Battery thermal management with phase change materials

(PCMs)

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By

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ABSTRACT

As people demand more and more strong lightweight electron devices, electric vehicles and battery driven tools, an advisable and increasing need appears for battery systems to availably fit these essential energy density and power density demands when operating. Due to their high voltage, high energy density, high power density and insignificant fade in power and capacity after cycles, lithium-ion batteries become the prevalent choice utilized in extensive applications, significantly in the use of electric vehicle. Nevertheless, operating in a high output power and manufacturing the lithium-ion battery packs with greater capacity density result in elevated operating temperatures, which brings about swift fade of capacity after continuous charge/discharge cycles and fade in total output power as well. The battery thermal management system relates deeply to the operating and safety issues of the battery. According to the difference of the heat transfer medium, the lithium-ion battery thermal management can be divided into three types: air cooling, liquid cooling and phase change material cooling. Among them, first two types are the active thermal management and the third one is passive thermal management. Although active thermal management systems are efficient enough in transferring heat away from the battery surface, their size which occupies a large amount of space and complexity are inhibited in applications for example portable electronics and battery-power tools. Passive thermal management systems provide briefness in design that mitigates the need for mechanical devices and additional power to operate them. But a uniform phase change material can’t handle the trade-off between the average temperature and total heat storage capacity. In this research, to overcome the shortcoming of uniform PCM cooling, a hierarchical structure is developed. Low, medium and high melting point PCM are combined together in a hierarchical structure to adapt well to the
different situations of thermal management. Several simulation researches are conducted in the Workbench and experiments under same conditions are processed to verify the simulation results.

Keywords: Lithium-ion batteries, Battery thermal management system, Phase change materials (PCMs), Hierarchical structure, Workbench simulation, Experimental verification.
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Chapter 1 Introduction

As is well known, the electric vehicle is a very important alternative transportation and gains more and more attention due to the shortage of conventional fossil energy. Because of its renewable property, zero pollution, zero emission and high energy utilization, electric vehicle has become a hot research topic in the automotive industry. For that reason, the United States, China, Japan and Europe have proposed their own development plans for renewable energy vehicles. In the United States, Obama firstly proposed a commitment to reach 1 million electric vehicles in 2015 in the state of the Union address in 2011. In 2012, China released the development plan of renewable energy automotive industry and clearly stated that by 2015 and 2020, the total sales volume of all-electric vehicles and plug-in hybrid vehicles should exceed 500,000 and 5,000,000 respectively. In 2010, the Japanese government announced the "new generation of automotive strategy", which planned to by 2020 develop electric vehicles and hybrid electric "new generation vehicle" to the level that total sales accounted for about 50% of its new vehicle sales. European major automobile country——Germany, in its "national electric vehicle development plan", proposed that the total number of electric vehicles in Germany would reach 1 million by 2020. The efforts made by all countries in the world for the development of electric vehicles have led to the continuous progress of electric vehicle technology.

Electric cars include three types: plug-in hybrid vehicles, pure electric vehicles, and fuel cell cars. The electric vehicle contains three main technologies: battery and its management system, motor and its controller, vehicle control technology. The main research of battery technology is concentrated on positive and negative materials, membrane materials, additives in electrolyte, and management system of battery pack. The battery management system also includes electrical management, thermal management and safety management.

1.1 Overview of lithium-ion batteries

In the 21st century, energy crisis and environmental pollution problems are increasing rapidly. Therefore, lithium-ion batteries carry the main role in the recyclable energy sources. Li-ion batteries were initially commercialized in the 1991 by the Sony
corporation, which have the advantages of high output voltage, high power density, high energy density and good cycle performance\[^1\]. Now, the application of li-ion battery has spread to the various fields of our life, ranging from mobile phones to the laptops, from the electric bicycles to the electric vehicles. Li-ion battery is composed of cathode, anode, separator and electrolyte, among which the cathode active material determines the electrochemical performance and the cost of a battery.

At present, the mainstream of the commercialized positive electrode includes LiCoO\(_2\), LiMn\(_2\)O\(_4\), LiNi\(_{1-x-y}\)Co\(_x\)Mn\(_y\)O\(_2\), LiFePO\(_4\) etc. LiCoO\(_2\) is the earliest commercialized material, which has the advantages of simple preparation process, stable material properties and high energy density while it has the disadvantage of poor thermal stability and security risks\[^2\-^3\]. LiMn\(_2\)O\(_4\) has the advantage of abundant resources, low price of cost and good security performance, but it has the disadvantages of low energy density, poor thermal stability and its crystalline structure easy to spoil. Therefore, it has poor high-temperature storage performance and poor cycle performance. LiNi\(_{1-x-y}\)Co\(_x\)Mn\(_y\)O\(_2\) combines the advantages of three elements, which has the advantages of large specific capacity, outstanding cycle performance and moderate price of cost, while it has the disadvantages of poor material surface stability due to property of hard oxidation of divalent Ni. LiFePO\(_4\) has the advantages of good cycle performance, good security performance but it has low mix conductivity, low energy density and poor rate performance\[^4\]. The comparison of different cathode materials for lithium-ion batteries is listed below.

| Table 1.1 Comparison of different cathode materials for lithium-ion batteries |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Crystalline structure       | LiCoO\(_2\)                  | LiNi\(_{1-x-y}\)Co\(_x\)Mn\(_y\)O\(_2\) | LiMn\(_2\)O\(_4\)          | LiFePO\(_4\)                |
| Theoretical capacity/(mAh/g)| 274                         | 278                         | 148                        | 170                        |
| Actual capacity/(mAh/g)     | 140–170                      | 145–190                     | 90–120                     | 110–160                    |
| Working voltage/V           | 3.7                          | 3.6                         | 3.8                        | 3.5                        |
| Material richness in nature | Short                        | Relative short              | Abundant                   | Very Abundant              |

Elemental sulfur exists in nature as a ring structure(S\(_8\)) consisting of eight S atoms. As one of the most abundant elements in the world, elemental sulfur has the characteristics of low price and environmental friendliness\[^5\-^6\]. A lithium-ion battery which has elemental sulfur for cathode and lithium metal for anode conducts the working
voltage from 1.9~2.3V.

Fig. 1.1 (a) Schematic diagram of principle; (b) Typical charge/discharge profile of Li-S batteries\[7\]

The main reactions of electrode discharge are:
Cathode: \( S_8 + 16Li^+ + 16e^- \rightarrow 8Li_2S \)
Anode: \( 16Li \rightarrow 16Li^+ + 16e^- \)
Total reaction: \( S_8 + 16Li \rightarrow 8Li_2S \)

In the organic electrolyte, the lithium sulfur battery discharge reactions are processed as below\[8\]:

\[
\begin{align*}
S_8 + 2e^- & \rightarrow S_8^{2-} \\
3S_8^{2-} + 2e^- & \rightarrow 4S_6^{2-} \\
2S_6^{2-} + 2e^- & \rightarrow 3S_4^{2-} \\
S_4^{2-} + 4Li^+ + 2e^- & \rightarrow 2Li_2S_2 \\
Li_2S_2 + 2Li^+ + 2e^- & \rightarrow 2Li_2S
\end{align*}
\]

1.2 Thermal Degradation Mechanisms

When people demand more and more strong lightweight electron devices, electric vehicles and battery driven tools, an advisable and increasing need appears for battery systems to availably fit these essential energy density and power density demands when operating. Due to the high voltage, high energy density, high power density of the cell and insignificant fade in power and capacity after cycles, lithium-ion batteries become the prevalent choice utilized in extensive applications, significantly in the use of electric vehicle. Nevertheless, operating in a high output power and manufacturing the lithium-ion battery packs with greater capacity density result in elevated operating temperatures, significantly when the battery is under peak loads. Because most commercial lithium-ion batteries are so susceptible to occur degradation or aging at the temperature of larger or no less than 60 °C, it brings about swift fade of capacity after continuous charge/discharge
cycles and fade in total output power as well.

Fig. 1.2 Cycling performance for batteries at 25 °C and 60 °C

Fig 1.2 demonstrates the cycle performance in capacity for the two batteries which include the changing discharging rate in the first 40 cycles and constant discharging rate in the next 100 cycles. The battery operated at 25 °C reveals that the capacity at the constant C/2 rate has lost less than 4% of its initial capacity after 100 cycles. While, the battery operated at 60 °C reveals that swift capacity drop occurs and the capacity has dropped to 80% of its initial capacity after 70 cycles, and 35% of its initial capacity after 140 cycles[9].

To better understand the mechanism of how ambient environment temperature influences the li-ion battery, it’s quite essential to identify the chief compositions of the batteries, since every component exerts an effect on the degradation process entity. The three main components of a battery or a single cell are anode, cathode and electrolyte. The two electrodes are insulated by the polymer membrane. The electrolyte is a chemical medium that allows ions to conduct. The electrolyte can be liquid state, solid state or polymeric state. The reactions happening at the electrode/electrolyte interface have occupied a considerable fraction of the battery thermal degradation process in the cell.
Anode Degradation Process

Under the conditions of high temperatures, the anode and electrolyte will interact more extensively, significantly with carbon anodes. The investigation on the aging effects on the anode/electrolyte interface over battery lifetime has been deeply processed. In general, when a lithium-ion battery discharges at the first time, a finite amount of electrolyte will decompose and some Li-ion will consume irreversibly at the electrolyte/anode interface because the output voltages at the anode is totally not stable. Then, a protective solid-electrolyte interphase layer which is called SEI layer is deposited by the irreversible decomposition of the electrolyte on the electrode surface. The solid-electrolyte interphase layer is penetrable for lithium ions but stops the electrolyte decomposing furtherly and electrode corroding. The SEI layer’s formation, components and morphology are all very essential for effective performance of anode. Alter in any of these aspects will adversely influence the battery capacity and cycle performance. High temperature largely promotes both solid-electrolyte interphase layer’s formation rate and its growth rate, which can bring about morphological revision and components changes that adversely exert effect on porosity of the layer. The lower porosity of the solid-electrolyte interphase layer increases irreversible electrochemical reaction rate with lithium ions and result in elevated battery impedance, mobile lithium ions drop, leading to capacity and power fade.

Cathode Degradation Process

In general, the cathodes for lithium-ion batteries includes a lithium metal oxide for an active material such as LiMn$_2$O$_4$, conductive additive such as carbon black to improve the ions/electrons electrical conductivity and binders such as PVDF to connect conductive additive and active material together on a copper negative current collector. Accordingly, cathode degrade process relates to all the active or inactive material in cathode electrode. That’s why the processes are so complex and are considerably material related. the inactive components of the cathode will be influenced negatively by the high temperatures. For instance, the incremental irreversible decomposition chemical reactions of the binder, elevated oxidation reactions of conductive additives, and intensely increased corrosion reactions of the copper negative current collector from the electrolyte. Based on the choice of the cathode electrode and constitute of both the lithium metal oxide for example LiMn$_2$O$_4$ or LiFePO$_4$ and electrolyte, increased temperatures will intensely boost decomposition process and promote structural transformation, negatively exerting effect on the phase changes during lithiation or delithiation processes. The above
battery thermal degradation processes lead to entity drop of mobile lithium ions, elevated cell impedance and capacity and power fade. The introduction above shows the complexity of thermal degradation processes in lithium-ion batteries, which is largely material related.

1.3 Overview of battery thermal management system

According to the difference of the heat transfer medium, the lithium-ion battery thermal management can be divided into three types: air cooling, liquid cooling and phase change material cooling\textsuperscript{[10]}. Among them, first two types are the active thermal management and the third one is passive thermal management.

Air cooling is the process that the external air enters into the inner channel of the battery pack. The heat convectively transfers on the surface of the battery and the heat flows out with the air. Based on whether the flow of air is spontaneous or not, air cooling can be of two types: free convective air cooling and forced convective air cooling. Free convective air cooling is usually the natural convection caused by vehicle driving. The heat transfer coefficient on the heat exchange surface is usually about $5 \text{ W/m} \ast \text{°C}$. Forced convective air cooling is driven by a fan to provide the flowing air. Its heat transfer coefficient on the heat exchange surface is usually large than $10 \text{ W/m} \ast \text{°C}$. Air cooling is very demanding for the design of the air duct, and the temperature consistency of the cell monomer is not good because it is difficult to make the flow field consistent.

![Free Convective Air Cooling](image)

**Fig. 1.3 Free Convective Air Cooling**

![Forced Convective Air Cooling](image)

**Fig. 1.4 Forced Convective Air Cooling**

Liquid cooling means that the heat transfer medium circulated in a battery group is
liquid. The liquid usually has a much larger heat transfer coefficient than air and a thinner liquid boundary layer which makes its effective thermal conductivity higher than air does. According to whether the liquid is directly contacted with the battery, the liquid cooling is divided into direct-contact cooling and indirect-contact cooling. The heat transfer medium used in direct-contact cooling is insulating mineral oil. Indirect-contact cooling usually uses water and ethylene glycol as heat transfer medium. Indirect-contact type liquid cooling should ensure liquid pipeline to have good sealing performance and ensure that the direction of pipeline is reasonable in order to achieve good effect of temperature control. So, indirect-contact type liquid cooling is demanding for the battery box design and processing. Direct contact type liquid cooling utilizes mineral oil with high viscosity. That means it need a larger pump power to operate, which is very unfavorable for the driving range of electric vehicle whose driving range is insufficient already.

![Diagram of liquid direct-contact or indirect cooling](image_url)

**Fig. 1.5 Liquid direct-contact or indirect-contact cooling**

From the above introduction we can know the deficiencies of the traditional active battery thermal management:(1) the system is complex, occupies large space and needs for mechanical devices and additional power to operate them; (2) the heat released by the battery fails to recycle, but only damages the battery. Fail to achieve energy saving and emission reduction.

The thermal management system with PCM material cooling is to absorb the heat of the battery by latent heat of PCM material in the phase change process and prevent the battery temperature from rising too fast. PCMs are equivalent to the energy storage tank\(^{[11]}\). It can not only reduce the temperature difference between monomers, but also
store energy in cold environment, and it can also transmit the energy into the battery so as to achieve the thermal insulation effect and improve the performance of battery in cold environment. From the point of view of saving energy and improving the driving range of vehicles, the PCM based thermal management system of lithium-ion battery has better cooling effect and thermal insulation effect in cold environment. The passive thermal management of battery shows that it can maintain the thermal stability of the current commercial chemical batteries, avoid the development of extensive materials and reduce the expensive new product line.

1.4 Battery thermal management system with phase change materials

Thermal management systems are based on the heat transfer from the surface of the battery, accordingly mitigating the temperature rise in the center of battery and inhibiting degradation process of materials. Both the ability to effectively shuttle heat away by the convection of air from the battery surface and the intrinsic thermal properties such as latent heat per volume of the battery materials determine the validity of mitigating center temperatures of cell. The decision to use active thermal management or passive thermal management systems in a battery or in a battery packs depends on application. Although active thermal management systems are efficient enough in transferring heat away from the battery surface, their size which occupies a large amount of space and complicacy are inhibited in utilizations for example man-pack electronics and electric driven tools. While passive thermal management systems that are PCM based management systems provide briefness in construction which mitigates the demand for mechanical devices and don’t need excess power to operate them.
Latent Heat Storage Materials (Phase change materials)

Latent heat storage materials also called phase change materials are based on transforming states of substances or phase changes so as to absorb heat or release heat during which remaining a relative stable temperature. Latent heat, in other words enthalpy of fusion, stands for the quantity of thermal energy demanded for a given amount of mass of material to go through a phase transformation, in general represented in the unit of J/g. The latent heat storage materials can experience different types of transformation such as solid to solid transformation, solid to liquid transformation, or liquid to gas phase transformation. PCMs could be inorganic compounds, organic complexes, or eutectic complexes\(^{[12]}\). As the temperature has run up to the phase change temperature of PCMs, the thermal energy will be absorbed by utilizing in changing the material to another phase, accordingly the temperature is kept in a relatively constant range (Figure 1.6). under the condition of a fixed heat flow rate, the time length of the temperature plateau shown in the temperature profile depends on both the specific enthalpy of fusion of the material and the utilized mass of PCM\(^{[13]}\).

Majority of popular phase change material type applied for handling of battery thermal management systems are either organic or inorganic compounds. Although inorganic PCMs for example salt hydrate holds a high enthalpy of fusion and large thermal conductivity, its disadvantages are also obvious, which are restricted melting/freezing cycles, corrosive, electrically conductive, and are easy to suffer from supercool. Organic PCMs, for example paraffin waxes, are more suitable for battery systems since they are capable of achieving larger than 1,000 melting/freezing cycles.
easily without severe degradation process. This property is useful to the indispensable demand of discharging/charging cycles applied for the present commercial batteries\textsuperscript{[14]}. With justified schematization to handle these problems, it has demonstrated satisfactory strengths and benefits for organic PCMs in being capable of mitigating the temperature elevation of core in battery during high discharge rate with current lithium-ion batteries\textsuperscript{[15]}.

**Fig. 1.7 PCMs classification according to the material property**

The advantages and disadvantages of organic or inorganic PCMs are listed below. Although organic PCMs has relative low latent heat than inorganic PCMs, due to its good chemical and thermal stability, the application of organic PCMs is much more than inorganic PCMs. To overcome the shortcoming of low thermal conductivity and inflammable, many researcher improved the performance of the PCM by doping with other substances\textsuperscript{[16-18]}.

<table>
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<tr>
<th>Characteristics</th>
<th>Organic PCMs</th>
<th>Inorganic PCMs</th>
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<tr>
<td><strong>Advantage</strong></td>
<td>noncorrosive, no supercooling and precipitation phenomena, good chemical and thermal stability</td>
<td>Relatively high latent heat</td>
</tr>
<tr>
<td><strong>Disadvantage</strong></td>
<td>Relatively low latent heat, low thermal conductivity, inflammable</td>
<td>Having supercooling phenomena, corrosive, low thermal stability</td>
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Organic PCMs can be further divided into paraffin wax and non-paraffin mixture. Paraffin wax is mainly composed of a straight chain of alkyl, which releases a large amount of latent heat during the crystallization of the alkyl chain. The melting point and the latent heat of fusion increase as the length of chain grows. Paraffin wax is safe, reliable,
cheap, non-toxic, having good chemical stability and wide range of melting point. The volume change is very little when melting and due to its low saturated pressure, it's almost non-volatile. Because the melting point of paraffin wax can be tuned in given temperature ranges by changing the length of alkyl chain, paraffin wax is good choice of phase change material. From the view of heat storage capacity, chemical property, cost and other essential factors, paraffin wax is the best choice of phase change material.

The research on the application of phase change materials used in the battery thermal management is late. In 2004, Al-Hallaj et al.[19] firstly applied phase change materials in lithium-ion battery thermal management system of an electric scooter. They used software modeling to simulate the temperature rise in battery system and compared the temperature rise curve before and after the addition of PCMs in the battery system. From the simulation result, they came to conclusion that the PCMs could effectively mitigate temperature escalation and reduce the inconsistency of the temperature between each cell. Meanwhile they proposed that if foam aluminum was added into PCMs, the battery temperature would be better controlled. In the next year, Al-Hallaj et al.[20] verified their simulation result with experiment result.

In 2008, Sabbah et al.[21] used software simulation to compare the heat transfer effect of air-cooling and PCM cooling on the lithium-ion battery system in an plug-in hybrid electric vehicle. They found in the severe operation conditions which meant relative large discharging rate and relative high ambient temperature, the air-cooling must increase the power of fans to obtain the same temperature control effect with PCM cooling. They also found that in the condition of 10A operating current, the maximum temperature difference between each battery unit was less than 0.5 °C in their simulation model for PCM cooling. While the maximum temperature difference between each battery unit was as large as 4.5 °C for forced convective air-cooling and the maximum temperature difference became larger when the flow velocity of air was increasing, which meant contradiction of reducing the overall temperature of battery pack and reducing the temperature difference between each cell.

Also in 2008, Kizilel et al.[22] investigated a method of embedding paraffin wax in the expanded graphite matrix to develop a new type thermal management system for lithium-ion battery. This PCM based system can effectively reduce the high temperature of the battery operating and can significantly narrow the temperature difference between the various monomers in the battery pack. At the end of a cycle of discharging, the global maximum temperature of the battery pack approaches to 70 °C under free convective air
cooling and the global maximum temperature of the PCM based battery pack is controlled to less than 45 °C. Furthermore, the temperature difference between the center of battery pack and its boundary region is only 4 °C under PCM cooling while the corresponding temperature difference between the center of battery pack and its boundary region is 10 °C under free convection. What is more, Kizilel et al also investigated how this PCM based cooling system influenced the battery pack capacity attenuation. The experiment results showed that the battery pack capacity attenuation rate in the PCM based thermal management system was only half of the battery pack capacity attenuation rate in the free convection thermal management system.

In 2009, Kizilel et al\cite{23} applied paraffin wax-expanded graphite matrix in the battery pack cooling system and PCM realized very good effect of controlling the temperature. They also did experiments to verify the PCM effect on the temperature uniformity in a cell monomer and among the cell monomers. They found PCMs controlled the temperature difference both in a cell monomer and among the cell monomers at less than 0.2 °C. In addition, they also used software to simulate the inhibition effect of thermal runaway by PCMs. They found that without PCMs in the thermal management system, the thermal runaway in a cell monomer would chain to other monomers very fast, while PCMs controlled the temperature at a normal level in the battery with thermal runaway.

In 2010, Duan et al\cite{24} processed the experiment on the electric vehicle battery with PCM based thermal management system. They used a cylinder heater to replace the battery to generate heat. They investigated the PCMs cooling effect on the condition of constant heat generation rate and changing heat generation rate. They also investigated the effect of thermal management system in different ambient temperature. They compared the PCM cooling with air-cooling and found that PCM could effectively control the temperature escalation. They also found that in the low ambient temperature, PCM cooling system worked better and PCM based thermal management system fitted well with different ambient temperature.

1.5 The research content of the essay

At present, the PCM based thermal management system are all uniform melting point phase change material based. The higher melting point PCM is chosen, the longer the chain of alkyl is applied with higher latent heat and larger heat storage capacity. But the global average temperature will also be higher when the higher melting point PCM is
chosen. On the other hand, lower melting point PCM provides lower average temperature of system but with smaller heat storage capacity. Therefore, a uniform phase change material can’t handle the trade-off between the average temperature and total heat storage capacity. In this research, a hierarchical structure is developed. Low, medium and high melting point PCM are combined together in a hierarchical structure. Under this hierarchical structure, we can combine the benefit of large heat storage capacity of high melting point PCM and low average temperature provided by low melting point PCM. That means when the battery heat generation rate is not very large, the low and medium melting point PCM will keep battery in a relative low temperature. And when the battery heat generation rate is very large, the low and medium melting point PCM will not have enough heat storage capacity and high melting point PCM will show its strength of relative large heat storage capacity, which will mitigate the temperature escalation in a longer time. I also compare my hierarchical structure PCM with uniform medium melting point PCM to demonstrate its wide applicability with different heat generation rate profile. In this research, I use software to simulate the thermal management effect by hierarchical PCMs and process experiments to verify the results in the simulation and also develop a method of inserting copper fins in the paraffin wax layer to improve the low thermal conductivity of paraffin wax layer.
Chapter 2 Phase change material cooling in battery thermal management simulation

I used Ansys Workbench as the software to simulate the transient heat transfer process. It can establish a two-dimension axisymmetric model which is shown below to represent three-dimension cylindrical battery and the surrounding PCM layers. From it we can see the simulation result and the temperature change as a function of time and position at the cross section visual angle. Another advantage of Workbench is the reality of simulation of phase change process. Because it utilizes the real physical property—latent heat to draw the curve of enthalpy per volume as a function of temperature. The real latent heat data makes phase change analysis convinced. Besides, the application of tabular data for the parameter load makes the heat generation power variable because the real operation of battery has the changing power output. For example, we can define the power output as a function of time in the list form to simulate the effect of PCM cooling when the battery is operated in the real condition.

The following figure shows the hierarchical layer model I developed. The center part is the battery surrounded by three layers of paraffin wax with different melting point.

Fig. 2.1 Sketch of hierarchical layer model with different melting point wax
I establish a cylindrical model in the workbench. This graph is the cross section of this cylindrical model in the $x \geq 0$ region of x-y plane. The center cylinder represents the heat generating battery, which has a height of 50 millimeters and a radius of 20 millimeters. Each cylindrical shell represents the paraffin wax layer with different melting point, which all has a thickness of 7 millimeters of the cylindrical shell.

![Diagram of simulation model in the Ansys Workbench](image)

**Fig. 2.2 Diagram of simulation model in the Ansys Workbench**

I choose 25, 35 and 50 ℃ as the melting point of paraffin wax, from inner layer cylindrical shell to outer layer cylindrical shell, respectively. Below is the physical property of the paraffin waxes.

<table>
<thead>
<tr>
<th>Melting point (℃)</th>
<th>Latent heat (kJ/kg)</th>
<th>Density (kg/m³)</th>
<th>Solid specific heat (J/kg/K)</th>
<th>Liquid specific heat (J/kg/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>242</td>
<td>778</td>
<td>1970.8</td>
<td>2299.6</td>
</tr>
<tr>
<td>35</td>
<td>247</td>
<td>785</td>
<td>1946.9</td>
<td>2337.6</td>
</tr>
<tr>
<td>50</td>
<td>255</td>
<td>795</td>
<td>1910.9</td>
<td>2394.6</td>
</tr>
</tbody>
</table>

### 2.1 PCMs with real thermal conductivity thermal management

I set 0.345 $W/m \times ℃$ as the thermal conductivity for solid state paraffin wax and set 0.167 $W/m \times ℃$ as the thermal conductivity for liquid state paraffin wax, which are the real thermal conductivity for paraffin wax according to the literature, to simulate temperature control effect of PCMs in the battery thermal management. The effective total heat generation rate is 10 $W$.

As the software does not have a setting for heat generation term, I set a heat flux of 8000 $W/m^2$ for the bottom surface of the battery region and set the thermal conductivity
as $100 \ W/m \cdot ^\circ C$ for battery body to conduct heat from the bottom. Due to the high thermal conductivity of battery body, the temperature gradient in the battery body is very low, which simulates an equivalent heat generation rate of $10 \ W$ in the battery region. I set initial temperature to be $20 \ ^\circ C$ and set surround temperature to be $20 \ ^\circ C$. I give an ideal value of $10 \ W/m^2 \cdot ^\circ C$ of free convective heat-transfer coefficient of air in the outer boundary of the model.

From the simulation result we can see, in the condition of real thermal conductivity of PCMs, the temperature rising curve has no plateau period and the benefits of great latent heat of PCMs are not fully utilized. Due to the poor thermal conductivity of the paraffin wax, the temperature in the battery region increases very fast and the temperature gradient is also very large in the radial direction of PCM layers. After 4000 seconds, the minimum temperature in the cell reaches $120 \ ^\circ C$ which is much larger than the upper limit of optimum operating temperature range.

![Fig. 2.3 Temperature profile of PCMs based system with real thermal conductivity](image)

**2.2 PCMs with improved thermal conductivity thermal management**

I set $20 \ W/m \cdot ^\circ C$ as the thermal conductivity for solid state paraffin wax and set 10
$W/m \cdot ^\circ C$ as the thermal conductivity for liquid state paraffin wax, which are the improved effective thermal conductivity for paraffin wax, to simulate temperature control effect of PCMs in the battery thermal management. I keep the other conditions same with the last model.

From the simulation result we can see, in the condition of improved thermal conductivity of PCMs, the temperature rising curve has obvious three plateau period that are located in the region of the corresponding melting point of each layer paraffin wax—25, 35 and 50 °C. The red curve and black curve represent the global maximum temperature and global minimum temperature in the battery body respectively. In the time period of large slope of temperature rise, the steep curve represents the heat is absorbed as the sensible heat of paraffin wax. Due to the limited sensible heat of material, the temperature increases sharply.

While in the period of melting, the paraffin wax mitigates the large temperature escalation by storing the heat as the latent heat. The heat is transferred fast enough in radial direction to mitigate the large temperature rise in the internal battery body when a layer of paraffin wax is melting. When the temperature approaches the corresponding melting point of each layer paraffin wax, the temperature lifting is less than 3 °C in more than 1000 seconds time. We can also find from the figure that the plateau period becomes longer with the higher melting point of paraffin wax. It is because the larger melting point paraffin wax has a larger latent heat per volume and occupies a larger volume of space, which ensures a larger total latent heat for high melting point paraffin wax.
2.3 Thermal management for low power output

I still set 20 W/m $\times$ °C as the thermal conductivity for solid state paraffin wax and set 10 W/m $\times$ °C as the thermal conductivity for liquid state paraffin wax, which are the improved effective thermal conductivity for paraffin wax. However, I set the effective total heat generation rate to be 1.25 W by giving a heat flux of 1000 W/m$^2$ on the bottom surface of the battery region. I set initial temperature to be 60 °C and set surround temperature still to be 20 °C. This situation is to simulate the temperature drop after a period of high power output. As the effective heat generation rate is only 1.25 W and the initial temperature of entity is 60 °C, the temperature will no longer increase but decrease instead. In the first 900 seconds, the temperature decline is more than 6.8 °C. After the first 900 seconds, the temperature in the outer region of paraffin wax reaches its freezing point 51 °C. Due to the existence of temperature gradient in radial direction, the temperature of battery region at that time is slightly larger than 51 °C. The temperature drop rate then slows down. In the following 3000 seconds, the temperature in the battery body only decreases less than 2.5 °C.
Due to the freezing of the outer layer paraffin wax, it will release heat continuously, which greatly weakens the heat generated by the battery transferring to the air. So, one disadvantage of utilizing a layer of high melting point paraffin wax is that when the temperature is decreasing, the layer of high melting point paraffin wax will also keep the battery body operating in a relative high temperature in a relative long time. As we assume the lower temperature in the optimum temperature range is better for the cycle performance and capacity of the battery, the higher average temperature kept by the phase change material does more irreversible damage to the structure of active and inactive electrode material.

Fig. 2.5 Temperature profile at low power output and 60 °C as initial temperature

Next, I keep this low power output and change a lower initial temperature of model entity. I still set 20 $W/m \cdot ^\circ C$ as the thermal conductivity for solid state paraffin wax and set 10 $W/m \cdot ^\circ C$ as the thermal conductivity for liquid state paraffin wax, which are the improved effective thermal conductivity for paraffin wax. However, I set the effective total heat generation rate to be 1.25 W by giving a heat flux of 1000 W/$m^2$ on the bottom surface of the battery region. This time I set initial temperature to be 40 °C and surround temperature still to be 20 °C to simulate the temperature change in the battery region when the paraffin wax with medium melting point is freezing. In the first 500 seconds, the temperature decreases about 2 °C, which has a slower temperature drop rate.
than the initial entity is 60 °C. As the heat flux rate is proportional to the temperature difference between the outer surface of the model and the ambient air temperature, it is easy to understand that a slower temperature drop rate occurs in this situation. And in the time range from 500 to 3000 seconds, due to the freezing of the medium part paraffin wax and heat release from the latent heat, the temperature drop rate slows down and the temperature only drops about 2 °C in this period.

So, does the existence of paraffin wax with high melting point always behaves worse than thermal management of the outer layer paraffin wax with lower melting point? In one aspect, it’s not. As the outer layer of paraffin wax with high melting point keeps the higher temperature difference between the outer model surface and the ambient air when temperature is decreasing, it can transfer more heat from the phase change material and help to revive the latent heat when the battery is in a low power output. While if there only exists paraffin wax with medium melting point in the outer layer, the temperature may drop more but it removes less heat from the phase change material and will need a longer time to revive the latent heat of PCM.

![Temperature profile at low power output and 40 °C as initial temperature](image-2-6)

Fig. 2.6 Temperature profile at low power output and 40 °C as initial temperature
2.4 Uniform paraffin wax with low melting point

For battery thermal management, I set two objectives. One is keeping the mean temperature as small as possible, the other is keeping the total control time as long as possible in the range of optimum temperature which I set 0-55 °C. The more fraction of utilization of low melting point paraffin wax makes first objective realizing and the more fraction of utilization of high melting point paraffin wax realizes the second objective better. So, there is a trade-off.

To verify the effect of hierarchical layer of PCMs on the trade-off to the two objectives, we should firstly observe the thermal management result in uniform phase change material. I keep the other conditions same with hierarchical one but only pack the three layers with the same paraffin wax with low melting point. As I assume the optimum temperature range is from 0 to 55 °C, I focus on the average temperature and total time during this temperature range. In the first 6049.7 seconds, the global maximum temperature reaches to 55 °C. The average temperature in the first 6049.7 seconds is 31.69 °C. The total time in the optimum operation temperature range is 6049.7s.

![Temperature profile with uniform 25 °C melting point wax](image)

**Fig. 2.7** Temperature profile with uniform 25 °C melting point wax
2.5 Uniform paraffin wax with medium melting point

I keep the other conditions same with hierarchical one but only pack the three layers with the same paraffin wax with medium melting point this time. In the first 6930.3 seconds, the global maximum temperature reaches to 55 °C. The average temperature in the first 6930.3 seconds is 38.21 °C. The total time in the optimum operation temperature range is 6930.3s.

![Temperature profile with uniform 35 °C melting point wax](image)

**Fig. 2.8 Temperature profile with uniform 35 °C melting point wax**

2.6 Uniform paraffin wax with high melting point

I keep the other conditions same with hierarchical one but only pack the three layers with the same paraffin wax with high melting point this time. In the first 8347.1 seconds, the global maximum temperature reaches to 55 °C. The average temperature in the first 8347.1 seconds is 49.47 °C. The total time in the optimum operation temperature range is 8347.1s.

Summary for 2.4, 2.5 2.6: The higher melting point paraffin wax is used, the longer time
is in the optimal temperature range but the higher average temperature is kept. If there is only uniform phase change material is applied, the only way to extend the control time in the optimal temperature is to choose paraffin wax with higher melting point. However, the temperature will also directly reach the melting point in a short time. And a higher operating temperature damages the structure of active and inactive material in both cathode and anode electrode irreversibly because of the mechanism of cathode and anode degradation.

Fig. 2.9 Temperature profile with uniform 50 °C melting point wax

2.7 Inner thick model with more 25 °C melting point paraffin wax

I increase the thickness of inner cylindrical shell layer to 14 millimeters and reduce the thickness of medium and outer cylindrical shell layer to 3.5 millimeters. So, the total volume of model is remained constant. The volume ratio of paraffin wax from inner layer to outer layer is 59:20:21. In the first 6532.5 seconds, the global maximum temperature reaches to 55 °C. The average temperature in the first 6532.5 seconds is 37.61 °C. The total time in the optimum operation temperature range is 6532.5s.

We can compare this result with uniform paraffin wax with 35 °C melting point. The
The total time in the optimum operation temperature range for the uniform paraffin wax with 35 °C is 6930.3s and the corresponding average temperature is 38.21 °C. This inner thick model has a shorter control time, which is not good, but has a lower average temperature. One advantage of this hierarchical model is it will fit a low power output battery better, which can keep the battery temperature below 30 °C for a longer time. Another advantage is that when it works a long time, the outer 50 °C melting point wax will transfer the heat faster and revive the outer PCM’s latent heat faster due to the higher temperature difference between outer surface of model and the ambient air.

![Graph showing temperature profile](image)

**Fig. 2.10 Temperature profile with inner layer thicker**

### 2.8 Medium thick model with more 35 °C melting point paraffin wax

I increase the thickness of medium cylindrical shell layer to 14 millimeters and reduce the thickness of inner and outer cylindrical shell layer to 3.5 millimeters. So, the total volume of model is remained constant. The volume ratio of paraffin wax from inner layer to outer layer is 12:67:21. In the first 6961.1 seconds, the global maximum temperature reaches to 55 °C. The average temperature in the first 6961.1 seconds is 40.28 °C. The
total time in the optimum operation temperature range is 6961.1s.

Fig. 2.11 Temperature profile with medium layer thicker

2.9 Outer thick model with more 50 °C melting point paraffin wax

I increase the thickness of outer cylindrical shell layer to 14 millimeters and reduce the thickness of inner and medium cylindrical shell layer to 3.5 millimeters. So, the total volume of model is remained constant. The volume ratio of paraffin wax from inner layer to outer layer is 12:14:74. In the first 7762.9 seconds, the global maximum temperature reaches to 55 °C. The average temperature in the first 7762.9 seconds is 46.62 °C. The total time in the optimum operation temperature range is 7762.9s.
Fig. 2.12 Temperature profile with outer layer thicker

2.10 Reverse sequence of paraffin wax layers

We go back to figure 2.3. The volume ratio of 25, 35, 50 °C melting point layer is 26:33:41. We can see in the figure 2.3 in the first 7068.9 seconds, the global maximum temperature reaches to 55 °C. The average temperature in the first 7068.9 seconds is 42.08 °C. The total time in the optimum operation temperature range is 7068.9s.

I reverse the sequence of layers this time. The volume ratio of 25, 35, 50 °C melting point layer is 41:33:26. We can see in the figure 2.12 in the first 7011.2 seconds, the global maximum temperature reaches to 55 °C. The average temperature in the first 7011.2 seconds is 39.39 °C. The total time in the optimum operation temperature range is 7011.2s. It seems the reverse one is much better with lower average temperature but similar control time. But actually, it’s the function of volume occupation for each layer. The longer temperature plateau around 25 °C in reverse sequence model is the only benefits of larger volume ratio. And because the real thermal conductivity may be not as good as I simulate, the real effect of thermal management may be not so optimistic as the simulation results.
Fig. 2.3 Temperature profile of PCMs based system with improved thermal conductivity

Fig. 2.13 Temperature profile with reserve sequence of layers
2.11 Comparison with uniform 35 °C melting point wax

<table>
<thead>
<tr>
<th>Volume ratio 41:33:26</th>
<th>Total time in the optimal temperature range (s)</th>
<th>Average Temperature during optimal temperature range (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform paraffin wax with 35 °C melting point</td>
<td>7068.9</td>
<td>42.08</td>
</tr>
<tr>
<td></td>
<td>6930.3</td>
<td>38.21</td>
</tr>
</tbody>
</table>

From the table above, we can see the similar total time in the optimal temperature range with a little larger average temperature of the hierarchical structure PCM under a constant large heat generation rate. However, if the heat generation rate decreases at the period of 500-2000 seconds, the hierarchical structure PCM will keep a much smaller temperature. Actually, a varied power output of battery happens more frequently in the practical use and the hierarchical structure PCM shows its strength on the different situations.

Fig. 2.14 Temperature profiles comparison with uniform 35°C melting point wax
Chapter summary:

1. The low thermal conductivity of paraffin wax will make the effect of thermal management very poor. Even if the paraffin wax has a large heat storage capacity, the heat generated by the battery can’t be effectively transferred to the outer layer. The temperature in the battery region will increase very fast.

2. In the simulation of improved thermal conductivity paraffin wax controlling the temperature, there are three clear temperature plateaus near the corresponding melting point. The length of time in the temperature plateau is quite long compared to the time when heat is being stored in the sensible heat.

3. When simulating the condition of a high initial temperature, which represents a long time use of battery, and a low present power output, the temperature drop rate in the battery region is also low due to the heat release by the freezing of paraffin wax.

4. If there is only uniform phase change material is applied, the only way to extend the control time in the optimal temperature is to choose paraffin wax with higher melting point. However, the temperature will also directly reach the melting point in a short time. And a higher operating temperature damages the structure of active and inactive material in both cathode and anode electrode irreversibly because of the mechanism of cathode and anode degradation.

5. It seems the reverse sequence model is much better with more than 2 °C lower average temperature but similar control time. But actually, the real thermal conductivity may be not as good as I simulate, the real effect of thermal management may be not so optimistic as the simulation results.

6. At the constant high power output of battery, the hierarchical structure PCMs perform similar with medium melting point uniform PCM. At the low power output of battery after a period of high power output, the hierarchical structure PCMs provides a much lower temperature compared with medium melting point uniform PCM.
Chapter 3 Experiments of battery thermal management with PCMs

I used the electrified metal alloy wire in helix structure to replace the battery to generate heat with controlled power. The heater wire contains 22% Cr, 58% Al and 20% Fe. Its diameter is 1 millimeter. The resistance of heater wire is 1.477 Ω/m. I used thermal grease HY400 to conduct heat generated by the heater wire. The thermal grease has a good thermal conductivity but it’s electric insulated. Its thermal conductivity is higher than 0.925 W/(m °C), which is larger than the thermal conductivity of water, which is about 0.6 W/(m °C). The phase change material I chose for the inner layer is octadecane, which has a melting point of 28 °C. The phase change material I chose for the medium layer is eicosane, which has a melting point from 35 to 37 °C. The phase change material I chose for the outer layer is lauric acid, which has a melting point from 44 to 46 °C. The height of the phase change material filled in the model from inner layer to outer layer are 21 mm, 21 mm and 17 mm, respectively. The model’s top and front view are shown below.

![Fig. 3.1 Sketch of the model in the experiment](image-url)
3.1 Constant 10 W heat generation rate

I set the output voltage of DC power supply to 4.0 V and the output current to 2.55 A. The heat generation rate is about 10 W. The figure 3.2-3.4 show the temperature profile at this heat generation rate from inner PCM layer to outer PCM layer, respectively. The duration of temperature plateaus compared to the duration of sensible heat storage are smaller than the simulation results of improved thermal conductivity PCMs. So, the equivalent or effective thermal conductivity is lower than the simulation assumption. Actually, the duration of temperature plateau period is still much longer than the duration of sensible heat storage, when the temperature increases very fast. The experiment data verify the feasibility of hierarchical structure PCMs based thermal management system.

Fig. 3.2 Temperature profile of inner layer at 10 W heat generation rate

The temperature profile shows that the medium part and outer part temperature exceed the inner part because the copper plate in the bottom transfers the heat generated by the heat wire. The medium part and outer part increase their temperature while the inner part is melting and keeping a temperature plateau. That’s why the reverse temperature gradient appears and the temperature in the medium layer can exceed the temperature in the inner layer for some time.
Fig. 3.3 Temperature profile of medium layer at 10 W heat generation rate

Fig. 3.4 Temperature profile of outer layer at 10 W heat generation rate
3.2 Constant 15 W heat generation rate

I set the output voltage of DC power supply to 4.9 V and the output current to 2A. The heat generation rate is about 15 W. The figure 3.5-3.7 show the temperature profile at this heat generation rate from inner PCM layer to outer PCM layer, respectively. The temperature plateaus are shorter than the simulation results. As the heat generation rate increases, the total control time becomes much shorter, decreasing from about 9000 seconds in 10 W to about 5000 seconds in 15 W. The temperature plateaus around 37 °C and 44 °C approaches each other and the transition of these two temperature plateaus becomes faint.

Fig. 3.5 Temperature profile of inner layer at 15 W heat generation rate
In the figure 3.6 there is still clear temperature plateau appears around 37 °C.

Fig. 3.6 Temperature profile of medium layer at 15 W heat generation rate

Fig. 3.7 Temperature profile of outer layer at 15 W heat generation rate
3.3 Constant 20 W heat generation rate

I set the output voltage of DC power supply to 5.6 V and the output current to 3.59A. The heat generation rate is about 20 W. The figure 3.8-3.10 show the temperature profile at this heat generation rate from inner PCM layer to outer PCM layer, respectively. The temperature plateaus are shorter than the simulation results. As the heat generation rate increases, the total control time becomes much shorter, decreasing from about 5000 seconds in 15 W to about 3000 seconds in 20 W. The temperature plateaus around 37 °C and 44 °C and the transition of these two temperature plateaus all disappear. The only clear temperature plateau appears near the 27 °C. The temperature plateaus disappear because the heat generation rate is so large that heat storing rate in the medium part is smaller than the heat generation rate. The heat generated by the heater wire can’t be effectively removed resulting in the temperature escalation of the inner part and disappear of plateau.

![Graph showing temperature profile](image)

**Fig. 3.8 Temperature profile of inner layer at 20 W heat generation rate**
In the figure 3.9 the temperature plateau around 37 °C almost disappears.

**Fig. 3.9 Temperature profile of medium layer at 20 W heat generation rate**

**Fig. 3.10 Temperature profile of outer layer at 20 W heat generation rate**
3.4 Constant 20 W heat generation rate with inserting copper fins

I set the output voltage of DC power supply to 5.6 V and the output current to 3.54A. The heat generation rate is about 20 W. This time I insert two copper fins in each phase change material layer. The fin has a same width with the gap of layer and same height with the model. The fins’ thickness is about 1.5 mm. The effective thermal conductivity is improved by the fins.

The figure 3.8-3.10 show the temperature profile at this heat generation rate from inner PCM layer to outer PCM layer, respectively. The curve of inserting fins is almost below the control group with no fins. It means the average temperature decreases.

Actually, it can be predicted by the analytical model.

![Temperature profile of inner layer at 20 W heat generation rate with fins](image)

**Fig. 3.11 Temperature profile of inner layer at 20 W heat generation rate with fins**
Fig. 3.12 Temperature profile of medium layer at 20 W heat generation rate with fins

Fig. 3.13 Temperature profile of outer layer at 20 W heat generation rate with fins
3.5 Comparison with simulation results under same conditions

Finally, I compare the experimental result with the simulation result under same 10W of heat generation rate. The simulation result conforms to the experimental data basically, while simulation result shows that the temperature plateau has finished early. The reason is that in my simulation it can not define a heat generation term in the solid body. So, I give a heat flux rate in the surface of the battery body instead. The inconsistency of heat generation rate makes the temperature control more difficult and shortens the temperature plateau.

![Temperature profile of experimental result and simulation result at 10 W heat generation rate](image)

Fig. 3.14 Temperature profile of experimental result and simulation result at 10 W heat generation rate

3.6 Analytical analysis of the influence of the thermal conductivity

To investigate more on the influence of the thermal conductivity of the material for future study, we focus on a forced convective air cooling in a cylindrical model.

\[ \rho C_p \frac{\partial T}{\partial t} = k \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + Q \]

where Q is the heat generation rate per volume.
The boundary conditions are below:

\[ r = R, -k \frac{\partial T}{\partial r} = h(T - T_f) \]
\[ t = 0, \quad T(0, r) = T_0 \]

Assume temperature function is decomposed into two parts, a final steady state and a deviation from steady state.

\[ T(r, t) = \bar{T}(r) + y(r, t) \]

Substituting

\[ \xi = \frac{r}{R} ; \quad \tau = \frac{kt}{\rho C_p R^2} \]

And

\[ N_k = \frac{QR^2}{k(T_0 - T_f)} ; \quad Bi = \frac{hR}{k} \]

\[ T(\xi, \tau) = \bar{T}(\xi) + y(\xi, \tau) \]

\[ = T_f + \frac{QR}{2h} + \frac{QR^2}{4k} (1 - \xi^2) + \sum_{n=1}^{\infty} \frac{2 \left(T_0 - T_f - \frac{QR^2}{k\lambda_n^2} \right) Bi}{(\lambda_n^2 + B i^2)} \cdot \frac{j_0(\lambda_n \xi)}{j_0(\lambda_n)} \cdot \exp(-\lambda_n^2 \tau) \]

Where \( \lambda_n \) is the series positive solutions of \( \lambda_n \cdot J_1(\lambda_n) = Bi \cdot j_0(\lambda_n) \).

When \( \tau \geq 0.2 \), the \( n \geq 2 \) terms in the infinite series could be neglected.

So,

\[ T(\xi, \tau) = T_f + \frac{QR}{2h} + \frac{QR^2}{4k} (1 - \xi^2) + \frac{2 \left(T_0 - T_f - \frac{QR^2}{k\lambda_1^2} \right) Bi}{(\lambda_1^2 + B i^2)} \cdot j_0(\lambda_1 \xi) \cdot \exp(-\lambda_1^2 \tau) \]

\[ \frac{T(0, \tau) - T_f}{T_0 - T_f} = N_k \left( \frac{1}{4} + \frac{1}{2Bi} \right) + \frac{2Bi \left(1 - \frac{N_k^2}{\lambda_1^4} \right)}{(\lambda_1^2 + B i^2)} \cdot j_0(\lambda_1) \cdot \exp(-\lambda_1^2 \tau) \]

The figure 3.14-16 show the dimensionless temperature as a function of time.

\[ N_k = \frac{\text{The rate of heat generation}}{\text{The rate of heat conduction}} \quad Bi = \frac{\text{The rate of heat convection by air}}{\text{The rate of heat conduction}} \]

As we only change the rate of heat conduction and keep the rate of heat generation and convection by air constant, the value of \( N_k \) and \( Bi \) drops at the same factor. The following figure shows how the rate of thermal conduction influence the dimensionless temperature profile. At the first curve of 1k, the value of \( N_k \) and \( Bi \) are 32 and 0.5, respectively.
Fig. 3.15 The dimensionless temperature as a function of dimensionless time with different heat conduction of model

The figure 3.18 explains the result in the figure 3.13 very well. When the effective thermal conductivity of the model increases, the new temperature profile as a function of time will be underneath the original temperature profile.

Fig. 3.13 Temperature profile of outer layer at 20 W heat generation rate with fins
Chapter summary:
1. The simulation result conforms to the experimental data basically, while simulation result shows that the temperature plateau has finished early. The reason is that in my simulation it can not define a heat generation term in the solid body. So, I give a heat flux rate in the surface of the battery body instead. The inconsistency of heat generation rate makes the temperature control more difficult and shortens the temperature plateau.
2. At higher heat generation rate the temperature plateaus disappear because the heat generation rate is so large that heat storing rate in the wax is smaller than the heat generation rate. The heat generated by the heater wire can’t be effectively removed which leads to the temperature escalation of the inner wax layer and disappear of plateau.
3. When the effective thermal conductivity of the model increases, the new temperature profile as a function of time will be underneath the original temperature profile.
Chapter 4 Conclusions and future plans

4.1 Conclusions

1) The single low melting point PCM may melt in advance in high ambient temperature and it also provides a relative low heat storage capacity. While the single high melting point PCM will make the average temperature very high. The multi-layer structure of PCM cooling adapts to the extreme high/low ambient temperature well. As it can manage the temperature layer by layer, it performs better than the single medium melting point PCM.

2) At the constant high power output of battery, the hierarchical structure PCMs perform similar with medium melting point uniform PCM. At the low power output of battery after a period of high power output, the hierarchical structure PCMs provides a much lower temperature compared with medium melting point uniform PCM. Actually, a varied power output of battery happens more frequently in the practical use of electric vehicles and the hierarchical structure PCM shows its ability to adapt well to the different situations of thermal management.

3) The simulation result conforms to the experimental data basically. The inconsistency of heat generation rate in the simulation model makes the temperature control more difficult and shortens the temperature plateau.

4) When the effective thermal conductivity of the model increases, the new temperature profile as a function of time will be underneath the original temperature profile.

4.2 Future plans

1) To improve the thermal conductivity of paraffin wax, some graphite powder can be added to dope with wax.

2) A varied power output profile of DC power supplier can be processed to verify the effect of controlling the temperature of PCM based thermal management.

3) Test the effect of enhanced air flowing combined with PCM cooling
References:


