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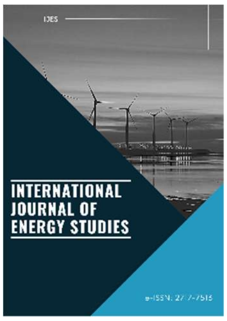

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Thermal management analysis with different PCMs in Sodium-Ion batteries

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Highlights

- The effects of different types of phase change materials on battery thermal management analysis were investigated.
- Phase change materials that can be used in the cooling of sodium ion batteries have been determined.
- A finned battery model is designed.
- Thermal management analyses are performed with two different phase change materials and the results are shared.

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ABSTRACT

The advent of modern technology has led to a significant increase in the utilisation of rechargeable secondary batteries. Despite the sustainability of lithium-ion (Li-ion) batteries, the limited availability of lithium has driven research into alternative energy storage technologies. Sodium-ion (Na-ion) batteries, as a potential alternative to Li-ion batteries, have emerged as a highly promising contender. However, for these batteries to become industrially viable, certain properties such as energy and power density need to be enhanced. To address this issue, batteries have been a focus of research, and battery thermal management systems have been developed. These systems aim to evaluate battery performance, which is strongly influenced by temperature. Effective thermal management ensures that the battery operates within the optimal temperature range. This study models a pouch-type battery and evaluates the effects of phase changing materials (PCM) on battery temperature control. Comparative analysis is conducted using different PCMs to understand their impact. The study analyses the battery's response to specific temperature ranges and assesses how different PCMs affect battery cooling performance. The results provide critical insights for ensuring efficient battery operation. Furthermore, this research supports the broader adoption of Na-ion batteries in industrial applications and contributes to the development of sustainable energy storage systems.

Keywords: Battery thermal modeling, Battery thermal management, Cooling with PCM, Sodium-Ion battery

1. INTRODUCTION

In the coming years, a new generation of studies is needed to implement sustainable and low-emission energy storage technologies in today's world to cope with important problems such as climate change, resource waste, and increasing urbanization. To ensure sustainability, renewable energy sources must be widely used. Therefore, the development of energy storage technologies plays an important role in providing affordable and continuous energy to consumers and in meeting and securing energy supply. Batteries are an integral part of this transition, and as technology continues to advance and evolve, so must battery technologies. Sodium ion batteries in particular have potentially very attractive features and prove to be an emerging technology [1].

Although studies on sodium-ion batteries date back to the 1970s, like studies on lithium-ion batteries, they were first commercialized in 1991 by Sony and Asahi Kasei [1]. By the end of the 2000s, concerns about meeting the lithium supply and the uneven distribution of reserves around the world increased the studies on sodium ion [2], which is abundant in the world, and research in this field started to come to the agenda frequently. Since the early 2010s, sodium-ion batteries have started to appear in the commercial market. Thus, the potential of sodium-ion batteries has become an important milestone in energy storage technologies. While the high availability of sodium has alleviated threats related to limited resources such as lithium, the commercialization of these batteries in the field of energy storage technologies has increased diversity [3].

Different energy storage methods can be used to stabilize energy supply and ensure energy reliability for society. The features required in an energy storage system are high charge-discharge, efficiency, and storage capacity, low self-discharge and capacity losses, long intervals of use, energy density, and low cost [4]. For this reason, sodium-ion batteries are among the options that attract attention today for future energy supply.

1.1. Sodium-Ion Batteries

Sodium-ion batteries are a lower-cost, more reliable and longer lasting option compared to the commonly used lithium-ion batteries. There are approximately 1000 times more sodium reserves in the world than lithium reserves. Sodium can also be easily obtained from salty water such as seawater [5]. In sodium-ion batteries, less costly aluminum is preferred instead of copper as an electron collector [6]. The reason for using aluminum is that no reaction can occur between sodium and aluminum. Sodium-ion batteries can be charged when the energy is completely discharged, i.e. 0% charge, while other batteries start to lose their capacity in this case. These are the general advantages and features of sodium-ion batteries. It is envisaged that these batteries can be produced faster and easier by using the infrastructure of lithium ion batteries. However, there are some problems in research and development.

1.2. Components and Working Mechanism of Sodium-Ion Batteries

Batteries have three main components: cathode, anode, and electrolyte. The cathode is the positively charged and oxidizing electrode. It accepts electrons from the external circuit and decreases during the electrochemical reaction. The anode is the reducing electrode, which is negatively charged. It is a structure that releases electrons to the external circuit and oxidizes during the electrochemical reaction. The anode gives electrons to the external circuit and is oxidized, while the cathode accepts electrons from the external circuit and is reduced. The electrolyte provides a suitable medium for charge transfer between the anode and cathode as ions within the cell. The electrolyte can be liquid or solid. Some solutions can be used as liquid electrolytes for ionic conductivity. Since solid electrolytes operate at cell temperature, they must be electronically insulating to prevent short circuits during battery operation. In addition, the electrolyte should not react with the electrodes and should not be affected by factors such as temperature [7].

Sodium-ion batteries work similarly to lithium-ion batteries. The components and electrical storage mechanisms of the two batteries are the same, the only thing that differs is the ion carrier. In lithium-ion batteries, the carrier is Li^+, and in ssodium-ionbatteries it is Na^+ ion. In Na-ion batteries, a system is usually formed in which the electrolyte in which the sodium salt is dissolved in an organic solvent is ionically combined with negative and positive electrodes [8]. Figure 1 shows the working mechanism of sodium ion batteries. As with other rechargeable batteries, the performance of sodium-ion batteries depends on both the battery components and the assembly within the cell [9].

In a life cycle analysis of batteries, it was found that the negative electrodes, i.e. anodes, which are one of the battery components, cover about 26% of a typical battery configuration, while this value for the cathode is about 35% [8].

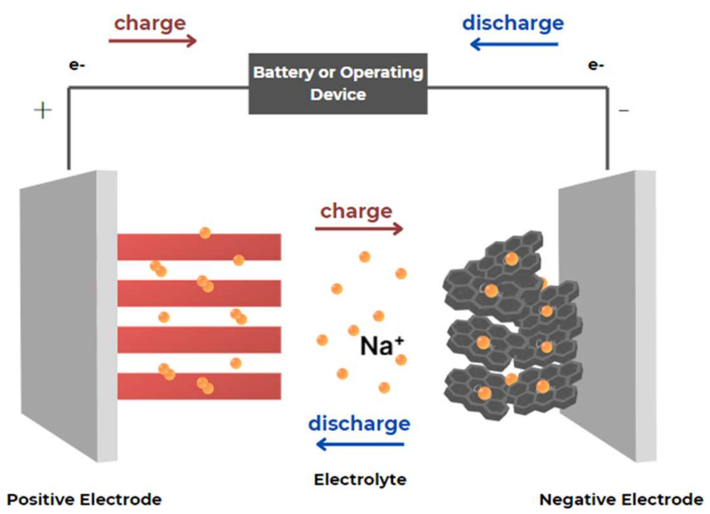

Figure 1. Operating mechanism of sodium-ion batteries. Adapted from ÖZSİN, G. (2021) [8]

1.3. Phase Change Materials (PCM)

Phase change materials (PCMs) are materials that can melt or solidify at specified temperatures and store latent heat. It is a passive cooling method that can maintain the temperature of batteries until the melting point. This method can be used in combination with other cooling methods or alone.

Bahru, examined that the use of Ansys Fluent application is advantageous in cooling applications related to heat transfer and fluid mechanics problem, and that there are many cooling studies with PCM in cooling applications [10]. Air cooling, liquid cooling and PCM applications are widely used in research on thermal management in battery systems. Considering the advantages of PCM-supported cooling, it has higher thermal conductivity and more uniform temperature distribution than air-cooled and water-cooled systems [11].

Hussain, conducted a study using 3 different PCMs, n-Octadecane, composite paraffin and RT-58, for cooling encapsulated li-ion battery packs. In his study, they investigated the cooling efficiency of PCM at different discharge rates and different ambient temperatures. They calculated that the maximum battery temperature decreased by 25.3 K and 19.5 K at 5C and 4C discharge rates, respectively. At 293 K and 300 K ambient temperature, n-Octadecane was the most effective PCM, while composite paraffin was effective at 313 K ambient temperature and RT-58 was effective at 323 K [12].

Rangappa, worked on PCM cooling system analysis with the help of Ansys Fluent programme using PCM between two batteries to maintain the cooling performance of the battery pack. For the PCM cooling system, they calculated that a 9 mm thick system is required for the battery with a heat generation rate of 30,046 W/m^3 to keep the battery surface temperature within 313 K (40 °C). They also studied a hybrid system that aims to improve the cooling performance by passing fluid in a pipe through the PCM [13].

Ianniciello, examined the research on cooling with PCMs and proposed new methods to improve the performance of these systems. They determined the most suitable PCM with theoretical or experimental methods and suggested optimizing the design of the system and increasing the surface area of the PCM by adding high heat conduction materials such as metal fins on the PCM and combining them with different materials [14].

Lv, increased the heat transfer surface area by adding fins to cool the lithium-ion battery pack and reduced the peak temperature by 4% and the temperature difference on the battery surface by 12% in his study [15].

Feng, aimed to cool Lithuim-ion batteries to 51 °C, the maximum temperature value to be reached at 3C discharge rate, by using PCMs in their study. They investigated the effect of PCMs with different fin thickness, PCM spacing and thickness parameters [16].

Since the end of the 2010s, concerns about meeting the lithium supply and the uneven distribution of reserves worldwide have increased the trend towards sodium-ion [17], which is abundant in the world. Although there are studies on the thermal performance of lithium-ion batteries in the literature, there are very few studies examining the thermal performance of sodium-ion batteries. Passive cooling system studies using PCM are gaining importance day by day and it has been concluded that systems using PCM can be useful [18]. Thermal management analysis with PCM will be performed using Ansys 2024 R1/R2 Fluent. The maximum temperature for the battery is set at 60°C, Comparisons will be made with different PCMs and it will be determined which one is more efficient.

2. MATERIALS AND METHODS

In this section, battery modeling, network structure, PCMs and their properties, and battery boundary conditions are presented.

2.1. Sodium-Ion Battery Modeling

Batteries generally consist of 3 parts; the outer cell region, the PCM layer, and the positive-negative regions. Figure 2 shows the sections of the modeled battery.

The battery modeling was done on SolidWorks, the height of the battery was determined as 192 mm, width as 145 mm and thickness as 3 mm. To ensure homogeneous and even heat distribution in the battery, it is modeled with fins. Placing the fins at equal intervals is an important parameter for heat distribution. Figure 3 shows the dimensions of the modeled battery.

The use of PCM in the cooling process ensures that the cell temperature is maintained during high discharge rates of the battery. When the battery needs to cool down, the PCM starts to solidify, releasing heat into the environment. This prevents the battery from overcooling and keeps it at its optimum operating temperature. The use of PCM optimizes the thermal management of the battery and improves battery performance and safety with uniformly distributed heat.

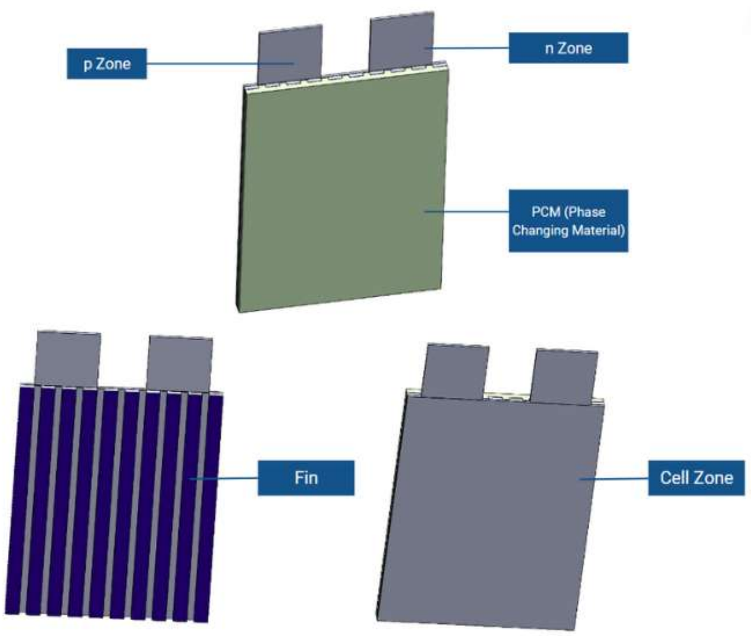

Figure 2. Sodium-ion battery modeling and explanation of battery sections

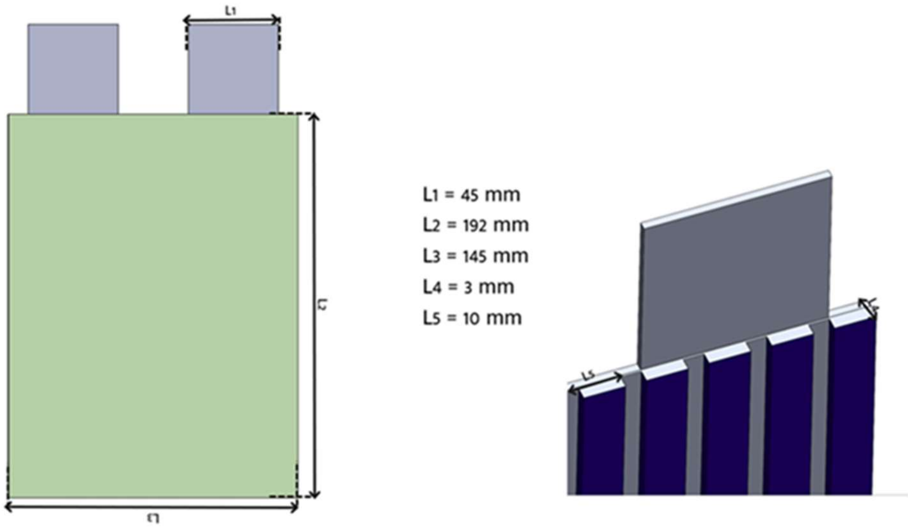

Figure 3. Dimensioning of the sodium-ion battery model

2.2. Modeling of Phase Change Material

In this section, the equations used in the calculations performed by Ansys Fluent in battery thermal management are shared. The equations for the PCM as follows:

In Ansys fluent calculation, the continuity equation including the density, time and velocity parameters is first considered. Equation 1 is the Contunity Equation[12] [19]:

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}.\left(\rho \vec{V}\right) = 0 \tag{1}$$

After the continuity equation, the 3D Navier Stokes momentum equations are considered. Equation 2 is the Momentum (Navier-Stokes) Equation:

$$\begin{aligned} &\text{X- direction : } (\frac{\partial}{\partial t} + \vec{V}.\vec{\nabla})(\rho u) = -\frac{\partial P}{\partial x} + \vec{\nabla}.\left(\mu \vec{\nabla} u\right) + S_x \\ &\text{Y- direction: } \left(\frac{\partial \rho}{\partial t} + \vec{V}.\vec{\nabla}\right)(\rho v) = -\frac{\partial P}{\partial y} + \vec{\nabla}.\left(\mu \vec{\nabla} v\right) + S_y + S_b \\ &\text{Z- direction : } (\frac{\partial}{\partial t} + \vec{V}.\vec{\nabla})(\rho w) = -\frac{\partial P}{\partial z} + \vec{\nabla}.\left(\mu \vec{\nabla} w\right) + S_z \end{aligned} \tag{2}$$

The source terms Sx, Sy, Sz and Sb modify the momentum equation in the porous region with both solid and liquid phases. The source terms S_x , S_y and S_z are functions of the respective velocity components and S_b represents natural convection due to buoyancy[12][19].

Equation 3 shares the general energy equation.

$$\left(\frac{\partial}{\partial t} + \vec{V}.\vec{\nabla}\right)(\rho H) = \vec{\nabla}.(a\vec{\nabla}H) \tag{3}$$

In Equation 4, the shared H represents the total enthalpy value, while H_s is considered as sensible heat and H_f as latent heat [12].

$$H = H_s + H_f \tag{4}$$

The effect of the temperature parameter on the sensible heat considered in the PCM analysis is calculated with the help of equation 5 [12].

$$H_s = H_{ref} + \int_{T_{ref}}^{T} C_p \Delta T \tag{5}$$

The latent heat due to the change of state in the PCM is calculated using equation 6.

$$H_f = f_l L \tag{6}$$

The corrected energy equations calculated with the help of sensible heat and latent heat are presented in equations 7 and 8 [19].

$$\left(\frac{\partial}{\partial t} + \vec{V}.\vec{\nabla}\right)(\rho H_s) = \vec{\nabla}.(a\vec{\nabla}H) \tag{7}$$

$$\left(\frac{\partial}{\partial t} + \vec{V}.\vec{\nabla}\right)(\rho H_s) = \vec{\nabla}.\left(a\vec{\nabla}H_s\right) - S_h \tag{8}$$

The source term S_h for the latent heat used in Equation 8 is calculated by Equation 9 [19].

$$S_h = \left(\frac{\partial}{\partial t} + \vec{V}.\vec{\nabla}\right)\left(\rho H_f\right) \tag{9}$$

2.3. Determination of Analysis Parameters

In this section, the identification and thermal properties of phase change materials will be explained in detail. There are some overriding factors when determining phase change materials. These are as follows:

A. Melting Point: Inorganic hydroxides, inorganic salts and inorganic alloys were determined not to be in the desired melting point range and were ignored.

B. Flammability: Organic polymers type PCMs such as alcohols, fatty acids and esters were disregarded as they are flammable.

C. Corrosion Properties: Inorganic hydroxides, salts and their alloys were discarded due to their poor corrosion properties.

D. Cost: Polymer-type PCMs were ignored due to their high cost.

Considering these features, n-Octadecane, and n-Hexadecane were chosen as PCMs. The properties of n-Octatadecane and n-Hexadecane are shown in Table 1. The PCM region on the designed sodium ion battery model is shown in Figure 4.

Table 1. Properties of selected PCMs (n-Octadecane and n-Hexadecane)

Phase Change Material	Melting Temperature T_m (K)	ΔH_m (J/g)	Solidification Temperature T_c (K)
n-Octadecane [20]	305	204.4 ±11.9	303
n-Hexadecane [21]	310	191.18	272

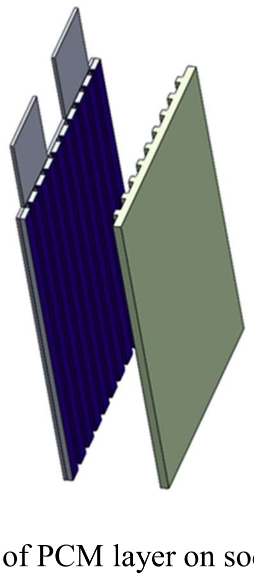

Figure 4. Demonstration of PCM layer on sodium-ion battery modeling

The thermal management analysis of the battery was performed using Ansys 2023/2024 R1 software. Since PCM was used, the overall simulation was performed to analyze the liquid fraction. Specific properties were determined to help simulate the solidification and melting zones within the PCM. The external temperature of the cell was set to 311 K, which corresponds to the operating temperature of the batteries. The maximum battery temperature was set at 333 K. In the study, the environmental temperature was determined as 300 K to keep the effect of ambient temperature constant. The properties of the PCMs and the values set for the analysis are shown in Table 2.

Table 2. Properties of the selected PCMs specified in the analysis

Properties	n-Octadecane [20]	n-Hexadecane [21]
Density [kg/m^3]	721	770
Cp (Specific Heat) [J/(kg.K)	2180	2200
Thermal Conductivity [W/(m.K)]	0.15	0.15
Viscosity [kg/(m.s)]	0.035	0.035
Melting Heat [J/kg]	1900	1980
Solidification Temperature [K]	303	272
Melting Temperature [K]	305	310

2.4. Sodium-Ion Battery Meshing

To perform the analysis of the modeled sodium ion battery on Ansys, the mesh structure of the three-dimensional model must be determined. Determining the mesh structure of the modeled battery is the process of separating the volume of the complex model into small parts where the analysis will take place. Compliance of the mesh structure with standard quality requirements increases the accuracy of the analysis. The battery meshing structure used in the analysis is shown in Figure 5.

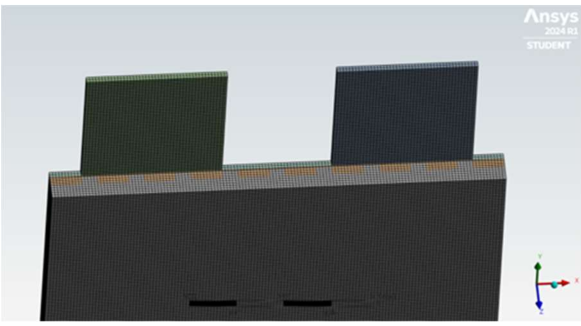

Figure 5. Sodium-ion battery meshing

Orthogonal quality measures the angle between the cell surface and the edges, closer to 90 degrees means better alignment and increases the accuracy of the solution. Minimum values indicate the worst quality value in the network, a low minimum value affects the accuracy of the analysis. The maximum value indicates the best quality cell, it is not as important a criterion as the minimum value. The orthogonal quality shown in Figure 6 is close to 1, indicating that the network quality is high.

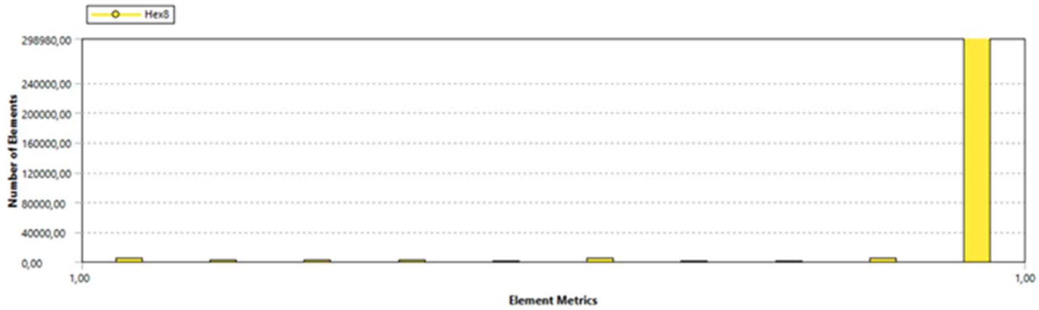

Figure 6. Orthogonal quality representation of the sodium-ion battery meshing

3. RESULTS AND DISCUSSION

Temperature distribution analysis and heat transfer analysis are important for evaluating the performance and reliability of batteries. Temperature distribution analysis is critical to maintain control over the temperature profile inside the battery. A homogeneous temperature distribution indicates uniform heating or cooling in all regions of the battery, while temperature increases or fluctuations in specific regions indicate points of attention in the development of thermal management strategies.

3.1. Thermal Management Analysis Results Using n-Octadecane Phase Change Material

Figure 7 shows the heat distribution of PCM. We can see that the heating process applied as a result of the given external temperature meets the phase changing property of the material. The use of this PCM reduced the temperature rise by 25% on average. In the absence of PCM, the surface temperature of the battery reached 75°C, whereas with the use of n-Octadecane PCM, this temperature decreased to 55°C. This result clearly shows the positive effect of n-Octadecane on thermal management.

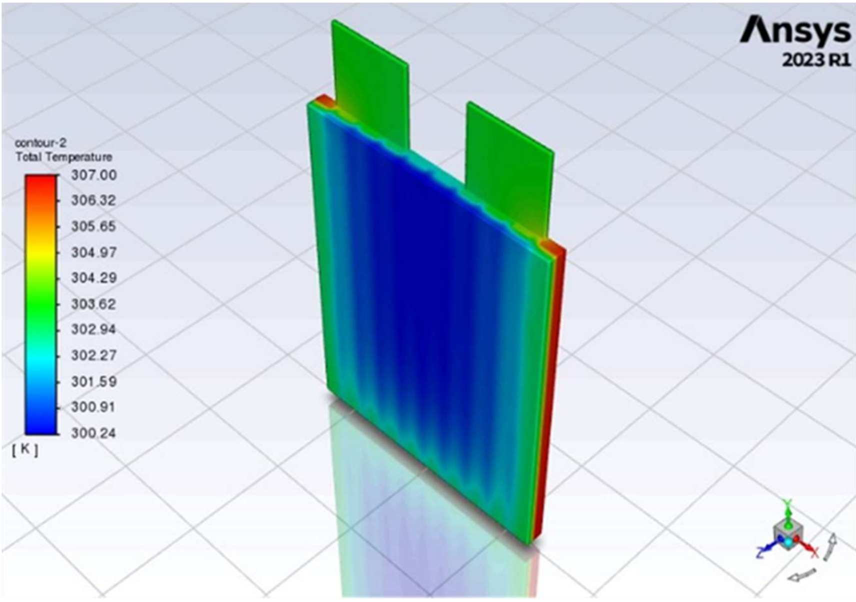

Figure 7. Temperature distribution over PCM

As can be seen in Figure 8, we can see that the edges of the cell are heated, but the thermal energy is effectively dissipated and cooled in the areas in contact with the PCM. Thanks to the heat absorption capacity of the PCM, the temperature of the battery is reduced and thermal fluctuations are stabilized. The n-Hexadecane PCM reduced the temperature rise by an average of 20 per cent. In the absence of PCM, the surface temperature of the battery reached 75°C, while with the use of n-Hexadecane PCM, this temperature decreased to 60°C. This shows that n-Hexadecane is an effective thermal management solution.

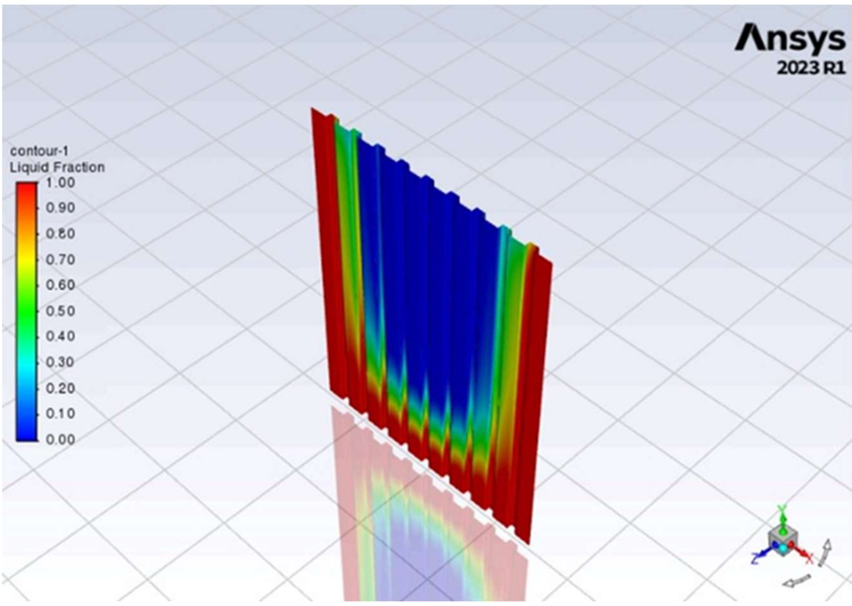

Figure 8. Temperature distribution over battery fin

3.2. Thermal Management Analysis Results Using n-Hexadecane Phase Change Material

In Figure 9, we see the temperature distribution of the battery on the cell region and the PCM. The phase change region has a lower temperature than the cell region and the fin area in contact with the PCM has started to cool down over time. It compares the thermal performance of n-Octadecane and n-Hexadecane PCMs. n-Octadecane PCM achieved a 5% greater temperature reduction than n-Hexadecane.

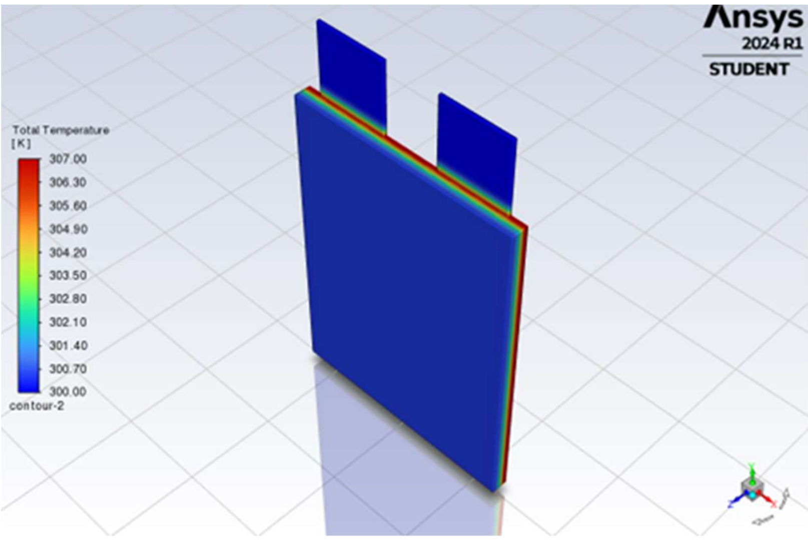

Figure 9. Temperature distribution on the battery model

In this study, n-Octadecane and n-Hexadecane PCMs were selected and their effects on thermal management in sodium-ion batteries were investigated. The results show that both materials are effective in regulating and optimizing the thermal behavior of the battery.

The temperature distribution analysis emphasizes the control of the temperature distribution inside the battery. It is observed that a homogeneous temperature distribution can be achieved with the use of both PCMs. While this indicates that heat dissipation occurs equally in all regions of the battery, the temperature distribution in certain regions should be taken into account in the development of thermal management strategies.

When the graphs of n-Octadecane and n-Hexadecane materials are examined, we can see that they increase linearly over time, while the PCM completely melts. The temperature increases seen in the graphs show how the battery heats up between high discharge rates. However, it was observed that both materials warmed up steadily and the specified temperature tolerances were not exceeded. This shows that the thermal stability of the battery is ensured.

4. CONCLUSIONS

This study investigated the thermal management of sodium-ion batteries using two different PCMs. Using PCMs selected as n-Octadecane and n-Hexadecane, the efficiency and performance of PCMs in maintaining the optimum battery temperature were evaluated.

- Both PCMs provided a uniform temperature distribution within the battery. This uniformity is critical for longevity and efficiency of battery performance.
- The use of PCM helped to dissipate heat effectively. The temperature in areas in contact with the PCM remained consistently lower compared to other areas.
- Both n-Octadecane and n-Hexadecane showed a constant temperature rise without exceeding the established tolerance limits, indicating good thermal stability.
- n-Hexadecane has a slightly higher melting temperature compared to n-Octadecane (310 K versus 305 K). This may make n-Hexadecane more suitable for applications requiring higher temperature tolerance.
- n-Octadecane solidifies at a higher temperature compared to n-Hexadecane (303 K versus 272 K), which helps n-Octadecane to release stored heat faster and cool faster.

Both n-Octadecane and n-Hexadecane are effective in managing the thermal profile of sodium-ion batteries, improving safety and performance. n-Octadecane provides better heat absorption and rapid heat release due to its higher latent heat of melting and higher solidification temperature, while n-Hexadecane offers slightly better stability at higher temperatures due to its higher melting point. The choice between these PCMs can be made depending on specific application requirements such as operating temperature ranges and desired cooling efficiency.

This study highlights the potential of using PCMs to improve the thermal management of sodium-ion batteries, contributing to their wider acceptance in industrial applications and enabling the advancement of sustainable energy storage solutions.

NOMENCLATURE

Li	Lithium
Na	Sodium
p	Positive
n	Negative
PCM	Phase Change Material

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DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Utku Cancı Matur: Writing, Investigation, Editing, Project Administration

Cansu Tüysüz: Analysis, Methodology, Writing

Ali Köse: Analysis, Methodology, Editing, Investigation

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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