-conductivity materials and hybrid PCMs [31].

The performance of the system changes when the PCM becomes completely melted (liquid fraction reaches 1.0, which shows as red zones in results). Active heat distribution becomes possible with liquid PCM because it can move through circulation. Liquid PCM observes a heating effect at the upper portion and a cooling effect at the lower portion that enables better heat transfer. The PCM has depleted its latent storage capacity thus it can store heat only through sensible mechanisms by raising its temperature. A heat sink or dissipation mechanism is necessary for liquid PCM since it lack causes thermal bottlenecks which degrade BTMS effectiveness. The rising temperature will exceed battery operating limits when heat generation persists alongside no external heat rejection capabilities in the PCM. During this state the practical use of liquid PCM delivered better heat dispersal while becoming unable to regulate temperature after complete melting occurred. The absence of cooling mechanisms such as air cooling, heat pipes and liquid cooling will make the liquid PCM ineffective during long-term battery cycling.

The PCM needs to turn solid after the battery discharges or receives external cooling so it can restore its thermal storage features for upcoming charge cycles. The solidification process of the PCM produces stored heat which maintains superior temperatures over low critical thresholds for the battery. The preventive design minimizes extreme thermal cooling and avoidance of thermal shock which helps prolong battery life. The solidification process begins in the areas that possess lower temperatures before moving to the rest of the substance. The inefficient rejection of heat during cooling causes PCM to remain partially melted which hinders complete thermal storage preparation prior to a new charging cycle. The PCM n-octadecane displays a supercooling effect which enables it to stay liquid after dropping below its solidification point until it rapidly changes to solid form. Heat dissipation rates become affected by this procedural action as it delays the rate of dissipation. Simulation results demonstrate that localized battery melts successfully yet lack uniformity. The results shows that heat transfer enhancement measures are needed because it takes PCM too long to melt and solidify. Optimization of the PCM-based system needs to safeguard against thermal runaway occurrences during full PCM liquid state. Table 4 below summary PCM state effects on battery thermal management.

Table 4. PCM state effects on battery thermal management.

PCM State	Key Effects	Thermal Behavior	Challenges	Possible Solutions
Solid PCM	Insulation, heat conduction	Slow heat absorption	Localized heating, slow response	Use high-conductivity inserts, heat spreaders
Melting PCM	Heat absorption via latent heat	Temperature stabilization	Non-uniform melting, slow heat spread	Use hybrid PCMs, add heat-enhancing structures
Liquid PCM	Heat dissipation via convection	Better heat spreading	No more latent heat storage	Integrate heat sinks, active cooling
Solidification PCM	Heat release, passive cooling	Thermal stabilization	Delayed freezing, supercooling	Controlled cooling mechanisms

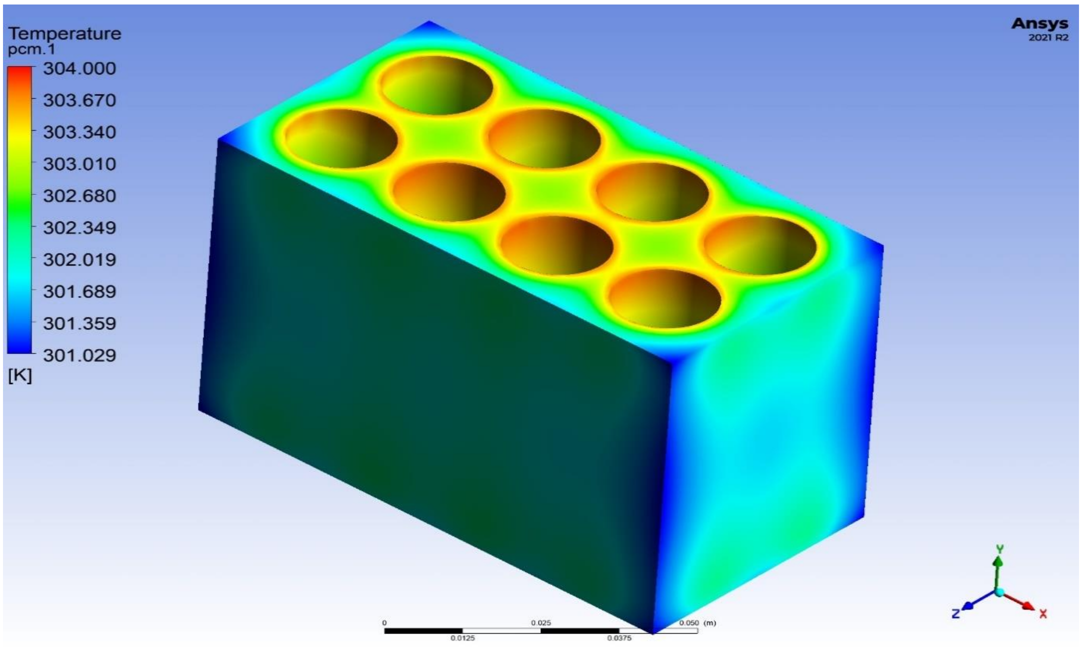
6.3 PCM case heat distribution analysis

Phase Change Materials (PCMs) currently receive wide recognition because of their ability to conduct thermal energy storage and management applications. The material n-octadecane has become popular for its appropriate thermal characteristics that combine high latent fusion heat with a melting range from 28 to 30°C. The property of this material to absorve then release heat during its phase transformations makes it suitable for thermal energy storage and battery cooling applications. The thermal behavior of PCM material in melting and freezing processes determines how effectively heat gets controlled. When the PCM n-octadecane experiences melting or solidification it transitions through its different phases. Visual representations in the images display temperature gradients generated by the phase change occurring in the material probably because they show thermal conductivity alongside latent heat transfer mechanisms.

Figure 7 (A) and (B) illustrated the PCM case heat distribution and the effects of its properties on the system thermal management.

The heat energy (red coloration) concentrates in the middle areas of the cylindrical holes because this region faces active heat absorption and more powerful heat sources from its central location. The (blue) color regions around the edges of the material show lower temperatures. The color shaded parts reveal heat reduction zones that lead to solidification within the substance. The phase change temperatures of the material need to shift between the melting and solidification ranges (28–30 °C according to the table data).

A



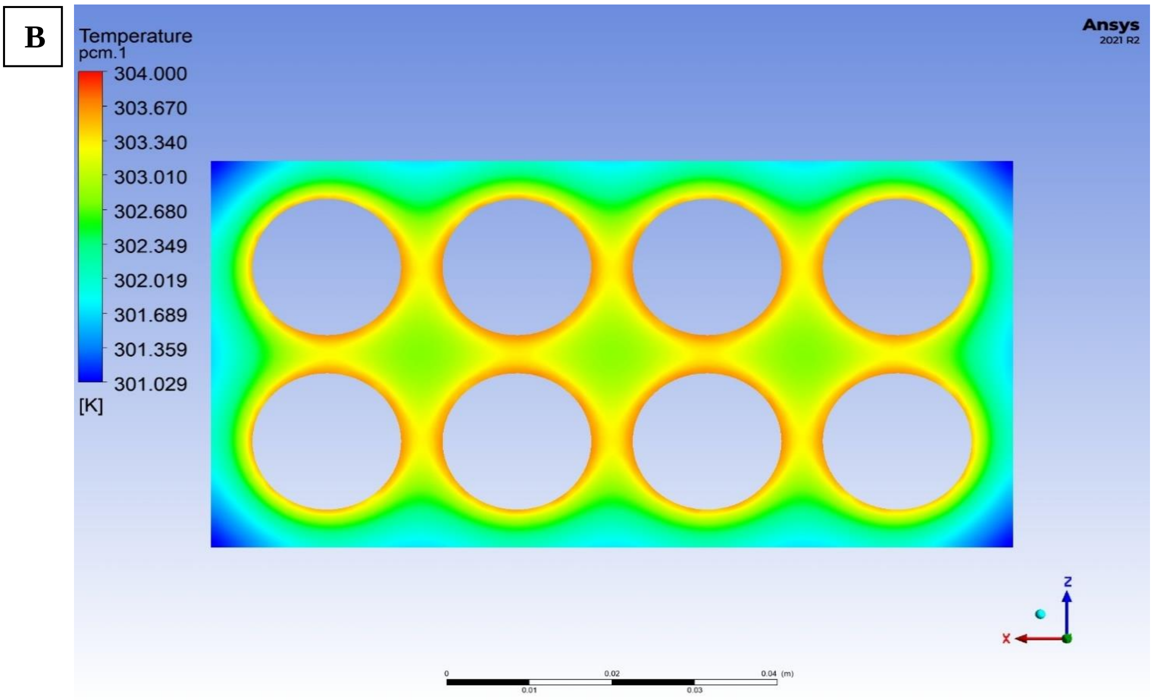


Figure7. PCM heat distribution map

The freezing point of n-octadecane lies within the temperature ranges of 28 °C–30 °C so any sample region above this freezing point will exist in liquid form but below this point will exist in solid form. N-octadecane undergoes phase transition by means of its thermal behavior explained in the provided table. A 200 kJ/kg latent heat of fusion enables the material to absorb or release substantial heat amounts during phase change operations thus improving battery system thermal stability. Thermal conductivity works as a critical factor enabling the material to transfer heat because the solid presents 0.222 W/mK and the liquid possesses 0.198 W/mK. The heat transfer behavior of the PCM becomes controlled by conductivity differences that exist between its solid state and liquid state. When the phase change material starts to melt its slower heat dissipation properties in the liquid form produce thermal variations which result in temperature non-uniformity. The flow characteristics of the liquid phase during melting are represented by its viscosity value at 4×10^{-4} P.S and kinematic viscosity at 4.27×10^{-7} m^2/s. Heat distribution possibilities and the liquid material flow rate depend on the properties of the material with their corresponding effects.

The cylindrical holes inside the material function to channel thermal heat either by transporting fluid across or by using heat distribution processes. The engineered regions serve two heat management purposes because they both enable rapid heat release to the environment and they function as efficient heat storage locations for PCM. The simulation demonstrates that holes throughout the material will reach temperatures at the top end of the range (304 K) when the material becomes liquid during melting which indicates heat absorption occurs at these points. The temperature in the solidified edges of the material shows a decrease that indicates heat release occurs during solidification. These images highlight the need to create heating systems with even heat distribution since they demonstrate why both thermal hotspots and inadequate cooling must be avoided. The heat absorption and release speeds in PCM-based thermal management systems directly determine how well the system works and survives in energy storage applications and electronic cooling and batteries. The cylindrical holes enable better heat transfer paths while working as storage areas for phase transition and both melting/solidification processes inside the PCM. Strategic changes to the positioning and quantity of holes throughout the system will enhance the thermal system control capabilities.

6.4 Battery cells system heat distribution analysis

The ANSYS simulation results displayed through figure 8 show how temperature spreads in a battery cell system that uses n-octadecane phase change material (PCM) casing during melting and solidification events within contact areas. The battery cells made from Lithium-ion and the outer case from n-octadecane, the heat distribution map in figure 8 below resulted from the heat absorbed and transfer between these two materials.

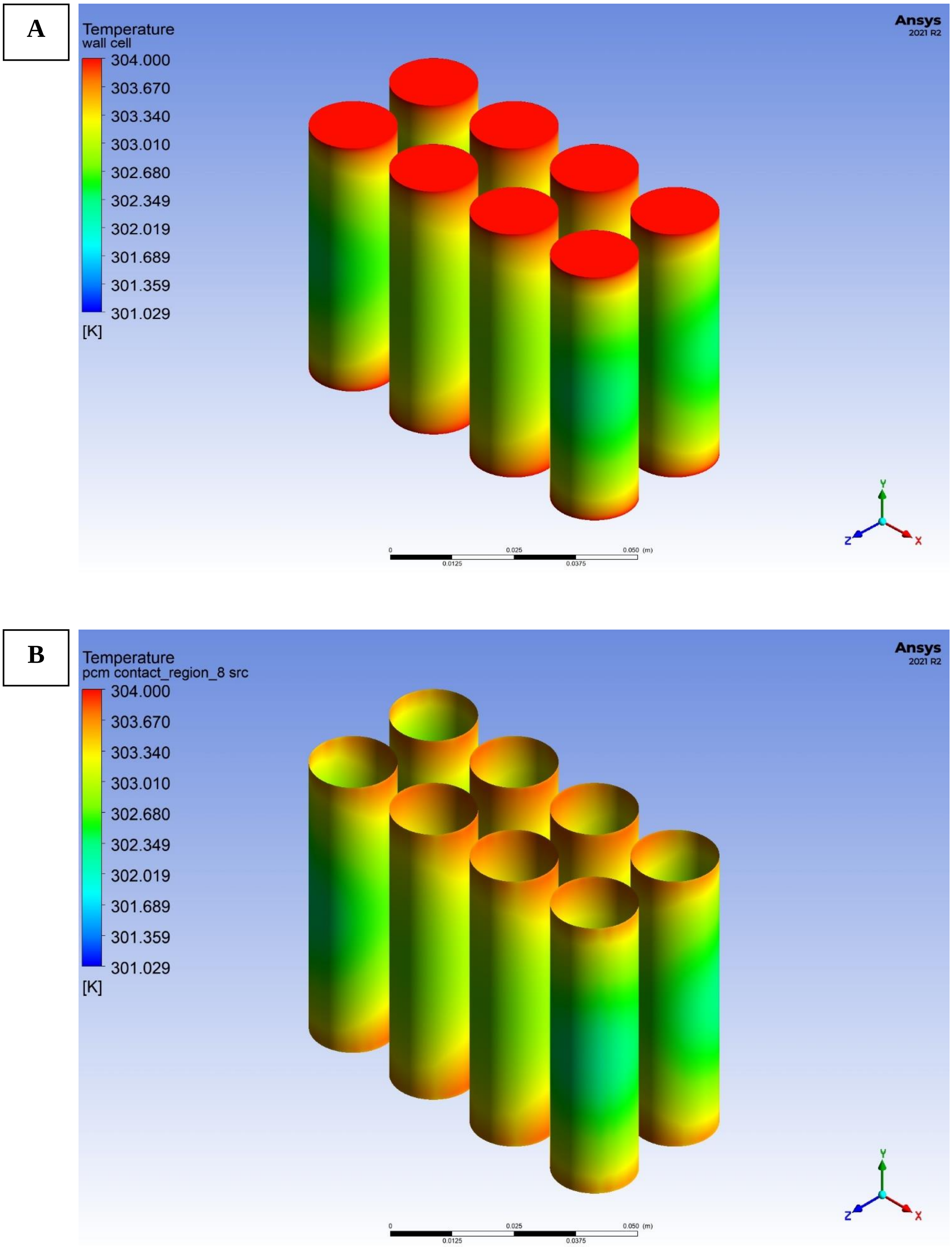


Figure 8. (A) battery cells system heat distribution map. (B) PCM with battery cells contact region heat distribution.

The figure 8 (A) demonstrates heat distribution patterns throughout the n-octadecane PCM case where battery cells are located. The simulation model demonstrates thermal distribution throughout the system while red elements reach maximum temperature levels at 304 K and blue elements touch minimum levels at 301 K. The heat transfer follows standard principles because battery cells serve as heat sources while n-octadecane PCM functions as heat absorbers. The colored heat zones at the battery cell outer surfaces indicate high temperatures caused by charging/discharging operations which occurs in the regions marked red. Because n-octadecane shows thermal characteristics of melting at 28-30 °C the PCM parts nearest to the battery cells reach their maximum temperature thus becoming liquid due to heat absorption. The measurements tally with the fusion latent heat capacity of 200 kJ/kg and demonstrate thermal conductivity performance of 0.222 W/mK for solids before elevating to 0.198 W/mK for liquids according to table data. The thermal conductivity works together with latent heat to create an efficient heat transfer cycle throughout phase change.

The second image in figure 8 (B) illustrated the contact regions between the battery cells and PCM case. The heat transfer operation strongly depends on this area. The temperature distribution pattern in this section differs from the previous image because the battery cells come in direct contact with the PCM material. Cells areas become crucial for thermal management because these are the specific points where battery heat energy transfers to the PCM. The temperature gradient displays noticeable variations across these sections where battery cells encounter the PCM because the cells maintain liquid PCM states near them and the outer edges receive cooler temperatures. PCM n-octadecane undergoes continuous solidification because the cells on the battery release heat until the PCM reaches its outer regions. The results confirm that n-octadecane completes a phase transition at the points of contact because it takes heat from cells during charging and emits heat during discharging.

The red-colored heat accumulations in figure (8) images mark the PCM locations where solid to liquid phase changes occur. The battery cells provide heat which n-octadecane absorbs through the melting point (28–30 °C) causing it to transition between solid and liquid states. The central parts of these areas in the images are characterized by dominant red and yellow tones that indicate higher temperatures. The solidification process of the PCM releases heat while blue and green shade regions exhibit the solid-to-liquid phase transition resulting in temperature control of the battery cells. The efficiency of heat transmission by the PCM material is supported by its thermal conductivity measurement which indicates 0.222 W/mK in solid form but slightly lower at 0.198 W/mK in liquid stage. Analysis proves that temperature progressively reduces at both edges of the PCM container and contact points. The substantial latent heat of fusion at 200 kJ/kg makes the substance effectively stabilize the battery temperature as it absorbs heat during its melting process.

The n-octadecane thermal management system operates as a phase-change component which keeps battery cells from overheating through heat storage and heat release processes. The design works effectively to protect both battery efficiency and prolong its operational lifetime. The successful operation of high-performance batteries requires effective thermal management techniques particular among vehicles powered by electricity or energy storage systems. A PCM solution made from n-octadecane regulates temperature variations which prevents battery overheat damage and protects both performance and safety. The PCM casing together with its appropriate connection to battery cells requires precise design optimization to achieve optimized heat dispersion results for the thermal management setup.

7. Validations

This research backs its findings about n-octadecane PCM thermal management in batteries through prior investigation of PCM temperature regulation in energy storage systems especially lithium-ion batteries. The literature shows that n-octadecane along with other phase change materials enhances battery performance while keeping temperatures balanced and stopping thermal runaway. Khateeb et al. (2020) [32] explained that PCM plays an essential role in thermal management systems because they show enhanced effects when combined with aluminum foam to reduce battery temperatures below the capacity of natural convection-based thermal control. The present investigation confirms that n-octadecane acts as a PCM which absorbs heat during battery operation transitioning between solid and liquid states to stabilize temperatures (Khateeb et al., 2020). Thermal conductivity presents itself as an essential factor that determines PCM performance. This research shows the same results as other studies such as Rao et al. (2018) [33] that n-octadecane's thermal conductivity in solid and liquid states matches their values at 0.222 W/mK and 0.198 W/mK respectively. The authors emphasize that improving PCM thermal conductivity achieves homogeneous heat flow like hybrid PCM systems as suggested in this analysis (Rao et al., 2018). Tests by Ye et al. (2019) [34] displayed how n-octadecane PCM utilizes its absorption capacity for heat in high-temperature scenarios thus proving the measurement of latent heat of fusion at 200 kJ/kg found in this study. Temperature variation inside the battery system becomes regulated through n-octadecane absorption of charging heat while it distributes heat during discharging (Ye et al., 2019).

This study by Zhao et al. (2017) [35] explains how edge effects inside PCM systems affect thermal management performance by causing battery cells located at pack edges to reach higher temperatures because heat dissipation mechanisms are insufficient. This research revealed localized melting specifically at the edges of the PCM system whereby findings prove thermal management proves ineffective due to rapid heat accumulation at battery pack edges which is hard to dissipate (Zhao et al., 2017). The findings of this research receive affirmation from numerous studies which investigate PCM-based thermal management within battery systems. Likewise, to earlier studies n-octadecane exhibits phase transformation characteristics together with latent heat storage properties and demonstrates temperature regulating features but further requires methods to maximize PCM effectiveness in modern battery solutions through heat distribution optimization and conductivity enhancement. Table 5 below summarized the results validation with similar research papers.

Table 5. The current study results validation with earlier studies

Study	Findings	Correspondence with Current Research
Khateeb et al. (2020)	PCM enhances battery thermal management and reduces temperature rise.	Current study confirms that n-octadecane helps regulate battery temperature through phase changes.
Rao et al. (2018)	Thermal conductivity impacts heat dissipation and uniform temperature distribution.	The low thermal conductivity of n-octadecane is highlighted, affecting heat dissipation efficiency in battery systems.
Ye et al. (2019)	PCM absorbs significant heat during phase transition, stabilizing temperature.	The latent heat of fusion of n-octadecane allows it to absorb large amounts of heat, helping to stabilize the battery temperature.
Zhao et al. (2017)	Edge effects in PCM systems cause non-uniform heat dissipation.	The localized melting observed at the edges of the PCM system supports the findings regarding edge effects in battery packs.

8. Conclusion

The authors performed simulations of lithium-ion battery thermal management by using n-octadecane as the phase change material (PCM). Simulation data confirms that n-octadecane controls battery temperature by absorbing and releasing thermal energy during its phase changes. The study first presents background information about its main focus before evaluating its discoveries regarding thermal performance alongside power level effectiveness results with suggestions for energy storage system improvements. This study main finding can be listed as:

1. Effective Temperature Regulation with n-Octadecane: The thermal management system that incorporates n-octadecane as a phase change material effectively controls lithium-ion battery temperature stability. During battery charging n-octadecane absorbs heat from its latent fusion heat for temperature equilibrium and during battery discharge it converts absorbed energy to maintain stability and avoid thermal runaway. Research findings agree that phase change materials enhance battery performance based on results in this study.
2. Phase Transition Behavior and Heat Absorption: data from the simulation demonstrates that n-octadecane experiences phase transition between 28°C and 30°C where it draws substantial heat to melt while providing thermal buffering to the battery. N-Octadecane demonstrates the desired latent heat capacity of 200 kJ/kg that helps manage battery temperature fluctuations to verify its compatibility with advanced battery technology.
3. Localized Melting and Thermal Conductivity: Hazardous events leading to localized melting occurred at battery cell and n-octadecane interfaces because heat transfer reaches its peak. The results demonstrate how PCM system efficiency depends on thermal conductivity because n-octadecane shows limited heat diffusion through its solid state with 0.222 W/mK and liquid state with 0.198 W/mK. The way PCM responds underloads shows that researchers need to develop enhanced PCM arrangements combined with supporting components to boost heat transfer.
4. Efficiency of Heat Distribution in PCM Systems: The heat transfer performed by convection in liquid n-octadecane enables better cooling compared to its solid state. The simulation data revealed non-uniform melting happens because the PCM material possesses poor thermal conductivity which demands either hybrid PCM solutions or enhanced thermal conductivity to promote better heat distribution and speed up melting operations mainly in the PCM bulk area.
5. Design Optimization for Enhanced Thermal Management: The PCM casing contains specifically placed cylindrical holes to enable better heat transfer pathways that help optimize phase transition operations. The placement of holes in this design arrangement combines better thermal control with improved phase change functionality as per experimental studies that promise better designs for upcoming thermal management systems.
6. Long-Term Performance and Battery Protection: Research demonstrates that n-octadecane functions as an effective component which strengthens the battery system's thermal stability across the long term. The phase change properties of n-octadecane work to protect batteries by absorbing and releasing heat these capabilities provide heat protection and maintain safe performance. Active cooling systems including air cooling and liquid cooling along with heat pipes need to back up n-octadecane PCM during extended time periods because the PCM loses its heat storage capability after transitioning to the liquid phase.
7. Potential for PCM-Based Thermal Management in Future Technologies: Research evidence shows n-octadecane PCM-based systems demonstrate remarkable thermal management suitability for electric vehicle battery systems that store electrical energy. Research has established basic foundation knowledge that enables the optimization of PCM designs and properties which will boost future energy storage system heat dissipation and operational safety.

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