



Master Thesis

Numerical Study on Thermal Performance of Phase Change Materials in a Lithium-Ion Battery

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Numerical Study on Thermal Performance of Phase Change Materials in a Lithium-Ion Battery

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Numerical Study on Thermal Performance of Phase Change Materials in a Lithium-Ion Battery

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ABSTRACT

The thermal performance of a large format (52.3 Ah) Li-ion pouch battery by PCM (noctadecane) is investigated. A simplified 1D model was employed to estimate the transient thermal behavior. Two design parameters such as the thickness and thermal conductivity of PCM are considered. 0.5 mm-thickness PCM, especially, n-octadecane integrating with aluminum foams reduced battery temperature to 34.3 °C and 50.7 °C at the end stage of discharging under 3C and 5C discharge rates, respectively. The 1D results compared to the three-dimensional results were enough to predict the temperature dissipation by PCM method at the end of discharging. 1D approach demonstrated evidently that it produces reliable results in predicting thermal behavior of PCM cooling and is superior in practical application with low cost and less time-consuming. Nevertheless, 3D CFD simulation has a capacity to give the detailed temperature uniformity in a cell, which is important factor to design and evaluate a battery cooling system. The cooling performance of fan and PCM-MF was considered to orient to practical applications. The use of four fans (9,000 rpm) can give a similar effective to the use of one fan (5,000 rpm) integrating PCM-MF.

Keywords: lithium-ion battery; phase change material, large format cell, electric vehicle

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NOMENCLATURE

Nomenclature

Α	Surface area (m ²)	t	Time (s)
A_1	Correlation constant (0.35)	Т	PCM temperature (K)
С	PCM specific heat (J/kg·K)	T_a	Environment temperature (K)
C_b	Battery specific capacity (J/kg·K)	T_b	Battery temperature (K)
d	PCM thickness (m)	T _{liquidus}	Liquidus temperature of PCM (K)
DOD	Depth of discharge (%)	T _{solidus}	Solidus temperature of PCM (K)
Ε	Open-circuit voltage (V)	U	Terminal voltage (V)
Н	Enthalpy (J/kg)	V_n	Nominal capacity (V)
Ι	Current (A)	ν	Velocity (m/s)
j	Volumetric transfer current density (A)	x	Distance (m)
k	PCM thermal conductivity (W/m·K)	X _{fa}	Volume ratio of fibers to brush
k _b	Battery thermal conductivity (W/m·K)	Greek lette	rs
k _{eff}	Effective thermal conductivity of PCM composite (W/m·K)	α	Thermal diffusivity (m ² /s)
k _f	Thermal conductivity of carbon $(W/m \cdot K)$	β	Liquid fraction
k _{l,eff}	Composite thermal conductivity in liquid state $(W/m \cdot K)$	ε	Porosity
k _{l,PCM}	PCM thermal conductivity in liquid state (W/m·K)	ΔH	Latent heat (J/kg)
k _m	Thermal conductivity of paraffin $(W/m \cdot K)$	ρ	PCM density (kg/m ³)
k _{s,eff}	Composite thermal conductivity in solid state $(W/m \cdot K)$	$ ho_b$	Battery density (kg/m ³)
k _{s,PCM}	PCM thermal conductivity in solid state (W/m·K)	σ_+	Effective electric conductivity for the positive electrode $(1/\Omega)$
k _{MF}	Metal foam thermal conductivity $(W/m \cdot K)$	σ_	Effective electric conductivity for the negative electrode $(1/\Omega)$
L	Latent heat of material (J/kg)	φ_+	Phase potential of the positive electrode (V)

m_b	Battery mass (kg)	φ	Phase potential of the negative electrode (V)
Nu	Nusselt number	Superscrip	t
Pr	Prandtl number	j	Quantity of interest at the present time level
q_b	Overpotential heat rate (J/s)	<i>j</i> + 1	Quantity of interest at the new time level
q_{irr}	Irreversible heat rate (J/s)	Abbreviatio	ons
q_{PCM}	Heat rate through PCM (J/s)	1D	One-dimensional
q_{rev}	Reversible heat rate (J/s)	3D	Three-dimensional
Q	Discharged battery capacity (Ah)	BTMS	Battery thermal management system
Q ₀	Fully charged battery capacity (Ah)	C-rate	A measure of the rate at which a battery is discharged relative to its maximum capacity
Q_n	Nominal capacity (Ah)	CFD	Computational fluid dynamics
R	Internal resistance (Ω)	Li-ion	Lithium-ion
R _{cas}	Thermal resistance of aluminum case (K/W)	NCM523	$LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$
R _{conv}	Thermal resistance for convection (K/W)	NTGK	Newman, Tiedemann, Gu and Kim
R _{int}	Thermal contact resistance (K/W)	PCM	Phase change material
Ra	Rayleigh number	PCM-CF	Phase change material and carbon fiber
S	Source term	PCM-EG	Phase change material and expanded graphite
SOC	State of charge (%)	PCM-MF	Phase change material and metal foam

1. INTRODUCTION

1.1 Overview of Li-ion battery

1.1.1 Li-ion battery demand

After a decade of rapid growth, in 2020 the global electric car stock hit the 10 million mark, a 43% increase over 2019, and representing a 1% stock share. Energy storage system plays an important role in pure EV and hybrid EV industry, such as fuel cells, batteries, flywheels, ultracapacitors. In the market, there are three leading battery types: Li-ion, lead-acid and nickel-metal hydride. Especially, lithium-ion battery is a potential candidate with outstanding features, including low self-discharge rate, high specific energy, fast charging capacity and no memory effect [1].



Figure 1.1 Li-ion battery demand by region for the 2015 - 2020 period.

Figure 1.1 shows that automotive lithium-ion battery production was 160 GWh in 2020, up 33% from 2019. Battery production continues to be dominated by China, which accounts for over 70% of global battery cell production capacity. China accounted for the largest share of battery demand at almost 80 GWh in 2020, while Europe had the largest percentage increase at 110% to reach 52 GWh. Demand in the United States was stable at 19 GWh. It has

been acknowledged that Li-ion batteries have become one of the most important components for the new generation of EVs.

1.1.2 Types of Li-ion battery

Basically, there are four main types of mainstream lithium battery structures, namely, button, cylindrical, rectangular and pouch cells, as shown in Fig. 1.2. Different lithium battery structure means different characteristics, and each has its own advantages and disadvantages.

Button cells are very small and light, great for small and low-power devices. They are also fairly safe, have a long shelf life and fairly inexpensive per unit. However, they are not rechargeable and has high internal resistance so it can't provide a lot of continuous current. The key advantage of prismatic cells lies in its ultra-thin profile, light in weight, effective space utilization and high battery energy density. But they are very expensive for the consumers and has a short life.



Figure 1.2 The structure of four categories.

Cylindrical cells have relatively low cost. However, the vehicle manufacturers have put forward higher requirements on the energy density, manufacturing cost, cycle life. Pouch cell is packaged in aluminum plastic film. When a safety problem occurs, the pouch cell will generally be blown apart. The pouch cell offers a simple, flexible and lightweight solution to battery design. Moreover, the pouch cell makes the most efficient use of space and achieves $90\% \sim 95\%$ packaging efficiency, which is the highest among battery packs. Eliminating the metal enclosure reduces the total cell weight, but additional support and allowance for swelling must be made.

1.1.3 Electrochemical fundamentals

The separator prevents electrons from flowing but allows positive and negative ions to migrate between the two electrodes through the electrolyte, as shown in Fig. 1.3. The positive and negative current collectors provide a pathway for electrons to flow through an external circuit.

During discharging, the negative electrode is the anode and the positive electrode is the cathode. Positive ions move from the anode to the cathode through the electrolyte and separator. Negative ions move in the opposite direction. The anode builds up negative charge and the cathode builds up positive charge, creating the cell voltage. Negatively charged electrons flow through an external load from the anode to the cathode, creating a current in the opposite direction.



Figure 1.3 Schematic diagram of a Li-ion cell under discharge and charge.

During charging, the negative electrode material dissolves in the electrolyte solution to

form a positive ion and an electron in what is called an oxidation reaction. The positive electrode consumes electrons by depositing positive ions from the electrolyte in what is called a reduction reaction. The ions move through the electrolyte under diffusion and migration. Diffusion results from the existence of a concentration gradient in the electrolyte. The positive ions migrate toward the negative electrode and the negative ions migrate toward the positive electrode. The movement of ions through the electrolyte and electrons through the external circuit enable the storage and release of energy.

1.2 Battery thermal management system



Figure 1.4 Classification of BTMS.

The internal electrochemical reactions and resistances in its cells produce a considerable amount of heat. This results in fairly high and non-uniform cell temperatures when it is charged and discharged. The optimal operating temperature of a Li-ion battery ranges from 25 °C to 40 °C [2]. In addition, the maximum temperature difference within a cell should be less than 5 °C to maintain a balance between its life cycle and efficiency [3]. When the maximum temperature is higher than 80 °C, thermal runaway could happen and exothermic reactions will occur, eventually leading to catastrophic results [4]. Various thermal management strategies have been proposed, which can be classified into the active (air and liquid cooling),

passive (phase change material (PCM) cooling and heat pipes), and hybrid methods, as shown in Fig. 1.4.

Chen et al. [5] optimized the distance between cells to improve the air cooling performance, whereby the maximum temperature of the battery pack was decreased by 4 K and the maximum temperature difference was decreased by 69%. It is nearly impossible to use natural air to cool down the battery individually. Because the air has small thermal conductivity, small heat capacity, forced convection can be used at rather low temperatures with simple devices. To achieve a similar performance of liquid cooling, the mass flow rate of air should be increased. Figure 1.5(a) shows the air cooling system using in Prius family.



(a)

(b)

Figure 1.5 (a) Air cooling system in Toyota's Prius; (b) GM's Chevrolet Votl uses liquid cooling system interwoven with battery cells.

Under uphill conditions (high heat generation and/or a high discharge rate), liquid cooling may be required to sufficiently dissipate the thermal energy, as seen in Fig. 1.5(b). Shang et al. [6] achieved the best performance of liquid cooling when the width of the cooling plate was 70 mm, the inlet had a temperature of 18 °C, and the mass flow rate was 0.21 kg/s. In that setup, the maximum temperature was decreased by 12.61% and the temperature uniformity was increased by 20.83%. Active BTMS based on the liquid can be categorized as the direct contact mode and the indirect contact mode.

- Direct contact mode: The battery surface is always directly immersed in the liquid. This method is not practical, but it has a high heat transfer efficiency.
- Indirect contact mode: The core concept is conducting heat to outer space by setting a plate exchanger or tube exchanger onto the surface of battery. This method is more practical and commonly used in commercial EVs due to its safety and stability.

PCMs have been shown to greatly improve the temperature uniformity of Li-ion batteries. As seen in Figure 1.6(a), AllCell's passive thermal management technology is based on the use of phase change composite to surround each cell, absorbing and conducting heat away. Wang et al. [7] showed that the melting process can be sped up by using a paraffin/aluminum foam composite. Compared to pure paraffin, the heat storage time of that composite PCM was 74.4% when the heat flux was 12,000 W/m². Jilte et al. [8] proposed the best design with seven cells, seven primary containers, and one secondary container. At the environment temperature of 40 °C, the use of a nanoparticle-enhanced PCM (nePCM) can reduce the temperature of a cell to under 46 °C with the effect of natural convection. It is not sufficient for pure PCM to transfer heat from the batteries to outer space due to its low heat conductivity. Many kinds of composite phase change materials are designed for heat transfer enhancement to solve this problem. Usually, the thermal conductive enhancement materials used in pure PCM are metal foam, graphite and carbon fiber. Moreover, the enhancement method like attaching fins on the surface of battery cells is also adopted in PCM-based BTMS enhancing heat transfer due to the larger contact area.

The working principle of a heat pipe is simple: working medium evaporates at the heating side (heat source) and condenses at the cooling side (heat sink). Heat pipes are employed as effective systems to maintain homogeneity on the evaporator surface at a constant temperature while having high thermal conductivity. Putra et al. [9] investigated the cooling capacity of alcohol, acetone and distilled water at a heat flux load of 1.61 W/cm². They

demonstrated that acetone is a potential candidate with a thermal resistance of 0.22 W/°C and an evaporator temperature of 50 °C. For the hybrid method, Yang et al. [10] studied the thermal performance of a battery thermal management system (BTMS) integrated with minichannel liquid cooling and air cooling. At 80% depth of discharge (DOD), the maximum temperature and the temperature difference were decreased by 11.12 K and 9.52 K, respectively, when the water flow rate increased by 2.2×10^{-4} kg/s. If the air velocity increased from 0 to 4 m/s, the battery temperature was reduced by 2.22 K, and the temperature uniformity was decreased by 2.04 K. Figure 1.6(b) shows the heat pipe technology of Miba group with high thermal conductivity.



Figure 1.6 (a) The use of PCM of AllCell Technologies; (b) The heat pipe cooling system of Miba group.

Kiani et al. [11] designed a hybrid thermal management system with a nanofluid integrating metal foam and a PCM. Compared to water cooling, the nanofluid with volume fraction of 2% increased the operating time of the battery by 29% at a Reynolds number of 420. Jilte et al. [12] investigated heat dissipation in cylindrical batteries with liquid channels and a PCM. At an environment temperature of 40 °C, the surface temperature of the battery was kept under 43 °C if the PCM was applied, and under 41.2 °C if the PCM and liquid channels were used simultaneously. It is well known that each strategy has its strength and weakness. Depending on the desired effectiveness, the BTMS can be applied either alone or

in combination, but it should meet several criteria: high reliability, easy maintenance, low power consumption, and insignificant mass.

1.3 Overview of PCM

1.3.1 PCM selection

There are several selection considerations to PCM applications, such as:

- The melting point of the PCM must be both below the temperature of the heat source and above the ambient conditions to which the device will be exposed.
- The latent heat of fusion: how much energy can be stored in a specified mass of material during melting.
- Should exhibit stability, both chemically and physically over repeated thermal cycling with repeatable and consistent melting cycles.
- Have a high thermal conductivity to prevent thermal bottlenecking at the source. It is challenging to find materials that have both high latent and specific heats as well as high thermal conductivities.

1.3.2 Types of PCMs

PCMs are listed in three main classifications: organics, inorganics and metals.

- Organics: are the most popular, available, relatively inexpensive and easy to work with; include a wide range of PCMs: the alkane family (paraffin) C_nH_{2n+2}, the fatty acids family CH₃(CH₂)_{2n}COOH; the melting range of materials tend to be from 35 °C to 70 °C.
- Inorganics: are commonly used in high and extremely high temperature ranges (don't overlap with those of organics), corrosiveness, tend to dehydrate as the water is driven off during the heating cycles, leading to breakdown of the material itself; include the

salts and salt hydrates; are widely used in solar energy applications; a wide range of operating point from 10 °C to 900 °C.

• Metal and metal alloy: are perhaps the most underused of all the common PCM families due to the low latent heat; have the high thermal conductivities and the physical and chemical stability at high temperatures; melt temperature range: Cesium and Gallium can melt at ambient conditions on a warm day (28.65 °C and 29.8 °C respectively), while magnesium melts at 648 °C and aluminum melts at 661 °C, and custom alloys can create tailored melt points for specific applications.

1.4 Study of battery cooled by PCM

Different numerical modeling approaches have been to used investigate the thermal behavior of Li-ion batteries. They vary from 1D thermal models without thermal interaction among the cells, to complex 3D thermal models which consider non-isothermal and heat generation rates. Jollyn et al. [13] developed a 1D transient battery model based on daily cycles such as 12 min and 72 min. They found that a proper PCM thickness was 1.75 mm when the maximum temperature decrease was 12.9 °C. Greco et al. [14] performed simplified battery thermal management using a PCM/compressed expanded natural graphite (CENG) composite. Their 1D solutions were in good agreement with their 3D results. Hallaj et al. [15] successfully demonstrated that the maximum temperature at the core of a battery pack was 80 °C with a small temperature variation of 3 °C at a 10-A discharge rate. Furthermore, they designed a battery pack integrating a PCM matrix with a significant decrease in charge time and weight for plug-in hybrid vehicles.

In the field of Li-ion battery research, for a 1D model, Hallaj et al. [16] developed a transient-state battery prototype with a thermally homogenous domain. An example is the Sony US18650 battery, which can be scaled up to a Li-ion cell of 100 Ah capacity in safe

operating conditions. Sato et al.[17] categorized the heat-generating factors of reaction in a battery as reaction heat, polarization heat, and joule heat. Yi et al. [18] estimated temperature variations over time from electrochemical reactions and ohmic heat. They found that under a constant discharge rate, the potential density on the electrodes is a function of discharge time. Akeiber et al. [19] predicted the heat storage capacity of a PCM of paraffin (40% oil and 60% wax) by solving a 1D numerical model. Fortunato et al. [20] obtained a 2D solution for different temperature profiles and total melting times with a PCM. Samar et al. [21] investigated 2D melting procedures for paraffin wax in ANSYS Fluent software, and showed that a PCM container induced a faster melting process.

1.5 Objectives

A single cell was picked up from battery pack to:

- Investigate the effect of PCM thickness and thermal conductivity on thermal management performance by 1D calculation.
- By using the NTGK model, the 3D simulations are compared to 1D calculations.
- Evaluate the cooling performance of fan and PCM on a battery pack (3 cells).

2. METHOD

A Li-ion battery with a 52.3-Ah pouch cell made by SM Bexel Co., Ltd. (Korea) was used here. A 2.3-mm-thick aluminum envelope covered the active zone, and the other fundamental characteristics of the battery are listed in Table 1.

Parameter	Value	Unit	
Width \times height \times thickness	$0.249 \times 0.227 \times 0.008$	m	
Nominal voltage, V_n	3.75	V	
Nominal capacity, Q_n	52.3	A.h	
Electrical conductivity, σ_+	$3.77 imes 10^7$	S/m	
Electrical conductivity, σ_{-}	$5.96 imes 10^7$	S/m	
Thermal conductivity, k_b	25.5	$W/m \cdot K$	
Specific heat, c_b	566	J/kg·K	
Density, ρ_b	2,695	kg/m ³	
Internal resistance, R	$6.1 imes10^{-4}$	Ω	
Positive electrode	Aluminum - NCM523		
Negative electrode	Copper - Graphite		
Electrolyte	Polyethylene		

 Table 2.1 Battery specifications.

Using the same battery model, previously, Ho et al. [22] conducted CFD simulations to study the performance of the air cooling method with fans. The maximum temperature in cells can decrease by 64.3 °C under 5C discharge condition, from 114 °C to 49.7 °C. Additionally, the performance of the liquid cooling method with various water channel profiles at the bottom of the battery pack was investigated. However, it demonstrated that the cooling performance was not desirable and resulted in considering PCM for further cooling capacity.

The melting point is the primary criterion when selecting a PCM. It must be both lower than the heat source temperature and higher than the ambient environment to which the system will be subjected [23]. For systems that are designed preferentially for thermal management, the usual advice is to choose a PCM with the highest possible melting point that is considerably below the desired thermal control point (40 °C). Based on our literature review, n-octadecane was suitable for this study with its $T_{solidus} = 301.15$ K (solidus temperature) and $T_{liquidus} = 303.15$ K (liquidus temperature). Its main properties are summarized in Table 2.

Doromotor	Solid phase	Mushy zone	Liquid phase	
	T < T _{solidus}	T _{solidus} < T < T _{liquidus}	$T > T_{liquidus}$	
Density, ρ (kg/m ³)	814	769	724	
Specific heat, c (J/kg·K)	2,150	225,000	2,180	
Thermal conductivity, $k (W/m \cdot K)$	0.358	0.255	0.152	
Pure solvent melting heat, L (J/kg)		225,000		

Table 2.2 The material properties of n-octadecane.

2.1 One-dimensional mathematical model

In this study it was assumed that heat transfer only took place through the side surfaces since the battery was thin (8 mm). In such cases, thermal behavior can be estimated in a cell without considering the thermal interaction among the cells [13]. Bernardi et al. [24] reliably predicted cell temperature and heat generation by a 1D model and proposed a simplified overpotential heat form taking into account irreversible and reversible heat:

$$q_b = q_{irr} + q_{rev} \tag{2.1}$$

$$q_{irr} = RI^2 \tag{2.2}$$

$$q_{rev} = -IT_b \frac{\partial E}{\partial T_b} \tag{2.3}$$

The battery is assumed to be a uniform heat source. Joule losses cause the irreversible heat

are always positive values. As seen in Eq. (2.2), this term is calculated with current through the battery and linear with the internal resistance. Figures 2.1 and 2.2 display experimental measurement of currents over time, which are provided by Bexel company.



Figure 2.1 Measured electric current through the battery under 3C discharge rate.



Figure 2.2 Measured electric current through the battery under 5C discharge rate.

The DOD is the percentage of the battery capacity that has been discharged from the fully charged battery as presented in Eq. (2.4). An alternative form of DOD is the state of charge (SOC), wherein 0% refers to a fully discharged battery and 100% refers to a fully charged battery, as shown in Eq. (2.5) and Fig. 2.3(a).

The open-circuit voltage is determined from the terminal voltage by Eq. (2.6). The entropic heat coefficient which is estimated in Eq. (2.7), is the derivative of the open-circuit voltage with respect to battery temperature, as shown in Fig. 2.3(b).

$$DOD = (Q/Q_0) \cdot 100$$
 (2.4)

$$SOC = 100 - DOD \tag{2.5}$$

$$E = U + I \cdot R \tag{2.6}$$

$$\frac{\partial E}{\partial T_b} = \frac{E^{j+1} - E^j}{T_b^{j+1} - T_b^j} \tag{2.7}$$

Reversible heat produces an entropy change that can be either negative or positive. Therefore, the entropic heat in Eq. (2.3) is positive if endothermic, negative if exothermic during discharge. The discharge capacity and terminal voltage are also experimentally measured.



Figure 2.3 (a) SOC over time at different discharge rates; (b) Entropic heat coefficient as a function of SOC.

The next step is to consider the energy conservation principle. The heat generation rate equals the rate of change in the thermal energy in the cell, plus the rate of heat loss by natural convection, as represented in Eq. (2.8). Thermal resistance for convection ($R_{conv} = 3.34$ K/W) on a vertical surface is determined by the Nusselt number, related with the Rayleigh number and the Prandtl number as shown in Eq. (2.9). The Grasof number is an important standard in determining whether there is laminar flow or turbulent flow in natural convection. In this vertical plate case, the fluid flow was laminar since the Grasof number was equal to 6.11×10^7 . The initial battery and environment temperature were set to 25 °C, the same as in the

experimental setup.

$$q_{b} = m_{b}c_{b}\frac{dT_{b}}{dt} + \frac{2(T_{b} - T_{a})}{R_{conv}}$$
(2.8)

$$Nu = 0.68 + \frac{0.67Ra^{1/4}}{[1 + (0.492/Pr)^{9/16}]^{4/9}}$$
(2.9)

The PCM was stored in an aluminum container, one surface of which was in contact with the battery and the other was cooled by natural convection. The dominant heat transfer mechanism was conduction in the PCM due to the thin PCM layers. Thermal energy was conducted from a battery source throughout the aluminum case and the PCM to the air at room temperature, as shown in Fig. 2.4. In accordance with the instantaneous energy balance, heat produced by the battery could either be stored by itself or flowed into the PCM region:

$$q_{b} = m_{b}c_{b}\frac{dT_{b}}{dt} + q_{PCM}$$
(2.10)

Figure 2.4 Schematic of the battery and PCM positions.

A 1D transient heat conduction equation without heat generation was applied to evaluate the temperature distribution in the PCM, as shown in Eq. (2.11) [25]:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial^2 x} \tag{2.11}$$

$$\alpha = \frac{k}{\rho \cdot c} \tag{2.12}$$

Boundary conditions were applied as follows:

At
$$x = 0$$
: $kA\frac{\partial T}{\partial x} = \frac{T_b - T(x)}{R_{int} + R_{cas}} = \frac{q_{PCM}}{2}$ (2.13)

At
$$x = d$$
: $kA \frac{\partial T}{\partial x} = \frac{T(x) - T_a}{R_{cas} + R_{conv}}$ (2.14)

It is truly necessary to clarify two forms of heat when using a PCM. Sensible heat results in a change in material temperature without a phase change. By contrast, latent heat does not increase the temperature within the material but does cause a change of substance state [23]. Assuming that the roughness of the aluminum plates was 10 μ m, thermal contact conductance was calculated to be 3,640 W/m²·K. Jollyn et al. [13] used a case thickness of 5 mm; accordingly, the thermal resistance for conduction was equal to 3.732×10^{-5} K/W. In order to obtain the explicit finite-difference form of Eq. (2.11), a central-difference approximation to the spatial derivatives and a forward-difference approximation to the time derivative are expressed in Eq. (2.15) over (2.17).

At internal nodes:

$$T_{i}^{j+1} = \frac{\alpha \cdot \Delta t}{(\Delta x)^{2}} \left[T_{i+1}^{j} + T_{i-1}^{j} \right] + \left[1 - \frac{2 \cdot \alpha \cdot \Delta t}{(\Delta x)^{2}} \right] T_{i}^{j}$$
(2.15)

At node 1 (between battery and PCM):

$$T_{1}^{j+1} = \frac{2 \cdot \alpha \cdot \Delta t}{\Delta x \cdot k \cdot A(R_{int} + R_{cas})} T_{b}^{j} + \frac{2 \cdot \alpha \cdot \Delta t}{(\Delta x)^{2}} T_{2}^{j} + \left[1 - \frac{2 \cdot \alpha \cdot \Delta t}{(\Delta x)^{2}} - \frac{2 \cdot \alpha \cdot \Delta t}{\Delta x \cdot k \cdot A \cdot (R_{int} + R_{cas})}\right] T_{1}^{j}$$
(2.16)

At node n (between PCM and ambient environment):

$$T_{n}^{j+1} = \frac{2 \cdot \alpha \cdot \Delta t}{\Delta x \cdot k \cdot A(R_{cas} + R_{conv})} T_{a} + \frac{2 \cdot \alpha \cdot \Delta t}{(\Delta x)^{2}} T_{n-1}^{j} + \left[1 - \frac{2 \cdot \alpha \cdot \Delta t}{(\Delta x)^{2}} - \frac{2 \cdot \alpha \cdot \Delta t}{\Delta x \cdot k \cdot A \cdot (R_{cas} + R_{conv})}\right] T_{n}^{j}$$

$$(2.17)$$

2.2. Three-dimensional mathematical model

Numerical simulation of the heat transfer was carried out using ANSYS Fluent software.

Kim et al. [26] introduced the multi-scale, multi-dimensional approach for solving interactions appearing in a vast number of length scales. This framework efficiently deals with separate solution domains at the particle $(10^{-9} \text{ to } 10^{-8})$, electrode $(10^{-6} \text{ to } 10^{-4})$, and cell $(10^{-2} \text{ to } 10^{0})$ levels. At the cell scale, the current flux is governed by the following equations:

$$\nabla \cdot (\sigma_+ \nabla \varphi_+) = -j \tag{2.18}$$

$$\nabla \cdot (\sigma_{-} \nabla \varphi_{-}) = j \tag{2.19}$$

The NTGK model assumes the current flux to be a function of the potential difference between the positive and negative electrodes. Ho et al. [22] estimated two empirical fitting parameters from their experimental data. Those depend on the DOD of the battery and the temperature. For a 3D thermal model of Li-ion batteries, the thermal source is roughly similar to 1D modeling and the ohmic heating is also considered in the batteries, as follows:

$$q_b = j \left[E - (\varphi_+ - \varphi_-) - T \frac{dE}{dT_b} \right] + \sigma_+ \cdot \nabla^2 \varphi_+ + \sigma_- \cdot \nabla^2 \varphi_-$$
(2.20)

where $j[E - (\varphi_+ - \varphi_-)]$ is expressed as an irreversible source term and $jT(dE/dT_b)$ refers to a reversible source term. The thermal energy generated in the current collecting tab and lead wire was neglected.

Voller et al. [27] successfully solved phase-change problems in the convection-diffusioncontrolled mushy zone with the enthalpy-porosity technique which relies on fixed-grid methodology. Depending upon the PCM temperature, the liquid fraction is defined as:

$$\begin{split} \beta &= 0 & \text{for} \quad T < T_{solidius} \\ \beta &= 1 & \text{for} \quad T > T_{liquidius} \\ \beta &= \frac{T - T_{solidius}}{T_{liquidius} - T_{solidius}} & \text{for} \quad T_{solidius} < T < T_{liquidius} \end{split}$$

Instead of tracking the melting interface, the liquid fraction referring to the liquid state in a computational domain is computed per iteration. The latent heat content:

$$\Delta H = \beta \cdot L \tag{2.22}$$

For melting simulations, the momentum equation is not employed. The energy equation analyzing the temperature distribution can be derived as follows:

$$\frac{\partial}{\partial t}(\rho H) + \nabla \cdot (\rho \mathbf{v} H) = \nabla \cdot (k \nabla T) + S$$
(2.23)

where **v** is the fluid velocity vector.

2.3. Validation

2.3.1 Validation of 1D modeling

The 1D battery heat transfer model was validated against the experimental data. The error between the 1D model prediction and the experimental data was found to be within 1% at the last stage of both the 3C and 5C discharge processes. Figure 2.5 shows good quantitative agreement for the 3C and 5C discharge rates.



Figure 2.5 Comparison of the 1D model and the experimental maximum temperatures in the battery.

2.3.2 Validation of 3D modeling

Ho et al. [22] conducted simulations on the same kind of Li-ion battery using ANSYS Fluent software. The NTGK model was used to predict the thermal behavior of the battery under various discharge rates: 1C, 2C, 3C, 4C, and 5C. A cell was immersed in air that had an initial temperature of 25 °C. As seen in Fig. 2.6, there were similar trend lines between this

current work and that of Ho et al. At the end of discharging, there was a 0.1 % error for the 3C rate and a 0.5 % error for the 5C rate. This confirmed that NTGK battery modeling was valid for various rates of discharge.



Figure 2.6 Comparison of temperatures in this study and Ho et al. [22].

A transient simulation of the thermal behavior of a Li-ion battery with a PCM was validated to the results of Javani et al. [28]. The error was found to be within an acceptable range (a maximum error of less than 1% at the end of discharging), as shown in Table 2.3.

Table 2.3 Comparison of maximum temperature for the validation of the battery at 20 min.

Configuration	Present study	Javani et al. [28]	Error (%)
Cell minimum temperature (K)	303.20	305.05	0.6
Cell average temperature (K)	305.23	307.58	0.8
Cell maximum temperature (K)	306.25	308.43	0.7

In order to model a cell, those researchers assumed a uniform heat generation rate within the cell domain. Due to the inconsequential thickness of the battery, this assumption was appropriate for the lumped system evaluation. We considered a transient model of a 54,374.5 W/m³ heat source, especially because there was anisotropic thermal conductivity in the cell: 25 W/m·K along the cell surface and 1 W/m·K normal to the cell surface. N-octadecane, the length of which was 3 mm, was integrated around the periphery of the battery with the same thickness. It was assumed that free convection took place at all the surfaces where the battery and the PCM interfaced with the ambient air. The heat transfer coefficient was 7 $W/m^2 \cdot K$ and the temperature of the environment was 294.15 K. The geometrical features of this model, which had 300,800 elements, are summarized in Table 2.4.

Geometry	Length (m)	Height (m)	Thickness (m)
Cell	0.146	0.194	0.0054
Terminal	0.035	0.015	0.0006
РСМ	0.003	0.003	0.0054

Table 2.4 Dimensions of the battery and PCM in the simulations of Javani et al. [28].

A thorough grid independence test should be done to demonstrate that the element size does not affect the quantity of interest. We recorded the temperature in the cell at the end of discharging at the 5C discharge rate. As shown in Fig. 2.7, the grid with 1,360,891 elements was sufficient to predict the temperature distribution in the computational domain.



Figure 2.7 Grid independence test with different numbers of elements.

3. RESULTS AND DISCUSSION

In this study, the effect of the thickness and thermal conductivity of a PCM on the cooling performance of a Li-ion battery are investigated. The PCM was of three different thicknesses, 0.5 mm, 0.55 mm, and 0.6 mm, and the thermal conductivity of the PCM was enhanced based on the practical application. Moreover, the 1D results are compared to the 3D results. The cooling performance of fan and PCM on a battery pack (3 cells) is investigated.

3.1. Effect of PCM thickness

The major drawback with most organics, particularly the family of paraffins, is that they possess low thermal conductivity. A thin PCM easily melts fully and does not produce sufficiently effective temperature reduction. With a thick PCM there is a solid region farther from the battery and a superheated liquid region next to the battery, so instead of behaving as a thermal sink, the PCM may behave as a thermal isolator.



Figure 3.1 Battery temperatures for different PCM thicknesses at: (**a**) 3C discharge rate; (**b**) 5C discharge rate.

As shown in Fig. 3.1, the maximum temperatures of the Li-ion batteries without a PCM were 64.86 °C and 86.83 °C at the end of the 3C and 5C discharge rates, respectively. As mentioned previously, the best temperature range is 25 °C to 40 °C and the safe temperature

range is -20 °C to 60 °C for Li-ion battery operation. Moreover, the capacity fade of Li-ion cells can be 36.21% after 800 cycles when the operating temperature is around 45 °C, and the loss can even reach 70.56% after 500 cycles when the operating temperature is approximately 55 °C. At the 3C discharge rate, a PCM with a thickness of 0.6 mm or thinner can maintain the battery temperature in a safe condition. With a 0.6-mm-thick PCM layer, the maximum temperature can decrease by 1.28 °C or 6.54 °C, depending on the fast or slow discharge rate.

Three stages along the temperature elevation curve clearly exist in the battery with a PCM (Fig. 8).

- From of starting temperature of less than 28 °C, it grows markedly. It takes about the first 3 s (5 s) to reach the limitation for the 5C (3C) discharge rate. The slope was similar to the one without PCM. The energy storage relies solely on low sensible heating (in this case, 2,150 J/kg·K).
- During the melting process, the battery temperature drops into the phase change temperature range. The temperature increases slightly since thermal energy is absorbed as the heat of transformation. Under the 3C discharge rate, this process occurred in 20 s to increase the temperature to ~ 31 °C. The PCM started to melt from the inner to the outer layer, and then melted entirely.
- Finally, the PCM was at a liquid state with both low thermal conductivity and low specific heat. The temperature of the battery climbed considerably again but the slope was still less than the one without a PCM. The predicted temperatures had almost identical trends in their final stages.

Figure 3.2 is a close-up of the battery temperature change at the initial stage of the discharging process. Under the high discharge rate of 5C, it took 17.4 s to rise above 40 °C. This process could be extended to 34.8 s when the PCM thickness was 0.5 mm. Similarly, with the 3C discharge rate, it took much longer (40.3 s) to reach 40 °C. This operation could

take up to 144.3 s with a 0.5-mm-thick PCM. Stage 1: Sensible heating of solid; stage 2: Latent heat of fusion; stage 3: Sensible heating of liquid.



Figure 3.2 Rapid increases in the temperature below 40 °C at: (**a**) The 3C discharge rate; (**b**) The 5C discharge rate.



Figure 3.3 The highest battery temperature as a function of PCM thickness.

As shown in Fig. 3.3, at the end of the discharging process the battery temperature linearly varied with the thickness of the PCM. When the thickness decreased by 0.05 mm, the temperature also declined 5.3 °C at the 5C discharge rate. This compares with a decline of 2.7 °C at the low discharge rate of 3C.

3.2. Effect of PCM thermal conductivity

The response time is a substantial factor in the design of a PCM system. There are several

approaches to improve heat dissipation, such as enhancing the thermal conductivity, setting the ullage space far from the heat source via a potential container, and installing the PCM in the heat flow path. It is generally agreed that a material that has a high energy storage capacity will have low thermal conductivity. Therefore, much research interest has been focused on enhancing the thermal conductivity of PCMs.

Recently, Venkateshwar et al. [29] investigated heat storage performance when embedding aluminum metal foam (MF) in n-octadecane. They used Eqs. (3.1) and (3.2) to determine the effective thermal conductivity of that PCM-MF composite, given as:

$$k_{s,eff} = A_1 \left[\varepsilon \cdot k_{s,PCM} + (1 - \varepsilon) k_{MF} \right] + \frac{1 - A_1}{\frac{\varepsilon}{k_{s,PCM}} + \frac{1 - \varepsilon}{k_{MF}}}$$
(3.1)

$$k_{l,eff} = A_1 \left[\varepsilon \cdot k_{l,PCM} + (1 - \varepsilon) k_{MF} \right] + \frac{1 - A_1}{\frac{\varepsilon}{k_{l,PCM}} + \frac{1 - \varepsilon}{k_{MF}}}$$
(3.2)

With the porosity ε set to 0.972, the structure with a thermal conductivity of 2.394 W/m·K conducted faster than pure n-octadecane without sacrificing the available volume.



Figure 3.4 Image of metal foam and paraffin/metal foam composite PCM with different pore sizes: (a) Metal foam; (b) Paraffin/metal foam composite PCM.

The use of metallic foams is similar in nature to the use of embedded heat sinks, in that the heat flows along a metallic path, in this case the ligaments to the foam, and then into smaller separated masses of PCM, as shown in Figure 3.4. For foams, the individual masses of PCM are that which are contained within each open cell in the foam. Experimental studies have shown though, that while the convection may be suppressed, the overall thermal performance is still significantly better with foams than without. The copper foams showed greater effective thermal conductivities than the nickel foams, reaching as high as 16 W/m·K for copper foams with 25 pores per inch and 88% porosity. Considering that the thermal conductivity of paraffin is around 0.2 W/m·K, this improvement is almost 80 times.

Sari et al. [30] examined the transient thermal influence of paraffin absorbed into expanded graphite (EG). They determined that the PCM composite with a 10% mass fraction of EG had stable properties. The thermal conductivity of the PCM-EG linearly varied with the mass fraction of the EG. Compared to pure n-octadecane, the thermal conductivity could reach 0.828 W/m·K when integrated with the proper amount of EG.

$$y_1 = 0.0524x_1 + 0.3038 \tag{3.3}$$



Figure 3.5 Scanning electron microscope (SEM) micrograph of the expanded graphite and the paraffin/expanded graphite composite PCM: (a) Expanded graphite; (b) Paraffin/expanded graphite composite PCM.

Figure 3.5 shows the SEM micrographs of the expanded graphite and the PCM composite. It can be clearly seen from Figure 3.5 (a) that the expanded graphite has a worm-like appearance of its particles. As shown in Figure 3.5 (b), after the paraffin had been absorbed into the pores of the expanded graphite, the expanded graphite remained in the worm-like structure, and the absorbed paraffin exhibited a uniform distribution in the paraffin/expanded graphite composite PCM owing to the capillary force and the surface tension force of the porous expanded graphite.

In a macroscopic approach, the use of carbon fibers (CF) was considered by Fukai et al. [31] as an advanced technique. The effective thermal conductivity of the PCM composite was around three times higher than the pure PCM at $X_{fa} = 0.012$, as calculated in the following formula:

$$k_{eff} = \left[\left(3.31 \times 10^{-3} + 1.69X_{fa} - 2.65 \times 10 \times X_{fa}^2 \right) \cdot \left(\frac{k_f}{k_m} - 1 \right)^{0.67} + 1 \right] k_m \qquad (3.4)$$

As a result, the thermal conductivity of paraffin combined with CF was 0.678 W/m·K.



Figure 3.6 SEM images of: (a) Carbon fiber sheet (CFS) surface before impregnation; (b) Composite PCM surface after impregnation.

In Figure 3.6a, a network structure comprising long carbon fibers can be clearly observed. This type of continuous network structure contributes to enhancing the thermal conductivity of the PCM. After impregnation, the spaces and pores among the carbon fibers were filled by paraffin, as seen in Figure 3.6b, with no visible pores remaining after impregnation (low porosity provided less pores, and gas pores were detrimental to heat transfer because of the low thermal conductivity of the gas). The anisotropic alignment of carbon fibers explains the appreciable difference between the thermal conductivities in the vertical and horizontal directions of the composite PCM. In practical applications of the latent heat storage system

(especially industrial waste heat recovery), anisotropic thermal conductivity of the PCM could be advantageous for achieving directed heat transfer and reducing heat loss in the unwanted direction. Directed high-speed heat transfer during system charging and discharging can improve the heat recovery efficiency, thereby reducing heat loss to the environment.



Figure 3.7 Battery temperature with various PCM composites at: (a) The 3C discharge rate; (b) The 5C discharge rate.

	Parameter	Pure PCM	PCM-MF	PCM-EG	PCM-CF
The	ermal conductivity (W/m·K)	0.255	2.394	0.828	0.678
3C	Maximum temperature (°C)	52.8	33.9	36.9	37.9
50	Percent reduction (%)	0	35.8	30.1	28.2
5C	Maximum temperature (°C)	74.9	49.7	55.2	57.1
	Percent reduction (%)	0	33.6	26.3	23.8

Table 3.1 Specifications of PCM composites and their performance.

Figure 3.7 shows the battery temperature change during the discharging process under natural convection. The higher the thermal conductivity of the PCM composite is, the more effective the heat dissipation capacity is. Additionally, aluminum foams make the melting process more uniform. The thermal improvements of PCM composites are summarized in Table 5. At the end of the discharging process, the percentage of temperature reduction with PCM-MF was about 1.2 and 1.3 times higher than with PCM-EG and PCM-CF, respectively.

3.3. Comparison of 1D calculation and 3D simulation

We compared our 1D analysis and a 3D simulation of the 0.5-mm-thick PCM-MF model. A hexahedral grid was generated for the battery and the PCM domain, while the ambient air domain was divided by polyhedral elements as shown in Fig. 3.8.



Figure 3.8 (a) Battery and PCM are immersed in the air; (b) Computational domain.

The bottom was set to be adiabatic and the other surfaces were set to atmospheric pressure. For the pressure-velocity coupling, the ANSYS Fluent coupled algorithm was employed. A second-order interpolation scheme was used to approximate the convection terms in the momentum, energy, and potential equations, whereas a PREssure STaggering Option (PRESTO) scheme was selected for the pressure field. For the conjugate heat transfer problem, these assumptions were applied:

- Only natural laminar convection took place in the ambient environment.
- The initial temperature of the battery and the PCM were set to the same as the ambient temperature (25 °C).

The data from the late stage of the analysis for the 1D calculation was excluded because it was too noisy; nevertheless, we found that the 1D and 3D solutions matched well when

extending the results while maintaining the curve slope (Fig. 3.9). This agreed with the results of Greco et al. [14], who showed that cooling paths were totally dissimilar in the initial periods of the analytical and computational approaches, but they definitely matched at the end stages.



Figure 3.9 Comparison of 1D and 3D results for battery temperatures under: (a) The 3C discharge rate; (b) The 5C discharge rate.



Figure 3.10 Investigation of temperature uniformity in the 3D Li-ion battery model.

Figure 3.10 shows the temperature uniformity in the 3D Li-ion battery model. At the low discharge rate of 3C, the tmperature disparity in the cell was maintained under 5 °C. At the higher discharge rate of 5C, it markedly escalated due to sudden heat generation. However, the PCM exhibited outstanding improvement, with a 6.6 °C peak difference of temperature.



Figure 3.11 (a) Temperature monitoring lines; (b) The temperature distribution at line 1; (c) The temperature distribution at line 2.

At the center plane of the cell, two monitoring lines were selected to explore the temperature change at z = 0.1245 m and y = 0.1135 m, as depicted in Fig. 3.11(a). Figure 3.11(b) shows the temperature along the vertical line at the end of discharging. There was a large difference of 15.5 °C between the top and bottom positions under the 5C rate without a PCM. The use of PCM-MF caused a sudden change in temperature in the lower area of the cell at the 3C discharge rate, due to a liquid-mushy PCM zone. It can be seen in Fig. 3.11(c) that the temperature varied slightly in the horizontal direction and tended to be more stable when the PCM was applied. All of the differences were below 1 °C. Because the heat source was concentrated in the region close to the current collecting tabs, the temperature variation was clearly greater in the vertical direction than in the horizontal direction.

Basically, the temperature distribution on the battery surface can be divided into two parts: an upper region with higher temperature and a lower region with lower temperature. Without a PCM, the battery temperature increased more continuously and homogeneously from the bottom to the top under the 3C discharge rate. This difference was 6.8 °C. However, there was greater difference in temperature (18.8 °C) under the 5C discharge rate. The highest temperature was located near the positive and negative tabs, as shown in Fig. 3.12.



Figure 3.12 Contour of temperature on battery surfaces (°C) at the end of discharging: (a) Without PCM; (b) With PCM.

Similar trends were observed in the case with the PCM. However, there was a smaller temperature difference at the 3C as well as the 5C discharge rates because thermal energy from the battery was absorbed into latent heat. The maximum temperature was located at the negative tab (left tab), which was not cooled by the PCM. For this reason, an active cooling method such as forced convection may be necessary. The differences in temperature were 4.5 °C and 8.2 °C on the entire battery surpface under 3C and 5C discharge rates, respectively.

Depending on the amount of heat generated, the PCM can be partly or totally melted. The PCM remained in the mushy zone in the lower region under the 3C discharge rate, while it completely transformed to a liquid state under the 5C discharge rate.

3.4 Comparison of air cooling and PCM cooling performance

Because the heat source is concentrated on close region to current collecting tabs, the study for thermal behavior for active cooling system with PCM is necessary. There is a battery pack with three cells put inside a box, as shown in Figure 3.13.



Figure 3.13 Box and fan dimensions.

The thermal behavior was investigated through two cases: Figure 3.14 (b) with fan and battery while Figure 3.14 (c) including fan, battery and PCM-MF. Moreover, various fan speed provided in Table 4.1 applied to each case.



Figure 3.14 (a) Isometric view; (b) Without PCM-MF; (c) With PCM-MF

Speed (rpm)	Mass flow rate (kg/s)
5,000	0.00140
7,000	0.00197
9,000	0.00240

Table 4.1 The specifications of fan were found at SENSDAR (China).



Figure 3.15 The maximum temperature in cells

Table 4.2	The p	performance	of fan a	at various	speed.
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Case	Speed	Temperature (°C)	Temperature reduction (°C)
5C	5,000	83.97	
	7,000	81.42	2.6
	9,000	79.68	1.7
5C, PCM-MF	5,000	50.24	
	7,000	49.37	0.9
	9,000	48.82	0.6
3C	5,000	59.87	
	7,000	56.71	3.2
	9,000	55.15	1.6
3C, PCM-MF	5,000	33.38	
	7,000	32.89	0.5
	9,000	32.62	0.3

The higher the fan speed is, the less the maximum temperature in cells is. Figure 3.15 shows the maximum temperature in battery pack at different speeds during discharging. The performance of heat dissipation is summarized in Table 4.2.

Without PCM-MF, the average reduction of temperature is estimated 1.2 °C for 3C and 1.075 °C for 5C per 1,000 rpm at the end of discharging. Compared to the battery cooled by PCM-MF and fan (5,000 rpm), the effective can be achieved similarly if the use of a fan with 34,000 rpm. Due to the absence of high speed fan in the market, it is suitable to consider four fans with 9,000 rpm instead. A cost comparison of the two cooling methods was proposed in Table 4.3. The mentioned prices should be considered as an approximation depending on the component supplier.

The cooling method by 5,000 rpm fan and PCM-MF costs a lot of money because aluminum foam is expensive. Many other aspects, such as the expected battery lifetime, consumption of the auxiliary system, maintenance, location flexibility, ... should also be taken into account when selecting the best configuration. It should be noted that the proposed cost comparison is not based on series productions.

Case	Components	Units	Cost (USD)	Total (USD)
Fan	Fan 9,000 rpm	4	3.96 [32]	3.96
Fan + PCM-MF	Fan 5,000 rpm	1	0.99 [32]	
	N-octadecane 138 g	1	210.99 [33]	1,618.41
	Aluminum foam 169,569 mm ³	1	1,406.43 [34]	

Table 4.3 The cost comparison of two kinds of cooling methods.

Without PCM-MF, the more the fan speed is, the more non-uniform the temperature in cells is. In contrast, with PCM-MF, the more the fan speed is, the more uniform the temperature in cells is. As shown in Figure 3.16, the temperature difference is maintained under 5 $^{\circ}$ C at low discharge rate of 3C.



Figure 3.16 The investigation of temperature uniformity in cell.

The temperature distribution in each cell was investigated at different conditions. The highest temperature concentrates on cell 2 in all of cases. The use of PCM-MF decreases not only the battery temperature but also helps to narrow the temperature difference, as it can be seen in Figure 3.17.



Figure 3.17 The maximum, average and minimum temperatures at the end of discharging, from left to right: cell 1, cell 2, cell3, respectively: (a) For 3C; (b) For 5C.

The high temperature locating near region to current collecting tabs was dissipated by fan at different speeds in Figure 3.18 and Figure 3.19. Heat on left tabs are almost removed while on right tabs are remained due to far from the fan. Based on contours, the battery temperature tends to be more stable from left to right when applying PCM-MF.



Figure 3.18 Temperature distribution on battery surfaces (°C) at the end of 3C discharging.



Figure 3.19 Temperature distribution on battery surfaces (°C) at the end of 5C discharging.

4. CONCLUSION

A 1D thermal management model of a large-format Li-ion battery (52.3 Ah) with different PCM properties was evaluated. This pouch-type battery was sandwiched between two n-octadecane layers, and the heat generation agreed well with experimental data under both the 3C and 5C discharge rates. The diffusion equation that governed the thermal transfer capacity in the PCM was also solved simultaneously. By considering different PCM thicknesses and thermal conductivities, a potential model was proposed, an asseblage with aluminum foam embedded in n-octadecane. The average conductivity of the resulting enhanced PCM-MF was 2.394 W/m·K.

Then 3D transient thermodynamic simulations were carried out with an NTGK model using ANSYS Fluent software. The maximum temperature of the Li-ion battery reached 72.40 °C and 101.87 °C under the 3C and 5C discharge rates, respectively, without a cooling system. It was shown that the 0.5-mm-thick PCM-MF composite reduced the maximum battery temperature to 34.33 °C and 50.65 °C at 3C and 5C discharge rates, respectively. Based on comparison with these 3D simulations, we found that the 1D analysis was capable of accurately estimating the heat dissipation by the PCM-MF at the end of discharging. The 1D approach clearly produced reliable results in predicting the thermal behavior of the PCM-MF cooling, and was superior in practical application terms with its low cost and less time consumption.

Moreover, a battery pack with 3 cells put inside a box investigated for thermal behavior. The effect of fan and PCM-MF was considered to orient to practical applications with simple and cost-effective functions. The use of four fans (9,000 rpm) can give a similar cooling performance to the use of one fan (5,000 rpm) integrating PCM-MF.

5. LIMITATIONS AND FUTURE WORKS

Limitations:

In this study, there was a lack of data at late stage of analysis for 1D calculation.

Future works:

Further study for thermal behavior for 10 cells with PCM-MF will be necessary. Besides, fan positions as well as outlet and inlet position should be investigated to optimize the cooling capacity.

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