Investigation of the thermal performance of phase change material/mini-channel coupled battery thermal management system

Zhonghao Rao *, Qingchao Wang, Congliang Huang

School of Electric Power Engineering, China University of Mining and Technology, Xuzhou 221116, China

HIGHLIGHTS

- Phase change material/mini-channel coupled battery thermal management system was proposed.
- Phase change temperature and thermal conductivity of PCM should be suitable for thermal management system.
- Maximum temperature difference of the battery thermal management system should not be neglected.

ABSTRACT

In order to extend the cycle life of power battery pack within electric vehicle, a phase change material (PCM)/mini-channel coupled power battery thermal management (BTM) system, as well as the three-dimensional battery thermal model, was designed in this paper. The effect of various influencing factors, especially mass flow rate of water, phase change temperature and thermal conductivity of PCM, were investigated numerically. The results showed that the liquid volume fraction of PCM was greatly influenced by the thermal conductivity and the phase change temperature of PCM. The increasing number of channels results in a decrease of the maximum temperature ($T_{\text{Max}}$) and maximum temperature difference ($\Delta T$) of battery packs. The optimal phase change temperature and thermal conductivity of PCM were 308.15 K and 0.6 W m$^{-1}$ K$^{-1}$ respectively when the number of channel was eight and the mass flow rate was $8 \times 10^{-4}$ kg s$^{-1}$. Moreover, a maximum temperature of 320.6 K was predicted for the PCM/mini-channel coupled BTM system, while a maximum temperature of 335.4 K was predicted for the PCM-based BTM system. Additionally, the PCM/mini-channel coupled BTM system presented more effective thermal performance and the research will be a clear indicator for the design of the PCM/liquid coupled BTM system.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

With the development of economy, the greenhouse effect and air pollution have received considerable attention in recent years. To reduce the pollution, some promising solutions to the energy use of electric vehicles (EVs) have been studied. The temperature distribution and uniformity play vital roles in the battery thermal management (BTM) system. The heat generated during rapid charge and discharge cycles will affect the battery lifetime and the thermal performance of electric vehicle [1]. So the EVs market requires high specific power and high specific energy density batteries to meet the operational needs of EVs. The electrode thickness has influence on the performance of the battery. For instance, the battery with thicker electrodes tends to have an uneven temperature response [2]. The lithium-ion battery was considered as a preferred alternative to store the electric energy due to its outstanding characteristics such as high energy density and long cycle life [3]. However, thermal management issues of electric vehicle battery packs can obviously influence the performance and life cycle [4]. Thus, effective BTM methods are significantly important for the EVs. The traditional BTM systems, including liquid based thermal management system [5] and air based thermal management system [6], will present good cooling effect if the system is reasonably designed. Some novel cooling methods have attracted more and more attention in the last decade, such as PCM-based thermal management system [7] and heat pipe-based thermal management system [8,9]. Jiang et al. [10] placed the heat pipe in a distributed configuration, compared with the forced convection...
under the same condition, the maximum temperature of the system was decreased to 297.05 K.

In recent years, because of the huge latent capacity of PCM, it has been applied to the air-condition [11], solar energy [12, 13], buildings [14, 15] and electronic equipment [16]. It also has been well applied to the BTM system. In our previous work [17], PCM was used in the ageing LiFePO4 power battery system. However, the heat could not be conducted immediately due to the low thermal conductivity of PCM. Furthermore, the PCM can lead to more homogeneous temperature distribution than other methods. If the PCM phase change temperature is below 318.15 K, it will be conductive to heat diffusion [17]. Various kinds of methods have been studied to increase the thermal conductivity of PCM. Due to the high conductivity of metallic particle, materials like copper particles [18], aluminum foam [19] and nickel particles [20] were added into PCM. Ultrathin-graphite foams were also added into PCM to enhance the thermal conductivity. With the volume fractions increasing from 0.8% to 1.2%, the thermal conductivity of PCM increases by 18 times [21]. Jiang et al. [22] pointed out that the PCM-based BTM system showed better performance than the forced convection BTM system under the same condition, the PCM was able to control the temperature of the system during the melting process. Furthermore, Duan and Naterer [23] designed two different cooling systems. One method is that the heater was surrounded by a PCM cylinder, while the other one is that the heater was wrapped by PCM jackets. They concluded that the two designs can control the temperature of the heater well. In a passive BTM system, expanded graphite was impregnated in the PCM and the performance of the BTM system was significantly improved compared with original battery packs [24]. Dincer et al. [25] studied the heat transfer in a PCM based BTM system where heat was generated due to the Ohmic law. Nevertheless, the heat would be absorbed by the PCM during the phase change process of PCM. They investigated the influence of the PCM thickness on the BTM. When the PCM thickness was 12 mm, the maximum temperature would decrease by 3.04 K. However, the temperature distribution became 10% more uniform when the PCM thickness was 3 mm. A novel PCM based cooling system proposed in Ref. [26] was one of the systems utilizing the active liquid cooling method. Hence, the heat exchange was obviously enhanced by the liquid. Wu et al. [27] designed a PCM board which was used for electronics. They concluded that the system performed better thermal properties than natural air cooling and the method can be used in various practical applications. Zhang et al. [28] built an effective PCM BTM system using the forced-air cooling method in their research and they concluded that the air speed plays an important role and the system presents good performance. They also studied another BTM system by using expanded graphite-based PCM, where they found that when the melting point of the PCM was 317.15 K, the temperature of the battery packs could be well controlled. In order to further study the effect of PCM on BTM, a detailed review was provided in Ref. [29]. The PCM based BTM systems present a good performance.

In conventional BTM, the liquid based thermal management system has good effects. It is confirmed that the heat of battery inputting and dissipating rests with charging and discharging, respectively [30]. And the battery module temperature uniformity (\(\Delta T\)) is a quite significant parameter in BTM system [4]. Liquid based BTM can well decrease the maximum temperature (\(T_{\text{Max}}\)) and the maximum temperature difference (\(\Delta T\)) during the charging and discharging process. The detailed comparison between liquid cooling and air cooling can be found in Ref. [31] and it was concluded that the liquid cooling effect was more effective than air cooling. Lee et al. [32] designed an ultra-thin mini-channel liquid cold plate for the BTM system, which can maintain the temperature of the battery below 323.15 K. Jiao et al. [33] researched the thermal behaviors in lithium-ion batteries and they concluded that different cooling methods should be adopted under different ambient temperature conditions. They pointed out that the liquid cooling leads to the strongest cooling effect under a normal ambient temperature condition and the Reynolds number can greatly influence the effect of the liquid cooling but be negligible in air cooling. The performance of the power battery only using mini-channel cold plate was studied in our previous work [34], and the increase of the mass flow rate, the cooling effect was enhanced. When the optimal mass flow rate was \(5 \times 10^{-4} \text{ kg s}^{-1}\), the system presented a well cooling performance.

In conclusion, liquid cooling method can achieve the good cooling-effect and PCM cooling method can yield the most even temperature distribution. Considering the large heat storage capacity of the PCM and the excellent cooling-effect of liquid cooling, we made some changes and added the PCM into the liquid cooling system in order to further optimize the performance of BTM system for EVs and improve our previous work [34]. The PCM/mini-channel coupled BTM system was proposed and a three-dimensional battery thermal model was simulated. In this
study, different influencing factors such as the phase change temperature and the thermal conductivity of PCM, the channel numbers and the mass flow rate of PCM/mini-channel coupled BTM system were discussed in detail.

2. Modeling

2.1. Physical problem

The schematic of the overall system is shown clearly in Fig. 1a. The system contains several cell modules. The power of the whole cycle was offered by a circulating pump. The heat exchanger was used to absorb the heat within the liquid and the water flow was controlled by a flow control valve. The system was simple and safe. The cell module without battery case and the structure of the mini-channels can be seen in Fig. 1b and c. We can see other mini-channel cooling systems in our previous works [34,35]. Fig. 2 shows the simplified model and it can be seen that the schematic of the PCM/mini-channel coupled BTM system in this simulation where PCM were filled into the gaps between the rectangular batteries. The model was symmetrical. In order to shorten the simulation time, only 1/4 part of the model was simulated in this paper. The phase change temperature of PCM was selected as 308.15 K, 313.15 K, 318.15 K and 323.15 K. Aluminum was employed as the material of mini-channels due to its high thermal conductivity and light weight. The mini-channels were designed as cylinder and they were equidistantly distributed of which the inner and outer diameter were 0.8 mm and 1 mm, respectively. In order to make the maximum temperature of the battery close to that of the actual battery, the constant heat flux of battery was set to 240 kw m$^{-2}$. The cooling water was assumed to be incompressible and laminar due to the short characteristic lengths and low flow velocity. Based on the viscosity and density of the working fluid, the Reynolds number of flow in this paper can be calculated, lower than 2300. The temperature of the inlet water, the initial temperature of batteries and PCM were all set as 298.15 K, which was equal to the surrounding temperature. Fig. 3 displays the number of channels were 2, 4, 6 and 8. The mass flow rates were chosen to be $5 \times 10^{-6}$ kg s$^{-1}$, $1 \times 10^{-5}$ kg s$^{-1}$, $8 \times 10^{-6}$ kg s$^{-1}$, $1 \times 10^{-4}$ kg s$^{-1}$, $5 \times 10^{-4}$ kg s$^{-1}$, $8 \times 10^{-4}$ kg s$^{-1}$ and $1 \times 10^{-3}$ kg s$^{-1}$, respectively. These variables could impact the performance, life cycle and cost of the batteries in EVs. The working performance was improved through reasonably change these variables in this paper. In order to study the performance of the battery under the abusive conditions, the battery was discharged at a high discharge rate of 5 C and it could last 720 s. In order to shorten the calculation time, the time step for integrating the temporal derivatives was set to 1 s. The number of iteration per time step was 50. The convection heat transfer coefficient was 5 W m$^{-2}$ K$^{-1}$ [34]. The radiation heat transfer and thermal contact resistances at the interfaces were neglected in this paper [36]. The motion of solid PCM and the volume change were also neglected during the phase change, so dropping of the heavier solid PCM is not treated [37]. The geometric sizes and parameters used in this simulation are summarized in Table 1 [17]. It is assumed that the properties of the PCM are constant and equal for both solid and liquid phases [36]. The software ANSYS FLUENT 14.5 was utilized in this simulation.

2.2. Conservation equations

The heat generation $Q_b$ (J) in the battery can be mathematically obtained from the equation as follows (the battery was under the adiabatic condition):
Here, \( T_{b1} \) (K) and \( T_{b2} \) (K) represent the initial temperature and the end of discharge temperature of battery, respectively. \( C_b \) (J kg\(^{-1}\) K\(^{-1}\)) is specific heat of the battery.

In the PCM based BTM system, when the battery is under the adiabatic condition, the mass (kg) of the PCM can be derived by the equation as follows:

\[
Q_{\text{dis}} = m \times C_{\text{pcm}}(T_1 - T_2) + m \times h
\]  

where \( T_1 \) (K) and \( T_2 \) (K) are the phase change temperature and the initial temperature of PCM, respectively. \( Q_{\text{dis}} \) (J) represents the heat generation in the battery and \( C_{\text{pcm}} \) (J kg\(^{-1}\) K\(^{-1}\)) and \( h \) (J g\(^{-1}\)) are specific heat and pure solvent melting heat of PCM, respectively.

In the PCM/mini-channel coupled BTM system, a part of heat, which is generated in battery, can be taken away by the cooling water and this part heat \( Q_w \) (J) is given as the following equation:

\[
Q_w = C_w \Delta T = \rho_w \mu_w \frac{\pi d^2}{4} C_w (T_{\text{out}} - T_{\text{in}})
\]

where \( T_{\text{in}} \) (K) and \( T_{\text{out}} \) (K) are the inlet and output temperatures of water, respectively. \( T_{\text{aver}} \) (K), which is determined by \( T_{\text{in}} \) and \( T_{\text{out}} \), is the average temperature of the water. \( \mu_w \) expresses the flow velocity of water. The values of \( \rho_w \) (kg m\(^{-1}\)) and \( C_w \) (J kg\(^{-1}\) K\(^{-1}\)) are the density and specific heat of water at \( T_{\text{aver}} \).

Table 1
Geometric sizes and parameters used in simulation.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery length</td>
<td>len (mm)</td>
<td>118</td>
</tr>
<tr>
<td>Battery width</td>
<td>wid (mm)</td>
<td>63</td>
</tr>
<tr>
<td>Battery thickness</td>
<td>th (mm)</td>
<td>13</td>
</tr>
<tr>
<td>Latent heat of PCM</td>
<td>( L_{\text{PCM}} ) (J kg(^{-1}) K(^{-1}))</td>
<td>190,000</td>
</tr>
<tr>
<td>Specific heat of battery</td>
<td>( C_b ) (J kg(^{-1}))</td>
<td>1108</td>
</tr>
<tr>
<td>Specific heat of water</td>
<td>( C_w ) (J kg(^{-1}))</td>
<td>4182</td>
</tr>
<tr>
<td>Specific heat of PCM</td>
<td>( C_{\text{pcm}} ) (J kg(^{-1}))</td>
<td>2100</td>
</tr>
<tr>
<td>Specific heat aluminum</td>
<td>( C_{\text{Al}} ) (J kg(^{-1}))</td>
<td>871</td>
</tr>
<tr>
<td>Thermal conductivity of battery</td>
<td>( K_b ) (W m(^{-1}) K(^{-1}))</td>
<td>3.9</td>
</tr>
<tr>
<td>Thermal conductivity of water</td>
<td>( K_w ) (W m(^{-1}) K(^{-1}))</td>
<td>0.6</td>
</tr>
<tr>
<td>Thermal conductivity of PCM</td>
<td>( K_{\text{pcm}} ) (W m(^{-1}) K(^{-1}))</td>
<td>0.2, 0.6, 0.8, 1, 2</td>
</tr>
<tr>
<td>Thermal conductivity of aluminum</td>
<td>( K_{\text{Al}} ) (W m(^{-1}) K(^{-1}))</td>
<td>202.4</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>( T_0 ) (K)</td>
<td>298.15</td>
</tr>
<tr>
<td>Density of PCM</td>
<td>( \rho_{\text{pcm}} ) (kg m(^{-3}))</td>
<td>910</td>
</tr>
<tr>
<td>Density of water</td>
<td>( \rho_w ) (kg m(^{-3}))</td>
<td>998.2</td>
</tr>
<tr>
<td>Density of aluminum</td>
<td>( \rho_{\text{Al}} ) (kg m(^{-3}))</td>
<td>2719</td>
</tr>
<tr>
<td>Density of battery</td>
<td>( \rho_b ) (kg m(^{-3}))</td>
<td>2450</td>
</tr>
<tr>
<td>Viscosity of PCM</td>
<td>( \nu_{\text{pcm}} ) (kg m(^{-1}) s(^{-1}))</td>
<td>0.01</td>
</tr>
<tr>
<td>Viscosity of water</td>
<td>( \nu_w ) (kg m(^{-1}) s(^{-1}))</td>
<td>0.001003</td>
</tr>
</tbody>
</table>

\[
Q_b = C_b \cdot m_b (T_{b1} - T_{b2})
\]  

Here, \( T_{b1} \) (K) and \( T_{b2} \) (K) represent the initial temperature and the end of discharge temperature of battery, respectively. \( C_b \) (J kg\(^{-1}\) K\(^{-1}\)) is specific heat of the battery.
As the natural convection was taken into consideration in the PCM/mini-channel coupled BTM system, a part of heat generation in battery can be taken away by the air and this part heat \(Q_{\text{air}}\) is described as the following equation:

\[
Q_{\text{air}} = h_{\text{air}} A (T_{\text{airf}} - T_{\text{air}})
\]

where \(Q_{\text{air}}\) stands for the heat taken away by air, \(h_{\text{air}}\) (W m\(^{-2}\) K\(^{-1}\)) represents the convective heat transfer coefficient, \(T_{\text{airf}}\) (K) and \(T_{\text{air}}\) (K) are the surface average temperature and the air temperature, respectively. \(A\) (m\(^2\)) is the surface area contacting with the air.

By substituting Eq. (1), Eq. (3) and Eq. (4) into Eq. (2), the following Eqs. (6) and (7) can be obtained (radiant heat transfer was not taken into account), so the idea dosage of the PCM can be mathematically calculated by Eq. (8):

\[
\Delta Q = Q_b - Q_w - Q_{\text{air}}
\]

\[
\Delta Q = m \times C_{\text{pcm}} (T_1 - T_2) + m \times h
\]

\[
D = \frac{Q_{\text{air}}}{Q_b} = \frac{m/C_{\text{pcm}} (T_1 - T_2) + h}{Q_b}
\]

---

Fig. 4. \(T_{\text{Max}}\) of the battery and liquid fraction of PCM versus time under different mass flow rate of water, \(K = 0.2\) W m\(^{-1}\) K\(^{-1}\), \(T = 308.15\) K, 2 mini-channels.

Fig. 5. \(T_{\text{Max}}, \Delta T\) of the battery and liquid fraction of PCM versus time under different mass flow rate of water, \(K = 0.2\) W m\(^{-1}\) K\(^{-1}\), \(T = 308.15\) K, 8 mini-channels.
Because the effect of the gravity was neglected, there is no natural convection within PCM during the melting process. Therefore, this is a problem of pure heat conduction that only occurs when the PCM is in phase change process. The energy conservation equation in PCM is as follows:

\[
q(t) = k \left( \frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2} + \frac{\partial^2 H}{\partial z^2} \right)
\]

where \( q \) (kg m\(^{-3}\)), \( H \) (J kg\(^{-1}\)), and \( k \) (W m\(^{-1}\) K\(^{-1}\)) are the density, enthalpy, and thermal conductivity of PCM.

The water was selected as the cooling medium in the PCM/mini-channel coupled BTM system. The energy conservation equation of liquid water within the mini-channels can be seen as the following equation:

\[
\frac{\partial}{\partial t} (\rho_w c_w T_w) + \nabla \cdot (\rho_w c_w \vec{v} T_w) = -\nabla \cdot (k_w \nabla T_w)
\]

The momentum conservation equation of liquid water is derived from Eq. (11):

\[
\frac{\partial}{\partial t} (\rho_w \vec{v}) + \nabla \cdot (\rho_w \vec{v} \vec{v}) = -\nabla P
\]

The continuity equation of the liquid water in the mini-channels is given as Eq. (12):

\[
\frac{\partial \rho_w}{\partial t} + \nabla \cdot (\rho_w \vec{v}) = 0
\]

where \( \rho_w \) (kg m\(^{-3}\)) and \( c_w \) (J kg\(^{-1}\) K\(^{-1}\)) are density and specific heat of water. \( T_w \) (K) is the temperature of the water, \( \vec{v} \) (m s\(^{-1}\)) is the velocity vector of water in mini-channels, and \( P \) (Pa) represents static pressure.

### 3. Results and discussion

A three-dimensional battery thermal model of the PCM/mini-channel coupled BTM system was studied in this study. The \( T_{Max} \) and \( \Delta T \) of battery packs and the volume liquid fraction of PCM were monitored. In this paper, \( P \) stands for PCM BTM system and \( P/M \) represents PCM/mini-channel coupled BTM system in Figs. 1–11. In order to investigate the cooling performance of the PCM/mini-channel system under the high power discharging, a high discharging rate of 5 C was considered and the discharge process lasted about 720 s. When the surface of the battery cell was under the adiabatic condition during the discharging process, the \( T_{Max} \) of the battery cell was 361.4 K at 720 s. If the battery worked under this high temperature condition for a long time, the performance of the battery will be reduced. When the PCM was added into the system, PCM can absorb the heat of the battery packs due to its large latent heat. However, because of the low thermal conductivity of the PCM, the heat cannot timely dissipate. Therefore, some effective measures should be introduced. The PCM/mini-channel coupled BTM system was built to solve this problem. Four different designs were projected as Fig. 3. The ideal dosage of the PCM in this paper can be mathematically calculated as Eq. (8). The cooling effects of PCM based BTM system and PCM/mini-channel coupled BTM system were compared in the following sections.

#### 3.1. Influence of mass flow rate

Fig. 4 shows the \( T_{Max} \) of the battery and liquid fraction of PCM versus time under different mass flow rate of water. The \( T_{Max} \) of battery without cooling increased to 361.4 K at 720 s. However, the PCM system and PCM/mini-channel coupled cooling system
the battery slowly decreased, the change temperatures. The $T_{\text{Max}}$, decreased from point 1. With the temperature of the battery decreased gradually. However, when the mass flow rate increased from $8 \times 10^{-4}$ kg s$^{-1}$ to $1 \times 10^{-3}$ kg s$^{-1}$, the $T_{\text{Max}}$ decreased by only 0.01 K. So it is not necessary that the mass flow rate have little influence on the temperature of the battery and the liquid fraction of PCM when the mini-channel was two.

Fig. 5 displays the $T_{\text{Max}}$, $\Delta T$ of the battery and liquid fraction of PCM versus time under different mass flow rate of water. As is seen in Fig. 5a, with the increase of the mass flow rate, the $T_{\text{Max}}$ of battery decreased gradually. However, when the mass flow rate increased from $8 \times 10^{-4}$ kg s$^{-1}$ to $1 \times 10^{-3}$ kg s$^{-1}$, the $T_{\text{Max}}$ decreased by only 0.01 K. So it is not necessary that the mass flow rate gets larger than $8 \times 10^{-4}$ kg s$^{-1}$. It can also be observed in Fig. 5b, the $\Delta T$ decreased from 5.08 K to 3.1 K when the mass flow rate changed from $5 \times 10^{-4}$ kg s$^{-1}$ to $1 \times 10^{-3}$ kg s$^{-1}$. However, the $\Delta T$ was larger than that of PCM system. With the increase of the temperature, the PCM began to melt, and the heat of the battery was absorbed as latent heat. When the minimum temperature of the battery decreased, the $\Delta T$ also decreased. However, when the minimum temperature dropping rate was lower than the maximum temperature increase rate, the $\Delta T$ gradually increased. The large heat storage capacity of the PCM disappeared when the PCM is totally melted, and the PCM will be disadvantageous to the heat diffusion. For the moment, the minimum temperature was speedily increased, so the $\Delta T$ decreased. In the PCM/mini-channel coupled cooling system, the PCM was not totally melted and the heat diffusion rate was lower than the heat generation rate, so the $\Delta T$ increased. Fig. 5c shows the liquid fraction of the PCM under different mass flow rate. In the PCM-based cooling system, the PCM started melting at 143 s and was totally melted at 720 s. However, the PCM melted at 152 s and melted 74.4% when the mass flow rate was $8 \times 10^{-4}$ kg s$^{-1}$ at 720 s in the PCM/mini-channel coupled BTM system. With the increase of the mass flow rates, the heat generated within battery was transported outside quickly by the liquid water, so the PCM close to the mini-channels melt slowly, the liquid fraction decreased.

### 3.2. Influence of phase change temperature of PCM

In Fig. 6, the $T_{\text{Max}}$, $\Delta T$ of the battery and liquid fraction of PCM versus time with different phase change temperatures of PCM. As is seen in Fig. 6a, the $T_{\text{Max}}$ was 334.5 K at 720 s when the phase change temperature was 308.15 K, and attained 338.9 K as the phase change temperature increased to 323.15 K. However, when the phase change temperature of PCM was 308.15 K, the $T_{\text{Max}}$ in the PCM-based cooling system was decreased only by 1.8 K compared to that of the PCM/mini-channel coupled BTM system. Fig. 6b shows the $\Delta T$ of the battery change under different phase change temperatures. The $\Delta T$ rapidly increased from point 1, then decreased from point 2, and also decreased from point 3. When the temperature increased to phase change temperature, the heat would be absorbed by the PCM due to the large latent capacity of itself, which leads to the minimum temperature of battery increased slowly, so the $\Delta T$ increased rapidly from point 1. With the melting of the PCM, the melting rate of the PCM beside the mini-channels started to slow, and the minimum temperature of battery increased faster than before, so the $\Delta T$ decreased from point 2. However, when the PCM was totally melting, the minimum temperature of battery increased rapidly because the huge latent capacity of PCM disappeared. Therefore, the $\Delta T$ suddenly decreased such as point 3. As is shown in Fig. 6c, before the
temperature rose to the phase change temperature, the PCM is not melting. However, the melting rate of PCM began to increase once the temperature increased to the phase change temperature. In the PCM based BTM system, the PCM started melting at 143 s and totally melted at 720 s when the phase change temperature was 308.15 K. However, when the phase change temperature was 323.15 K, the PCM started melting at 354 s and 73.3% of it melted at 720 s. In the PCM/mini-channel coupled BTM system, the PCM started melting at 147 s and was 95.9% of it melted at the end of the discharging when the phase change temperature was 308.15 K. However, when the phase change temperature was 323.15 K, the PCM began to melt at 370 s and 56.4% of it melted at 720 s. In fact, when the PCM totally melt, it would be disadvantageous to the diffuse of the heat. Therefore, 308.15 K was the optimal phase change temperature in the PCM/mini-channel coupled cooling system. The results showed that the cooling effect of the PCM/mini-channel coupled BTM system was better than PCM based BTM system when the system was under the same condition.

3.3. Influence of the thermal conductivity of PCM

Fig. 8 displays the $T_{\text{Max}}$, $\Delta T$ of the battery and liquid fraction of PCM versus time with different thermal conductivity of PCM. The increase of the thermal conductivity leads to the decrease of the $T_{\text{Max}}$ of the battery at the end of the discharging. However, the $\Delta T$ was increased. The PCM started melting from point 1, and the heat can be absorbed as latent heat by the PCM because of the large heat storage capacity of PCM. Therefore, the minimum temperature decreased, the increase rate of the $\Delta T$ decreased. It can be seen that the melting rate dropped from point 2. With the melting of the PCM, the melting rate of the PCM beside the mini-channels became slow due to the liquid cooling. On the contrary, the melting rate of the PCM would keep the growth trend. In the PCM/mini-channel coupled BTM system, when the thermal conductivity was 2 W m$^{-1}$ K$^{-1}$, the $T_{\text{Max}}$ was 324.8 K at 720 s. However, the $\Delta T$ did not hesitate to increase to 12.13 K. The $T_{\text{Max}}$ decreased while the $\Delta T$ was increasing. The high $\Delta T$ could be a disadvantage to the battery cycle life, so the thermal conductivity should not be too high. The thermal conductivity has great influence on the performance of the system.

Fig. 9 reveals the $T_{\text{Max}}$, $\Delta T$ of the battery and liquid fraction of PCM versus time with different thermal conductivity of PCM. It can be clearly seen that the $T_{\text{Max}}$ of the battery was controlled under low temperature in the PCM/mini-channel coupled BTM system.
When the thermal conductivity is 0.2 W m\(^{-1}\)K\(^{-1}\), 0.6 W m\(^{-1}\)K\(^{-1}\), 0.8 W m\(^{-1}\)K\(^{-1}\), 1 W m\(^{-1}\)K\(^{-1}\), and 2 W m\(^{-1}\)K\(^{-1}\), the \(T_{\text{Max}}\) of the battery is 331.4 K, 320.6 K, 318.2 K, 316.6 K, and 313.3 K, respectively. Compared with the PCM based cooling system under the same situation, the \(T_{\text{Max}}\) decreased by 5 K, 14.8 K, 16.9 K, 18.3 K, and 20.9 K, respectively. This is due to the enhanced thermal conductivity of the PCM, so the heat can be quickly conducted to the outside. However, the high thermal conductivity can lead to the high \(\Delta T\) which will be harmful to the battery. As can be seen in Fig. 9b, in the PCM based BTM system, the curve rises slowly at first and when the PCM begins to melt, the curve rises rapidly with the increase of the time, which is because the heat of the battery was stored by the PCM, the curve becomes mild, when the PCM totally melt, the curve rapidly declined. However, the PCM was not totally melted in the PCM/mini-channel coupled BTM system while the \(\Delta T\) continuously raised. Because of the heat storage capacity of the PCM, the heat was stored in the PCM due to the increase of the \(\Delta T\). In the PCM/mini-channel coupled BTM system, the \(\Delta T\) can be controlled under 6 K and the \(T_{\text{Max}}\) can be controlled in a reasonable range when the thermal conductivity of PCM is below 0.8 W m\(^{-1}\)K\(^{-1}\). In order to further improve the performance of the system, 0.6 W m\(^{-1}\)K\(^{-1}\) thermal conductivity is suggested.

3.4. Influence of mini-channel quantity

Fig. 10 shows the \(T_{\text{Max}}\), \(\Delta T\) of the battery and liquid fraction of PCM versus time under different mini-channels. When the mini-channels were 2, 4, 6, and 8, the \(T_{\text{Max}}\) of the battery were 330.3 K, 325.5 K, 323.1 K and 320.6 K, and the corresponding liquid fractions of PCM at 720 s were 97.8%, 90.9%, 79% and 58%, respectively. In the PCM based BTM system, the \(T_{\text{Max}}\) of the battery was 335.4 K and the liquid fraction of PCM at 720 s was 100%. With the increased of the number of the mini-channel, the \(T_{\text{Max}}\) decreased. However, it did not mean that it would be advantage to the system, the high \(\Delta T\) could be harmful to the battery. When the mass flow rate was 8 x 10\(^{-4}\) kg s\(^{-1}\), it can be clearly seen that the temperature distribution under different mini-channel numbers at the end of the discharge in Fig. 11. The PCM near the mini-channels would be harder to melt. With the increase of the number of channels, the heat distribution of battery will be more uniform. The maximum temperature of the battery could be controlled under 320 K. The thermal performance of the PCM/mini-channel coupled BTM system presented more effective results compared to the PCM based BTM system.

4. Conclusions

Considering the liquid cooling can lead to the desirable cooling effect as well as PCM cooling can yield the most even temperature distribution, therefore, the liquid and PCM were coupled together. In order to improve the working performance of the electric vehicle, the PCM/mini-channel coupled BTM system was designed and numerically analyzed. Factors such as phase change temperature, thermal conductivity of PCM, number of channels and mass flow rate were discussed in this paper to research their influences on the maximum temperature (\(T_{\text{Max}}\)), maximum temperature difference (\(\Delta T\)) of battery packs and liquid volume fraction of PCM. The numerical results are included:

---

**Fig. 9.** \(T_{\text{Max}}\), \(\Delta T\) of the battery and liquid fraction of PCM versus time under different thermal conductivity of PCM, \(Q = 0.0008\) kg s\(^{-1}\), \(T = 308.15\) K, 8 mini-channels.
Fig. 10. $T_{\text{max}}$, $\Delta T$ of the battery and liquid fraction of PCM versus time under different mini-channels, $K = 0.6 \text{ W m}^{-1} \text{ K}^{-1}$, $T = 308.15 \text{ K}$, $Q = 0.0008 \text{ kg s}^{-1}$.

Fig. 11. Temperature distribution under different numbers of mini-channels, at the end of the discharge, $K = 0.6 \text{ W m}^{-1} \text{ K}^{-1}$, $T = 308.15 \text{ K}$, $Q = 0.0008 \text{ kg s}^{-1}$. 
(1) The simulation for the PCM/mini-channel system, predicted a maximum temperature of 320.6 K. However, a maximum temperature of 335.4 K was predicted for the PCM-based cooling system. Overall, the performance of the PCM/mini-channel cooling system was better than that of other cooling systems. The number of mini channels should not less than four due to not obvious decrease the temperature of the whole system. With the increment of the cooling channels, the \( T_{\text{Max}} \) of the BTM system can be effectively controlled.

(2) The capacity of decreasing the temperature of the cooling system is limited by the mass flow rate and phase change temperature. In order to obtain better cooling performance, the optimal mass flow rate should be \( 8 \times 10^{-4} \text{ kg s}^{-1} \) and suitable phase change temperature of PCM should be 308.15 K.

(3) The \( T_{\text{Max}} \) of the BTM system decreases as the thermal conductivity increases. The \( \Delta T \) of the BTM system was high and even increased to 12 K at 720 s. In this paper, the optimal thermal conductivity was 0.6 W m\(^{-1}\) K\(^{-1}\) when the number of channels was eight, where the temperature can be effectively controlled and \( \Delta T \) can be controlled under 6 K.

The Numerical modeling could overcome the limitations in the experiment, it can provide internal information that are difficult to obtain by the experiments such as the liquid volume fraction, temperature distribution, and heat generation. However, numerical simulation maybe have some deviations with the experiment. So an experiment of the whole system about this simulation will be built in order to verify the impact of the assumptions made in the following-on studies. Some future work need to study the thermal performance of the battery packs under the practical high charge and discharge rate. Also, the whole system with PCM and mini-channel cause increase of weight and volume. There are a lot of work need to be further investigated to improve the total efficiency of the whole system.

Acknowledgements

The authors are grateful to Ms Rui Zhu for technical English. This work was supported by the National Natural Science Foundation of China (No. 51406223).

References


