Thermal Management System Using Phase Change Material for Lithium-ion Battery

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Abstract. The lithium-ion battery is promising energy storage that provides proper stability, no memory effect, low self-discharge rate, and high energy density. During its usage, batteries generate heat caused by energy loss due to the transition of chemical energy to electricity and the electron transfer cycle. Consequently, a thermal management system by cooling methods in the battery is needed to control heat. One of the cooling methods is a passive cooling system using a phase change material (PCM). PCM can accommodate a large amount of heat through small dimensions. It is easy to apply and requires no power in the cooling system. This study aims to find the best type of PCM criteria for a Lithium-ion battery cooling system. The research was conducted by simulations using computational fluid dynamics. The variations were using PCM Capric Acid and PCM Hexacosane, with thickness variations of 3 mm, 6 mm, and 9 mm. Hexacosane PCM with 9 mm thickness indicates the best result to reduce heat up to 6.54°K, demonstrating a suitable passive cooling system for Li-ion batteries.

1. Introduction
Lithium-ion (Li-ion) batteries are promising candidates among types of batteries [1]. Lithium-ion is known for its preferable stability, no memory effect, low self-discharge rate, and high energy density [2]. In electrochemical batteries, modules and battery packs generate a certain amount of heat during discharge [3]. This phenomenon occurs due to electrochemical exothermic reactions and ohmic heat effects. The ineffectively removed heat accumulates and causes an increase in battery temperature. This excessive heat decreases the battery cycle performance, lifetime, safety factor and causing battery thermal runaway [4]. The thermal runaway is known as the process of a sudden and uncontrolled increase in battery temperature followed by a sudden voltage drop [5]. Thus, battery thermal management is needed to control its heat, minimize the risk of damage, and increase the safety factor for Li-ion batteries.

One of the thermal management methods is, passive cooling system. The thermal management cools down outside the battery, with low additional equipment needed (pumps, compressors, pipes). This study focuses on the use of passive cooling in batteries using phase change materials (PCM). PCM is a material that undergoes a phase change and uses its chemical bonds to absorb and release heat. The PCM at room temperature can be in solid form. Once the temperature gets high, the PCM absorbs the excess heat until its melting point. At this high temperature, the PCM changes to a liquid melting phase, then retreat to solid when the temperature reverts to normal. Besides integrating the system, PCM as a passive cooling system is also an efficient, easy to maintain, long-term, low price,
good heat distribution, and dissipation. To get an optimum PCM for batteries, a passive cooling system, preferable type, and thickness of PCM are needed [6].

Verma. et al [7] performed passive cooling methods using PCM (Capric acid) on a battery management system. In this study, PCM (Capric acid) is used to decrease the battery temperature and enhance the uniformity of temperature in the battery. Therefore, the PCM can avoid any localized heat that causes battery damage and safety problem. The result demonstrates that PCM could absorb the peaks of extreme temperatures and improve the uniformity of temperature distribution in the battery. On the other hand, Al hallaj and Selman [8] proposed the PCM-based battery cooling system (BCS) using a paraffin mixture of hexacosane. The result suggests that the PCM have changed phases between solid and liquid and cooled the Li-ion cylindrical batteries

Accordingly, Two PCM-based BCS using capric acid and hexacosane are applied in this research. The heat transfer and temperature change on the battery are investigated. The objective of this study is to provide an effective passive cooling method for a battery thermal management system using phase change material

2. Methodology

2.1. Heat absorption
The heat absorption process of the PCM occurs through the energy equation below [9]:

\[ \frac{\partial (\rho_{PCM} H)}{\partial t} = \nabla (K_{PCM} \nabla T) + s_h \]  

\[ H = h + \Delta H \]  

\[ \Delta H = \beta H \]  

\[ \beta = 0, T > T_m \]  

\[ \beta = 1, T < T_m \]  

Where \( s_h \) is heat generation rate, \( H \) for the PCM enthalpy, \( \Delta h \) for PCM latent heat, \( h \) for PCM sensible heat, \( K_{PCM} \) as thermal conductivity PCM, \( \rho_{PCM} \) as PCM density, \( \beta \) for the PCM liquid fraction, and \( T_m \) as melting temperature or namely liquidus temperature.

Equation (1) support the possible total of absorbed heat by the PCM. Indeed, the high absorbed heat of the PCM occurs on the PCM with a high value of melting temperature, density, specific heat, and thermal conductivity. These conditions can be used as a reference for choosing a good PCM.

2.2. Simulation set-up for the thermal management
In the simulation set-up, the stages are formation of battery geometry (shows on Figure 1), meshing, set-up the boundary condition and entering the required data during simulation and post-processing in the form of contours and plots of temperature graphs on the battery.
**Figure 1.** Battery Geometry (a) Without PCM (b) Thickness of 3 mm, (c) Thickness of 6 mm, (d) Thickness of 9 mm

The simulation of the geometry using boundary conditions as written on Table 1

| Boundary Condition | Information |
|--------------------|-------------|
| MSMD Battery Model | Cell Capacity 2 Ah |
|                    | C-rate 3 |
|                    | Initial DoD 0 |
| Battery Material   | Density (constant) 2604.92 Kg/m³ |
|                    | Speisific Heat (constant) 894 J/Kg°K |
|                    | Thermal Conductivity 1.035 |
| Outer Wall (Battery and PCM) | Convection h = 7 W/m²K |
|                    | Free Stream Temperature 306 °K |
|                    | Heat Generation Rate 181466.2 W/m³ |

2.3. **Numerical Solution**

The numerical solution of this thermal management study is using Computational Fluid Dynamics to perform and analyze heat transfer and its fluid flow of battery cooling system. The first stage start with meshing, which dividing geometry into small element of volume control for the mathematical calculation. Tetrahedral mesh type is used in this study, for the main mesh construction. The boundary conditions are determined after the meshing process. The outer wall of the battery cell simulation is set as free convection boundary conditions, with the heat transfer coefficient as written on Table 1 of 7 W/m²K.

2.4. **Validation**

Validation is done by comparing the obtained simulation results and the experimental results [10]. The experiment uses a battery with the same models, type, and voltage, namely Li-ion type 18650 with a
voltage of 3.7 Volt. These experiments produce a visualization of battery temperature with a set-up discharge rate (C-rate) of 3.5. Based on the experimental results, the maximum temperature of the battery is 55.4°C, while the maximum temperature from the simulation is 323.9°K or 50.75°C. The error calculation reached was 8.3%.

3. Result and Discussion

3.1. Analysis of the ambient temperature effect on the cooling process

The variation is to change the ambient temperature of the battery and PCM to determine the effect of environmental conditions on the passive cooling process. The temperature variation is done by changing the ambient temperature to be higher than the temperature in the previous simulation (306°K) to 325°K (51°C). The graph of the maximum temperature drop of the battery is depicted in Figure 3.

![Figure 2. Validation with –rate of 3.5 a) Experiment result [10] b) Simulation result](image)

It was found that PCM under extreme ambient conditions was able to lower the temperature greater than under normal condition. But, PCM was not able to keep the battery temperature below the operating temperature recommended by the manufacturer, which is 323°K (50°C). This result is similar to a previous study [7], which showed a better temperature reduction performance when the PCM was in extreme environmental temperature conditions but was unable to keep the battery temperature below 323°K (50°C).

The above result is then compared with the decrease in battery's normal ambient temperature (306°K), which is presented in Table 2.
Table 2. Decrement of Battery Temperature with Variation of Ambient Temperature

| Variation of Ambient Temperature | PCM Thickness of 3 mm | PCM Thickness of 6 mm | PCM Thickness of 9 mm |
|----------------------------------|-----------------------|-----------------------|-----------------------|
| Normal (306°K)                   | 1.39°K                | 2.26°K                | 2.84°K                |
| Extreme (325°K)                  | 3.26°K                | 3.95°K                | 4.39°K                |

3.2. Analysis of the effect of PCM type variations

The variation is to change the type of PCM used as passive cooling in the battery, the type of PCM used is Capric Acid (CH$_3$(CH$_2$)$_8$COOH) and Hexacosane as a comparison.

![Figure 4](image)

Figure 4 demonstrates that Hexacosane PCM can reduce battery temperature better than Capric Acid PCM at the same thickness. At a thickness of 3 mm, Capric Acid can reduce the maximum battery temperature by 1.39°K, while Hexacosane PCM can reduce the maximum temperature by 2.26°K. At a thickness of 6 mm, Capric Acid can reduce the maximum temperature of the battery by 2.26°K. At the same time, the Hexacosane type PCM is able to reduce the maximum temperature of 3.37°K. And at a thickness of 9 mm, Capric Acid is able to reduce the maximum temperature of the battery by 2.84°K. Meanwhile, Hexacosane PCM can reduce the maximum temperature by 6.54°K. Furthermore, the cooling effectiveness for each PCM thickness is calculated as shown in Table 3.

Table 3 Cooling Effectiveness of Hexacosane PCM

| Thickness variations | Cooling Effectiveness |
|----------------------|----------------------|
| 3 mm                 | 0.15                 |
| 6 mm                 | 0.22                 |
| 9 mm                 | 0.43                 |
Based on these results, it can be concluded that 9 mm Hexacosane PCM has the highest cooling effectiveness value compared to other PCM thickness variations. These results are similar to [6], the PCM with the best cooling effectiveness value is the PCM with the greatest thickness by showing better cooling of the battery.

3.3. Analysis of the effect of thickness variations

The thickness variation of the PCM for the passive cooling in the battery, using the type of PCM used is Capric Acid (CH₃(CH₂)₈COOH) with variations in the thickness of 3 mm, 6 mm, and 9 mm.

![Figure 5](image.png)

**Figure 5.** Battery contour temperature (a) without PCM, (b) thickness of 3 mm (c) thickness of 6 mm (d) thickness of PCM 9 mm.

Based on Figure 5, it shows that a battery without PCM has a maximum temperature of 321°C. In contrast, a battery using a PCM passive cooling system shows a maximum decrease in temperature. A battery that uses a PCM with a thickness of 3 mm has a maximum temperature of 320°C. In comparison, a battery that uses a PCM with a thickness of 6 mm has a maximum temperature of 319°C, and a PCM with a thickness of 9 mm has a maximum temperature of 318°C.

3.4. Phase Change Analysis on Hexacosane PCM

PCM Hexacosane specification data shows a solidus temperature of 327 °K and a liquidus temperature of 329 °K. It means that when the surrounding temperature of the battery exceeds 327 °K, Hexacosane PCM starts to experience a phase change. Between 327 °K and 329 °K, Hexacosane PCM is in a phase between solid and liquid.

Based on the simulation results, it is found that the maximum temperature of the battery only reaches 321°C, so the Hexacosane PCM material has not yet experienced a phase or form change because the solidus temperature of the battery is 327°C. Based on this analysis, PCM Hexacosane at the time of the simulation had not yet changed its form. As an illustration of how PCM changes the phase or form of the Hexacosane PCM, the thick red line shows the maximum temperature of the simulated battery (Figure 6). In contrast, the black line shows the pattern of the Hexacosane PCM phase change to changes in temperature and time.
4. Conclusion
The simulation result concluded that as the thickness of the PCM increases, the decrease in battery temperature also increases. This is because the greater the volume and mass of the PCM increase the value of heat absorbed by the PCM from the battery. When examined in terms of heat transfer, a good PCM criterion is PCM, which has a large value of melting temperature, density, specific heat, and thermal conductivity. The PCM can absorb and store heat with large values. PCM Hexacosane has better cooling performance than PCM Capric Acid. PCM Hexacosane with a thickness of 9 mm can reduce the maximum battery temperature by 6.54°K. In comparison, PCM Capric Acid with a thickness of 9 mm can only reduce the maximum temperature of the battery by 2.84°K. 9 mm thick PCM has the best cooling effectiveness due to Hexacosane PCM has higher melting temperature, density, specific heat, and thermal conductivity values than Capric Acid PCM. Hexacosane PCM is better at absorbing and releasing heat since the thickness of the PCM is also more efficient. Therefore, the authors suggest Hexacosane PCM with a thickness of 9 mm as a reference for passive cooling systems in batteries.

5. References
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